

THE PHYSICS OF SUBATOMIC PARTICLES

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CHAPTER ONE: THE EARLY HISTORY OF PARTICLE PHYSICS.

In the fifth century B.C. a Greek philosopher named Democritus predicted the existence of 'atoma' (indivisible things), of which, in different patterns and motions, he believed everything to be made. At about this time, with the teaching of Democritus and Leucippus, an idea of mass conservation and the discontinuity of matter began to take shape. During its existence, the Pythagorean School of philosophers put forward for the first time the theory that light was composed of discrete corpuscles emitted from luminous bodies. In the first century B.C., the Roman poet Lucretius colourfully expressed these and other ideas on the nature of the universe, in his great didactic poem 'De Rerum Natura' (On the Nature of Things). But however much these ancient theories of discontinuity may seem to be ahead of their time, it should be remembered that at the same time, almost equal support was gained for a continuous theory of the universe, which was upheld with much zeal by Heraclitus and the Eleatic philosophers. But neither of the two theories had any experimental proof to back them up, and so were both of purely philosophical interest.

Between the time of these Classical philosophers and the discovery of the first experimental basis for either theory, the controversy continued, and in the intervening twenty-three centuries many great scientists and philosophers, notably Newton and Descartes, considered the problem. On the whole, the continuous theory of matter and light, as a wave, was favoured and it was not until the work of Brown in 1827 that the balance began to tip. He noticed some seemingly unprovoked movements of light particles in aqueous solutions, and proposed a discontinuous molecular theory to account for this. Then, after the work of Delsaux, Wiener, and Carbonelle in the period 1863 to 1895, the Molecular Theory of solids, liquids, and gases, became firmly established. This had, among other things, the regular structures of crystals and the similarities between these and the proposed structures of molecules of particular substances (notably left- and right-handed Tartaric acid, as investigated by Pasteur), to back it up.

It was after the discovery of electricity that the history of Particle Physics as a true science began. This discovery made Crookes investigate the nature of an electric charge when passed through a near-vacuum inside a sealed glass tube. In 1878 he made a spark from an induction coil traverse a sealed glass tube in which there was rarified inert gas, and observed a number of interesting phenomena. The first of these was the rotation of the vanes of a radiometer, a tiny mica 'windmill', when it was placed inside one of these tubes, and this he attributed to 'molecular pressure'. He also performed the now classic experiment of putting flat aluminium discs of varying shape between the two electrodes, and then observing the sharp shadows produced on a screen at the end of the tube (by the positive electrode). He found that light was evolved when the rays were stopped by the glass walls of the tube, and that this light was caused by an actual luminescence of the surface of the glass rather than by the excitation of gas molecules. If this was happening then the emitted light would bear some of the spectral characteristics of the gas filling the tube. Crookes also found that some substances, for example mica and quartz, did not emit light however close they were brought to the negative electrode, and that, generally speaking, the more fluorescent the substance was, the greater the luminosity produced. Crookes also found that cathode rays discharged electroscopes (see chapter 8), and, which was even more important, they were deflected by a magnetic field. Crookes believed that he had found

something even smaller than the atoms which had been believed to be the ultimate stage in the division of matter and to behave like billiard-balls.

In 1895 Jean Perrin, amid the controversy between scientists concerning the nature of cathode rays (some scientists, especially German ones, believed them to be due to some hitherto unknown process in the ether, while others believed them to consist of material particles with negative electric charges) repeated Crookes' experiment of deflecting cathode rays by a magnetic field. He proved that they were negatively charged, and even collected the negative charges, but failed to perform any worthwhile experiment on single particles. Thus he had practically proved that cathode rays were streams of electrified particles in rapid motion, and in 1897, J.J.Thomson, in his much celebrated experiment, discovered the constant ratio of the electric charges of these particles to their masses. Although Hertz had previously tried to deflect cathode rays by making them pass between two parallel metal plates across which an electrostatic field had been produced by connection to a battery of electric cells, but had been unsuccessful, Thomson succeeded by using a more complete vacuum. The details of the experiment he performed were as follows: cathode rays were produced by a hot wire at the cathode, and passed through two metal plugs which served as the anodes, and then between two aluminium plates 1.5 cms. apart, both rectangular with dimension 5 cms. by 2 cms., and finally hit a fluorescent screen on which they produced a dot. When there was a high vacuum in the tube, the rays were seen to be repelled by the negative plate and attracted by the positive one. The angle of deflection was shown to be directly proportional to the potential difference between the two plates. Thus the ratio of the electric charge of these particles to their mass was found to be of the order of ten to the power of seven (ten million), a value much higher than any previously observed for other particles. The highest value then observed was that for the hydrogen ion, which was ten to the power of four. The charge to mass ratio for an electron is now accepted as being $1.758796(6) \times 10^{-10} \text{ C kg}^{-1}$. But although Thomson's measurement of this fundamental constant was a great step forward, it gave no idea of the independant values of either the electric charge or the mass of the cathode ray particle. The cathode ray particle was christened the electron by Thomson.

However, in 1924, R.A.Millikan did manage to measure the charge of the electron on its own. In his experiment oil droplets which had passed through a commercial atomiser using specially purified air, were allowed to fall in a large chamber, at the bottom of which there was a circular brass plate 22 cms. in diameter, with a pin-hole at its centre. This plate formed one pole of an air condenser, whose other pole was a brass plate held 16 mms. beneath the first by three ebonite rods. A three-way switch made it possible to control the charges of the plates, so that they had a potential difference of ten thousand volts when the switch was in two of its positions (in one, a given plate was positively charged, in the other it was negatively charged), and a potential difference of zero when it was in its third position. Any oil droplet which passed through the pin-hole were strongly illuminated, so that they could be observed, and were then allowed to drop until they were very close to the negative plate (the lower one), when the switch was closed, and a potential difference was created between the plates. This forced the oil droplet, which had been electrified by friction in the atomiser, to rise, but when it was near the upper plate, the switch was opened again and the droplet fell under the influence of gravity. This cycle was repeated many times, and the time of fall, and therefore speed, of the droplet during each cycle was carefully measured.

Millikan assumed, as had his predecessors, that the velocity of a droplet is

proportional purely to the force acting upon it, and has nothing to do with the charge on the droplet itself. As an electrified droplet passed through the air between the two plates of the condenser, it sometimes picked up one or two ions, which increased its electric charge, and thus the velocity with which it was attracted to the plate of opposite charge. It was found that the addition of an ion to the droplet caused a constant decrease in the time taken between the two plates on the upward journey, except in a few cases, when two ions had attached themselves onto the droplet, where the time was decreased by precisely twice the usual amount. From this experiment, Millikan went on to suggest that all charges are composed of electrons, and that these are not just statistical means, but actually do exist. From his experiment he deduced that the charge on the electron is approximately equal to 1.6×10^{-19} C, and thus that the mass of the electron is about 9.1×10^{-31} kg, or 1/1840 of the mass of a hydrogen atom. The charge of the electron is now acknowledged to be $1.60210(2) \times 10^{-19}$ C, and its rest mass to be $9.10908(13) \times 10^{-31}$ kg.

Three years after H. Becquerel's accidental discovery of the fogging effects of radiation issuing from uranium on photographic plates in 1896, Giesel and Meyer discovered an electrically charged radiation, with similar powers of penetration. In 1900 Becquerel, Mme. Curie, and Villard found another radiation which was shown to be uncharged. A third radiation, which was heavier than the others, and doubly charged, was discovered by E. Rutherford in 1902, and was named alpha radiation by him. In 1908 Rutherford, Geiger, and independently Regener, measured the charge on a single alpha particle. First it was necessary to find out how many alpha particles were emitted by one gram of radium in a second. For this purpose, one of the first ever radiation counters was used. A sample of the radioactive radium was placed at a distance from a hollow metal tube with a mica window at one end, and an insulated rod at the other. When a potential difference was applied between the outside of the tube and the rod, and a particle passed through the low pressure gas in the tube, usually at about 100 mms. of mercury, it ionised some of the molecules in the gas, allowing discharge to take place between the two charged terminals. This was sensed by means of a galvanometer, whose movements were recorded by fast-moving film. Regener used a different method for counting the emitted alpha particles. It had been shown that light was emitted when an alpha particle hit zinc sulphide (ZnS), and he actually counted the number of scintillations on a zinc sulphide screen using a microscope. The number of alpha particles emitted by one gram of radium in one second was thus established to be about 3.70×10^{19} .

The charge on an alpha particle was found by the following method: some radium was placed in a small container covered with aluminium foil, in order to stop the parent atoms of the alpha particles from escaping, but to allow the alpha particles themselves to escape. A strong magnetic field was applied to stop beta rays from any radium products present in the sample from escaping. At the other end of the tube was a collector, which was connected to a sensitive electrometer. Thus the charge collected per second was measured, and from this, knowing the number of alpha particles emitted per second, the charge on a single alpha particle was deduced. This charge was found to be $3.20420(4) \times 10^{-19}$ C, twice the charge on the electron, or electronic charge. Thus, knowing e/m for alpha rays from Becquerel's experiments, the mass of an alpha particle could be deduced. This was found to be about 6.64×10^{-27} kg (the actual figure is nearer $6.64172(8) \times 10^{-27}$ kg), that is, four times the mass of the hydrogen ion.

The radiation found by Giesel and Meyer was named beta radiation, and that discovered by Becquerel, Curie, and Villard, gamma radiation. Rutherford found that these

three types of radiation had very different powers of penetration. Alpha radiation was stopped by about 0.003" of aluminium leaf, beta radiation by about 0.125" of aluminium, and gamma radiation only by about 1.5" of lead. More interesting still was the behaviour of the radiations in a magnetic field. If the radiations issuing from a radioactive source, for example salts of uranium, were made to pass through a lead collimator, so that only the radiations travelling straight through the hole in the collimator were not absorbed and stopped, and were then deflected by a magnetic field, it was found that the alpha rays were positively charged, and thus were attracted to the negative pole of the magnet, the beta rays were negatively charged, and, as Becquerel showed in 1900 by measurement of their charge-to-mass ratio, were simply cathode rays travelling at a slightly higher velocity than had previously been observed, while the gamma rays were not deflected at all, and therefore were electrically neutral. It was found that alpha rays were the most ionising of the three radiations, followed by beta rays and finally gamma rays. From the charge and mass of the alpha particle, it was suggested that it was a helium nucleus, and in 1909 this was proved by Rutherford and Royds. They passed alpha rays produced by a sample of unstable radon gas through the walls of a thin glass tube, inside which the alpha particles combined with free electrons to form a gas which was shown by spectral analysis to be helium.

Around 1909 experiments were carried out by Marsden and Geiger on the scattering of alpha particles by certain metallic foils (for example, aluminium, copper, silver, and gold). The alpha particles were directed towards the foil by a lead collimator. On the opposite side of this, off the line which any non-deflected alpha particles would follow, there was a zinc sulphide screen with a microscope behind it. Most of the alpha particles were not deviated at all, but of those that were, a large percentage were deflected back to the side of the foil from which they had come. The possibility that most of this wide-angle scattering was caused by successive collisions was dismissed because not nearly so many particles would be deflected if this were the cause. In fact, about one in 20 000 alpha particles were scattered through an angle greater than 90° by a gold film 0.4 microns thick. Geiger later showed that the most probable angle of deflection was 0.87°. Rutherford mathematically predicted the number of scintillations, y , produced on a screen ϕ from the line of motion of undeviated particles, by a total of Q particles, each of mass m , hitting the foil, and found this relationship to be:

$$y = \frac{Qdm}{2\pi r^2 \sin^2 \theta} ,$$

which agreed very well with experimental data. This experiment indicated that atoms are mostly composed of space, but that there exists somewhere inside the atom a very massive positively charged particle, so as to make the whole atom electrically neutral. In Rutherford's paper 'The Scattering of Alpha and Beta Particles by Matter, and the Structure of the Atom', which he read in February 1911, he suggests that an atom contains a charge $1Ne$ at its centre surrounded by a sphere of electrification supposed uniformly distributed throughout a sphere radius R . Here e is the electronic charge. This theory gave birth to the idea of the nucleus and the hypothesis of the proton, a positively charged particle within the nucleus.

The next difficult problem was 'How big are atoms and their nuclei'. We cannot see atoms by means of an optical microscope, and therefore we may deduce that the diameter of an atom is less than the wavelength of visible light, which is in the order of 4×10^{-10} m. We may achieve a slightly better result if we use Avogadro's number, and this indicates an atomic diameter of about 3.4×10^{-10} m for an argon atom, for example.

More accurate measurements using x-ray crystallography soon followed these crude approximations, and it is now possible to draw up an accurate table of atomic and ionic radii. It was later found that the size of a nucleus consisting of A particles was given by the approximate equation: $d = 2r_0 A^{1/3}$, where d is the diameter of the nucleus, and $r_0 = 1.3 \times 10^{-15} \text{ m}$.

Rutherford's conception of the atom had been to consider it as a miniature solar system, with the electrons orbiting, like planets, in ellipses, around the nucleus at the centre, acting like a sun. However, such an atom would not be nearly so stable as observations of atoms suggested. But in 1913 the brilliant young Danish physicist Niels Bohr came to Manchester to work with Rutherford on subatomic structure. One of Bohr's greatest ambitions throughout his life was to produce conditions under which international cooperation in science could flourish. As the Maxwell-Lorentz theory stated that all electric charges not moving uniformly in a straight line produce light, all electrons would emit light constantly as they orbited the nucleus in Rutherford's model of the atom. If this were the case the orbiting electrons would quickly lose their energy and fall into the nucleus, which was obviously not what was happening.

The Quantum Theory postulates that all particles must have an energy, and hence an angular momentum, of an integral multiple of a small constant known as Planck's constant (\hbar). Angular momentum is the speed at which a body rotates about a fixed point. Bohr realised that because an electron has angular momentum when it revolves in its orbit around the nucleus, it can only occupy various discontinuous orbits, because it must have an energy of an integer multiple of $\frac{1}{2}(\hbar/2\pi)$. Bohr primarily considered the protium (hydrogen) atom, because it was the simplest possible atom. In this atom, he postulated that the single electron orbits, when the atom is in its normal state, so that it has an angular momentum of $1/2$. When the atom is excited it changes its orbit to one where its angular momentum is some integer multiple of $1/2$ greater than one.

Bohr suggested that in its 'ground state' the hydrogen atom has an energy of $-R$, where R, or, more usually, R_∞ (denoting an assumption of infinite proton mass) is a new constant called Ryberg's constant. The currently acknowledged value of R_∞ is $1.0973731(1) \times 10^{-19} \text{ J}$. The reason why the energy of hydrogen was said to be negative was that the electron is in a 'bound state', and an energy value of 0 would indicate that the electron and the nucleus were infinitely far apart. Bohr stated that the energy of a hydrogen atom was $-R/n^2$, where n was any positive integer. However, the most revolutionary thing proposed by Bohr in his atomic model was that when the electron 'jumps' from a higher to a lower-energy orbit, energy in the form of electromagnetic radiation is given off. He found that the frequency of the emitted light was given by $h\nu_{AB} = E_B - E_A$, where ν is the frequency, h is Planck's constant, E_B is the energy of the higher-energy orbit, and E_A that of the lower-energy one. From this it may be seen that $h\nu_{AB}$ corresponds to the line in the spectrum of hydrogen produced when a hydrogen atom loses the energy $E_B - E_A$.

It had been shown by Balmer as early as 1885, that the first four lines of the spectrum of hydrogen had wavelengths in almost exact agreement with the formula $\lambda \cdot \lambda_0 n^2 / (n^2 - 4)$, where λ_0 is any constant, and n is a positive integer greater than two. However, no theoretical justification had been found for this formula. But Bohr discovered, as a result of the formula $h\nu_{AB} = E_B - E_A$ mentioned above, that

$$\frac{1}{\lambda_{AB}} = R_\infty \left(\frac{1}{n_A^2} - \frac{1}{n_B^2} \right),$$

where λ_{AB} is the wavelength of the spectral line produced when two positive integers

n_A and n_B are substituted in the formula, and R_{∞} is Ryberg's constant. Taking many values of n_A and n_B , it was found that the resulting values of λ_{AB} agreed to an accuracy of 0.1% with experimental results. This was certainly a great triumph for Bohr's atomic model, and soon after 1913, A. Sommerfeld extended Bohr's theory, which could only describe atoms in which the electrons occupied circular orbits, into a universal theory describing all atoms. He also, by an ingenious method, calculated the intensities of hydrogen's spectral lines, and did much work on the internal or 'fine' structure of these lines.

Furthermore, in Bohr's model of the hydrogen atom, it was possible to calculate the angular velocity of the electron, the radius of the atom, and the energy of the electron less its rest energy. To calculate the angular velocity, ω , the formula $\omega = \pi \gamma^2 m_e e^2 / 2 \epsilon_0 n^2 h^3$

was used, where $\gamma = 1$ if rationalised electric units are used, or 4π if unratinalised ones are used, m_e is the rest mass of the electron, e is its charge, Z is the number of protons in the nucleus (atomic number), ϵ_0 is the permittivity of free space, n is the principal quantum number (a positive integer denoting the energy-level or exciment of the atom), and h is Planck's constant. Also, with the same letters denoting the same quantities:

$$r = \epsilon_0 n^2 h^3 / \pi m_e e^2 Z$$

$$\text{and } E = V_0 - \gamma^2 m_e e^2 Z^2 / 8 \epsilon_0 n^2 h^3.$$

Thus we find that an electron rotates about the nucleus of a hydrogen atom in its ground state about 6.6×10^{15} times per second, at a speed of about $2.2 \times 10^6 \text{ ms}^{-1}$ (about 0.007 c, where c is the velocity of light in vacuo), and that the hydrogen atom, in its ground state, has a radius of the first Bohr radius, a , which is approximately equal to $5.29167(?) \times 10^{-11} \text{ m}$. $E - V_0$ is negative because the electron is in a bound state within the atom.

For some years after the confirmation of Bohr's atomic model, there were thought to be only two types of particles in atoms: positive protons and negative electrons. But in 1920 Rutherford speculated on the existence of a neutral doublet within the nucleus consisting of a bound state of a proton and an electron. He was led onto this idea, which, though wrong, was nearer the truth than previous ones when he realised that the phenomenon of isotopes could not be explained by the old two-particle theory of atomic structure. Isotopes are different forms of an element, with the same number of protons in their nuclei, but with differing atomic masses. In 1930 a series of experiments was begun in Heidelberg by W. Bothe and H. Becker and in Paris by Frederic Joliot and his wife Irene Curie, on the radiation issuing from radioactive beryllium and boron, which could eject fast protons from hydrogen atoms. These fast protons had an average velocity of about $3 \times 10^7 \text{ ms}^{-1}$, and so Joliot and Curie calculated, on the hypothesis that the energy of the unknown neutral particles emitted from the beryllium or boron was transferred to the hydrogen protons, that the initial particles must have an energy of about 5×10^4 electron volts. An electron volt is defined as the energy imparted to an electron when it falls, in free space, between two plates whose potential difference is one volt.

There was a certain difficulty, however, in the value of 5×10^4 eV for the energy of the new particle, namely: how could the interaction of an alpha particle of kinetic energy 5×10^6 eV and a beryllium nucleus produce a particle of this energy? The only possibility was that when the alpha particle hit the beryllium nucleus, it was incorporated into the latter's structure, thus changing it into the carbon isotope C-13 (meaning that there are thirteen particles in the nucleus of this isotope). If this

were what was happening, as the mass defect of ^{12}C is about 10^7 eV, and that of ^9Be around zero, a particle of energy about 1.4×10^7 eV would be produced. The mass defect of a given isotope is the difference between its actual mass and its predicted mass, that is, its atomic number times the average mass of the proton and neutron. The nuclear reaction in question would be written as follows: $^9\text{Be} + \alpha \rightarrow ^6\text{C} + \text{particle}$. The theoretical energy of the particle if this reaction were taking place was approximately in agreement with experimental values, and so it was assumed that this was the reaction taking place. Chadwick found in 1932 that this new particle also ejected particles from many other light elements apart from hydrogen.

It was Chadwick who continued the research into this type of radiation, and he decided, assuming the validity of the law of the conservation of energy and momentum, that the new particle must have a mass near that of the proton. This being so, he suggested that the newly discovered particle was the neutron predicted by Rutherford some twelve years before. Feather and Chadwick determined the approximate mass of the neutron as follows: inside a vacuum chamber, alpha particles from a sample of polonium were made to hit beryllium foil, thus producing neutrons. These neutrons travelled out through a window in the vacuum chamber until they reached some paraffin (CH_4) or paracyanogen (CN) from which they ejected protons which were then counted by means of a proportional counter (see chapter 8). By careful integration of the results obtained with paraffin slabs and those with paracyanogen ones, a value of 1.006 proton masses was deduced for the mass of the neutron. Chadwick believed that this mass, just slightly less than the sum of the masses of the proton and the electron, represented a bound state of these two particles. The fact that the subsequent mass was less than the sum of its component parts, he explained as being caused by the bonding energy necessary to hold the two constituent particles together. However, it can be shown, using modern techniques, that it is impossible to achieve this bound state without using an energy far in excess of the mass of the electron. Thus the atomic nucleus came to be considered as a system containing two types of particles: protons and neutrons, which soon became considered by most physicists as particles in their own right.

CHAPTER TWO: SOME BASIC PRINCIPLES.

The Quantum Theory, together with Relativity, has probably been the greatest advance in physics during this century. It was initiated in 1900 by Max Planck, who, while studying black-body radiation spectra, came upon the idea that electromagnetic energy is only emitted and absorbed by matter in integral multiples of some minute unit of energy or quantum. Black-body or 'cavity' radiation is electromagnetic radiation emitted from a hole in a heated black-body, usually an oven, the hole being small enough not to let any outside radiation enter the cavity, yet large enough for the radiation in it to be monitored. The Black Body theory which had been derived at the end of the nineteenth century by Rayleigh and Jeans in England, and Kirchoff and Wien in Germany, postulated that the intensity of the higher frequencies should be very high, decreasing towards the lower frequencies, so that a graph of wavelength to intensity would look like a hyperbola with its asymptotes at the two axes. However, Planck noticed that the actual curve looked nothing like this. For low frequencies, the old curve was comparatively accurate, but below a certain maximum wavelength λ_m , intensity rapidly decreased to zero, instead of becoming infinite. This discrepancy between the Black Body Theory and the new experimental results soon became known as the 'Ultraviolet Catastrophe', because it was in the ultraviolet region that the curve should have become an asymptote to the intensity axis, but instead fell away to zero.

Classical physics stated that the emission and absorption of light and other energies was a continuous process, but Planck made the revolutionary suggestion that it was in fact discontinuous. Reinforcement for this idea soon came from a most unexpected angle. In 1887 Hertz had taken a piece of zinc and illuminated it with ultraviolet light, and had found that it became electrically charged, thus discovering an effect which quickly became known as the Photoelectric Effect. It was soon found that however bright a red light was made to impinge on a piece of metal, no electrons would ever be liberated, but on the other hand, only a very low intensity of blue light would liberate electrons, and when the intensity was increased, the number of electrons produced remained constant. Classical wave mechanics, however, stated that the energy of light beam was related purely to its intensity (amplitude) and was independent of its frequency. With his new knowledge, Planck was soon able to formulate the equation: $E = hv$,

where E is the energy of the light beam, v is its frequency, and h is Planck's constant, whose value is now acknowledged to be $6.62559(16) \times 10^{-34}$ Js. But, due to the measurements of Lenard and Millikan in 1905 and 1916 respectively, it was realised that the energy of an electron produced in the photoelectric effect was not hv , but $hv - W$ where W is a new constant. Millikan measured this constant in the following way: he placed newly-cut electrodes of lithium, sodium, and potassium on a turntable in a vacuum chamber, making sure that there was no metallic oxide on them. Light entering through a window at one end of the chamber produced photoelectrons at the cathode, which were then attracted to a positively charged cage at the window end of the chamber, which was connected to an electrometer. Having compensated for the 'contact' potential difference between the cage and the cathode, Millikan's results agreed very well with the Planck-Einstein formula $E = hv - W$, and his values for W were almost the same as those postulated from a study of thermionic emission.

Soon after the great success of Bohr's quantised atomic model, another convincing argument for the Quantum Theory was found by A.Compton while he was studying the scattering of x-rays by matter. X-rays had first been observed by Röntgen when he was experimenting with a cathode ray tube enclosed in black paper. He noticed some fluorescence in a barium platinocyanide screen nearby, and found that even when various materials were placed between the cathode ray tube and the observation screen, the fluorescence was never radically decreased. He attributed this phenomenon to a new radiation, which he named 'x-rays'. He discovered that x-rays affected photographic plates, and that they were not easily refracted. For a short time there was controversy among scientists about the nature of x-rays, but by 1913 they had been shown to be similar in nature to light, but with the much shorter wavelength of around 100 pm.

The discovery that x-rays were produced whenever fast-moving electrons were stopped soon caused the development of the x-ray tube. In the most primitive of these, electrons were emitted by the bombardment of a cathode with positive ions, as in simple discharge tubes. The newly-produced electrons were then accelerated by the potential difference between the cathode and the target, which served as an anode. The cathode was concave, so that only a very small area of the target was bombarded by electrons, thus producing an almost point source of x-rays. But in 1913, Coolidge made a great improvement on this so-called 'cold cathode' tube. He constructed an x-ray tube which used a hot filament as its source of electrons, which greatly increased the x-ray intensity obtainable. Using x-rays produced by this new kind of tube, Bragg and others soon initiated such principles as x-ray crystallography and spectrometry.

When J.J.Thomson used the comparatively long wavelength x-rays produced by cold cathode tubes to probe into atomic structure, there was no noticeable change in wavelength where the x-rays were scattered by matter. But when later experimenters used higher-frequency x-rays, they noticed a considerable change in frequency when their x-rays were scattered by some of the lighter elements. In 1923 Compton and Debye found that the only way to explain this increase in wavelength was to assume that x-rays consisted of discrete 'packets' of electromagnetic energy, which bounced off individual particles in the atoms of the scattering substance. Using this hypothesis, they found that:

$$\lambda - \lambda_0 = \frac{h}{m_e c} (1 - \cos \theta),$$
 where λ is the new wavelength, λ_0 is the original wavelength, m_e is the rest mass of the electron, h is Planck's constant, c is the velocity of light in vacuo, and θ is the angle through which x-ray quanta or photons are scattered. This formula was soon adequately borne out by experimental results for all values of the scatter angle less than 150° .

Ever since the beginning of the nineteenth century, the wave theory of light had had the upper hand over the corpuscular theory, and the latter had been almost completely rejected. But suddenly Einstein showed that the two theories were not mutually exclusive, and that each had its role in physics. In 1923 L.de Broglie realised that the 'dual' idea of light suggested by Einstein must similarly apply to all other matter, notably electrons. De Broglie knew Einstein's celebrated mass-energy conversion equation $E = mc^2$, and, substituting for E in the Planck-Einstein equation $E = hv$, he found that:

$$\lambda = h/(mv),$$

where m is the mass of an object, v is its velocity, λ is its 'wavelength', and h is Planck's constant. Thus he suggested that any moving particle has a matter wave associated with it, and initiated the principle of 'duality'.

Let us now consider the evidence for de Broglie's so-called 'matter waves'. In 1927 C. Davisson and L. Germer set up equipment to detect electron diffraction patterns. Electrons were emitted from a heated tungsten filament, and then passed through charged slits which both narrowed the beam, and accelerated it to an energy of between 15 and 350 eV. The accelerated electrons struck a nickel crystal at a normal to its face. The deflected beam was then collected in a receptacle connected to a sensitive electrometer, which could be moved so as to make angles of between 20° and 90° with the original beam. Bragg's formula for constructive interference is

$$d \sin \theta = \lambda n ,$$

where d is the distance between neighbouring atoms in the crystal lattice, n is any positive integer, λ is the wavelength of the radiation, and θ is the angle between the incident and reflected beams. The interference phenomena observed gave correct values of λ in Bragg's formula, according to the de Broglie equation. In fact, electrons of the energy used by Davisson and Germer had de Broglie wavelengths of the same order of magnitude as 'soft' x-rays, and behaved very similarly to Laue-Bragg beams of x-rays. A similar experiment of rather more dramatic nature was soon performed by Thomson using the so-called Debye-Scherrer method in x-ray diffraction work. Here, a unidirectional monochromatic beam of x-rays is scattered by a sample consisting of a large number of very small, randomly orientated crystals. Theory predicted that the diffracted waves would emerge from the group of crystals along the surfaces of cones, centred about the incident direction. Thus, if the resultant radiation is recorded by means of a photographic plate placed at a normal to the incident direction, we receive a series of concentric circles. Thomson caused a beam of cathode rays to pass normally through a very thin film of white tin crystals. About 32.5 cms from the sample, there was a photographic plate, on which images similar to those with x-rays were obtained. To prove that the image was caused by the electrons themselves, and not by a secondary radiation consisting of x-rays or the like, a magnetic field was applied to the diffracted beam, and the resultant pattern was found to move position. A slightly easier experiment of the same type as G. Thomson's was soon performed by M. Ponte. Ponte, instead of using delicate crystalline films, used metallic oxides (for example zinc, magnesium, and cadmium oxide) deposited on a thin metal wire.

The fact that x-rays and electrons were found to be diffracted in the same way by crystals led to the suggestion that they also behaved similarly in the case of diffraction by a ruled grating. This hypothesis was confirmed by Rupp and Worsnop in 1920. The next question was: can larger particles, such as gas molecules, also be shown to exhibit wave characteristics? The de Broglie wavelength for a hydrogen molecule travelling at the most probable velocity at room temperature is 100 pm. T. Johnson investigated the reflection of hydrogen by crystals, and found, using a plate smoked with molybdenum trioxide, which is blackened where it is struck by hydrogen, as his detector, that hydrogen molecules also display wave characteristics. Ellett, Olson, and Zahl soon performed experiments with mercury, cadmium, and arsenic beams, using rock salt crystals as detectors, and found the same results. Stern, Knauer, and Estermann later performed another experiment which demonstrated the diffraction of hydrogen and helium molecules. Some gas was ejected from one chamber, through a slit, into another chamber, towards a crystal. The first chamber was at a pressure of about 100 pmHg, while the second was at one of about 10 pmHg. A small movable receptacle was used to collect the reflected gas molecules, and its pressure was compared with that of the surrounding volume by means of a Pirani hot-wire manometer. The results of this experiment were in exact agreement with the predictions made by de Broglie. A few years

after this experiment, W.Zinn showed that neutrons were also subject to de Broglie's equation. Neutrons from a chain-reacting pile were slowed down by graphite blocks, and were then collimated by a series of cadmium slits. They were then reflected from the face of a calcite crystal, and detected by means of a boron trifluoride counter.

In 1926, two comparatively contemporary theories of particles as waves grew up. The first was the matrix mechanics of W.Heisenberg, and the second the wave equation of E.Schrödinger. Although very different in their approach, Schrödinger, as we shall discuss later, finally showed that the two theories were equivalent. We shall first discuss the Schrödinger equation, because it is the simpler of the two methods. As it was first formulated, the Schrödinger equation made two assumptions about the particle system which it attempted to describe. First, it assumed that no particles were either created or destroyed, and that therefore the number of particles of a given type in our system always remained constant, and second, that the velocities of all the particles concerned were small enough for non-relativistic approximations to be valid. We represent our wave function by $\Psi(x, t)$. Born's interpretation of this wave function states that the probability that we find our particle in a small region of space, volume $d^3(x)$ is proportional to $|\Psi(x, t)|^2 d^3(x)$. Thus the probability density is proportional to the absolute square of the wave function. Similarly the intensity of a classical light wave is said to be proportional to the square of its amplitude. There was at first considerable discussion concerning the reality of mechanical waves, but Born's idea puts this aside. It implies that the wave-like character of particles is essentially to do with the fact that the probability function Ψ satisfies a wave equation. Thus, if we have, for example, a shower of scattered electrons, we may say that if there are a large number of particles, we are most likely to find particles in the regions where the absolute squares of their wave functions are large. The probability of finding a particle in a space, volume $dxdydz$ units, is defined as $|\Psi|^2 dxdydz$. As the particle must exist somewhere in space, and as most probabilities are measured as a fraction of unity, it is natural that we should apply what is known as a normalisation factor in order to make $\int |\Psi|^2 dxdydz$ equal to one. In fact, Schrödinger's wave equation was defined such that:

$$i\hbar \frac{\partial}{\partial t} \Psi(x, t) = -\frac{\hbar^2}{2m} \nabla^2 \Psi(x, t),$$

where i is the square root of minus one, \hbar is Planck's constant, and ∇^2 is the Laplacian operator, which is defined by:

$$\nabla^2 \equiv \frac{\delta^2}{\delta x_1^2} + \frac{\delta^2}{\delta x_2^2} + \frac{\delta^2}{\delta x_3^2}.$$

Let us now discuss an important principle in wave mechanics known as the superposition of waves. A light beam is very rarely truly monochromatic. Thus, its classical wave is not pure, but consists of a number of partial waves, each of a different frequency, superposed on each other. A pure wave has a well-defined energy given by the Planck-Einstein formula, and thus, in a superposed wave, the intensity of each of its partial waves is a measure of the probability that the complete wave has the same frequency as that wave at the moment when it is measured. Using a superposition method, Schrödinger showed that Bohr's model of the atom could be derived using wave mechanics, because all the waves of the electrons must be stationary or standing waves. A standing wave is one in which there are a number of fixed nodes, between which oscillations take place.

We must now consider the more important consequences of W.Heisenberg's matrix mechanics, which he developed in 1925, while studying under M.Born at Göttingen. Heisenberg realised that very little was known about atoms, except for the nature of

the light they emit. Heisenberg knew, from the Planck-Einstein equation, that the frequency of the light emitted when an electron jumps between the i- and k-energy quantum levels is given by:

$$\nu_{ik} = \frac{E_i - E_k}{h},$$

where ν_{ik} is the transition frequency, E_i is the energy of the i th orbit, and E_k that of the k th orbit. According to Einstein's theory of light, the intensity of each frequency is determined by the number of photons of that frequency emitted by a group of excited atoms. Thus we need to know the probability of transition from the i th to k th levels. It is obvious that we may represent this probability as $P(i,k)$. If we substitute a series of numbers for i and k, then we can build up, as Heisenberg did, a matrix in the form of an infinite square. But the parameter we represent in our matrix need be neither the frequency of the emitted photon, nor the transition probability, but any parameter associated with electron levels. Let us have one parameter A, represented by the matrix a, and another, B, represented by b. We can see that the matrix addition is commutative, that is, $a+b = b+a$, but that the matrix multiplication is non-commutative. Using this curious non-commutativity of his new algebra, Heisenberg managed to obtain the equation

$$xv-vx = h/2\pi m,$$

where x is the position of a particle, v is its velocity, m is its mass, i is the square root of minus one, and h is Planck's constant. However, as Planck's constant is very small indeed, the equation will only become important when m is also very small, otherwise the factor $h/m \neq 0$. Heisenberg had now established an algebra, in which, instead of using finite numbers, he used infinite matrices. These he decided to apply to the equations of classical mechanics. He did this with considerable success, arriving at Bohr's atomic model and the Planck-Einstein formula.

In his work on wave mechanics Schrödinger associated every physical parameter with an operator or operation. For example, the symmetrical nature of an object might be related to the operator P, the space reflection operator (see chapter 7). Each possible electron orbit in an atom, Schrödinger saw, could be represented by one of the stationary waves in the series $\Psi_1, \Psi_2, \Psi_3, \Psi_4, \dots$. He considered a physical parameter A, with its associated operator a. For the transition between the i th and k th levels he defined a number a_{ik} , which depended both upon the physical parameter A, and the two stationary waves Ψ_i and Ψ_k . By considering all the possible transitions, he drew up a table for all the corresponding values of a_{ik} , which he proved, because of the nature of the operator he had chosen, was equivalent to one of Heisenberg's matrices, and behaved in the same way.

Now let us consider one of the most important consequences of the new methods of wave and matrix mechanics: Heisenberg's Uncertainty Principle. One would, at first sight, assume that it would be possible to measure the position and velocity of, for example, a falling stone, as accurately as was required, so long as the measuring equipment was good enough. The simplest way to measure both the velocity and position in this case would be to take a film of the stone's motion with a cine camera using an infinitely fast-moving, infinitely small-grained, film. But in order to photograph the stone, we must illuminate it. However, the photons which we use to illuminate this stone will not strike it precisely evenly from all directions, and so they will alter the parameters which we are trying to measure. If we decrease the intensity of the light, which corresponds to reducing the number of photons in the beam, then the light-pressure on the stone will become even more irregular. However, let us assume that we

can decrease the illumination to the absolute minimum: one photon. Then, when this photon hits the stone, it will cause it to change its course. So, let us now try and decrease the energy of the photon. To do this, we must increase its wavelength, but this blurs the image in the camera. So it seems that we have a limit to our accuracy in measurement.

Let us now consider the illustration which Heisenberg himself gave. We wish to locate an electron by means of gamma rays. It is known that the error in determining the position of an object by means of a microscope is in the order of the wavelength of the radiation used. In fact, two points can not be resolved or recognised as distinct by means of a lens if they are closer than λ/A to each other, where λ is the wavelength of the radiation used, and A is the angle subtended at the lens by either of the two points. The error in the determination of the position of the electron we say to be δs , and we know that $\delta s \sim \lambda/A$. But the rays which fall on the electron give it momentum, according to the Compton effect, and each photon has a momentum of hv/c , where v is its frequency, c is the velocity of light in vacuo, and h is Planck's constant. But our photon could have come from any part of the lens, and so the uncertainty in its vector is in the order of the width of the lens. This distance, because angle A is small, is in the order of hv/c , the momentum of the electron, times angle A . Thus we may say that $\delta p \sim hvA/c$, where p is the momentum of the electron, and therefore

$$\delta p \delta s \sim h.$$

This example brings out the point that the uncertainty in a measurement arises from the disturbance introduced in the process of measurement.

Before we discuss the Uncertainty Principle, as it is known, in any more detail, let us first discuss two more methods of arriving at it. The first is as follows. We shall consider the problem of the accurate measurement of position and momentum in a one dimensional world, where there exist units such that $\hbar = 1$. This means that in our world, $p = 2\pi/\lambda$, and thus the accuracy with which we may measure the wavelength of the de Broglie wave of this particle is linearly related to the accuracy with which we may measure its momentum. Let us assume that the wave of this particle is a sine one of finite length. The more full cycles of the sine we may observe, the more accurately we may measure its wavelength, and hence the momentum of our particle. However, the more cycles we observe, the less accurately we may find the position of our particle at any one moment. Thus, if we say that the uncertainty in measuring the position, x , of our particle is δx , then we may say that $\delta x \sim n\lambda$, where λ is the wavelength of our sine curve, and n is the number of full cycles we may observe. Furthermore, we know that $1/n \sim \delta\lambda/\lambda$, where $\delta\lambda$ is the uncertainty in measurement of the wavelength. In our world where $\hbar = 1$, we know that $\lambda = 2\pi/p$, and so $\delta\lambda/\lambda = \delta p/p$, and $n\lambda = 2\pi n/p$. Combining our equations, and returning to the normal system of measurements, we find that $\delta x \delta p \sim h$. However, we have here considered a particle whose wave is a sine curve, the simplest and most regular of all wave functions. Thus, in a real situation, we may say that

$$\delta p \delta x \geq h,$$

because all real curves will have wavelengths which are much more difficult to measure. Generalising, we obtain the first set of so-called 'uncertainty relations':

$$\delta x \delta p \geq h, \quad \delta y \delta p \geq h, \quad \text{and} \quad \delta z \delta p \geq h.$$

Our second method is simply to take an analogy from classical wave theory, and apply it, with modifications, to de Broglie waves. Suppose that two coincident sources of sound emit notes of frequency v and δv respectively, δv being small compared with v .

Beats are heard of frequency δv . If the occurrence of beats is relied upon, then at least one beat must be heard in order to detect the difference in frequency. Thus, a certain time, δt , of order $1/\delta v$, is taken up by this observation. From the Planck-Einstein equation we know that $E = hv$, and therefore we can derive the important uncertainty relation:

$$\delta E \delta t \geq h,$$

assuming that we may apply the same principles to de Broglie waves as to mechanical ones. As we will see in chapter 5, the energy-time uncertainty relation is of great use in the study of resonance particles.

An important consequence of duality and the Uncertainty Principle is the so-called 'Theory of Measurements'. To illustrate this theory we will consider a very simple experiment. We have a bank of photomultiplier tubes, and we periodically release one photon from a light bulb. Each time we release one of these, we record which photomultipliers recorded the passage of the photon by 'clicking'. If we perform our experiment a total of N times, so that in N , of these times, counter 1 clicks, then we define p_1 , the probability that counter 1 clicks as:

$$p_1 = N_1/N.$$

Similarly we may define a probability p_{12} representing the number of times when both counter 1 and counter 2 clicked, such that

$$p_{12} = N_{12}/N.$$

In defining these probabilities we are making a very important assumption, namely that, if we were to continue so that N became as large as possible, then the fraction N_1/N , for example, would tend to a limit of the order of our original p_1 . In this experiment we are obviously trying to prepare each photon from the light bulb in exactly the same way, so as to produce stable and reproducible readings from our photomultipliers. But, if each photon is really prepared in exactly the same way, then why do we obtain different reading from each experimental run? The obvious answer is that, try as we may, we can not generate a series of photons which can be guaranteed to be identical. An immediate reason for this is that the thermal motion in the bulb's filament is purely random, and, according to the energy-time uncertainty relation, we cannot measure its energy if we wish to do this in too short a time. If we were to take a very large number of probability readings in the bulb-photomultiplier system for every possible physical variable, then all the probabilities will define a statistical ensemble of the system. Each single measurement in the system is known as an element of the ensemble. We often measure the spread or dispersion in a particular set of readings, and in most practical situations, this is greater than zero.

We end with an argument which demonstrates that, although the interpretation of duality given by Born and the Copenhagen School is usually very adequate, it is not entirely correct. As Bohr so admirably demonstrated in his 'complementarity' principle, we need never worry lest we may not know whether a particular phenomenon should be attributed to the wave or particle interpretation of matter. For a wave picture to be preferable, we must know a precise value for the wave's frequency and hence velocity, whereas in a particle interpretation, we must have an exact position for the particle. However, according to the velocity-position uncertainty relation, we can not know precise quantities necessary for both a wave and a particle picture. Thus every phenomenon must be primarily a wave or a particle one, but not a combination of both.

According to Born, it is impossible to discover at all where a particle is unless

it interacts with our detector. We can not say with any certainty that a particular photon will hit a particular photomultiplier tube, but only that the probability that it does so is high. This idea led Schrödinger to invent his so-called 'cat paradox'. A cat is sealed in a lightproof box, with a gun directed at it. The gun is triggered by the entrance of a photon into a photomultiplier. At one end of the box there is a tiny hole, behind which there is a half-mirror, so that a photon will either be transmitted into the photomultiplier, or will be reflected away harmlessly. If only one photon passes through the hole, then it will potentially be reflected and potentially be transmitted by the mirror. Thus the cat will be both dead and alive at the same time, and will only be killed or saved by the intervention of an observer. Although this paradox of Schrödinger's makes Born's interpretation appear unlikely, it does nothing to disprove it. However, Renninger's so-called 'experiment with negative result' suggests that Born's interpretation is not entirely correct. Consider a point source of electrons. To one side of this is placed a hemispherical detecting screen. Within the outer hemisphere is another part of a sphere, whose centre is the same as the large hemisphere, but whose radius is smaller. The apparatus is arranged so that a given electron can either hit the inner screen and be absorbed, or proceed on to the outer screen. If the electron is recorded by the inner screen, then Born's interpretation remains good, since we had no prior information about the electron before we observed it. However, if the electron fails to hit the inner screen, then we may be certain that it will hit the outer one, and hence Born's interpretation fails.

CHAPTER THREE: THE EXCLUSION PRINCIPLE, ANTIMATTER, AND YUKAWA'S HYPOTHESIS.

Pauli formulated the Exclusion Principle in 1924 in order to avoid the embarrassment that somewhere Bohr's atomic model (see chapter 1) had gone wrong, because it postulated that in an unexcited atom, all the electrons would occupy the lowest-energy quantised orbit. If this happened, atoms would differ greatly in size, because the radius of the first quantum orbit is inversely proportional to the mass and charge of the nucleus. However, from experimental results, it was clear that atoms did not differ very much in size, so that Bohr's atomic model had to be adjusted. Pauli tried to make this adjustment, and suggested that each quantum orbit could hold, at the most, two electrons. Thus when the first quantum orbit was full, the next electron must orbit in the second quantum orbit, and so on. When the first electron shell was full, the next electrons must orbit in the four orbits, one circular and three elliptical, of the second shell, and so on. It was from the number of electrons in various shells of unexcited atoms that the modern periodic table was constructed.

But not long after 1924, the electron's spin and magnetic moment were discovered, and so it was seen that electrons which before were permitted by the Exclusion Principle to move in the same orbit, must now move in slightly different orbits because of their mutual magnetic repulsion. Pauli realised that in fact the two electrons must be spinning in different directions (see chapter 4), or rather, one must have its spin 'up' and the other 'down'.

However, the Exclusion Principle is certainly more general than to apply simply to electrons in atomic orbits. Physicists usually consider electric currents in matter as motions of free electrons. These drift randomly in the substance until an electric current is applied, when they tend to travel towards the positive terminal. Physicists sometimes talk of these free electrons as an 'electron gas' which permeates freely within the metal, and which is not able to escape from it due to surface forces. It was expected that when a metal was heated, not only the vibrations of the atoms in the crystal lattice, but also the motions of the free electrons would be accelerated. However this was shown not to be the case, and so a new idea had to be brought into use. This idea was that even free electrons can only occupy a series of discrete energy levels, and that only two free electrons may occupy each energy level. Of course, in contrast to the hundred or so possible energy levels in an atom, there were billions of possible ones in a piece of metal. Naturally, the lowest energy-levels, with the same order of energy as the thermal vibrations of the metal's atoms were filled up first. The energy of the higher energy-levels was obviously proportional to the number of electrons in the substance: if there were few electrons, few energy levels would be necessary, but the more electrons present, the more energy-levels would be needed. Thus, in a sizeable piece of material, a very large percentage of the electrons will have energies far in excess of any of the thermal vibration energies of the metal's atoms, and, even when the metal is heated to such a degree that its crystal structure breaks down and it liquefies, the motion of most of the electrons will remain unaffected. An example of a true electron gas may be found in the interiors of dying stars. In white dwarf stars, giant pressures have completely crushed all the atoms leaving electrons free to form a gas. But due to the Exclusion Principle, most of the electrons in this gas have very high energies, causing them to move about very energetically, putting great pressure on the outside of their container, the white

dwarf, and stopping the star, which would otherwise have gravitationally collapsed, from collapsing inwards.

But the Exclusion Principle does not only apply to electrons in any condition. In the mid-1950's it was found that protons and neutrons also obeyed it, so that no two protons in a given atomic nucleus could have the same energy and spin, and similarly, neither could any two free protons. This extension of the Exclusion Principle led to the discovery of the so-called 'magic numbers', which are simply the numbers of nucleons which each nuclear shell can hold. These numbers are 2, 8, 14, 20, 28, 50, 82, 126...., and, apart from corresponding to the number of particles which a nuclear shell can hold, they also correspond to the number of electrons which electron shells can hold.

Now let us consider the Exclusion Principle from the standpoint of wave mechanics. We interpret different energy levels as being different 'vibration modes'. Thus, when in classical theory we would say that an electron moved into another orbit of higher energy, we would now say that it is statistically likely that one vibration mode dies out, and another, at a higher energy, is born. Now our Exclusion Principle states that, just as one can not strike a key on a piano twice simultaneously, so no two vibration modes or waves with the same energy and spin can exist at the same time. It was in terms of wave functions that Pauli initially stated and proved his Exclusion Principle. We find that, if the particles in question are p and q, and the parameter we are attempting to measure is A, then, adding a normalisation factor of two, we have:

$$\Psi(A_p, A_q) = (\psi_p \psi_q + \psi_q \psi_p)/\sqrt{2} \text{ and } \Psi(A_p, A_q) = (\psi_p \psi_q - \psi_q \psi_p)/\sqrt{2}.$$

The first of these wave functions is said to be symmetric, because when we interchange the two particles, this does not result in a change of sign, whereas the second function is antisymmetric, because, by swapping around p and q, we change the sign of the overall function. But how can two functions be both equal and opposite in sign? The only answer is that both are zero, and that therefore the probability of two particles being identical in any set of parameters is zero. We see that the Exclusion Principle does not only apply to energy and spin, but also, for example, to space and time. In this example, we discover the fact that no particles which obey the Exclusion Principle may be in the same place at the same time. It is this result that stops all matter from disintegrating immediately, because particles like photons may be hoarded together in as large a quantity as is desired in the same space-time.

But probably the most important consequence of the Exclusion Principle was Dirac's theory of positrons. In 1928 P. Dirac developed a wave equation, known as the Dirac equation, in accordance with Relativity and wave mechanics, which described the motion and properties of the electron in exact agreement with its experimentally observed characteristics. However, one of the most far-reaching results of this equation was that it was found that the electron could have negative energy and mass because of the existence of a negative root of the expression $\sqrt{((m_e c^2)^2)/(1-(v/c)^2)}$ which was found to represent its relativistic energy. Dirac did not immediately understand the significance of this negative root and would have simply assumed it to be an unreal solution to his problem, had it not been for the discovery of the positron in 1933.

On August the second, 1933, while photographing cosmic ray tracks obtained in a 15 000 gauss vertical Wilson cloud chamber, C. Anderson noticed some tracks which could only be explained as having been produced by the passage of a particle of similar mass to an electron, but carrying a positive charge. Inside the cloud chamber there was a 6 mm thick lead plate, through which the new particle passed, and in doing so, changed the curvature of its track. If this positive particle were a proton, then, in

order to have the radius of curvature which its track had, it would have to have an energy of 300 000 V, and if it did have this energy, then it would go only about a tenth as far as the observed track went, so that the idea that the new particle was a proton was discounted. The other major possibility was that a photon, which naturally did not leave a track in the cloud chamber, hit the lead plate and knocked two particles out of one of the lead nuclei, one of which went above the plate and one below, but this hypothesis still leads to the conclusion that one of these particles was an anti-electron or positron.

This discovery caused Dirac to continue his theory of positive electrons. He finally came up with the hypothesis that there exists, in the same space-time as this universe, a kind of aether or sea of negative mass electrons possessing negative energy. These would be permitted by the Exclusion Principle, and would be, under normal circumstances, unobservable, because they are always there, and no instruments are calibrated so as to measure without their presence. Much the same type of reason stopped scientists from finding out what air really was for many centuries. Dirac's theory led to the slightly unlikely idea that the 'extraordinary' negative energy and mass states were in fact more stable than the ordinary positive energy ones. However, the tendency of an electron to jump to a lower energy level by the emission of a gamma ray would mean that all electrons would try and jump into the negative energy state. But Dirac suggested that all the negative energy levels were full up, and so the Exclusion Principle would not permit any more electrons to attain a negative energy. The total energy of an electron is given by $T + m_e c^2$, where T is its kinetic energy and m_e is its rest mass. Thus no positive energy electron may have an energy less than m_e , the rest mass of the electron, and no negative energy one of more than $-m_e$. Hence, in order to raise a negative energy electron to a positive energy, it is necessary to give it an energy of at least $2m_e$, which is about 1.022 MeV. When a gamma ray of more than this threshold energy passed through, for example, the Coulomb or electrostatic field of an atom, a negative energy electron was raised to positive energy, and a bubble was left in the sea of negative energy electrons. This bubble had exactly opposite characteristics to the electron, and had a positive charge. Sometimes, the so-called 'virtual pair' of an electron and a positron would form an atom of positronium, a sort of anti-hydrogen atom consisting of a positron in orbit around an electron, which, after a mean life of 8 ns would decay again into two gamma rays, each with the energy of an electron. Alternatively the electron and positron would travel freely for about 7 μ s and then decay into two or three gamma rays. Dirac's theory proposed that when this happened, the electron fell back into the hole in the negative energy aether, so that, due to the Law of the Conservation of Mass and Energy, the final gamma rays must have exactly the same energy as the initial gamma ray. Possibly each of the final gamma rays are emitted at different points in the electron's descent into the negative energy state.

But Dirac postulated that not only electrons had antiparticles, but also that all particles have their corresponding antiparticles. Thus in 1956 Chamberlain and his co-workers began to search for the antiproton. They calculated that the threshold energy for its production was about 5.6 GeV. It was proposed that when two high-energy protons collide, two other protons and a proton-antiproton virtual pair are produced. At Berkeley, Chamberlain, Segre, Wiegand, and Ypsilantis accelerated a proton beam to an energy of around 6.2 GeV in their Bevatron accelerator, and then made it hit a copper target. The resultant particles then passed through a series of magnets, so that only particles with a negative charge, and with a mass in the order of that of

the proton would be directed into the rest of the equipment. If a given particle was an antiproton, then it would be stable, and would not decay during its passage through the testing equipment, and this served as another test. At the selected momentum, 1.19 GeV, the experimenters knew that pions would have a velocity of about 0.99 c, kaons of 0.93 c, and antiprotons of about 0.78 c. But only about one in 40 000 particles produced was an antiproton, so some method of distinguishing between negative mesons and antiprotons had to be found. The beam was focused to a point, and was recorded when it passed through the first of two scintillation counters. 40 feet further on, there was another identical scintillation counter. The readings from both counters were then displayed on a screen, and the distance apart that the two peaks representing the passage of a particle were, was proportional to the time taken for that particle to travel from one counter to the next. It was calculated that a meson would take around 40 ns for the journey, and an antiproton around 51 ns. But some method had to be devised to guard against the possibility that two mesic events might trigger the counters at an interval apart typical of an antiproton. The experimenters decided to set up two velocity-selective Cerenkov counters after the second scintillation counter. A Cerenkov counter works on the principle that when a particle passes through a medium at a velocity greater than the velocity of light in that medium, it emits photons, the angle of emission being proportional to its velocity. The first Cerenkov counter, which was made of $C_8 F_{16} O$, which has a refractive index of 1.276, was made sensitive to all particles with a velocity greater than 0.79 c. The second Cerenkov counter, made of fused quartz of refractive index 1.458, was designed to detect particles with a velocity of between 0.75 and 0.78 c. By this time, any antiproton should have been slowed down to a velocity of about 0.765 c by its passage through the two scintillation counters and the first Cerenkov counter. Thus, any antiproton passing through the testing equipment would trigger the two scintillation counters 51 ns apart, would leave no trace in the first Cerenkov counter, and would be recorded by the second one. In October 1956, the discovery of the antiproton was officially announced, after sixty correct sets of readings had been obtained. A few months later another research team trapped an antiproton in glass, and observed the Cerenkov radiation produced by its annihilation products. This proved that the particles selected by the team at Berkeley were true antiprotons. At the same time Chamberlain, Chupp, Segre, Wiegand, Goldhaber, and some Italian physicists tried to find antiproton disintegration stars in photographic emulsions exposed to beams containing antiprotons. After a short time, some events were recognised by scanners at Rome, and, when it was realised that the velocity absorbers used destroyed antiprotons, many more tracks were found.

Soon after the discovery of the antiproton, Cork, Lambertson, Piccioni, and Wenzel found evidence of the antineutron while working at the Lawrence Radiation Laboratory. They employed an improved version of the Chamberlain-Segre antiproton selector to produce a beam of antiprotons. This then entered a liquid scintillator in which charge exchange took place, and any antiprotons became antineutrons. The newly-produced antineutrons passed through two more scintillation counters without detection, but any high energy photons, which were also neutral, were revealed by the presence of a lead plate $1\frac{1}{4}$ " thick between the two scintillation counters, which made them materialise into a virtual pair of an electron and a positron, which was then detected in the second scintillation counter. After encounter with the second scintillation counter, the beam of particles was directed into a large lead-glass Cerenkov counter in which the antineutrons decayed. By the time it was announced that the antineutron had been discovered, 114 flashes of light in the Cerenkov counter from antineutron annihilation

had been definitely recorded.

Let us now consider anti-atoms, which consist of positrons orbiting around nuclei of antiprotons and antineutrons. When the 28 and 70 GeV proton synchrotrons came into operation at CERN, Geneva and Serpukhov respectively in 1971, it became, for the first time, possible to search for antideuterons and antihelium nuclei. The machine at Serpukhov managed to produce around 50 000 antideuterons per day, which made it possible to make detailed statistical observations of them. Using time-of-flight measuring apparatus accurate to one part in 10^{10} , experimenters at Serpukhov managed to find five antihelium-3 nuclei or antialpha particles in 200 000 million particles tested. No atoms of higher atomic number made of antimatter have been discovered to date.

Let us now discuss the possibility of the natural existence of antimatter in our universe. We must start by asking how this could be detected, if it did exist. It is obvious that two galaxies which were intrinsically the same, but one of which was composed of antimatter, and the other matter, would look the same, and so it is useless to use ordinary optical telescopes to search for antimatter. However, we could look for the products of matter-antimatter collisions, which we would find in the form of 90% high-energy gamma and neutrino radiation, and 10% energetic electrons and positrons. The former would be able to cross great distances of space without reacting with anything, but the latter would be trapped within their original galaxy by its weak magnetic field. Let us consider the possibility of antimatter in the vast, but very tenuous, hydrogen clouds which fill interstellar and intergalactic space, but which are so spread out that on average, there is only one hydrogen atom per cubic centimetre. These tenuous hydrogen clouds would be slightly excited by the electrons and positrons trapped within the galaxy by its magnetic field. Let us assume that all the energy of this interstellar hydrogen is derived from matter-antimatter collisions. We know from various observations that the energy of this hydrogen is only about 10 pJ m^{-3} , and thus we see that the ratio of the amount of matter in the universe to the amount of antimatter is greater than ten million to one. From this we can also deduce that if matter could segregate itself from antimatter, as in the Leidenfrost phenomenon, then it would be very unlikely that there would be any antimatter stars in our own galaxy.

We know that electrons or positrons which have been accelerated in a magnetic field emit an electromagnetic radiation called synchrotron radiation. This synchrotron radiation can take the form of radio waves, so that the question of whether antimatter-matter annihilation is responsible for some of the intense radio waves which reach Earth from such astronomical anomalies as the Quasars (quasi-stellar radio sources) is raised. We find that if one part in ten million of the gas in, for example, the Crab Nebula was antimatter, then the amount of synchrotron radiation produced by electrons issuing from matter-antimatter annihilations would roughly correspond to the amount of radio energy which is produced by the Crab Nebula. On a wider front, we find that if the concentration of antimatter in matter is one part in ten million in each galaxy, then the amount of radio noise produced by the two colliding galaxies Cygnus A, would almost exactly correspond to that produced in theory by high-energy electrons and positrons being accelerated by the large field produced by the collision of the two galaxies' small magnetic fields. Messier 87's bright jet might also consist of antimatter, as might many high-energy anomalies all over the universe. However, the fact that the universe is usually symmetrical would raise the question 'Why is there not the same amount of antimatter as there is matter in the universe?' This is at present unanswerable, but many physicists and astronomers hope that it will be answered, otherwise

some of the well-established symmetries in the universe may have to be abandoned.

In about 1930 it was noticed that when a proton passed closer than about 1.4 fm to the nucleus of an atom, it was attracted to it, rather than repelled, as Coulomb's law would suggest. However, when two protons actually came into contact, they were naturally repelled, because of the Exclusion Principle. It was already accepted that electromagnetic forces were caused by the exchange of massless quanta, photons, between particles. As we can see from looking at the binding energies of different nuclei on a Periodic Table, these are all roughly the same, and equal to 8 MeV, whereas the ionization potentials of different elements are very irregular. This suggests that the nuclear force, which is responsible for holding nuclei together is 'saturated', unlike the Coulomb force, and this fact led Heisenberg to propose, in 1932, that the nuclear force was a so-called 'exchange force'. An exchange force is one in which the properties of the particles interacting through it are exchanged. For this reason, it cannot be represented simply by a simple potential $V(r)$, but only by the product $P_{ab} V(r)$, where P is the so-called 'permutation operator' and a and b are the particles taking part in the reaction. Thus, if the wave function of the pair of interacting particles is $\Psi(a,b)$, we see that
 $P_{ab} \Psi(a,b) = \Psi(b,a)$.

Before we discuss the nature of the strong nuclear force in any greater detail, let us first consider how H. Yukawa managed to make his startling predictions about its quanta in 1935. Yukawa reasoned that, because of the very short range of the nuclear force, its quanta must be comparatively massive. But, if this were the case, how was it that mass fluctuations were not observed in protons and neutrons? The only answer to this question was that the emission and reabsorption of quanta took place in too short a time for the Uncertainty Principle to allow one to observe. Invoking the time-energy uncertainty relation we then have
 $mt < \hbar c^2$,

where m is the mass of our new quantum, and t is the time taken for it to travel between two particles. Such a process is known as the 'virtual exchange' of quanta. If we call the force between two particles interacting through the nuclear force $V(r)$, where r is the distance between the particles, then, using advanced quantum mechanics, we have

$$V(r) = \frac{g^2}{r} e^{-mc/r/\hbar}$$

where e is Euler's constant and g is a constant with the dimensions of electric charge, known as the 'coupling constant' for a given interaction. $V(r)$ is called the Yukawa potential. We wish to find the two unknowns m and r_0 , denoting the mass of the quantum of the nuclear force and its range. We find that $r_0 \cdot \hbar/mc \sim 2\text{fm}$. Substituting this in our original expression we have $m \sim 200\text{ MeV}$, which was Yukawa's prediction for the mass of the quantum, and $g^2 \sim \hbar c$. From our uncertainty relation we now have $t \sim 4 \times 10^{-24}\text{s}$.

An important property of the nuclear force was that it was found that the force between a proton and a proton ($p-p$) was the same as that between a proton and a neutron ($p-n$), or a neutron and a neutron ($n-n$). This led to the idea that the nuclear force was a charge independent force. It was also found that the exchange predicted by Heisenberg did not always occur, and this led to the conclusion that there existed both charged and uncharged forms of the new quantum. Yukawa also made predictions concerning the lifetime of the new quantum, through a study of beta decay, but these were found to be incorrect. So, knowing the mass and charge of the particles they

were looking for, experimenters set out to try and find Yukawa's quanta.

It was postulated that, just as photons are released when charged particles collide, so Yukawa's new quanta would be produced when nucleons collided. But the only place where sufficiently energetic collisions could occur was in cosmic rays. Thus, in 1936, extensive research on cosmic ray particles began. Most of the research was done using cloud chambers. Experimenters measured the radius of curvature and lengths of tracks obtained in these, and could thus calculate the mass of the particle which had produced them. Late in 1936, while doing research at mountain altitudes, C. Anderson and S. Neddermeyer found the tracks of a new particle having a mass of around 106 MeV in their cloud chamber. They named this particle a 'mesotron' and this word was soon shortened to meson. After a short gap in research caused by the war, further tests were carried out on these newly-detected particles. It was found that they could be detected at sea-level and even in deep mines, suggesting that they did not interact with atomic nuclei nearly as much as Yukawa's mesons should. It was suggested that the new particles formed the hard component of cosmic rays. It was discovered that layers of lead appeared to stop less of these new particles than did the air, and so it was concluded that the particles were unstable, and integration of a large number of results yielded a mean lifetime of 2 microseconds. A direct method to determine the lifetime of the new meson was employed by Rasetti. He had four counters, two above and two below, a 10 cms thick iron absorber. Mesons which stopped in the iron, as recorded by the anticoincidence of the second set of counters with the first set, tended, after a period of about 2 μ s to emit another charged particles which was detected by the second two counters.

Doubts began to grow as to whether the new meson was in fact Yukawa's meson. It had the right mass, but it did not interact sufficiently with atomic nuclei. In 1947 Conversi, Pancini, and Piccioni obtained more concrete evidence that this was not the Yukawa meson. They studied the absorption of negative mesons by blocks of iron and carbon. It was found that the absorption rate was directly proportional to the atomic number, and in carbon, where $Z=12$, about half the mesons were captured, indicating an average capture time of 1 μ s. The process of meson capture is that the meson is captured by an atom and goes into an electron-type orbit, and quickly cascades down to the lowest possible orbit, about two hundred times as close to the nucleus for a meson as for an electron, because of its greater mass. Thus, any particle which interacts with nucleons will be absorbed by the nucleus in about 10^{-13} s, the characteristic time of the strong nuclear reaction. But the newly-found meson were taking about 10^7 times too long to react with atomic nuclei, and so it was concluded that they were not the particles predicted by Yukawa.

Later in 1947, Bethe and Marshak suggested that there must be another meson which corresponded to Yukawa's particle, and at the end of 1947, Lattes, Muirhead, Ochialini, and Powell observed the decay of a very short-lived meson into another meson in photographic emulsion. When many tracks of this type had been produced by flying emulsions at high altitudes in balloons, it was seen that an initial particle of mass around 140 MeV decayed into a second particle of mass 100 MeV, which itself eventually decayed into an electron. It has been found that the first particle in this chain is the pion, which fits very well with Yukawa's predictions, and the second is the muon.

As we have seen, crude measurements were made of pion and muon properties in early work with cosmic rays, but it was obvious that much more precise measurements would be possible if the particles were to be produced artificially. It was calculated that the threshold energy for the production of charged pions from the collision of two nucleons

was 285 MeV. In fact, due to Fermi motion in the target, a beam of only about 180 MeV needs to be directed at a stationary target to produce pions. In 1948 the first artificial pions were obtained by E.Gardner and J.Lattes using the new 184" cyclotron at Berkeley. The momenta of the resultant pions, muons, and protons were analysed in a magnetic field, and their range was measured using a stack of nuclear emulsions. The charged pion was found to have a mass of about 139.6 MeV, and the muon of about 105.6 MeV. The muon mass was then found even more precisely by measurement of the frequencies of x-rays produced by muonic atoms, and this yielded a mass of about 105.66 MeV for the muon.

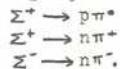
It was found that the energy of the muon produced in pion decay was always 4.1 MeV, indicating that there was only one other particle involved in the decay. According to the law of charge conservation, this particle must have a neutral charge, and, knowing the mass of the pion, it was estimated to have zero mass. There are only two particles which have zero mass known at present: the photon and the neutrino (see chapter 4). If the particle were a photon, it should have been able to produce virtual electron-positron pairs, but O'Cealleigh showed in 1950 that it did not, and so the particle was inferred to be a neutrino. The lifetime of the charged pion was estimated by stopping a pion in a scintillator, and then measuring the time until the flash from the decay muon was observed. This yielded a value of 2.56×10^{-8} s. By a similar method, the lifetime of the muon was found to be about 2.203×10^{-6} s. The electron in muon decay was found to have a whole range of kinetic energies, and so it was inferred that at least two other particles must take part in the decay, and must both be massless. Conservation laws indicate that these two particles must be a mu-neutrino and an anti-e-neutrino.

But the charge independence of the force also demanded a neutral pion. It was consistent with the conservation laws for this particle to decay into two gamma rays, thus indicating a short lifetime in the order of 10^{-6} s. In 1949 various physicists suggested that neutral pions might be responsible for the soft component of cosmic radiation. In 1950 Bjorkland, Crandell, Moyer, and York showed that it was impossible to attribute the gamma rays in cosmic radiation to any form of nuclear excitation. In the same year Carlson, Hooper, and King measured the angles and energies of photons detected in emulsions at a height of 21 km, and found these to be consistent with production from a neutral pion of mass about 150 MeV. Their experiments also put the upper limit of 5×10^{-4} s on the lifetime of the neutral pion. It was thought best to find the more accurate mass of the π^0 by finding the mass difference between itself and the π^- . By considering the reactions $\pi^- p \rightarrow n \pi^0$ and $\pi^- p \rightarrow n \gamma$, the mass difference $m_{\pi^0} - m_{\pi^-}$ was found to be about 5.4 MeV. The first accurate measurements of π^0 lifetime were made by studying the decay $\pi^0 \rightarrow \gamma e^+ e^-$, and measuring distances in a track-forming detector. However, the extreme smallness of the times concerned meant that this method was not very accurate. The best estimate to date for the π^0 lifetime was obtained in 1965 by Bellettini et al., making use of the Primakoff Effect. This is the photoproduction of a π^0 by the encounter of a gamma ray with a virtual gamma ray in the Coulomb field of a nucleus, which should take the same time as the decay of a Π^0 into two gamma rays. Using this method, the best estimate obtained for the π^0 lifetime was 7.3×10^{-17} s.

CHAPTER FOUR: THE 'PROLIFERATION OF PARTICLES'.

In 1944, Leprince-Ringuet's team obtained tracks, in a cloud chamber at mountain altitude, of a particle not corresponding to any then known. The primary cosmic ray particle produced a high-energy delta ray or recoil electron in the chamber, and from measurements of the latter's energy, it was inferred that the initial particle had a mass of around 500 MeV, but no significance was attached to the event. In 1947, Rochester and Butler at Manchester University built a new type of detector consisting of a cloud chamber placed in a magnetic field and triggered by a set of Geiger counters when these detected cosmic ray showers. In the course of a year, about fifty photographs were obtained using this equipment, two of which showed a new type of particle which was named the 'V particle'. In these photographs there was a 'V'-shaped track which could have been caused by any of the following events: first, a particle could have been scattered through a very wide angle by an atomic nucleus, but if this had happened, one would expect to find the recoil track of the nucleus, and no track of this type could be discerned. Furthermore, the radii of curvature and drop densities of the two sides of the 'V' track were measured and found to be different, thus making this hypothesis untenable. The second possibility was that the 'V' was caused by the decay of a charged particle at its apex, but various measurements showed this theory to be incorrect. The third hypothesis, which was found to be completely consistent with all the data was that a neutral particle produced by the interaction of a cosmic ray particle with the 30 mm thick lead plate inside the chamber had decayed into two oppositely-charged particles which had left a 'V' track. Further tracks were found by the Manchester cosmic ray group in England and by R. Thompson's group in America over the next few years, and it was confirmed that the 'V' tracks were produced by the decay of a neutral particle into two, and only two, particles. At this time much useful work was being done with stacks of nuclear emulsion flown to high altitudes, and a few 'V' tracks were detected in these.

A number of tracks in nuclear emulsions were found to be produced by particles with a mass of around 1200 MeV which decayed into one charged and one uncharged particle, and thus must have been themselves charged. The new particles were named sigma particles, and their dominant decay modes were



By range measurements of both the primary sigma particles and their decay products, the mass of the Σ^+ was found to be 1189.35 MeV and that of the Ξ^- to be 1197.6 MeV. By this time, the high-energy particle accelerator at Brookhaven was in operation, and so it was possible to produce hyperons or supernucleons, as the 'V particles' came to be called, artificially, using the right targets. By studying the distribution of track lengths before decay in nuclear emulsion, the lifetimes of the Ξ^- and the Σ^+ were found to be 8.10×10^{-11} s and 1.65×10^{-10} s. It is now thought that the reason why the lifetime of the Σ^+ is precisely twice that of the Ξ^- is because the former has twice as many possible decay modes as the latter. But the 'Eightfold Way' of Gell-Mann and Nishijima (see chapter 6) predicted that there should also exist a Ξ^0 particle, which would decay into a lambda particle and a photon in about 10^{-6} s. The first mass determination for the Ξ^0 was made by measuring the missing momentum in the reaction



and this yielded a value of 1193 MeV for the Σ^0 mass. More accurate measurements have been made by observing the reactions



and measuring the kinetic energy of the Λ^0 particles. This method gives the mass difference as 4.9 MeV. The lifetime of the Σ^0 particle has not been accurately determined to date, but information from nuclear emulsion suggests a value $< 10^{-4}$ s, and various theories predict a value of 5×10^{-17} s.

Another hyperon discovered soon after the charged sigma hyperons was the Λ^0 particle. From precise measurement of the coplanarity of tracks, the two-particle decay



was found to be dominant. The mass of the Λ^0 particle was calculated as 1115.58 MeV from momentum measurements of the decay products in cloud chambers and photographic emulsions. The mean life of the Λ^0 has been obtained as 2.51×10^{-6} s by careful production-decay timing in a bubble chamber.

In 1949, the Bristol cosmic ray study group obtained a track of the K^+ meson in nuclear emulsion, which was found to decay



By measurement of decay product momenta, a value of around 494 MeV was obtained for the charged kaon mass. In 1953 O'Ceallaigh was studying a π^+ decay, in which a muon and a neutrino were produced, but he found that the muon, which should only travel about 6 mm in nuclear emulsion before decay, when it is produced by a π^+ , in fact travelled over 1.1 mm. Thus he deduced that the original particle was not a π^+ but a K^+ meson. By the following year, the decay mode



had been discovered. It was thought at first that the particles which had three decay products were a different type from those which had two. For that reason, the particle which decayed into two pions or a muon and a neutrino was named the Θ^+ meson, and that which decayed into three pions the Ξ^0 meson. The best measurement of the K^+ mass has been made by studying the Ξ^0 momentum in the reaction



and this yields a value of about 493.7 MeV. The first good measurement of the K^0 mass was made using a proton beam from the Bevatron. A beam of charged kaons were momentum-analysed in a quadrupole magnet and their ranges were obtained using a stack of nuclear emulsion. This method gave a value of 493 MeV for the K^0 mass. The best determination of the K^0 lifetime has been made using the Brookhaven proton synchrotron. A beam of electrostatically separated K^0 particles passes through scintillation counters set at 620", 1290", and 1950" from the target, and accurate time-of-flight measurements are made. Either K^+ or K^- particles can be produced by changing the polarity of the separating magnet. By this method the lifetimes of the K^+ and K^- particles have been found to be the same and equal to about 1.2265×10^{-8} s.

Early observation of 'V' particles suggested a neutral particle of mass about 500 MeV, which would correspond very well to the K^0 particle, and in 1954, the K^0 was definitely identified in nuclear emulsion, and the decay



was found to predominate. From momentum measurements of these two decay products, the mass of the K^0 meson was inferred to be about 492 MeV. Time-of-flight measurements in a 12" bubble chamber filled with liquid propane soon established the K^0 lifetime as

about 9.5×10^{-10} s. A few years later the decay mode
 $K^+ \rightarrow \pi^+\pi^-\eta^+$

was discovered, and in 1957, using their knowledge of this decay Franzinetti and Morpurgo obtained a more accurate value for the K^+ lifetime. They produced K^+ 's by the collision of a high energy proton beam with a target, and, having purified their beam, they measured the distance travelled by K^+ mesons before the emission of π^0 particles and hence gamma rays. They found the lifetime to be about a hundred times greater than that of the K^0 meson which decayed to two pions. This difference in lifetimes opened up many interesting chains of thought, which we shall discuss more fully in chapter 7.

In 1952 the Ξ^- particle was first observed in a cloud chamber by the Manchester cosmic ray group, and the decay



was dominant. By 1955, Ξ^- particles were being obtained in large numbers using beams of K^2 mesons produced by high-energy particle accelerators. Since both decay products of the Ξ^- are easily observable, especially in heavy-liquid bubble chambers, the Ξ^- mass was soon established as 1321.2 MeV, and track-length measurements yielded a value of 1.74×10^{-10} s for its lifetime. A prediction of the Gell-Mann - Nishijima scheme was that there should exist a Ξ^0 particle with a decay



which could be produced in the reaction



The search for this particle lasted many years, and finally, near the end of 1958, after thousands of photographs had been analysed, an event which could only be attributed to the decay of a Ξ^0 particle was observed. From this one picture, the Ξ^0 mass was established as 1314.7 MeV and its lifetime as 3.0×10^{-10} s.

Physicists always try to find conservation laws and conserved quantities in order to predict which reactions can and can not take place. The earliest and perhaps the most important conservation law was the one introduced by Lavoisier: the law of the conservation of energy. Lavoisier and those after him always relied upon a mass conservation law, but when such elements as radium were discovered at the end of the nineteenth century, this law had to be abandoned, and even the law of the conservation of energy was thrown into doubt. But luckily, in the 1930's, Einstein showed in his celebrated Relativity Theory that mass and energy were equivalent, and were connected by the equation

$$E = mc^2.$$

The law of the conservation of energy has been verified down to one part in 10^{12} by means of the Mossbauer effect. A metal nucleus, usually iron, is cooled to a very low temperature, and in its decay, it emits a gamma ray. This gamma ray travels for about a metre through free space and is then reabsorbed by another cold nucleus, which behaves in exactly the same way as the original nucleus did, thus showing that the gamma ray has maintained the same energy. The law of the conservation of mass and energy has never been found to be in error, and much of modern physical thought is based upon it.

Perhaps the second most important conservation law in the whole of physics is the law of the conservation of electric charge, which was firmly established in the eighteenth century by Franklin, Faraday, and others. This law has been verified using the 70 GeV proton synchrotron at Serpukhov down to one part in 10^7 by showing that all the products of a proton-antiproton annihilation reaction are neutrally charged.

This conservation law or selection rule is important because it does not allow a very large number of reactions, such as

$$p + K^- \longrightarrow K^+ + p + \pi^+$$

to take place.

In 1925 Uhlenbeck and Goudsmit noticed that the bands in atomic spectra, which had previously been assumed to be continuous, were in fact made up of two or more thinner bands, the number of bands increasing as a greater magnetic field was applied to the sample (Zeeman Effect). This led them to suggest that, in addition to the angular momentum it obtained from orbiting around an atomic nucleus, the electron also possessed its own angular momentum or spin. According to Schrödinger's theory which he postulated in 1926, atoms have at least three basic quantum numbers, as they are called, which describe the state of the atom's electrons. The first of these was the principal quantum number, n , which described the degree of excitation of the atom, and could take the value of any positive integer. The second was the orbital quantum number, l , which described the angular momenta of the electron orbits, and could take any positive integral value less than n ; and the third was the magnetic quantum number, m , which described the spatial orientation of the electron orbits, and could take any integral value between $-l$ and $+l$, where l is the orbital quantum number. In 1927 Pauli showed that if spin, s or J , was added to the atomic or spectral quantum numbers, then the state of an atom could be defined uniquely by giving its spectral quantum numbers, and in 1928, using Relativity Theory, Dirac showed that it was possible to predict these quantum numbers theoretically. Soon after, Stern and Gerlach, in a very complicated experiment, measured the magnetic moment of the electron and found it to be about $9.2732 \times 10^{-24} JT^{-1}$, and verified the idea that a particle of spin s can align itself in $2s+1$ ways with respect to a uniform magnetic field. Since angular momentum is a form of energy, it must be quantised, and it has been found that the minimum possible positive spin is $\frac{1}{2}$, and, because of some of the findings of quantum electrodynamics, this was the spin assigned to the electron. We see that we may 'project' this spin in two ways, so that an electron may have a spin of either $\frac{1}{2}$ or $-\frac{1}{2}$ units.

It is often the case that an equation yields some conservation law because some quantity is found to be equal to a constant. So it was with the Lagrangian equations of motion. It was found that both angular and linear momentum must be conserved quantities. The former has been verified by observing the motion of neutral pions produced in stationary proton-antiproton annihilations, and has been found to hold good down to one part in ten thousand. The conservation of angular momentum has been checked to a much lower accuracy by observing scatter angles in various elastic collisions. The conservation of angular momentum has been proved at great length by making use of wave mechanics, notably by Schrödinger. We may think of the conservation of linear and angular momenta as natural consequences of the fact that the geometrical transformations of translation and rotation are isometries wherever they may be applied. We may therefore say with confidence that in any reaction the sum of the spins of the initial particles is equal to the sum of the spins of the resultant or final particles.

Let us now consider how we might measure or calculate the spins of various particles. The electron, proton, and photon are thought to have spins of $\frac{1}{2}$, and it is on this assumption that the spins of most other particles are calculated. We may say whether a particle has integral or half-integral spin by examining its decay, since we know that spin is conserved. Hence we may say, from the decay



that the π^* has integral spin. We may evaluate its spin, as did Cartwright et al. in

1953, by seeing what, if any, polarisation there is in the directions of the decay products. If there is no polarisation, as in this case, then we may say that our particle has zero spin. We shall discuss methods of establishing the values of nonzero particle spins when we consider the so-called 'resonance particles'.

Soon after the discovery that some particles have integral and some half-integral spins, de Broglie suggested that those with integral spin were compound particles composed of an even number of half-integral spin ones. However, this hypothesis seems, in the light of modern research, to be very unlikely indeed. But there is one very important intrinsic difference between integral and half-integral spin particles. Using quantum spin formalism, we find that only particles with half-integral spin are subject to the Exclusion Principle (see chapter 3). Let us consider whether two alpha particles obey the Exclusion Principle. If we interchange the first pair of protons then we reverse the sign of the wave function describing the alpha particles, but when we exchange the second pair of protons we set it back to its original value, and so, when we have also interchanged the two neutrons, we find that the wave function is symmetric, and the overall interchange of particles has not affected it. Thus we may say that alpha particles do not obey the Exclusion Principle, and so it would be possible for us collect together as many alpha particles as we wished at the same point in space-time, without any reaction taking place. Those particles which, like the alpha particle, have integral spin are called Bosons, and are said to obey Bose-Einstein statistics, and those with half-integral spins to be Fermions, and to obey Fermi-Dirac statistics.

Mesons and the photon, which is a rather special case, are said to be Bosons, and leptons and baryons are said to Fermions. We know that the proton is stable, or nearly stable, since some experiments seem to indicate that it has a mean life of 2×10^{28} yrs, longer than the lifetime of the universe, but so far, we can not see why this is so. However, if we assign an arbitrary quantum number, B, to all particles, so that baryons have B=1, antibaryons have B=-1, and all other particles have B=0, then, if this new quantum number is conserved in all reactions, since the proton is the lightest of the baryons, there are no possible decay modes for it. In 1949, Wigner named this quantum number 'baryon number', B. Stückleberg and Wigner have verified the conservation of baryon number to one part in 10^{-33} by studying the stability of the proton. In 1955 Chamberlain et al. suggested that the other type of Fermions: leptons, might also be subject to a conservation law. It is now conventional to assign a lepton number of 1 to leptons, -1 to antileptons, and 0 to all other particles. No examples of the non-conservation of lepton number have been found to date.

The next quantum number which we will consider is that of 'strangeness'. With the advent of high-energy particle accelerators it was found that the creation of a 'V' particle took only about 10^{-23} s, whereas its decay took about 10^{-10} s. There is an important symmetry in particle physics known as T symmetry (see chapter 7) which requires that any reaction can go in either direction under the same conditions, and takes the same time to occur whichever way it goes. In 1953, after a number of unsuccessful theories, an explanation of this anomaly was offered by Gell-Mann and Pais and independently by Nishijima. They postulated that the particles were produced in pairs ('associated production') by the strong nuclear interaction, and, once they were on their own, they could only decay through the weak or Fermi interaction, which is comparatively slow. To account for this phenomenon they decided to introduce a new quantum number, strangeness, S, which was zero for all particles except for the so-called 'V' particles. Thus, in 'associated production' the particles produced must

have strangeness of opposite sign, so as to make their total strangeness zero, and to allow such reactions as
 $p + \pi \rightarrow K^+ + K^-$.

They also postulated that in the weak decays of these so-called 'strange' particles, strangeness is not conserved, thus inhibiting and slowing down the decays. It is an experimental fact that the difference between the initial and final strangeness of a weakly interacting system is ± 1 . This type of rule is known as a 'partial' conservation law.

We say that a group of particles of roughly the same mass is a multiplet. Members of the same multiplet are denoted by the same Greek letter, upper-case for baryons and lower-case for mesons. Let us consider the average charges, Q , or centres of charge, of these multiplets. If we double the values of the average charges, we obtain a useful quantum number known as hypercharge, Y . The average charge of the nucleon multiplet is $\frac{1}{2}$, but that of, for example, the Λ^0 is 0. Thus we say that the Λ^0 is displaced from the normal by $-\frac{1}{2}$ units. Let us call this displacement A . We find that $A_K = -\frac{1}{2}$ and $A_\pi = -1$. For mesons, we say that the normal is the average charge of the pion multiplet, which is zero. Thus, $A_K = \frac{1}{2}$. If we double all our values for A , we find that we have no other quantum number than strangeness, and so we see that strangeness is given by:

$$S = Y - B.$$

We might also have achieved this results by consider reactions which do and do not take place. For example, since the reaction



does not take place, and we arbitrarily assign $S=0$ for the nucleons, we may say that the K^0 has nonzero strangeness.

Soon after the discovery of the strong nuclear force, which is charge independent, W. Heisenberg suggested the idea that the proton and neutron are simply different facets of the same particle, the 'nucleon'. He realised that, so far as the strong interaction was concerned, they did behave in exactly the same way. An analogous system to that of subatomic particles is to be found in atomic spectra. A given spectral line depends upon the orbital quantum number, l , and the magnetic quantum number, m . We find that m can take any integral value between $-l$ and l . When no magnetic field is applied to the atom in question, spectral lines corresponding to different values of m have the same energy, and are said to be degenerate. However, if a weak magnetic field is applied to the atom, spectral lines with different values of m form small groups called multiplets. This term has been borrowed by particle physics. If similarly, we could 'turn off' all electric charge in the universe, then, just like spectral lines with differing values of m , the proton and neutron would appear identical.

Heisenberg suggested the assignment of a new quantum number to each multiplet, which could, like ordinary spin, be projected according to the charge of a given particle. He argued that if we are to call the proton and neutron truly different particles because of their difference in charge, then we should also call protons with spins of $\frac{1}{2}$ different particles from those with spins of $-\frac{1}{2}$. He denoted the proton by the vector $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and the neutron by the vector $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$. Using the Pauli

matrices, which are defined

$$2\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad 2\sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad 2\sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

he built up a new algebra. We see, for example, that $2\epsilon p = n$, and vice versa. Heisenberg suggested that the Pauli matrices might be considered as geometrical transformations acting upon the vectors of the nucleons in i- or charge space, although he did not attempt to attach any physical significance to this concept. He named the new quantum number isospin. This is abbreviated from isotopic spin, which is in fact a misnomer, since members of the same isotopic multiplet do not have the same charge. There is a movement, especially in France and Switzerland, to rename it isobaric spin. The number of particles in a given multiplet is known as the multiplicity, M , of that multiplet. Heisenberg realised that, if a different projection were to be given to each different charge state in a multiplet, then isospin would have to be defined $I = (M-1)/2$.

Due to the work of a British physicist, Kremmer, who devised n-dimensional equivalents of the Pauli matrices, isospin is now defined for every hadron. The first component of isospin, I_1 , is defined by

$$I_1 = 2\epsilon, V,$$

where V is the vector, in charge space, of the particle in question. The vectors, of, for example, the pion triplet are given as

$$\pi^+ = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad \pi^0 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad \pi^- = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}.$$

Similarly, the second component, I_2 , is given by

$$I_2 = 2\delta_1 V,$$

and so on. The third component, I_3 , is the 'projected' component. By analogy with the real spin components, J_x , J_y , and J_z , the third component of isospin is sometimes represented as I_z . By studying the third Pauli matrix, we obtain the result $Q = I_3 + (B+S)/2$.

It has been found that isospin is conserved in strong interactions only, and its third component in strong and electromagnetic interactions. We might have guessed this, since isospin is charge independent like the strong interaction, and I_z is, like the electromagnetic interaction, concerned with charges.

Let us now consider some of the predictions of the Strangeness Scheme, which was suggested by Gell-Mann and Nishijima around 1952. They realised that when the law of the conservation of isospin is broken in a decay, then that decay will be much slower than an equivalent one in which it is not. They noticed that the electromagnetic decay mode

$$\Sigma^0 \rightarrow \Lambda^0 + \gamma$$

was open to the Σ^0 particle, but not to any of the other members of its triplet. Thus they predicted a lifetime of about 10^{-16} s, which is typical of an electromagnetically-decaying particle. This estimate has been slightly improved lately, but no direct experimental values have been obtained for the Σ^0 lifetime. Gell-Mann and Nishijima knew that the process

$$\Xi^- \rightarrow \Lambda^0 + \pi^-$$

was a weak one, and that therefore $|\Delta S| = 1$, yielding a value of 0 or -2 for the strangeness of the Ξ multiplet. If $S_{\Xi} = 0$, then one would expect the decay

$$\Xi^- \rightarrow n\pi^-$$

to be dominant, because it has $|\Delta S| = 0$, but it has been found not even to occur. Thus we are forced to conclude that $S_{\Xi} = -2$, and that therefore $I_{\Xi} = \frac{1}{2}$, so that a Ξ^0 particle must exist. Such a particle was found at the Lawrence Radiation Laboratory in 1958. Let us now discuss the kaons. We know that the process



takes place, so that $S = 1$ for the K^+ , and hence $I_3 = \frac{1}{2}$. This implies that the K^+ is one member of an isotopic doublet, whose other member is neutrally charged. We are forced to conclude that this other member is the K^0 . But what, then, is the status of the $\bar{\Lambda}$? The only reasonable conclusion is that this has $S = -1$, and that it is the antiparticle of the K^+ . But it too must form a doublet, the other member of which must be the anti-particle of the K^0 , the \bar{K}^0 particle. Thus we see that, unlike, for example, the π^* , the K^0 is not its own antiparticle. As we shall see in chapter 7, this fact has profound results on particle symmetries.

Let us now consider the quantum number of parity. We first define an operator, P , such that

$$P\psi(x, y, z) = \psi(-x, -y, -z),$$

which corresponds to a rotation through 180° about the x -axis, followed by a reflection in the plane $x = 0$. From our studies of angular momentum, we know that all wave functions are invariant under the transformation of rotation, and so the only real significance of the operator P is in its space reflection component. It is a fact of wave mechanics that for all physically meaningful waves ψ , $|\psi|^2$ must be invariant under the P or \bar{P} operation. But, taking a square root, we find that

$$P\psi(x, y, z) = +\psi(x, y, z) \text{ or } -\psi(x, y, z).$$

In the first case we say that the wave function ψ has even parity, and in the second, that it has odd parity. Hence, by knowing the wave function of a given particle, we may assign to that particle an intrinsic parity, P , which can take the values of either $+1$ or -1 . There can be no absolute measure of parity, and so we measure all parities relative to that of the proton, which we call $+1$.

In particle physics, however, we are often concerned with systems containing more than one particle, and thus we need to know what the parity of a system of two particles, A and B, which are rotating around each other with a an angular momentum of $L \neq 0$, is. We know that the wave function of the complete system is

$$\psi(A)\psi(B)\psi(L),$$

and that therefore

$$P(A+B) = P(A)P(B)P(L).$$

We find that $P(L)$ is given by the formula

$$P(L) = (-1)^L,$$

by studying the spherical harmonics. Let us now attempt to deduce theoretically the intrinsic parities of the charged pions. We know that the reaction



where d is the deuteron, takes place. It has been shown that nearly all π^- particles are captured and cascade into the lowest energy level orbit in about 10^{-6} s. Thus, since the angular momentum in this orbit is zero, the parity of the $d-\pi^-$ system will be the same as the parity of the π^- particle on its own. Now let us consider the total parity of the $n-n$ system. The Exclusion Principle (see chapter 3) forbids $L=0$ for this system, and therefore the lowest possible value is $L=1$. Since the neutron has even parity, we see that the $n-n$ system must therefore have odd parity, so that the parity of the charged pions is odd, because parity is conserved in a strong interaction of this type.

The assumption that parity is conserved in strong interactions brings about some interesting comments. It implies that the laws of nature are the same on both sides of a mirror. In a comparatively macrocosmic sense, this is not true, since complex organic molecules are more often right- than left-handed. However, if we have a beam of, for example, polarised Ξ^+ particles, then we find that the direction in which

lambda particles are preferentially emitted by Ξ^0 particles travelling in the $+z$ direction is precisely the same as the image of that of Λ^0 's emitted by particles travelling in the $-z$ direction under reflection in the $z=0$ plane. Thus, in this decay, total parity is conserved, or this decay is invariant under the space reflection operator P . We might note that in some books intrinsic parity is denoted by ϵ and not P .

There is not only parity in real, but also in charge or i -space. There exists an operator C which reverses the charge of any particle, so that, for instance $C(\pi^+) = -(\pi^+)$.

and particles are transformed into their antiparticles. For particles where $B=S=0$, the effect of the operator C is purely to reverse their charges. There is another operator, R , which inverts the third component of the i -spin of a given particle, or rotates its charge vector in i -space through 180° about the y - or I_3 -axis. Thus R is defined

$$R = e^{i\pi I_3},$$

working in radians. We define another operator, G , as
 $G = CR$.

The net effect of the G operator is to reflect a given particle's charge vector in the plane $I_3 = 0$, and then to rotate it through π about the I_2 -axis, which is the same as the P operator's effect in real space. We find that $G(\pi^+) = -(\pi^+)$,

and so we say that the G -parity, G , of the pion is -1 or odd. G is sometimes defined as $G = C(-1)^{\frac{1}{2}}$,

where I is the isospin of the particle in question. It is an experimental fact that G -parity is conserved in strong interactions, so that, in a reaction where only pions or other particles for which $B=S=0$ and $G=-1$ are involved, the difference between the initial and final number of pions in the system must be even. G -parity is useful in theoretical work on π and η resonances, though of no practical value, since targets of pure pions can not be obtained with present technology.

One type of radioactive decay, that in which electrons are released, is known as beta decay. The free neutron is an example of a subatomic particle which decays in this way. Ever since the discovery of this type of decay, physicists could not understand where the extra decay energy went to. At one point, the law of the conservation of energy was actually thrown into doubt. In, for example, the decay of the neutron, 780 keV seemed to be disappearing. But, in 1931, W. Pauli proposed a hypothesis which would account for this. He postulated that there exists another particle, which he called the neutrino or neutrino, which takes away this extra energy. By 1935, Pauli and Fermi had worked out all the quantum numbers of this particle, and had found that it had practically no detectable properties, and, moreover, it was hardly produced in any reactions except for the rare beta decay. The first thing to do was to measure the angles and momenta at which the proton and electron left the scene of the decay $n \rightarrow p + e^- \dots$.

If no neutrinos were produced, then these two particles should be coplanar and mono-energetic. However, this was found not to be the case, and so it was assumed that the neutrino existed.

But the neutrino is the most unreactive of all subatomic particles known at present, and a neutrino is calculated to interact with only 1 out of 10^{23} particles which it comes near to. Thus the detection of the neutrino was a difficult problem, since it did not interact with any sort of detector, and it did not, so far as anyone knew,

decay. Thus it was necessary to look for some inverse reactions in which neutrinos take part. Although very few neutrinos out of those which would come near enough to the other particles would take part in the reaction, it would be possible to detect those which did take part. The inverse reactions suggested were



which is the well-known electron-capture reaction in reverse, and



In 1956, twenty-five years after the existence of the neutrino was first postulated, Cowan, Reines, Harrison, Kruse, and McGuire started their search for it. Their first problem was to find a sufficiently strong source of neutrinos. They decided to use the newly-built Savannah River nuclear power station as their source. Here, the uranium fission products produced antineutrinos so that the neutrino flux was about 10^{17} m^{-2} . They hoped to observe the second of the reactions mentioned above. If this reaction occurred, the positron would produce a trail of ionization in a liquid scintillator (see chapter 8), and when it came to rest, its annihilation by a negative electron would produce two gamma rays. Furthermore, if some cadmium compound was dropped into the scintillator liquid, this would pick up the slow neutron, and in doing so, would produce two high-energy gamma rays, which would show up as flashes in the scintillator. For this reason, the experimenters sandwiched some cadmium salt solution between two scintillators, so that the three events connected with the positron would all occur practically simultaneously in the cadmium salt layer, and after about $10 \mu\text{s}$, the flash from the neutron capture would be seen in the cadmium salt together with the scintillations from the two gamma rays produced by the capture. It was necessary to have a great volume of liquid (~ 10 tonnes) in the scintillators, and about five hundred sensitive photomultiplier tubes to detect the tiny flashes of light.

Spurious events were sometimes detected by some discrepancy in timing and sometimes by the use of a third target and scintillator fixed in anticoincidence with the photomultiplier tubes. The experiment ran for around 1400 hours, with about one event per hour. When it had finished, various checks were run, such as substituting heavy water (D_2O) for water, in which case no events were detected, and in late 1956, the discovery of the neutrino was formally announced.

While Cowan and Reines were searching for neutrinos by the method outlined above, Davis, Harmer, and Hoffmann, a group of chemists from Brookhaven, were trying to detect them by other means. It had been shown that when a neutrino interacted with the isotope chlorine-37, the radioactive gas argon-37 was produced, with the emission of an electron. In their first experiment, the chemists placed a tank containing 500 gallons of carbon tetrachloride (CCl_4) in a heavily-shielded position near the Savannah River plant. Helium was bubbled through the tank to clear it of any argon, and the tank was then left untouched for about thirty days. After this time, helium was again bubbled through the liquid, and any radioactive argon came out with it. The two miscible gases were then cooled in a liquid nitrogen cooling apparatus, and were fractionally separated. The argon was then tested with a Geiger counter, and it was found to exhibit traces of K-electron capture radiation.

One of the most important reactions thought to be taking place in the sun is



and this should produce a neutrino flux of about 10^{15} m^{-2} on the surface of the earth. For this reason, it was decided that a larger and better neutrino detector should be built to study these solar neutrinos. Using the same principle as Davis' first detector, a tank containing 500 tonnes of liquid perchloroethylene (C_2Cl_4) was placed in the

Homestake gold mine in South Dakota, U.S.A. Many more detectors of this type have been built since 1958, notably the new one in south Africa, which is buried 10 750' below ground level in a disused mine.

The background noise of neutrinos from cosmic sources is about 0.3 events per day. It was calculated that there should be about four or five events per day due to solar neutrinos in the larger detectors. However, the maximum figure obtained so far is 1.2 events per day, much less than predicted. Various theories were advanced to account for this seeming lack of solar neutrinos, of which we shall here discuss the most important ones. Bachall and Fowler soon suggested the obvious solution that some of the accepted values for the sun's age, luminosity, or composition, are in error, thus causing the low neutrino flux, but there is no substantial evidence to back up their theory, and so we must probably search for a more fundamental cause. Cameron suggested that the neutrino-producing reaction did not occur to such a large extent as was assumed in the sun's interior. It was originally thought that the exterior regions of the sun were spinning much slower than the interior ones, thus allowing a number of uncommon nuclear reactions to occur in the latter, but Cameron suggests that in the centre of the sun, large-scale mixing occurs, thus reducing the neutrino flux to the upper limits of current observations. In fact, Cameron's theory gains support from a most unlikely source: Dicke's attempt to disprove the General Theory of Relativity. Dicke believes that the sun is flattened because the interior is spinning about sixteen times faster than was previously thought, thus causing it to have a slightly different gravitational field than is thought, and causing Mercury to advance its perihelion, which is usually thought of as a relativistic effect. Dicke and his co-workers have made accurate measurements of the sun's shape, and are convinced that it is slightly oblate.

But the sun is by no means the only star which should emit neutrinos. It seems likely that every hot star in the universe is a neutrino emitter, and, because neutrinos are so unreactive, this neutrino flux should reach Earth intact. The brightest neutrino emitters appear to be novae, supernovae, and quasars. An idea by Gamow and Shoenberg, called the Urca process, could link the formation of novae and their high rate of neutrino emission. This theory proposes that in certain stars, vast amounts of energy are converted into neutrinos, possibly in the form of neutrino-antineutrino pairs, which then propagate freely in space. After this release of energy, the star's central, and previously hot, region, from which the neutrinos were emitted, cools down, causing the star to implode. The Urca process is the absorption of an electron with an energy greater than 10 MeV by an atomic nucleus in which a proton, with the emission of a neutrino, becomes a neutron. The newly-formed unstable isotope will soon decay again into the original stable nucleus with the emission of an electron and an antineutrino, as in the Fermi process. The Urca process would begin when the temperature inside a collapsing star rose above about 200 MK.

Let us now consider the possible emission of neutrino-antineutrino pairs from very hot stars. Obviously photons can not, in a one-stage process, yield these pairs. But, if sufficiently high-energy photons are produced, these will tend to materialise into virtual electron-positron and sometimes neutrino-antineutrino pairs. Due to the extreme unreactiveness of neutrinos, these pairs will tend not to annihilate each other. However, the electron-positron pairs will soon decay into more gamma rays, which will materialise again, and so on. The only comparatively stable constituent of this cycle are the neutrino-antineutrino pairs which would then propagate freely in space. If electron-neutrino reactions are found to occur, they might be slightly hindered, but

not by any measurable amount. Since neutrinos are massless, they must propagate through space at the velocity of light in vacuo and in straight lines, and they must have Doppler effects similar to those of light. Neutrino astrophysics promises to be one of the most interesting and fruitful branches of physics in a few years' time, when better neutrino detectors have been built.

Let us now consider the nature of neutrinos themselves. Various problems concerning the weak interaction, which we shall discuss in chapter 7, led Gell-Mann and Feinberg, in 1961, to the idea that for some reason the neutrino and the antineutrino in muon decay can not annihilate each other. They suggested that this was because there exist two distinct types of neutrinos, those associated with the electron, and those associated with the muon. In 1959 B.Pontecorvo had calculated that it would be possible to produce a medium-energy neutrino beam from a particle accelerator, and in 1960, Schwartz, Steinberger, and Lederman worked out that the newly-built AGS at Brookhaven would be able to do this. Therefore, with the support of the Atomic Energy Commission, Schwartz, Steinberg, Lederman, Danby, Goulianos, Mistry, and Gaillard, set up their experiment to test the two-neutrino theory. They were going to produce what they hoped to be muon-neutrinos from pion decay, and then make these react with protons and atomic nuclei in order to produce muons. If there was only one type of neutrino, muons and electrons would be produced by this process in equal numbers.

They decided to use half the available beam energy: 15 GeV. They directed protons of this energy at a beryllium target, where they produced pions and kaons, with energies of around 3 GeV. Any of the resultant particles which were inside a 14° cone, entered the experimental apparatus. The particles, predominantly pions, were first directed down a 21 m decay tube in which about 10% of the pions decayed, and the resultant muons and neutrinos were mostly collimated into the forward direction by centre-of-mass motion. Then all the particles struck 13.5 m of steel from the armour-plating of an old battleship. All the pions were captured by about the first 30 cms of this, but the muons survived slightly longer. The only particles which emerged from the other end of this target were the neutrinos. They then entered a series of ten spark chambers (see chapter 8) with dimensions $1\frac{1}{2}$ m x $1\frac{1}{2}$ m x $\frac{1}{4}$ m, each composed of nine 25 mm thick aluminium plates. The total mass of material in the spark chambers was about 10 tonnes.

One of the major problems of the experiment was to eliminate as much background cosmic radiation as possible. The first precaution taken was to place scintillation counters at the top and ends of the spark chambers, and connected so that only no count in the upper counters and a count in the counters nearest the target would trigger the spark chambers. However, about 80 cosmic ray particles still penetrated per second. Therefore it was decided that the synchrotron beam should be pulsed in $25 \mu s$ pulses, at 1.2 s intervals, between which time the spark chambers could not be triggered by any particle. The pulses themselves consisted of twelve bunches, each 22 ns long, and separated by a time of 220 ns. During the running of the experiment, between September 1961 and June 1962, some 1 700 000 pulses were accepted, although the total running time of the synchrotron was only 5 $\frac{1}{2}$ s.

The experimenters had estimated that about 10^{14} neutrinos would pass through their apparatus, of which about 25 would yield useful reactions. The counters triggered the spark chambers about ten times an hour, thus producing a total of about 5000 pictures. Out of these, over half were blank, but the reason for this is not understood. Of the remainder 480 were caused by cosmic ray particles, leaving 51 photographs for study. By removing $1\frac{1}{2}$ m of shielding, it was possible to test whether any of the tracks were caused by particles from the primary beam, and by replacing it with lead,

so that 90% of the pions were absorbed before they had time to decay, which caused the number of events attributed to neutrinos to decrease by a factor of nearly five. The next problem was to prove that most of the tracks observed were caused by muons. It was found that, on average, the particles appeared to pass through 8.2 m of aluminium in the spark chambers, and no other charged particles except for muons are this unreactive. A few years later a similar type of experiment was performed at CERN, Geneva, with slightly better apparatus, and this confirmed the idea of two neutrinos. The neutrinos are denoted by ν_e and ν_μ .

Most theories of the weak nuclear force assume that the masses of the two neutrinos are zero, but this is far from confirmed. The upper limit for the electron-neutrino's mass is 0.00006 MeV, but that of the muon-neutrino is only 1.15 MeV, nearly twice as much as the mass of the electron. This second estimate was obtained by Shrum and Ziolk of Virginia University at the end of 1971. They measured the energy of the muon in pion decay by means of a germanium detector, which is more accurate than previous methods using momentum-defining magnets. A new measurement of the pion mass by Backenstoss et al. at CERN seems to indicate that the square of the mu-neutrino mass is negative, which may open up some exciting new prospects.

The existence of two neutrinos suggests a conservation law which appears to be valid in all reactions, and explains why, for example, the decay

$$\mu^- \rightarrow e^- + \gamma$$

can not take place. This law or selection rule is the law of the conservation of electron and muon number. We assign the electron number, e , of 1 to the e^- and -1 to the e^+ , and 0 to all other particles. Similarly, we assign the muon number, μ , of 1 to the μ^- and -1 to the μ^+ , and 0 to all other particles.

CHAPTER FIVE: REACTIONS.

From the types of ageing that we are accustomed to, we might assume that, if there were two unstable particles, then the one which had lived longer would be more likely to decay than the other. However, this is not case, and, if the two particles mentioned were of the same type, then each would have an equal probability of decaying first. All that it is possible to say is that, if we have a large number of a given type of particle, then the average decay time will be the lifetime or mean life, τ , of that type of particle. We find that the probability, P_s , that a particle of mean life τ decays in the next short interval of time s is given by

$$P_s = s/\tau,$$

so long as $s \ll \tau$. Thus we may deduce that the number of particles remaining after a time t , $N(t)$ is given by

$$N(t) = n e^{-t/\tau},$$

where n is the initial number of particles, τ is their lifetime, and e is Euler's constant. This exponential decay function has been amply tested by both practical and theoretical work. We must note that the lifetime of a given particle is measured when the particle is at rest, and that when a group of particles travels at a relativistic velocity, as in a high-energy accelerator, the Fitzgerald-Lorentz time dilation equation

$$t' = \frac{(v/c^2)x}{(1-v^2/c^2)^{1/2}},$$

becomes important.

Let us now consider how we may represent pictorially the reactions between particles. The best method is to use Feynman diagrams, which were first suggested in 1949 by R. Feynman. These diagrams are graphs, where time is plotted along the x-axis, and one dimension of space is plotted along the y-axis. We will discuss the significance of Feynman diagrams at a later stage. We will consider two basic types of reaction here. Let us have four particles, P, Q, Y, and Z, taking part in our reactions. In the first type of reaction, P and Q enter a 'black box' and Y and Z emerge from it, and there was no virtual emission of quanta involved. This type of reaction is known as a single-vertex reaction. A reaction in which one virtual quantum is involved, such as



is known as a two-vertex reaction, because the particles interact at two distinct points in space: first, where the π^- is emitted, and second where it is absorbed. It is often found that there are more virtual exchanges occurring in the 'black box' than were initially thought. It is useful to use the rule that a particle entering the black box is equivalent to its antiparticle leaving it. An example of a black box reaction in experimental particle physics might be



where an important particle in the reaction is uncharged and therefore difficult to detect. Examples of Feynman diagrams may be found in most text-books on particle physics.

From our study of quantum numbers, we know that there are various conservation laws which are never broken in particular types of interaction. A interesting consequence of the conservation laws is the theory of decays known as the theory of 'communicating channels' or states. A decay is considered to be complete when the particles produced in it have travelled out of the field of influence of the initial particle. The theory of communicating states, which we will meet again in chapter 6,

postulates that any particle exists, some of the time, in a virtual state, as a group of two or more particles with the same quantum numbers as itself. Obviously we can write down a considerable number of these decay channels or nuclear states for a hadron or strongly-interacting particle. However, for decay to take place into one of these channels, the sum of the masses of the particles in this channel must be less than the mass of the original particle, so that decay into the channel would not violate the law of the conservation of mass-energy. The sum of the rest masses of the particles in a given channel is known as the threshold energy of that channel. If decay is possible into a given communicating state, then it is known as an open channel, if it is not, it is known as a closed channel. Let us take an example of a particle, and see how this theory helps us to predict its possible decay modes. Our example is the ρ meson, a pion resonance of mass 750 MeV and J^P of 1-. We find that this has altogether seven sets of communicating states, as follows: two-pion, four-pion, six-pion, kaon-antikaon, kaon-antikaon-pion, kaon-antikaon-many-pion, and nucleon-antinucleon. We have listed these channels in order of increasing threshold energy, starting at the minimum, 300 MeV, and finishing at about 1800 MeV. Thus we find that the only open decay modes are
 $\rho \rightarrow 2\pi$,
 $\rho \rightarrow 4\pi$.

These are the only observed decays of the ρ meson.

We have a ball consisting of three pieces of plastic loosely stuck together. Two of them are invisible and the third is visible. The ball represents a subatomic particle, and the pieces of plastic its potential decay products. When we throw the ball, we run along side it, but, after a few seconds, it disintegrates due to aerodynamic stresses. However, we continue to run where the ball would be if it still existed, and we find, that, due to the law of the conservation of linear momentum, we are at the centre of mass of the system created by the exploding ball. When we talk of a decaying particle or a reaction, we often say that the momenta of particles are x units in the centre of mass system, abbreviated c.m.s. Thus, if we are watching the decay
 $\Sigma^+ \rightarrow p + \pi^0$,

and the initial Σ^+ had a velocity of 40% c , we are rarely interested in the extra momenta of the decay products caused by the high velocity of the initial particle, and so we transform the decay into the centre of mass system for the original particle, so that its initial velocity is effectively zero.

Returning to the ball analogy, let us consider measuring the momentum of the visible fragment after the disintegration. If we plot a graph of momentum to frequency for this, we will find it is roughly a normal or Gaussian curve, equation:

$$y = (1/\sqrt{2\pi}) \cdot e^{-\frac{x^2}{2}}$$

its nearness to the precise curve increasing linearly with the number of readings we take. If however the two invisible pieces of plastic joined together, then our momentum-frequency graph for the visible fragment will be a straight line, and so we say that it is 'monoenergetic'.

Much of our present-day knowledge of subatomic particles is derived from studies of collision processes. Let us therefore discuss these. If two particles, A and B, collide, but no new particles are produced, then we say that the collision was elastic, and if new particles were produced, that it was inelastic. The results of certain collision experiments are often expressed in terms of a quantity known as cross-section, σ , or probability of interaction. Let us first consider the simplest type of cross-section: total cross-section, σ_{tot} . We imagine that the target for our particle beam is a very thin layer of material in which n particles are randomly distributed.

Thus we may say that

$$\sigma_{\text{tot}} = P/n,$$

where P is the probability that the A particles from the beam react with the B particles in the target. We may think of cross-section using the following model: a circular disc, corresponding to its field of influence, of area σ_{tot} units is assigned to each B particle in the target. The discs are orientated perpendicularly to the approaching beam, and if an A particle hits a disc, it undergoes change, whereas if it does not, it proceeds unaffected. We have n B particles, each of area σ_{tot} per unit area of our thin target. Thus the total area, T , covered by the B particles is $n\sigma_{\text{tot}}$. Thus an area T of the target is 'opaque', while the rest of the area, $(1-T)$ is transparent to the approaching particles. Thus the probability of interaction, P , in this thin target, between the A and B particles is seen to be $n\sigma_{\text{tot}}$.

Let us now try and generalise our result for σ_{tot} for thicker targets. Let $P(n)$ be the probability that an A particle is removed from the beam by a thin layer of B particles of projected surface density n . $G(n)$ is the probability of transmission through this layer. Obviously $G(n) = 1 - P(n)$.

Let us place two layers, one of projected surface density n_1 , and the other of projected surface density n_2 on top of each other, so that their total surface density is $(n_1 + n_2)$. Thus, the probability that a particle passes through both layers is given by $G(n_1 + n_2) = G(n_1).G(n_2)$.

This equation must be true for any positive real numbers n_1 and n_2 . Thus the general solution is

$$G(n) = \exp(-Kn),$$

where K is any real constant. Thus we have

$$P(n) = 1 - \exp(-Kn).$$

As n tends to zero, $P(n)/n$ tends to K , so that we may conclude that $K = \sigma_{\text{tot}}$. Thus we have the relation

$$P(n) = 1 - \exp(-n\sigma_{\text{tot}})$$

for our probability of interaction. The cross-section of a collision process is usually computed using this formula. A common measurement of cross-section in subatomic processes is the barn (b) or millibarn (mb). 1 barn = 10^{-26} m^2 , and 1 mb = 10^{-24} m^2 .

Total cross-section, σ_{tot} or σ_t is defined as the cross-section of all the processes which scatter or otherwise remove particles from the primary beam. Elastic cross-section, σ_{el} , is the cross-section for elastic scattering, for example $p + p \rightarrow p + p$.

Inelastic cross-section, or reaction cross-section is given by

$$\sigma_{\text{inel}} = \sigma_t - \sigma_{\text{el}}.$$

We can also define a differential cross-section, $d\sigma/d\Omega$, by the equation

$$\Delta I/I = ((d\sigma/d\Omega)\Delta\Omega)Nx,$$

where x is the target thickness, and $\Delta I/I$ is the fraction of the total beam flux scattered into a solid angle $\Delta\Omega$, and N is the number of particles in the target per unit area. It is often useful to define this differential cross-section so that it is relativistically invariant, but we will not do this here.

Until now, we have concerned ourselves purely with those particles which decay via the weak or electromagnetic interaction in a comparatively long amount of time. Particles with weak decay modes are termed semi-stable, and those with electromagnetic ones, meta-stable. But we might ask ourselves if there are also particles which decay by the strong interaction, in a correspondingly short amount of time. The

type of particles which decay in this way are the resonance particles.

Perhaps the commonest and most important of all systems in high-energy physics is the pion-nucleon, π -N, system. We know that $I_\pi = 1$ and $I_N = \frac{1}{2}$. Thus, the possible i-spin states for the system are

$(I_1, I_2) = (3/2, 3/2), (3/2, 1/2), (3/2, -1/2), (3/2, -3/2), (1/2, 1/2), (1/2, -1/2)$. Thus we can say that the first four and the last two of these states behave

identically under the strong interaction, since it is charge-independent. Using the Clebsch-Gordan coefficients, we find that the following i-spin waves are possible

$$(3/2, 3/2) = \pi^+ p$$

$$(3/2, 1/2) = \sqrt{1/3} \pi^+ n + \sqrt{2/3} \pi^0 p$$

$$(3/2, -1/2) = \sqrt{2/3} \pi^0 n + \sqrt{1/3} \pi^- p$$

$$(3/2, -3/2) = \pi^- n$$

$$(1/2, 1/2) = \sqrt{2/3} \pi^0 n + \sqrt{1/3} \pi^0 p$$

$$(1/2, -1/2) = \sqrt{1/3} \pi^0 n + \sqrt{2/3} \pi^0 p.$$

Thus we see that we can represent the 'scattering amplitude' for the π -N system using two cross-sections instead of six, since all the possible i-spin states except for two are compounded from pure i-spin states $3/2$ and $1/2$. We see that there are only three processes with pure i-spin states:



By finding the scattering amplitudes $A(3/2)$ and $A(1/2)$ it is possible to calculate the ratio between the cross-sections for these processes. It is almost impossible to predict scattering amplitudes of this type using current principles, so we will have to resort to experimental results.

A beam of charged pions is produced by the interaction of a synchrotron proton beam with a metal target. The resultant beam is then momentum-analysed in a magnet and suitably collimated, after which it impinges on a liquid hydrogen (proton) target. The resultant pion and protons are then detected by counter telescopes and again momentum analysed. If the cross-section of interaction is plotted against the pion's kinetic energy, then a striking peak is obtained when the pion energy is around 180 MeV. At this point, the cross-sections for the three processes mentioned earlier are respectively 195 mb, 23 mb, and 45 mb, so that the ratio of cross-sections is about 9:1:2. This indicates that the reaction is caused at this point primarily with particles whose total i-spin, T , is $3/2$. This experiment was first performed by E.Fermi in 1952 using the Chicago University cyclotron.

A few years later it was suggested that this anomaly could be accounted for if a new composite particle was formed when the incident pion energy was around 180 MeV. By measuring the final momenta of the pion and proton, it was possible to establish that this new particle, if it existed, had a mass of around 1238 MeV. It was the first resonance particle to be discovered, and was named the Δ particle. We remember that the i-spin of its decay products tends to be $3/2$, and so we must conclude that it has a multiplicity of four and is thus a quadruplet. If we measure the bandwidth, Γ , of the peak representing the Δ particle on our initial graph, we find that it is about 120 MeV. This therefore is the uncertainty in our mass measurement. Recalling the uncertainty relation (see chapter 2)

$$\Delta E \Delta \gg \hbar,$$

and remembering that energy is equivalent to mass, we find that the lifetime of this resonance is about 10^{-23} s, as we would expect from its strong decay. We may therefore

deduce the general relation

$$\tau = \frac{\mu}{\Gamma}.$$

The shape of the cross-section - energy graph at resonance is given by the Breit-Wigner formula

$$\sigma_r = \frac{1}{((E-E_r)^2 + (\Gamma/2)^2)},$$

where E_r is the energy at resonance, and Γ , has been measured. The spin of a resonance is measured by the careful observation of the angular distribution of its decay products, and, in the case of the Δ it is $3/2$. We know that the orbital angular momentum, l , of the pion and nucleon in the Δ particle is 1. Thus we know that its parity is $P(\pi) P(N) (-1)^l = +1$.

The Δ particle was the first resonance discovered in a formation experiment, using cross-section - energy graphs. However, its status as a resonance was not confirmed until it was also detected in a production experiment, where it acted as a particle, rather than a favourite interaction energy. It was not, in fact, the first resonance to be revealed in a production experiment, but, for the sake of homogeneity we will discuss its production experiment. We consider the reaction $pp \rightarrow n\Delta^{++} \rightarrow np\pi^+$.

If there were no intermediate stage, then the neutron produced should have a complete range of different energies. However, when protons of 2.8 GeV were used, only a very small spread of values, corresponding to the mass uncertainty of the Δ , peaked around 1.62 GeV was found. It can be shown that this corresponds to the neutrons recoiling from a single particle of mass 1256 MeV, which is an acceptable experimental error.

The first particle to be discovered in a resonance production experiment was the Y^* particle. In late 1960, Alston, Alvarez, Eberhard, Good, Graziano, Ticho, and Wojcicki set out, using the accelerator at the Lawrence Radiation Laboratory, to study the process



to see if any resonances could be produced. They allowed a magnetically-separated kaon beam to enter a liquid hydrogen bubble chamber, and steadily increased its energy. Every 20 - 100 MeV, batches of photographs were taken of the reactions in the bubble chamber. By 1960, there was good evidence from decay product momentum analysis, to show that the process



was occurring. The mass of the Y^* resonance was found to be about 1385 MeV and its bandwidth to be about 60 MeV.

We will not, at this point, follow the historical development of resonance physics, but we will consider our current knowledge of the baryon resonances. Not only have a considerable number of $S=0$ and $S=-1$ baryon resonances been found, but also a few $S=-2$ ones. An example of one of these is the Ξ^* particle with a mass of 1530 MeV discovered by Bertanza et al. in 1962. They showed that the process



took place by measuring the recoil energies of the K particle, and demonstrating that they were consistent with recoil from one rather than two other particles. The angular distribution of the decay products favoured a J^P of $3/2^+$ or $5/2^+$, but the former seems more likely bearing in mind the $SU(3)$ symmetry which we shall discuss

A large number of π -N resonances have been discovered to date, and it has been found that these fall into two distinct groups. When we plot the total cross-sections of the $\pi^+ p$ and $\pi^- p$ systems, we find that the ratio of peak heights at resonance is either 0:1 or 3:1. Thus we can produce resonances with i-spins of either $\frac{1}{2}$ or $3/2$ in π -N reactions. It is the convention to term those with $I = \frac{1}{2}$ N^* resonances, and those with $I = 3/2$ Δ resonances. K-N resonances also fall into two groups, one with $I = 1$ and the other with $I = 0$. These are conventionally represented as Y_1^* and Y_0^* , or Σ and Λ respectively. Similarly resonances with $S = -2$ are represented as Y_{-2}^* or Ξ . It is common practice to put the mass as it was first measured in brackets after the name of a resonance. Hence one might write $N(1750)$, although this resonance actually has a mass of about 1785 MeV according to modern measurements. There is some movement towards a completely new nomenclature for resonances. It makes use of the essential quantum numbers connected with a resonance, and the letters denoting orbital momenta borrowed from atomic spectroscopy. A given resonance would be written

(ORBITAL MOMENTUM) ISOSPIN (TOTAL ANGULAR MOMENTUM)

The atomic spectroscopy letters are, in order, starting from $I=0$: S, P, D, F, G, ... Thus, using this nomenclature, the $\Delta(1238)$ particle would be represented: $P_{3/2}^{1/2}$.

It is unlikely that there exist any baryon resonances other than those types mentioned above. The easiest type of resonance to study is obviously the N-N resonance, but it is almost certain that no resonances of this type exist. There are also the \bar{N} -N resonances, but convincing proof of these is still lacking. It is also unlikely that any particles with isospins higher than $3/2$ exist, although it is possible that there exist two strange resonances: $Y_2^*(1451)$ and $D(2520)$ with $I=2$, though these have not yet been confirmed.

In 1957 and 1959 respectively Nambu and Chew showed that the vector part of the nucleon's internal electromagnetic field observed by Hofstadter could be explained in terms of boson resonances. In 1960 Frazer and Fulco applied dispersion-relation methods to Hofstadter's findings and again predicted boson resonances. Accordingly, in 1961, Hofstadter et al. found a di-pion resonance at about 750 MeV which they named the ρ particle. It was produced in the reaction



However, the interesting thing about the ρ particle is that its decay:

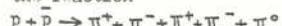


appears to violate the law of the conservation of mass-energy, since the total energy of its decay products is rarely above 350 MeV. According to a new theory by Gestalt, it becomes a new type of matter which absorbs much of its energy before decay. However, the ρ particle becomes more enigmatic as time goes on: in 1968 the reaction



was observed, indicating that the ρ particle was similar to the photon in some way. Regge's theory, which we will discuss later in this chapter, suggests that the ρ is an excited state of the vacuum, which would possibly account for some of its odd characteristics.

Late in 1959, Chew suggested that the scalar part of charge lately observed by Hofstadter in the nucleon could be explained in terms of a tri-pion resonance. In 1961 Maglic, Alvaraz, Rosenfeld, and Stevenson studied the annihilation of antiprotons by protons in the 72" bubble chamber at the Lawrence Radiation Laboratory, according to the reaction



Over 2500 photographs were taken of this process, of which only 800 showed the neutral pion necessary to conserve momentum if a resonance were to be formed. By computing the effective mass of the $\pi^+\pi^-\pi^0$ resonance by means of high-speed digital computers the researchers were able to show that in 93 cases a tri-pion resonance, which they named ω had been formed. By momentum-analysis of decay products, the ω mass was fixed as 790 MeV. The ω was found to be a singlet with zero isospin.

In the formation reaction



the cross-section - energy graph was found to have two peaks: a large one with an effective mass of 790 MeV and a bandwidth of about 13 MeV, and a smaller one with an effective mass of 550 MeV and a bandwidth of 2.6 KeV. The particle represented by the smaller peak was another singlet, which was named the η . Three of the four possible decays of this particle include two or more photons, and it has a long lifetime, so we conclude that it is not a resonance in the true sense of the word, but decays via the electromagnetic interaction and is hence meta-stable. As the η decay has only $S=0$ particles in it, it is possible to establish a G-parity for this particle, and it is found to be +1, since there are three pions in its pions-only decay modes.

Let us now consider the experimental methods used in finding mesic resonances. Apart from the bubble chamber method, as used in the search for the η meson, there exists also a piece of apparatus known as a missing-mass spectrometer. The principle of this is that a beam of, for example π^- 's with a well-defined momentum hits a liquid hydrogen target producing the reaction



where X^- represents a whole group of particles produced, whose net charge is -1. The vector momentum of the recoil proton is then measured and the mass of the resonance particle corresponding to X^- , if such a particle exists, is given by

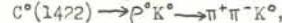
$$m_{X^-}^2 = (E - E_p)^2 - (p_{\pi^-} - p_p)^2$$

If no resonance exists, then the recoil proton will have a continuous range of energies, and will not be mono-energetic. The first operational missing-mass spectrometer was set up in 1968 by Kienzle at CERN, Geneva. Behind the hydrogen target, in line with the primary beam of negative pions were two wire chambers, and behind these, there was a matrix of counters. At an adjustable angle to the target, there were a series of about ten sonic spark chambers, which made up a proton telescope. The whole piece of equipment, including the target, was on a turntable, so that the target could present itself to the beam at different angles. Much useful work has been done using the CERN MMS (Missing-Mass Spectrometer). A slight improvement on the MMS is the CERN Boson Spectrometer (CBS). This can study different energy regions from the MMS. It analyses the momenta of recoil electrons emerging near 0° using a wide-gap magnet and two pairs of wire spark chambers. The whole apparatus can be revolved about the main magnet in order to study different mass regions. The great usefulness of the MMS and CBS is their extreme speed, so that 100 000 readings can be taken to a very high accuracy in a matter of a few months.

We will not discuss the discoveries of the hundreds of mesic resonances now discovered in great detail, but we will consider a few interesting examples. In 1965 the first composite mesic resonance was found. It was named the Buddha, B , and had a mass of around 1215 MeV. Its dominant decay mode was the two-stage process



Another composite resonance, the C^0 particle, with decay



was discovered in the course of the next year.

In 1965, using the CERN MMS and bubble chambers, the $A_2(1320)$ meson was found. Its dominant decay modes were found to be

$$A_2^0 \longrightarrow K_1^0 K_1^0,$$

$$A_2^+ \longrightarrow K^+ K^0,$$

$$A_2^- \longrightarrow \pi^- \rho^+.$$

All the data was consistent with $I=1$ and $G=-1$. The $K_1^0 K_1^0$ decay mode requires a J^P of $0^+, 2^+, \dots$, and the $\pi^- \rho^+$ decay forbids $J^P = 0^+$, so that the next lowest possible assignment is 2^+ . The angular distribution of decay products also favours $J^P = 2^+$. However, late in 1965 collaboration at CERN revealed that the peak corresponding to the A_2^- was in fact 'split'. The lower peak (A_2^L) was at about 1289 MeV and the higher one (A_2^H) at 1309 MeV. But in 1970, experiments at Berkeley showed no such splitting of the A_2 peak. In 1971, using the CERN CBS Kienzle et al. again examined A_2 's produced in the reaction



and again found splitting for particles with all three decay modes. However, Barbaro-Galtieri et al. have also investigated A_2^0 mesons while working at Berkeley, and have found no splitting in A_2^0 's produced by the reaction



and decaying by all three decay modes. Neutral A_2 's produced at CERN by Zichichi et al. in the reaction



have also been found to be split and to have a fine structure very similar to that of the A_2^- . SU(3) symmetry (see chapter 6) postulates that if the A_2 meson is split, then other mesons with $J^P = 2^+$ should also be split. These other resonances, $K^*(1422)$, $f(1264)$, and $f'(1514)$, were investigated by Flatté at Berkeley in 1969. He found a slight dip in the centres of their peaks, but rigorous statistical computer analysis favoured single peaks and no splitting. There appear to be three possible explanations, according to current ideas, for the A_2 splitting. Dalitz proposes that there exist two resonances with around the same mass, the same bandwidth (~ 22 MeV), and possibly even the same J^P . He uses the example of the oscillations of the CO_2 molecule as a precedent from another branch of physics. The second possibility is that it is a new type of 'dipole' resonance, with a more generalised Breit-Wigner formula than for the normal monopoles, but whose physical significance is not yet understood. Thirdly the effect could be due to a broad A_2 resonance with another destructively interfering narrow resonance exactly at its centre. In 1971, the R^- resonance was discovered in the CBS and was found to be a triple peak with masses of 1632, 1700, and 1748 MeV. However, the g meson, with mass ~ 1700 MeV, $J=3(?)$, and decay



has lately been found in bubble chamber experiments at CERN and may correspond to some part of the R^- complex.

The question of the precise nature and status of the resonance particle now arises. There seems to be no way of knowing whether, for example, the $\Delta^+(1238)$ is a single entity which, after the short time of 10^{-23} , decays into a N^+ and a π^+ , or whether the nucleon and pion simply interact very briefly with each other, for example, by the strong nuclear force or by whirling around each other, and then return to their original courses. It is possible that when times of only 10^{-23} s are involved, then the distinction between these two possibilities becomes meaningless. An interesting idea was suggested by Bruecker at Indiana University in about 1963. He noticed that, as in

classical mechanical systems, the wave of the scattered pion in the π -N system is shifted precisely a quarter of a wavelength (90°) at resonance.

At present, over two hundred hadron resonances have been detected, and the number known increases by the month, and so it is obvious that physicists are keen to find some sort of pattern among this bewildering mass of particles. One method of classifying and predicting them is to use SU(3) symmetry, which we shall discuss in the next chapter. Another method is to use the One Particle Exchange (OPE) model, which leads on to Regge's hypothesis.

In any scattering process, a change of momenta must result. We represent the four-momentum transfer as q , and consider its square. It is obvious that, for any real scattering process, $q^2 \geq 0$. We know that the matrix element or scattering amplitude in a non-relativistic strong interaction is given by

$$f(q^2) = (k \cdot g^2) / (\mu^2 + q^2),$$

where g^2 is the strong coupling constant, k is any real number, and μ is the mass of the exchanged quantum. Thus, in any real scattering, since $q^2 \geq 0$, the denominator $(\mu^2 + q^2)$ is always finite. However, in the unphysical region, $f(q^2)$ has a singularity or pole at $q^2 = -\mu^2$. In the OPE model, we usually assume that pion exchange, if it is allowed by conservation laws, dominates the scattering amplitude. If, however, we consider ρ exchange instead, then the physical region for strong scattering processes would be even further from the pole, since μ has increased. Thus, the higher the mass of an intermediate particle, the less influence it has on physical scattering amplitudes.

As an example of the OPE model, let us consider the reaction



If the exchanged particle is a pion, and this is consistent with conservation rules, then there should be no connection between the planes of the momentum vectors of the incident pion and resultant rho particle, since a zero-spin scalar particle like the pion, can not carry information about vectors. Experimentally, the so-called 'Treiman-Yang' angle between the planes is isotropic so long as $q^2 < 0.2(\text{GeV}/c)^2$.

At this point, non-zero spin propagators begin to play a part. In 1965, Jackson measured differential cross-sections for our rho-production process for increasing momentum-transfers. After correcting for the many $\pi\pi\pi$ systems which failed to form a rho particle, it was found that the experimental agreement with the OPE model was excellent for low q^2 , but deteriorated as higher-order terms began to affect the process. By a somewhat complex consideration of s- and t-wave scattering, we may arrive at the equation

$$d\sigma/dt \propto s^{2j-2},$$

where s is the momentum-transfer and j is the spin of the propagator. Thus, for $j > 2$, the OPE model predicts $d\sigma/dt \rightarrow \infty$ as $s \rightarrow \infty$, which is contrary to all experimental results.

In 1959, while working on the solutions of the non-relativistic Schrödinger equation in a Yukawa-potential well, the Italian physicist T. Regge suggested that scattering amplitude could be an analytic or continuous function of angular momentum, j , as well as energy. The idea was taken up by Chew and Frautschi in 1961, who applied it to high-energy processes. In the reaction



we define two numbers, known as Mandelstam variables, which are Lorentz invariant. We say that

$$s = E^2,$$

$$t = -q^2,$$

where s and t are the Mandelstam variables, E is the total energy of the system, and q is the momentum transfer between any two particles on opposite sides of the equation. At energies not in excess of about 1 GeV the scattering amplitude is dominated by s -channel quantities and resonances, but after about 10 GeV the scattering amplitude varies very smoothly with energy, and hence we consider it as dominated by the t -channel. But, since t is negative, virtual quanta may only be exchanged in the unphysical region. We can overcome this problem by substituting \bar{b} and \bar{c} for b and c in our reaction, according to crossing symmetry. Crossing symmetry states that the interchange of an antiparticle entering a reaction for a particle leaving a reaction or vice-versa does not have any effect on the overall reaction. In the crossed reaction

$$a + \bar{c} \longrightarrow \bar{b} + d,$$

particles exchanged in the t -channel now become \bar{s} -channel resonances, but now appear in the physical region. From crossing symmetry

$$\bar{f}(\bar{s}, \bar{t}) = f(t = \bar{s}, s = \bar{t}),$$

and hence we must be able to continue the function f into the unphysical region of the s, t plane. This requires $\bar{s} > 0$, and hence $t > 0$, which is unphysical.

We now write

$$j = \alpha(E),$$

where α is a continuous function. Hence j is a complex number, with real and imaginary components. We say that

$$l = \operatorname{Re} \alpha(E).$$

The trajectory described by $\alpha(E)$ on the complex j plane is known as a Regge trajectory. The trajectory starts off along the negative section of the real axis, and may or may not cross the origin depending on the strength of the scattering potential. Under some circumstances, the particles a and b may possess a bound state of energy E and l equals, for example, one. This pole will occur at $\operatorname{Im} \alpha(E) = 0$, $\operatorname{Re} \alpha(E) = n$, where n is an integer. At $E_1 (= m_a + m_b)$, the trajectory leaves the real axis, so that $E_t > E$ for a real bound state. Whenever l is integral, we have an unbound s -channel resonance of energy E and angular momentum l . Using the Taylor expansion, we may thus obtain the usual Breit-Wigner formula for a resonant peak. Eventually, the trajectory turns parallel to the real axis and heads for $l = -\infty$, where $E \rightarrow \infty$. Thus there will be no more resonances on this trajectory. The number of resonances on a particular trajectory will depend on the strength of the interaction potential. The Regge pole hypothesis predicts

$$d\delta/dt = s^{2m-2},$$

where α is a smoothly-varying angular momentum variable. This avoids the divergence difficulties encountered by the similar formula in the OPE model, provided that $\alpha \ll 1$ when $t < 0$ in the s -channel.

It is obvious that all resonances along a particular Regge trajectory must have exactly the same quantum numbers except for angular momentum. Since s -channel resonances must also describe exchanges in the t -channel, it is obvious that successive poles must be separated by two units of angular momentum. Physically, we may plot E against l , and graphs of this kind are known as Chew-Frautschi plots. The amazing thing about Chew-Frautschi graphs is that when the square of the resonance mass is plotted against angular momentum, we obtain a series of parallel straight lines for sets of resonances with the same quantum numbers except for j . We find that

$$m^2 = m_0^2 + 0.91 j.$$

We may easily calculate the fact that there are four fundamentally different types of trajectories for baryons. These are designated α , β , γ , and δ . They begin with

$J^P = 1/2^+, 1/2^-, 3/2^-, 3/2^+$ respectively. We define a quantity T , called the signature, for all trajectories. For bosons
 $T = (-1)^J$,
and for fermions
 $T = (-1)^{J-\frac{1}{2}}$.

The hypothesis of Regge poles has had both a number of successes and a number of failures. It predicted that a dip should occur at $t \sim -0.6$ GeV in the process



which did in fact exist. However, by the same method, the recoil neutron was predicted to have zero polarisation, but experimentally, the polarisation was of the order of 15 %. The phenomenon of photoproduction appears to contradict the Regge hypothesis, but Fox reconciled experiments with theory by proposing that the Regge poles in photoproduction are fixed, and do not move as a function of the Mandelstam variables. The Regge amplitude suggests that

$$\sigma_T \propto s^{\alpha(\epsilon)-1}.$$

At high-energies, σ_T appears to be roughly constant, and the only way in which it can do this is if $\alpha(\epsilon)=1$. No known trajectory passes through the point $j=1, m=0$, but nevertheless the so-called 'pomeron' trajectory has been invented, which does pass through this point. Since no states are altered in any way in forward elastic scattering, we may conclude that the trajectory has zero internal quantum numbers, and, from a study of diffraction peaks in forward elastic scattering, it has been deduced that the gradient of the pomeron trajectory is in the order of 0.5 GeV⁻². The pomeron or vacuum trajectory is predicted, by the Pomeranchuk theorem, to have positive signature. One of the predictions of the Regge hypothesis is that daughter trajectories should exist. These, however, do not appear to exist, although Chung and Snider did manage to find some doubtful ones in 1967. In the same year, Barger and Cline used Regge's hypothesis and SU(3) to predict resonance properties, and obtained excellent agreement with experiment. There appears to be no obvious reason for the extreme linearity of resonance Regge trajectories, although this would be predicted by the theory of quark orbital excitation.

We have seen that low-energy phenomena may often be interpreted in the form of s-channel resonances, whereas high-energy phenomena can be interpreted as t-channel parameters. Obviously, in the intermediate energies, there must be a region of overlap between these apparently differing interpretations. In 1966 Kormanyos et al. measured the elastic cross-section for



against increasing values of the Mandelstam variable, s . Their results showed a number of distinct dips in the intermediate energy region, which were quickly interpreted by Barger and Cline as being due to the interference between the amplitudes associated with s- and t-channel effects. This idea agreed so excellently with experimental findings that spin-parity assignments were given to two non-strange resonances, with masses 2190 and 2420 MeV, from it. However, as Dolen, Horn, and Schmid pointed out in 1968, an interference phenomenon would violate the finite energy sum rules, and hence they proposed the so-called 'duality model'. This was based on the principle that at medium energies, either t- or s-channel analysis can give a complete description of the scattering amplitude, so long as each is averaged over the same energy range. By studying the charge-exchange reaction



they verified this hypothesis, and Schmit suggested, with some justification, that at

any single energy, both the s- and t-channel predictions are correct.

The principle of duality suggests that there is some connection between representing a scattering amplitude as a sum of s-channel resonances and as a sum of crossed t- and u-channel ones. u is the third Mandelstam variable. In 1968 Veneziano put forward a model in which an infinite sum of resonances behaved as Regge trajectories, and a sum of Regge terms yielded resonances. The model displays crossing symmetry, and, unlike many of its predecessors, does not break the finite energy sum rules. Veneziano considered so-called 'gamma functions' of the Mandelstam variables, and showed that this predicted linear Regge trajectories. However, it also predicted daughter trajectories with spins of between 0 and $j-1$, which, as we have mentioned, have not been found. He showed that no double poles could ever exist. The Veneziano amplitude is acceptable in that it is analytical, and displays duality in s-t interchange. However, at the present time, it has not been convincingly applied to half-integral spin particles. Experimental tests of the Veneziano model, notably by Lovelace in 1968, have met with only limited success, since too many poles appear to be predicted.

To end, let us reconsider the theoretical methods which we may employ to predict phenomena in collisions or reactions. In order to see how different angular-momentum states in the incident beam behave in the scattering process, we use so-called 'phase shifts'. We shall consider spinless and non-relativistic particles. We write the incident wave as

$$\psi(r, \theta) = e^{ikz},$$

where

$$k = p/\hbar,$$

j is the square root of minus one, r and θ are polar co-ordinates, and z is a variable equivalent to distance. The resultant wave, at large distances from the point of interaction, may be written in the so-called 'asymptotic form'

$$\psi(r, \theta) = e^{ikz} + f(\theta)e^{ikr}/r,$$

where f is the scattering amplitude. Thus the resultant wave will consist of the incident one and an outgoing spherical one. The latter's intensity will be dependant on the absolute square of the last term:
 $|f(\theta)|^2/r^2$.

We find that the differential cross-section in our elastic scattering process is given by

$$d\sigma/d\Omega = |f(\theta)|^2.$$

If we derive this cross-section in terms of eigenvalues and eigenfunctions of the Schrödinger equation, then we find that it is a summation of Legendre polynomials. The summation index, l , is usually identified with the orbital angular momentum of states contributing to the scattering amplitude. Different orbital momentum waves are known as 'partial waves'. For each partial wave in a scattering process, we define a phase shift, δ_l , which is zero if no interaction occurs. We find that the highest-spin partial wave which contributes to the scattering is given by

$$\delta_{l_{\max}} \sim pr,$$

where $r_0 = 1.4$ fm, the range of the strong interaction, and p is the momentum of the incident beam. The phase shift, δ_l , is dependant on l , and when it equals 90° , as we have mentioned before, that spin state causes a resonance peak.

We may obtain a number of important results by considering the forward scattering amplitude, $f(0)$, for $\theta = 0$. For backward scattering $\theta = 180^\circ$. By considering partial wave phase shifts, we obtain the important so-called 'optical theorem':

$$\text{Im } f(0) = \sigma_T / 4\pi\lambda,$$

where σ_T is the total reaction cross-section and λ is the de Broglie wavelength of the incident beam over 2π . Although the optical theorem is usually derived with reference to elastic scattering processes, it is also true for inelastic ones.

Obviously,

$$d\sigma/d\Omega(0^\circ) = (\text{Re } f(0))^2 + (\text{Im } f(0))^2.$$

At high energies,

$$\text{Im } f(0) \gg \text{Re } f(0),$$

and thus, by the optical theorem

$$d\sigma/d\Omega(0^\circ) \propto p^2,$$

where p is the c.m.s. momentum.

In inelastic processes, we find that the phase shift factors become complex numbers. In order to avoid the necessity of manipulating these, we define a new variable:

$$\eta_i = e^{2it\delta_i}.$$

We then find that

$$\sigma_{\text{el}} = \pi\lambda^2 \sum (2l+1) |1 - \eta_i|^2,$$

$$\sigma_{\text{inel}} = \pi\lambda^2 \sum (2l+1)(1 - |\eta_i|^2),$$

$$\sigma_T = 2\pi\lambda^2 \sum (2l+1)(1 - \text{Re } \eta_i).$$

Thus zero absorption corresponds to $|\eta_i| > 1$, and complete absorption to $|\eta_i| = 0$. We find that, for total absorption by a 'black disk' of radius R ,

$$\sigma_T \sim 2\pi R^2.$$

However, we might have expected that

$$\sigma_T = \pi R^2.$$

This is not true, because, apart from inelastic contributions to the scattering amplitude, there is an elastic contribution caused by diffraction around the target. For particles with spin, phase shift analysis becomes considerably more complicated, and we must define at least two amplitudes: the spin-flip one, and the nonflip one.

CHAPTER SIX: SYMMETRY AND STRUCTURE.

In 1960 and 1961 respectively, following Ohnuki's suggestion, Gell-Mann and independently Ne'eman and Salam applied Lie's theory of groups to subatomic particles. Gell-Mann named his theory the 'Eightfold Way' after an aphorism attributed to Buddha. Before we discuss the $SU(3)$ group symmetry upon which this theory is founded, let us consider the simpler group of $SU(2)$ or $R(3)$. In 1949 Fermi and Yang suggested that pions could be considered as combinations of nucleon-antinucleon pairs. As we showed in chapter 5, nucleons and pions can combine together to give final states with $I = \frac{1}{2}$ or $I = 3/2$. Using multiplicities, we might represent this fact symbolically:

$$3 \otimes 2 = 4 \oplus 2.$$

Using the Pauli matrices (see chapter 4) we find that two nucleons can combine together to give a triplet and a singlet, or

$$2 \otimes 2 = 3 \oplus 1.$$

However, it is obvious that we can not build other subatomic particles using nucleon-nucleon pairs, since they will all have $B = 2$. For this reason, we apply the G operator (see chapter 4) to one of the nucleons to transform it into its antiparticle. If we now consider the nucleon-antinucleon wave function, we get a triplet:

$$p\bar{n}, -n\bar{p}, (n\bar{n} - p\bar{p})/\sqrt{2},$$

and a singlet:

$$(n\bar{n} + p\bar{p})/\sqrt{2}.$$

We find that the triplet has $B = 0$, $J = 0$, $P = -1$, $G = -1$, and the singlet has $B = 0$, $J = 0$, $P = -1$, and $G = +1$. Fermi and Yang had no difficulty in recognising the triplet as the pions, and we can now say that the singlet is the η^0 . It is important to note that the singlet state is invariant under C and G operators, and that it is impossible to transform it in a single operation into any member of the triplet. Members of the triplet may be transformed into each other by rotations about various axes in i -space.

An obvious defect of the Fermi-Yang model is that it does not incorporate strange particles. Sakata proposed to remedy this by enlarging the group to include also the Λ particle and its antiparticle. It is customary to plot the possible resultant states so that I_3 is plotted along the abscissa, and S or Y along the ordinate. We find that we have nine possible combinations, of which only $(n\bar{n} + p\bar{p} + \Lambda\bar{\Lambda})$ is invariant under the C and G operators. This is the $SU(3)$ singlet, which is usually identified with the eta prime particle (η'). Our eight other combinations represent the kaon and antikaon doublets, the pion triplet, and the eta singlet. On our graph, we find that the combinations form a hexagon, so that we have three particles at the centre. We say therefore that, in terms of waves:

$$\pi^0 = (n\bar{n} - p\bar{p})/\sqrt{2},$$

$$\eta^0 = (n\bar{n} + p\bar{p} - 2\Lambda\bar{\Lambda})/\sqrt{6},$$

$$\eta'^0 = (n\bar{n} + p\bar{p} + \Lambda\bar{\Lambda})/\sqrt{3}.$$

However, if we attempt to apply the Sakata scheme to baryons, we run into difficulties, because we get no states at all with the required $B = 1$. If we try and build up $B = 1$ groups using such combinations as $p\bar{n}\Lambda$, we run into difficulties because we predict a particle $p\bar{n}\Lambda$, with $B = 1$, $S = +1$, which has not been found in nature. In 1964 G.zweig and Gell-Mann independently suggested the existence of three truly fundamental particles with $B = 1/3$ and fractional charges, so that baryons would be combinations of three of these, and mesons combinations of these and their anti-

particles. These new particles were named quarks (from 'Finnegan's wake', by James Joyce) or aces by Gell-Mann. We shall discuss them at a later stage.

We see that for baryons we have groups as follows:

$$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10.$$

Let us try and identify these supermultiplets, as they are called, and the particles in them. The first baryon octet has $J^P = \frac{1}{2}^+$, and contains the nucleon and xi doublets, the sigma triplet, and the lambda singlet. We notice that we have two particles, the Σ^0 and Λ^0 , for which $I_3 = S = 0$. Thus we invent two new compound particles, defined as follows:

$$\Sigma_u = \frac{1}{2}(\Sigma^0 + \sqrt{3}\Lambda^0),$$

$$\Lambda_u = \frac{1}{2}(\sqrt{3}\Sigma^0 - \Lambda^0),$$

where the symbols for particles represent their wave functions, which are superposed. Squaring the amounts of each pure wave (see chapter 2) in the final wave, we see that there is a probability of $\frac{1}{2}$ of finding the Σ_u as a Λ^0 , and a probability of $\frac{1}{4}$ of finding it as a Σ^0 . Similarly, there is a probability of $\frac{1}{4}$ of finding the Λ_u as a Λ^0 , and a probability of $\frac{1}{2}$ of finding it as a Σ^0 , so that the theoretical and experimental probabilities are similar. The bottom line of the baryon decuplet with $J^P = \frac{3}{2}^+$ appears to contain the $\Delta(1236)$ resonance. The triplet is $\Sigma(1385)$ and the doublet is $\Xi(1530)$. However, when the 'Eightfold Way' was first proposed, there existed no singlet to fill up the top line of the triangle. It was predicted to have $Q = -1$, $I = 0$, and $Y = -2$. If we work out the mass differences between successive lines of the decuplet, we find that, in terms of masses,

$$P - \Xi = \Xi - \Sigma = \Sigma - \Delta$$

where P is the new particle. Thus Gell-Mann predicted that the new particle should have a rest mass of about 1673 MeV. This mass-difference rule in the decuplet is known as the 'equal-spacing rule', and we shall meet it again when we discuss the mass formulae of the 'Eightfold Way' more generally.

Gell-Mann predicted the decay modes

$$\Omega^- \rightarrow \Xi^- + \pi^0$$

$$\Omega^- \rightarrow \Xi^0 + \pi^-$$

$$\Omega^- \rightarrow \Lambda^0 + K^-$$

for the new particle, which he named the Ω^- . In about 1962, a massive search was mounted for this particle. At Brookhaven, a beam of magnetically-separated K^- 's with an energy of 5 GeV were made to hit a liquid hydrogen target in an attempt to produce the reaction

$$K^- + p \rightarrow \Omega^- + K^+ + K^0$$

for which the relativistic threshold energy was calculated to be 3.2 GeV. Finally, in late 1964, after 100 000 photographs of the Brookhaven bubble chamber had been taken, the Ω^- was finally identified by scanners, because in this particular case, the two gamma rays from the π^0 in the Ω^- decay both materialised into e^+e^- pairs within the bubble chamber. Soon after, an experiment at CERN, using a 6 GeV momentum beam of protons, confirmed the Brookhaven findings, and identified the decay

$$\Omega^- \rightarrow \Xi^- \pi^0$$

The discovery of the Ω^- particle was one of the greatest victories for SU(3) and perhaps for the whole of theoretical physics. To date, over thirty events containing the Ω^- have been observed, in some of which the decay

$$\Omega^- \rightarrow \Lambda^0 K^-$$

has been identified. The best value for the Ω^- mass, from track-length and angle measurements in bubble chambers is 1672.4 MeV, and the best value for its lifetime

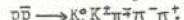
is 1.3×10^{-10} s. The leaders of the team which discovered the Ω^- were J.Jensen, N.Samios, W.Tuttle, R.Shutt, N.Webster, W.Rowler, and D.Brown. Soon after the discovery of the Ω^- , another search was started for its antiparticle, the Ω^+ . It was obvious that, since both the Ω^- and the Ω^+ have $|S|=3$, they would only be very rarely produced. However, it was expected that there should be equal production rates for both particles. The Ω^+ was only discovered early in 1971. At the Stanford Linear Accelerator Centre (SLAC), a beam of electrostatically-separated kaons with an energy of 12 GeV were directed into a bubble chamber containing liquid deuterium. After half a million photographs had been taken and scanned, the Ω^+ was finally identified, with the decay mode



It had travelled 2.5 cms through the bubble chamber liquid, and thus its lifetime was calculated as about 1.5×10^{-10} s, about the same as that of the Ω^- .

Apart from the Regge occurrence supermultiplets, there were also expected to be recurrence supermultiplets. The first of these to be found was a recurrence of the octet, with a J^P of $5/2^-$. It is thought to consist of the resonances $N(1688)$, $\Lambda(1815)$, $\Sigma(1765)$, and possibly $\Xi(1820)$. There is also a recurrence octet with $J^P = 3/2^-$, containing $N(1512)$, $\Lambda(1520)$, $\Sigma(1660)$, and some currently undiscovered Ξ resonance with a mass ~ 1600 MeV. The occurrence singlet is probably $\Lambda(1405)$.

The mesons are usually grouped into nonets, although strictly they should be in octets and singlets. The meson octet, like the baryon octet, has an 'identity crisis' with two particles having the same quantum numbers: the π^0 and the η^0 . The singlet is usually taken to be the η' or χ^0 particle, with mass 958 MeV, although some favour the E meson produced in the reaction

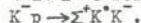


The status of the meson singlet is in doubt, and it possible that the $\eta(549)$ and $\eta'(958)$ particles should be considered as a mixed particle. The other 'identity crisis' is solved in a similar way to the baryon one, by creating the two new particles

$$\pi_u = \frac{1}{2}(\pi^0 + \sqrt{3}\eta^0),$$

$$\eta_u = \frac{1}{2}(\sqrt{3}\pi^0 - \eta^0).$$

This first octet (or nonet) of mesons with $J^P = 0^-$ are usually termed pseudo-scalar, due to the fact that their spin behaves like an asymmetric scalar in space. The next octet is the vector octet. It is thought to contain the $\rho(765)$, $\omega(783)$, K^* and \bar{K}^* (890) resonances, and to have the $\phi(1020)$ as its singlet. There is no direct evidence that $I=0$ for the ϕ , but the reaction



in which charged ϕ 's would be plentifully produced, has been studied extensively, but no charged ϕ 's have been observed. The octet has $J^P = 1^-$. The last nonet known with any certainty is the tensor nonent, with $J^P = 2^+$. Its members are usually taken to be $f(1264)$, $A_2(1297)$ (see chapter 5), $K^*(1400)$, and $f'(1514)$. No further meson supermultiplets have been predicted with any certainty, although, by extrapolation, the next one should be called the 'eight-vector' nonet.

Let us now consider more carefully the first baryon octet. Apart from the baryon octet there is also an antibaryon octet. The two may be transformed into each other on our graphs by reflection in the point $Y=0$, $I=-1$. If we join the three particles of equal charge (the Ξ^0 , Σ^0 , and N^0) in the baryon octet, then we have drawn a line which can be considered as the axis of V_3 , where V is a new quantum number very similar to isospin. If we now join up the Ξ^0 , Σ^0 , and N^0 , we have created an axis of U_3 , where U is another quantum number similar to isospin, and sometimes called unitary spin. Thus we have three axes inclined at 120° to each other, so that geometrically we

can see that for any particle in the octet

$$U + V + I = 0;$$

so that one of these quantum numbers is redundant. We choose this to be V . Just as the particles with the same values of I are said to be isotopic multiplets, so the particles with the same charge and hence the same values of U are said to be unitary multiplets.

We may deduce that, in order to move from any particle in our octet to any other particle in the octet, we must use one of six step operators which are defined as follows:

T_+ and T_- leave Y unchanged but change I_3 by ± 1 ,

B_+ and B_- change Y by ± 1 and I_3 by $\pm \frac{1}{2}$,

C_+ and C_- change Y by ± 1 and I_3 by $\pm \frac{1}{2}$.

This is important as it helps us to predict certain facts concerning the U , V , and I quantum numbers and axes.

$SU(3)$ symmetry in nature is not quite perfect $SU(3)$ because it is broken by the different values of U - and i -spin for particles in the same supermultiplet. We know that the mass splitting along the I_3 axis between particles in the same isotopic multiplet is caused by their different charge, and by the non-conservation of i -spin in the electromagnetic interaction. Using perturbation theory, we can say that the difference from the 'bare' mass of a particle, Δm , caused by the electromagnetic interaction, is the same for all members of a unitary multiplet. Hence we see that

$$\Delta m_{\pi^0} = \Delta m_\eta$$

$$\Delta m_{\pi^+} = \Delta m_{\pi^-} & c.$$

Adding these, we obtain the Coleman-Glashow formula

$$m_p + m_{\pi^0} + m_{\pi^0} = m_{\pi^+} + m_{\pi^-} + m_\eta$$

which can be rearranged as

$$m_\eta - m_{\pi^0} = (m_{\pi^+} - m_{\pi^-}) - (m_\eta - m_p).$$

This is found to be very accurate and to agree very well indeed with experimental mass estimates.

Similar to the mass splitting encountered along the I_3 axis due to the electromagnetic interaction, we can also attribute the mass splitting along the U_3 axis to a new interaction which we call M or the medium strength interaction, which treats particles with different 'U-charges' in a different way. Ne'eman suggests calling the new interaction the Xenodynamic field and suggests that its quantum might be the $\phi(1020)$ particle. It is possible to show that mass is linearly related to U_3 , and thus

$$M = a + bU_3,$$

so that the M interaction is a combination of a vector and a scalar in U -space. In the quark model, the difference in masses of particles in a unitary multiplet could be explained by assigning different masses to each of the quarks. There might be a difference of about 100 MeV caused by the medium strong interaction in the masses of the doublet and the singlet, and a difference of about 1 MeV between the members of the doublet, caused by the electromagnetic interaction. Remembering the Σ_u and Λ_u particles, we can obtain the famous Gell-Mann - Okubo mass formula:

$$(m_u + m_{\pi^0})/2 = (m_{\pi^+} + 3m_\eta)/4.$$

One side of this comes to 1127.2 MeV and the other to 1134.8 MeV, which is comparatively good agreement. This mass rule is a special case of the more general relation

$$M = a + bY + c(I(I+1) - \frac{1}{4}Y^2),$$

where a , b , and c are constants depending on the supermultiplet. This leads to the so-

called 'parallelogram rule' of Matthews and Feldman, which states that if 1, 2, 3, and 4 are particles at the corners of a parallelogram in any supermultiplet, then $m(1) - m(2) + m(3) - m(4) = 0$.
This is well borne out by experiment.

For mesons, we can also use the Gell-Mann - Okubo formula. With the same rules as for the baryon octet, the η^0 mass was predicted to be 615 MeV - slightly more than it was found to be. It was noticed that the mass equations for mesons worked much better if the squares of the masses were used, and the eta mass was then predicted as 567 MeV. The proposed justification for the use of m^2 is that the wave equation for bosons involves m^2 , while that for fermions only involves m . Thus we have, for example, the relation

$$m_A^2 = \frac{1}{4}m_1^2 + \frac{3}{4}m_2^2,$$

where the subscripts represent the i -spin of the multiplets in question. Using a formula of this type, we obtain a mass of about 928.9 MeV for the ω^0 in the vector octet. However, its true mass is only 782 MeV. In 1962 Sakurai proposed a remedy for this, and suggested that mixing occurred between the singlet and the $I=0$ particle in the meson octet. He said that the mixing was due to the medium strong interaction, which breaks $SU(3)$ symmetry. Using wave mechanics, we can write the amount of mixing for each octet in terms of an angle. We find that the $\eta^0 - \eta^0$ mixing in the pseudo-scalar mesons is about 10.4° , so that the η^0 nearly obeys the Gell-Mann - Okubo formula. In the vector octet, the $\omega^0 - \phi^0$ mixing is about 39.9° , and in the tensor octet the $f^0 - f^0$ mixing is about 29.9° . It is because of this mixing that the mesic $SU(3)$ octets and singlets are sometimes referred to as nonets.

Since the magnetic moments, μ , of particles are eigenvalues of the I_3 operator, we can predict an equal-spacing rule such that

$$\mu_{z^+} + \mu_{z^-} = 2\mu_{z^0}.$$

Since the electromagnetic interaction is independent of U-spin, we can also say that

$$\mu_p = \mu_{z^+},$$

$$\mu_n = \mu_{z^-},$$

$$\mu_\Lambda = \mu_{z^0} = \mu_{\Sigma^0}.$$

Remembering the Σ^0 and Λ particles, we have

$$\mu_\Lambda = \frac{2}{3}\mu_{\Sigma^0} + \frac{1}{3}\mu_n,$$

$$\mu_{z^0} = \frac{1}{3}(3\mu_n - \mu_{\Sigma^0}).$$

In the limit of exact $SU(3)$, all the quarks have zero charge, zero strangeness, and equal masses. Thus we may say that the net magnetic moment of the baryon octet is 0, since the violations of $SU(3)$ symmetry are symmetrical about the I_3 and U_3 axes. Putting together all our magnetic moment equations, we can make the following predictions:

$$\mu_{z^+} = \mu_p$$

$$\mu_{z^-} = -(\mu_n + \mu_\Lambda) = \mu_{z^0}$$

$$\mu_{z^0} = \mu_n$$

$$\mu_\Lambda = \mu_n/2$$

$$\mu_{\Sigma^0} = -\mu_n/2.$$

The observed values are: $\mu_p = 2.79$, $\mu_n = -1.91$, $\mu_{z^+} = 2.4$, $\mu_\Lambda = -0.70$, in units of $eB/2Mc$, where M is strictly the nucleon mass, but probably it is more accurate to take it as the mass of the particle in question. These values agree comparatively well with our theoretical predictions.

Let us now consider how we might measure the magnetic moment of, for example, the Λ^0 . In 1965, Charrière et al., working at CERN, used the following method. Λ^0 's were

created by a 1 GeV pion beam interacting with a liquid hydrogen target. The Λ^0 's produced were then polarised at a normal to the production plane, and made to traverse a uniform magnetic field of strength B . The particles then precessed with the Larmor frequency, which is given by

$$\nu_L = \mu_N B/h,$$

so that in a time t , the particle will altogether have rotated through
 $\Theta = \mu_N B t / h$ radians.

If $t = 3 \times 10^{-6}$ s, and $B = 2 \times 10^5$ G, then we find that $\Theta \approx 0.3$ rad. by analysing Λ decays in a stack of nuclear emulsions. This yields a value of $-0.70 (\pm 0.07)$ for the magnetic moment of the lambda particle. Similar experiments conducted by the same team fixed the Σ^+ magnetic moment as $2.4 (\pm 0.6)$. The 'Eightfold Way' also makes predictions about total cross-sections for various reactions, but the agreement between these and current experiments is relatively poor.

Various enlargements of the 'Eightfold Way' have been suggested over the last few years, of which we shall discuss two. The first is the orbital excitation model for quarks given by Dalitz at Oxford. He suggests that in mesons, the QQ pair may rotate about each other with a relative orbital angular momentum $1\frac{1}{2}$. We can define a quantum number C called C-parity such that if the wave of a particle is invariant under the charge conjugation operation, the $C=+1$, if it is not, then $C=-1$. The mesons proposed by Dalitz must have some specific properties. Their P-parity must be given by

$$P = (-1)^{s+1},$$

and if $S=0$ for the meson in question, its C-parity must be given by
 $C = (-1)^{s+1}$,

where s is its total angular momentum. Thus, for any natural $S=0$ resonant meson $C=P$, according to the Dalitz model. We find that this model gives comparatively good agreement with observation for the pseudo-scalar and vector mesic nonets, but more research needs to be done in order to establish or fault the theory. There is also, of course, a corresponding orbital excitation model for the quark triplets in baryons, though this is considerably more complicated.

The second is the more elaborate symmetry derived from $SU(3)$ and called $SU(6)$. We can obtain a symmetry $SU(4)$ by the addition of a supplementary quantum number, which we call C, and thus our hexagons become three-dimensional, with I_3 , Y, and C along the axes. We know that a particle of spin J has $2J+1$ possible projections or alignments in real space. We say that this number is the particle's spin multiplicity, and it is described by $SU(2)$ formalism. We can now apply this spin multiplicity to $SU(3)$.

Spin-projecting each of the quarks, we have the 'group equation':

$$6 \otimes 6 \otimes 6 = 20 \oplus 70 \oplus 70 \oplus 56.$$

Let us consider our 56-plet. We find that it is divided up into the four spin projections of the baryon $3/2$ decuplet and the two spin projections of the $1/2$ octet. We may represent this as

$$56 = (2,8) + (4,10),$$

where the first numbers in the brackets are the particles' spin multiplicities, and the second numbers are their $SU(3)$ multiplicities or supermultiplicities. In the groups containing 70 members, we find that we have some 27-plets. These contain the so-called 'exotic' particles with $S=2$ and so on. We find also that if we multiply the baryon $J=1/2^+$ by the pseudo-scalar meson octets, we obtain a 64-plet which appears to consist of many of the resonance particles currently known. If we multiply the first mesic octet by itself, we get some of the mesic resonances, and if we multiply the first baryon octet by itself we get some bound states of two baryons. The only recognisable one of these seems to be the deuteron.

Let us now consider the quarks or aces themselves. Their properties are summarised in Appendix A.1. We see that they have fractional electric charges of $2/3$ e and $-1/3$. Current quantum mechanics assumes that this type of charge is impossible in this universe, though there is no theorem to prove it, and no experiment to conclusively demonstrate it. It is possible that $1/3$ e is the basic charge in the universe, though if this is the case, we need some new theory to account for the charges on the electron and muon, because, since these are not hadrons, they can not be composed of quarks according to current theories. Quarks are denoted by A, B, and C, or Q_1 , Q_2 , and Q_3 , or sometimes, with analogy to Sakata's model, p, n, and Λ , in which case they are sometimes referred to as 'sakatons'. It is not at present certain whether quarks actually exist, or whether they are simply hypothetical generators for the SU(3) supermultiplets. The main argument against the physical existence of quarks seems to be their fractional charge, and it is for this reason that Schwinger has proposed his trions. He postulates that these must be of two types: baryonic, S, and analogous to Sakata's pn Λ group, and leptonic, L, and analogous to the e μ ν group. In order to distinguish between these two types of trions, we must introduce a new quantum number, A. A has been given such names as supercharge, magic, charm, wit, and so on. We find that

$$Q = I + (Y/2) + (A/3)$$

for any particle. A must obey new conservation laws.

The quarks form themselves into a nonstrange isotopic doublet and a strange singlet. The members of the doublet probably have lifetimes of about three minutes, and the singlet probably about a millennium. It seems likely that the quarks are bound together very tightly, perhaps by a 'superstrong' force, in deep potential wells, in the observed subatomic particles, thus making their free observation difficult. Let us now discuss the wide search for free quarks, which started in 1964 and is still going on now.

The masses of the quarks are not at all certain, but it seems likely, considering the failure of all experiments to detect free quarks to date, that it is very high (~ 1 TeV), and that the masses of ordinary subatomic particles simply represent the masses of their constituent quarks minus a large bonding energy. There seem to be two main methods of quark search which are being pursued: first, there is the search for less-than-minimum ionisation in track-forming particle detectors, and second, there is the search for fractionally-charged particles in matter.

We know that particles with charges of $1/3$ and $2/3$ e will produce $1/9$ and $4/9$ of the ionisation of a singly charged particle travelling at the same speed, thus making fainter tracks than usual in a bubble chamber. In 1964 Blum et al. scanned 1.5×10^5 tracks from the liquid hydrogen bubble chamber at the CERN proton synchrotron, and located nineteen faint tracks. However, the sensitivity of a bubble chamber varies with time, and it was found that in these nineteen cases, the oscilloscope showed that an early beam had arrived 1 or 2 ms before the maximum sensitivity of the bubble chamber, thus causing the low-density tracks. A somewhat different technique was used by experimenters at the 70 GeV proton synchrotron at Serpukhov. By clever use of targets and momentum-analysing magnets Antipov et al. in 1969 produced a beam in which singly-charged particles would have a momentum of 80 GeV, and quark momenta would be 26.7 or 53.4 GeV depending on charge. From this experiment the quark mass was shown to be above 4.5 GeV and the cross-section of quark production for 70 GeV protons on aluminium was shown to be less than $3 \times 10^{-37} \text{ mm}^2$.

Much quark searching has been done in both primary and secondary cosmic rays. On board the Russian satellites Proton 3 and 4, quark-hunting apparatus was sent into

Earth orbit, but drew a blank. A typical example of an experiment on secondary cosmic ray showers is that performed by Gomez et al. in 1967. They sandwiched two spark chambers, with dimensions 50.8×50.8 cm, in between scintillation counters, and measured the energy loss in particles traversing the apparatus. Altogether 1.5×10^8 cosmic ray particles passed through the detector, but no quarks were found. Experiments of this type have established that the quark flux at 450 m above sea-level is less than 1.5×10^{-12} quarks/ m^2 s sr. However, in 1969, McCusker and Cairns found tracks which could be attributed to quarks. On the top of a high mountain, they placed an expansion cloud chamber which was triggered by a counter array. It was expanded 100 ms after triggering, and a photograph was taken 100 ms after expansion. During a year of operation, four low-density tracks were recorded. Unfortunately, many points remain to be answered concerning these tracks, primarily because the behaviour of the cloud chamber gas is not properly understood. However, since the energies used to trigger the McCusker-Cairns experiment were $\sim 3 \times 10^6$ GeV, we may have to rely on primary cosmic rays for our study of quarks for some time, if this is about their threshold for production.

If quarks have been bombarding the Earth for a long time, then we might expect to find some of them trapped in matter. This hypothesis has been the basis for many experiments. A typical example of these is that conducted by Chupka, Schiffer, and Stevens in 1966 on seawater. They evaporated large quantities of this and passed it between charged plates. The negative ions from the plates were then transferred to a positive filament, and the evaporation rate from this was observed when a given potential difference was created across it. Similar methods were used to test air, meteorites, and dust samples. Millikan's method for establishing the charge on the electron has been used extensively in searching for quarks. One elegant method of trying to detect quarks trapped in matter is the magnetic levitometer used by Becci, Gallinaro, and Morpurgo, in 1965. Using a concave magnet, they levitated particles with masses of up to 5×10^{-7} g, which is 50 000 times the mass of a typical Millikan droplet. When alterations are made in the magnetic field, the particle is displaced by $d = n\delta$,

where n is an integer and δ is the displacement for a singly-charged particle, which is about 250 μ m. If there are any quarks in the sample, then it will be displaced by $d = (n \pm 1/3)\delta$.

Displacements are measured using an optical microscope. The large number of particles observed in this and other experiments sets a lower limit of no quarks in 2×10^{12} nucleons.

Symmetries based on truly elementary particles, such as the quark model, are termed hierarchical, and those which do not consider some particles to be more elementary than others, are termed democratic. The best example of one of the latter type of symmetries is the 'Bootstrap' hypothesis developed by Chew and Frautschi. The name is derived from the eighteenth century character Baron Münchhausen. The theory is not concerned with the leptons and photon, and terms these the aristocracy. The rest of the particles are said to form a democracy. The theory was first formulated to explain Mandelstam's hypothesis concerning the self-consistency of the strong interaction with regards to scattering amplitudes. In chapter 5 we discussed Feynman diagrams, which lead to the so-called 'Feynman Rules' which include the fact that the reactions



and so on, are equivalent because of 'crossing'. Thus we may say that the forces

in the first reaction are due to its crossed equivalent (see chapter 5). From knowing the physical scattering amplitude in our first reaction, we may deduce the t-channel forces at work, and from these, we may again deduce the physical scattering amplitude. Hence the physical scattering amplitude is determined by itself, and not by any external Hamiltonian or interaction potential. This property of the scattering amplitude is known as self-consistency. However, the scattering amplitude in the crossed reaction is not only determined by the original reaction, but also by so-called 'cuts' from practically every other strong interaction. Thus, all the scattering amplitudes in strong reactions are connected to each other by complicated consistency relations.

At low energies, we can use the bootstrap hypothesis in a limited way to make various predictions. In practically every calculation concerning the strong interaction, a Cauchy formula containing the denominator $(z - z_0)$ will appear, where z and z_0 are some combinations of the Mandelstam variables. At low energies we assume that the value of z is small, and hence, in order to make $1/(z - z_0)$ as large as possible, we must have a correspondingly small value for z_0 . We hope that our calculation will be dominated by large values of $1/(z - z_0)$, and hence small values of z_0 . This assumption is known as the 'dominance of nearest singularities'. Accepting this, we see that only at low energies are our reactions significantly influenced by their crossed equivalents which determine forces. However, as we saw in the last chapter, the most important features of a low-energy scattering amplitude are the poles or singularities which correspond to bound states and resonances. This implies that the forces in a reaction are mostly determined by resonances which appear in its crossed equivalents. Let us take the example of pion-pion scattering. This must be dominated by the rho resonance formed in its crossed reaction. But, once we know the forces at work in a reaction, we are then able to calculate the resonances which will appear. In the case of the pion-pion reaction, the most important of these is the rho meson itself. Thus, by considering the rho as a force, we create the rho as a particle. This process was named 'bootstrapping' by Chew.

Thus we see that, according to the bootstrap model, the set of particles and forces in Nature is wholly self-consistent, and thus that the universe as it is now is the only possible one. It is possible that such intrinsic properties as SU(3) symmetry and CPT (see chapter 7) are purely consequences of self-consistency. However, further consideration of the implications of 'Bootstrap Dynamics' lies more in the field of philosophy than physics, and there is little doubt that Leibnitz or Spinoza would have agreed with the bootstrap hypothesis.

Let us now consider the internal structures of subatomic particles. We can see that a particle such as the neutron must be spatially extended, because it has an overall neutral charge, and yet it possesses a measurable magnetic moment, so that it must be divided into at least two parts: one with a negative charge, and one with an equal positive one. We define two quantities known as form factors for subatomic particles with finite magnetic moments. We say that, for elastic electron scattering from an extended particle with zero magnetic moment

$$\delta_T = \delta_{\text{POINT}} |F(q^2)|^2,$$

where F is the so-called 'charge form factor' and q is the Lorentz invariant four-momentum transfer (see chapter 5). Obviously, for a pointlike particle with zero magnetic moment, $F=1$. For a particle with magnetic moment, we must define a second form factor, G , which describes the magnetic distribution of the particle. The total cross-section is connected to F and G by the Rosenbluth formula, which assumes that only one virtual photon is ever exchanged, as in the Born approximation.

Let us now consider how we might conduct practical experiments into the form factors and internal constitutions of particles. The first successful experiments of this type were performed by Hofstadter et al. at Stanford University in the late 1950's. It was known that the radius of a subatomic particle was in the order of 1 fm. Hence, using de Broglie's formula, Hofstadter was able to calculate that he would need electrons with an energy of at least 1 GeV. Hofstadter set up a liquid hydrogen target in the path of the high-energy electron beam, and measured the momentum and line-of-flight of either the scattered electron or the recoil proton or both. In order to study e-n scattering, Hofstadter replaced the liquid protium target by a deuterium one. At large q^2 Hofstadter found that the scattering amplitudes were about 10^{-3} times that from a pointlike particle, and hence he concluded that the nucleon was 'mushy'. He deduced the so-called scaling law which states that $F_p(q^2) = (G_p(q^2)) / |\mu_p| = (G_n(q^2)) / |\mu_n|$. This rule has been verified in the 0 - 10 GeV energy range.

By applying a Fourier transformation to the values of F and G , it was possible to build up a picture of the basic internal structure of the nucleon. The charge of the proton was found to fall to zero only at a distance of about 1.4 fm from its centre, which explained the discrepancies between Hofstadter's results and earlier ones obtained by scattering particles from atomic nuclei. The mean radius of the nucleon was calculated as about 0.74 fm. Hofstadter calculated that the charge distribution of the proton corresponded closely with the Gaussian or normal curve. He proposed that the proton consists of a bare pointlike nucleon surrounded by a spinning meson cloud which spends a few tenths of its time outside the nucleon.

Attempts were soon made to interpret Hofstadter's results in terms of strong interaction dynamics. In 1957 Nambu postulated the existence of a new particle, which mediated the reaction between the nucleon, now assumed to be structureless, and the virtual photon. This particle must be neutral and must have a J^P of 1^- , making it a neutral vector meson. It must also, in order to be similar to the photon, have odd C-parity. In 1959, Chew also suggested that there must exist a scalar meson. The only comparatively low-mass candidates for these mesons were ρ^0 , ω , and ϕ . ω and ϕ have $I=0$, and ρ^0 has $I=1$. We define an isoscalar form factor such that

$$F_S = \frac{1}{2}(F_p + F_n),$$

and similarly with the magnetic form factor, and an isovector form factor such that $F_V = \frac{1}{2}(F_p - F_n)$.

We find that

$$F_T = F_S + F_V,$$

$$F_0 = F_S - F_V.$$

As Nambu and Chew pointed out in 1960, F_S is the same for the proton and neutron, suggesting that it is a scalar in isospin space, whereas F_V is of opposite sign for the two nucleons, corresponding to two different projections in i-space. Nambu suggested that the scalar could be a tri-pion resonance, and the vector could be a di-pion resonance. Although he predicted too low masses for these particles, they were nevertheless quickly found (see chapter 5). Using multipion resonances, it is now possible to explain most comparatively low-energy e-N scattering experiments. A new theory is that the nucleon's cloud, which could contain even virtual pairs of strange particles, is excited by high energies, in a somewhat similar manner as orbital atomic electrons are excited. It is even possible that the nucleon resonances are simply ground-state nucleons with excited clouds. Searches are being conducted to investigate this theory, working on the hypothesis that, when it is excited, the

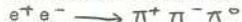
charge of the nucleon cloud is slightly increased. It is possible that, near the centres of nucleons, many-pion resonances exist simply to stop the nucleons from collapsing inwards from the sheer strength of the strong interaction.

In about 1968, Panofsky et al. studied energetic collisions at around 20 GeV c.m.s. at SLAC between electrons and nucleons. They found that, at a sufficiently high energy, the form factor of the nucleon became scale invariant and lost its linear dependence on q^2 . Thus the nucleon appeared to behave like a pointlike particle at high enough scattering energies. In 1969, Feynman and independently Bjorken and Paschos suggested the so-called 'parton model'. This predicts that the nucleon core is composed of very massive and tightly-bound pointlike particles called partons. At very high momentum transfers, a single parton only can be affected in the scattering process, and can be considered as completely independent of its neighbours. An analogous situation is encountered in electron-nucleus collisions at high energy. In this case, when the impulse is large enough, a nucleon can become 'quasi-free' for the scattering process. We find that the ratio of magnetic to electric scattering from partons implies a parton spin of $\frac{1}{2}$. This is also the tentative spin assignment given to quarks, and hence it is very tempting to connect partons with quarks.

In 1972 Litke, Wilson, et al. studied the yield of particles from high-energy electron-positron collisions in the newly-built storage rings at SLAC. At low energy the ratio of muon-antimuon to hadron-antihadron pair production is roughly 1:1. In 1967 and 1968 experiments had been carried out at Orsay and Novosibirsk with low-energy electron-positron collisions which had verified this ratio and had shown that rho, omega, and phi particles were produced most plentifully. Measurements at Orsay by Augustin et al. in 1969 showed that the reaction



demonstrated a Breit-Wigner type peak probably corresponding to the rho meson, and with a correct bandwidth and mass. Experiments on the reaction



yielded predominantly phi mesons. At Novosibirsk pion-antipion collisions were observed, and the square of the pion form factor was plotted against c.m.s. energy. This departed markedly from unity, and hence it was concluded that the pion was not pointlike. Furthermore, a Breit-Wigner type peak was formed around 760 MeV c.m.s., which almost certainly represents the formation of rho mesons. However, in 1971, experiments were conducted at Frascati with 2 GeV colliding electron-positron beams which yielded extremely high cross-sections for pion production, forcing some physicists to believe that the pion is pointlike.

At energies below about 1350 MeV in the c.m.s. the ratio of muon to hadron production is about 1:1, and below about 1100 MeV most of the hadrons produced are pions and multipion resonances. But experiments at Frascati and Cambridge (U.S.A.) show that at about 4 GeV the ratio of hadron to muon production becomes about 4:1. According to the parton model, hadron production occurs as follows: the positron annihilates the electron and both turn into a high-energy gamma ray. This then materializes into a virtual quark-antiquark pair, which is transformed, possibly by the superstrong interaction, into hadrons. When the SPEAR 2.5 GeV electron-positron storage ring came into operation at SLAC in early 1974, one of the first experiments to be attempted was the measurement of the hadron-muon production ratio. The scaling law predicts that this ratio should remain constant, but Richter managed to show that, at a high enough energy, it increased linearly with energy, despite the fact that neutrino experiments at Batavia tended to confirm the scaling law. Information at

3 GeV from Frascati (ADONE) and 5 GeV from Cambridge confirms Richter's results. The parton-quark model predicts that hadron-muon production should occur in the ratio of the squares of the charges of the particles concerned, which implies a ratio of 2:3, which is certainly incorrect. It postulates that this ratio should be constant, and that hadron (and hence muon) production should decrease as $1/E^2$. Neither of these predictions appear to be at all correct. By considering the so-called 'coloured quark' model, which concerns the nine SU(6) quarks, we may obtain a ratio of 2:1, but this is still not correct.

One idea for explaining the increase in hadron production at high energies is that the nonet containing the rho prime (ρ') particle is responsible. The ρ' was discovered in 1973 at SLAC, during collisions between a relativistic electron beam and a LASER beam. 10 GeV photons were produced, and these were made to interact with protons in a liquid hydrogen bubble chamber. Before interaction, some of the photons materialized into ρ' mesons, and these decay by the mode

$$\rho' \rightarrow 4\pi.$$

Altogether two million bubble chamber photographs were taken and analysed by Chadwick and Rosenfeld, and in about 350 of these, a rho prime decay was found. The ρ' has a mass of about 1600 MeV and the amazingly large bandwidth of 500 MeV.

Despite the disencouraging results of electron-positron collisions, the quark model does predict that different quarks will contribute to the scattering amplitude according to the squares of their charges, and new results from CERN with high-energy neutrino beams verify this. Feynman now suggests, since it seems that quarks will not be released from particles with currently-obtainable energies, that the super-strong interaction's strength is independant of distance, and that hence infinite energy will be necessary to separate quarks.

CHAPTER SEVEN: INTERACTIONS.

Physicists talk of two kinds of fields: classical fields and quantum fields. It seems probable that the former is simply a macrocosmic manifestation of the latter, which is the only type of field existing in nature. A classical field can be imagined as a liquid which has a definite velocity or strength and direction of flow. But the quantum field can not be visualised as a smooth, flat, liquid; instead it consists of fluctuating particles, which can, according to the Uncertainty Principle (see chapter 2) only be described quantitatively, as in the classical field. Thus, the smaller the object under observation, the more it tends to fluctuate with the field's quanta. The same type of thing occurs with Brownian motion: the smaller and lighter the particle in a liquid or gas, the more it is influenced by the random buffetting of molecules. In the late 1940's, Lamb and Rutherford almost conclusively proved the correct nature of the quantum field by observing the fluctuations of a hydrogen atom in a microwave cavity resonator.

When electromagnetic theory and Maxwell's wave equations were first proposed, physicists tried to produce mechanical models of the medium which actually oscillates in accordance with the wave equations. For this purpose they invented the ether, which they believed filled the whole of space-time, and oscillated at the bidding of the electromagnetic field equations, just as air does to produce sound waves. But, after much effort had been spent on this useless theory, the Special Theory of Relativity and the Michelson-Morley disproof of the ether wind by interferometry finally brought about its downfall, and the Maxwell equations began to be considered simply as equations which describe experimentally observable parameters and phenomena, and which do not have any real physical significance.

Let us first consider the interactions between particles in a non-relativistic manner. We might think that the force acting upon a given particle depended upon the position of that and other particles, and that if the position of a particle changed, this would be sensed instantaneously by the other particles because of the change in field strength. However, Relativity Theory tells us that no signal of any kind can travel faster than the velocity of light in vacuo, so that when one particle moves, the change in field strength on another particle is not sensed at least until the time that it would take light to travel between the two particles has passed. The earliest solution to this problem was the introduction of a classical field which propagated in all directions from a particle at a speed not exceeding the speed of light, and which could influence the motion of a particle going through it even before the light-signal could reach the second particle. This field was always spread out, and, like an aircraft passing through a cloud, any particle could be influenced immediately when it entered it. A further important distinction between the non-relativistic and the relativistic classical fields, is that the non-relativistic one only needs a finite number of parameters to describe it completely, because by describing the positions and velocities of P particles interacting through a non-relativistic classical field, we can predict the future behaviour of these particles. However, an infinite number of parameters are necessary to define a true classical field, because it has an infinite number of degrees of freedom, and it is necessary, for example, to describe the state of every particle and field in the universe, before the state of our initial field can be determined.

Another important feature of the relativistic classical field is that it predicts that a certain fraction of the total energy of a particle system will reside in the field. This is in fact necessarily the case for any relativistic field-mediated theory of particle interactions. The reason for this is not difficult to see: consider a system of three particles, P, Q, and R. P and Q are interacting with each other via a field, when R suddenly collides with P. This then causes a change in the strength of the field applied by P at the location of Q, and thus the state of motion of Q will change after at least the time necessary for a light-signal to pass from P and Q. This change in Q's state of motion will almost certainly be accompanied by a change in its kinetic energy, T, and so an exchange of energy will have taken place between the particles P and Q via the field of P. If we are to accept the law of the conservation of mass-energy, then we must conclude that energy resides in the field of P at least between the time when R collides with P and the time when Q changes its kinetic energy. If, in our model, the particle Q is absent, P will still radiate just as much energy through its field as when Q is there, and so we must decide where this wasted energy goes to. Certainly, if our field is an electromagnetic one, then the collision of our two charged particles will result in the production of some electromagnetic energy, in the form of a light wave, which will be absorbed at infinity. In 1927 Dirac quantised the electromagnetic field by considering it as a superposition of harmonic oscillators, and thus he explained the emission and absorption of light by atoms. In the following year Jordan and Wigner quantised the electron field, and in 1930 Fermi described the difficulty in quantising the Coulomb field, which holds electrons in their atomic orbits. Two years after that, Dirac, Fock, and Podolsky quantised the complete electromagnetic field including the Coulomb field, and began the science of quantum electrodynamics, which is the quantised study of electromagnetism.

We can describe the cross-section for a given reaction (see chapter 5) in terms of the matrix element M_{ba} , which is a measure of the physical probability of state a becoming state b. We find that the transition rate, R, from a to b is given by

$$R_{ba} = M_{ba} \rho(E_i),$$

which is often referred to as Golden Rule number 2 in quantum mechanics, where $\rho(E_i)$ is a kinematical factor called the density of states, which gives the number of available energy states per unit energy range. In our crude approximations it is good enough to assume that $\rho(E_i) \sim 1$. In general, we find that

$$(R_{ba})^2 \sim g^2,$$

where g is a new constant depending on the type of interaction, and called the coupling constant for that interaction. We have already come across this constant in chapter 3, during our discussion of Yukawa's hypothesis. For the electromagnetic interaction, $g_{em}^2 = e^2/\hbar c$,

where e is the electronic charge. This constant is known as the fine structure constant, α , because it determines the magnitude of the splitting in atomic spectra caused by the existence of electron spin. The currently acknowledged value of α^{-1} is 137.0388(6). Remembering our definition of decay from chapter 5, we see that a decay by the electromagnetic interaction will take about

$$T = R_0/c,$$

where R_0 is the range of the electromagnetic interaction. Thus T is found to be in the order of 10^{-16} s, which is comparatively slow for subatomic reactions. Decay by the electromagnetic interaction is said to be a weak interaction. In fact, the weak interaction laws would have to be broken if the decay were by another interaction. Electromagnetic decay is defined as decay in which real or virtual photons play a part. The net result

of an electromagnetic decay need not necessarily contain a photon, as in
 $\gamma^{\circ} \rightarrow \pi^0 + \pi^- + \pi^+$,
which is definitely electromagnetic. Often an electromagnetic reaction is noticed by the time it takes.

Let us now consider the gyromagnetic ratios of the electron and muon, which are charged and thus subject to the electromagnetic interaction, but do not take part in strong reactions. We know that the magnetic moment, μ , associated with a particle of spin s and mass M is given by

$$\mu = g_s (e\hbar)/2Mc,$$

where g is the Landé or g -factor of the particle, which was first used in 1961 by Eisberg in atomic spectroscopy. We find that

$$e\mu_s = \mu/s,$$

where μ_s is the Bohr magneton, and μ/s is the gyromagnetic ratio of our particle, that is, the ratio of magnetic to mechanical moment. The currently acknowledged value of the Bohr magneton is $9.2732(2) \times 10^{-24}$ JT. Dirac's theory for pointlike particles with $s = \frac{1}{2}$ predicts that they should have $g = 2$. However, the g -values of the electron and muon have been measured, and a very noticeable departure from the value of 2 has been observed. Let us now consider how we might measure the anomalous magnetic moment of the muon, or the departure of its g -value from 2. For many years, measurements were made of the muon's magnetic moment and then correlated with its mass to obtain its g -factor, but the limit imposed on the accuracy of mass measurements caused a 10% error in the anomalous magnetic moment value. The most accurate value obtained by this method was that of Hutchinson, Menes, Patlach, and Penman at CERN, using the G-2 apparatus. They measured the precession of the muon's spin axis, as indicated by the preferential emission direction of electrons in decay, and thus found its magnetic moment. They used the value of the muon mass obtained by Rainwater by observing x-rays emitted by muonic and ordinary atoms. A much more direct method was employed by Bailey et al. at CERN in 1968. They stored muons produced in pion decay in a storage ring, and again used the emission direction of decay electrons, but this time they calculated the precession period of the anomalous magnetic moment of the muon, and obtained the value of 1.16616×10^{-3} for it. This implies that the laws of quantum electrodynamics remain valid down to a distance of about 2×10^{-11} m or more. From arguments based on the difference in the Earth's magnetic field due to longitude, we can also say that quantum electrodynamics is correct even when dealing with distances of over 5×10^8 m. Thus quantum electrodynamics is one of the most universal of all principles.

We know that it is possible to think of electromagnetic interactions between particles as due to the virtual exchange of photons. Because of the law of the conservation of mass-energy it is obviously impossible for a stable particle to emit a real photon. The mass-energy-time uncertainty relation forbids the exact observation of a particle's mass, but there is no corresponding uncertainty relation relating to electric charge. Thus it is possible that we may be able to detect slight changes in the electron or muon's charge due to the emission of virtual photons, and thus electron-positron pairs. The amount of correction necessary to Dirac's estimate is proportional to the probability of photon emission, which is determined by α . In fact, anomalous magnetic moment has the form of a perturbation series in α , which gives the theoretical value of 1.159641×10^{-3} , agreeing well with experiment.

Let us now consider the enigmatic muon. It seems that it differs only in mass from the electron, and so there seems no reason for which Nature could need both a muon

and an electron, and their corresponding neutrinos and conservation laws. In 1972 Ross suggested that the muon was a composite particle consisting of an electron with a zero mass particle in orbit around it. Ross named this new particle the 'wavon', and postulated that it must have a spin of one. From Relativity Theory we know that the space-time continuum is bent around a massive body, and using this fact, Ross has shown that the mass of his muon model should be 206.55 MeV, which is very close to the observed value of 206.77. The wavon must interact only by the gravitational interaction, making the muon an excellent testing-ground for Relativity. It seems that the wavon could easily be a $\bar{v}_e - v_\mu$ pair, which is attractive, because it accounts for the decay of the muon. But Ross' hypothesis can probably only be tested in high-energy electron-muon scattering, and experiments on this have been started at SLAC. It is now possible to measure transition energies in muonic atoms to an accuracy of one part in 10^4 . In 1972 Sunderesan and Watson measured the energies of 400 keV transitions in barium and lead. They corrected for electron screening, relativistic effects, and vacuum polarisation caused by $e^+ - e^-$ pairs, but still found an unexplained extra 70 eV in their x-ray energies- more than the measurement uncertainty by a few orders of magnitude. The new unified theory of the weak and electromagnetic interactions by Weinberg at MIT predicts a new meson with a mass of around 8 MeV. If this meson coupled strongly with the muon and only weakly with the electron, then it would account for this residual shift and explain the existence of the muon. Much research is currently being performed to find Weinberg's scalar meson.

But the electron and muon are not the only particles which possess anomalous or Pauli magnetic moments. According to Dirac's theory, the magnetic moment of the proton should be 1 nuclear magneton (n.m.), and that of the neutron should be zero. However, the observed values are: $\mu_p = 2.79$ n.m. and $\mu_n = -1.91$ n.m. Thus the anomalous magnetic moments of the proton and neutron are roughly equal but are opposite in sign. Since the nucleons are hadrons, and $g_{\text{strong}}^2 \sim 1$, whereas $g_{\text{em}}^2 \sim 1/137$, we should expect some considerable anomalous magnetic moment, and this is yet another argument for the spatial extension of the nucleons (see chapter 6).

We have discussed the strong interaction at some length in chapters 5 and 6. However, it is very complicated and there is still no universal theory for it, and it has many more interesting characteristics which we have not yet considered. Its coupling constant is dimensionless and varies from reaction to reaction, but in general $g_{\text{strong}}^2/\hbar c \approx 15$.

In the late 1950's experiments began to be performed on the forces binding together the components of the deuteron. It was found that the strong part of the forces could be divided into at least two sections: a central part and a non-central part. The central component was the same for all relative directions of particles, whereas the non-central component's strength changed according to the relative spin orientations of particles interacting through it. But the deuteron is a very simple strongly-bonded system, with only two particles in it, each having their spin axis in the same direction, and a considerable number of fermis (femtometres) apart. Better experiments were carried out on scattering of high-energy nucleons by targets of protons, deuterons, or heavier nuclei. It was found that when the total spin of a nucleon system was zero, the non-central part of the strong force vanished, thus proving that it was spin-dependent. But this tensor non-central component is not the only non-central part of the nuclear force. Apart from intrinsic angular momentum, any particle system must have orbital angular momentum. Thus we find that for particles with parallel spins, there is a vector non-central force dependent on their orbital momenta.

Different scattering graphs caused by different values of orbital momentum are termed 'S-wave', 'P-wave', and so on, according to the atomic spectroscopy lettering (see chapter 5). The higher the energy of the incident nucleon beam, the more high-l waves contribute to the scattering process.

Let us now consider how we might find out about the complexities of the strong interaction experimentally. In 1953 Oxley et al., using the 240 MeV Rochester synchrocyclotron, found that high-energy proton beams were strongly polarised when they were scattered from hydrogen targets. Immediately, other groups, notably at AERE Harwell, Liverpool, and California, took up the study of nucleon scattering and obtained similar results. Theorists realised that these could be interpreted in terms of the non-central components of the strong force, because all spin-up particles would go to one side, and all spin-down ones to the other, if the strong nuclear force consisted purely of a tensor component. A second target was used to ascertain the different strengths of the force according to the N-N distance and relative spin. If the strong interaction consisted purely of a central force, then we should expect no asymmetry in a double-scattering experiment, which is not what occurs. Various triple-scattering experiments have been carried out by Segre, Chamberlain et al., and these have yielded even better results. In recent years it has been possible to polarise particle beams and targets, thus allowing the degree of disorder resulting from the complexity of the strong interaction to be monitored. Unfortunately, it has not been possible to polarise pure hydrogen in targets, and so organic compounds such as glycol, butanol, and hydrated lanthanum magnesium nitrate must be used instead. Usually about 1% of the sample by mass consists of free protons. The targets are then placed in high magnetic fields of between 18 and 40 kG, and are cooled to below 1K. For $T = 1K$, and $B = 20 \text{ kG}$, using the formula

$$P_z \approx e^{-\mu_p} B / kT,$$

where P_z is the degree of polarisation and k is the Stefan-Boltzmann constant, we find that we have approximately 0.2% polarisation, which is good. The currently acknowledged value of the Stefan-Boltzmann constant is $1.38054(6) \times 10^{-23} \text{ J K}^{-4}$.

According to the calculations of Signell, Bryan, Gammel, Thaler, and Marshak, a very complicated picture of the nuclear force is revealed, containing two central and two non-central forces. The only simple part of the force is that the n-n coupling is identical to the p-p coupling, and thus the force is truly charge-independent, and the basis of Heisenberg's isospin (see chapter 4) remains. New results indicating that hadron-hadron cross-sections continue to rise between 20 and 60 GeV, despite ideas to the contrary, have just been obtained using the CERN ISR, which opens up interesting room for speculation.

Only 10^{-51} times as powerful as the strong interaction, and perhaps the most curious of all the forces in nature, is gravitation. However, in contrast to its extreme weakness and insignificance on a microcosmic scale, gravity can make stars collapse and crush matter out of existence in gravitational collapse. This occurs when a body is compressed below its gravitational or Schwarzschild radius, which, for a man is about 10^{-25} m . From earliest times, scientists have studied the effects of gravity on massive bodies, and the movements of these bodies. But even now, no firm picture of the nature of gravity has been produced. Einstein believed, and attempted to prove, that, just as the oscillation of a charged body produces electromagnetic waves, so the oscillation of a body with mass produces gravitational waves. In 1918 Einstein published a famous article in which he outlined his ideas concerning gravity. He said that it was caused by the bending of space-time, hence the famous experiment

of the starlight which was bent by 1.75" when passing the sun, and that gravitational waves could exist which propagated about the universe at the velocity of light. These gravity waves must carry energy, but it has been calculated that the Earth has only emitted 0.001 W of energy in the form of gravity waves during the last billion years, causing it to fall 10 nm towards the sun in its orbit. In 1958 J. Weber of Maryland University began a search for gravitational waves. He used as his detector a number of large aluminium cylinders suspended on thin wires in vacuo. Each weighed about 1400 kg and were about 153 cm long. Optical methods of detection for the oscillations of the cylinders were precluded by the accuracy required, and so Weber bonded a number of piezoelectric crystals onto his cylinders and monitored their electrical output. After a decade of work, he announced that he had found gravity waves with a frequency of about 1660 Hz. Although many physicists dismissed his results as due to seismic activity and the like, a number of other gravity wave detectors were built and some were sent into orbit. A detector was even taken on board the moon flight of Apollo 15, but it failed. Detectors at Tel-Aviv found, in 1972, a considerable amount of gravitational radiation coming from the pulsar CP 1133, and later from the galactic centre, and this has caused three British research teams, at Reading, Bristol, and Glasgow, to begin their own gravity wave experiments. It seems likely that more results from these types of experiment will be forthcoming in the near future.

Despite the comparative success of the gravitational wave experiments, in 1959, Dirac quantised the gravitational field. we know that

$$R = M/mc,$$

where R is the range of an interaction, and m is the mass of its quantum. Since the range of gravity is infinite, m must be zero. Thus the graviton, as the quantum of gravity has been named, has zero mass. It has been calculated that it must have $J = 2$, and this consideration led Bohr, in 1933, to postulate that the graviton was simply a bound state of a neutrino and an antineutrino or some similar neutrino structure. However, it is known that gravity treats all massive bodies equally, independent of the magnitude of their mass. This consideration led Einstein to propose that gravity was simply a curvature in the continuum, and that hence the speed of gravity was infinite. No conclusive experiment to measure the speed of gravity has been performed to date. It can be shown that, whereas it takes a charged particle about 10^{-4} s to emit a virtual or a real photon, it should take it nearly 10^{60} s, or 10^{55} years to emit a graviton, so that graviton detection is extremely difficult. It seems possible that the proton and electron, whose lifetimes have been established as greater than 2×10^{24} and 2×10^{21} years respectively, may decay by the gravitational interaction.

In 1955 an interesting proposal was made by Dirac, which has lately been revived by F.Hoyle and his followers. Dirac realised that any unified theory of gravity and electromagnetism would have to account for the magnitude of the ratio of the electromagnetic coupling constant to the gravitational one. Taking two pions as his objects, he obtained the value of

$$e^2/m_\pi^2 G$$

for this ratio, where e is the electronic charge and G is the gravitational constant. The current value of G is $6.670(5) \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$, thus making this ratio $\sim 10^{19}$; and a numeric. The age of the universe was then estimated to be about 5×10^9 years, and, taking a non-arbitrary unit, this age was found to correspond to Dirac's ratio. The non-arbitrary unit was the time taken for light to cross a subatomic particle

of radius about 3×10^{-13} m, which is $\sim 10^{-21}$ s. Since Dirac found no reason to suppose that the electronic charge was increasing with time, he suggested that instead, the gravitational constant was decreasing with time, which would account for the observed expansion of the universe. However, Teller pointed out that this would imply that the surface temperature of the Earth in the pre-Cambrian era would have been 150°C, but paleontologists have retorted that this would explain the non-emergence of higher forms of life during this period.

Despite the fact that Relativity Theory forbids it, some physicists have suggested that gravity may exert a repulsive force on antimatter. Since large pieces of antimatter are not currently available, the best choice of material is a beam of positrons with very low energy. In 1968 a team led by W. Fairbank at Stanford University produced positrons by the following means: the particles were initially generated by a radioactive source, and were then trapped in a magnetic bottle. Every ten seconds, a gate was opened, allowing them to pass into another bottle, this time with electrically resistive walls. These dissipated most of the positrons' kinetic energy, and the particles were then allowed out of the second bottle at a rate of about one per second. On average they had energies of less than 100 neV. The positrons were then allowed to fall or rise in screened copper tubes, kept on course by a supermagnet. Experiments are still being carried on in this vein, but no conclusive evidence has yet come to light.

Probably the second most curious interaction after gravity is the weak, universal, or Fermi interaction. This was first noticed by Fermi in the so-called 'beta decay' process

$$n \rightarrow p + e^- + \bar{\nu}_e.$$

The rate of this decay is characterised by the square of the Fermi constant, G, which is about $1.4 \times 10^{-45} \text{ Jm}^3$, and kinematic factors. A dimensionless measure of the strength of the weak interaction can only be obtained if we define a length, because the quantum of the weak force has probably not yet been discovered, and so its mass is not known. If we take the Compton wavelength of the pion as our dimension of length, we obtain a coupling constant $\sim 10^{-7}$ for the weak interaction. The Compton wavelength of the pion is the amount by which the de Broglie wavelength of the pion is increased due to the Compton Effect (see chapter 2). There appear to be three basic types of weak reaction: leptonic, semileptonic, and nonleptonic. Leptonic reactions are those which contain only leptons, for example

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu,$$

the decay of the muon. Semileptonic reactions contain both leptons and hadrons, either strange or nonstrange, for example

$$\Lambda^0 \rightarrow p + e^- + \bar{\nu}_e,$$

the beta decay of the lambda particle. Nonleptonic reactions occur between hadrons only, and are characterised by

$$|\Delta S| = 1.$$

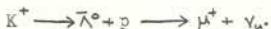
As example we might take the decay of the charged kaon:

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^+.$$

As Puppi suggested in the 1950's, all the leptonic, semileptonic, and nonleptonic weak processes can be accounted for in terms of six basic four fermion couplings and various virtual strong reactions. We know that in Feynman diagrams for weak processes, there will always be one weak coupling and an arbitrary number of virtual strong ones. Thus, for example, it would be valid to say that the decay usually represented as

$$K^+ \rightarrow \mu^+ + \bar{\nu}_\mu,$$

in fact occurred as



Puppi summarised much of our current knowledge of weak reactions in his tetrahedron. The vertices of the tetrahedron are $p\bar{n}$, e^+v_e , $p\bar{\Lambda}$, and $\mu^+\nu_\mu$. The legs of the tetrahedron, representing the possible weak couplings are

- C: $p\bar{n} e^+v_e$,
- D: $p\bar{n} \mu^+\nu_\mu$,
- E: $e^+v_e \mu^+\nu_\mu$,
- F: $p\bar{n} p\bar{\Lambda}$,

G: $p\bar{\Lambda} \mu^+\nu_\mu$ and H: $p\bar{\Lambda} e^+v_e$

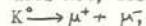
The three legs F, G, and H all involve a change in strangeness of ± 1 , and the other legs of zero. Thus, in a first-order weak process, $|\Delta S| = 0$ or 1, forbidding such reactions as



These may appear as second-order weak processes, but their rates would be very small, and no process of this type has been observed to date. First-order weak reactions involving more than two neutrinos also appear to be forbidden, and none have been found, but no physical significance has yet been attached to the Puppi tetrahedron. Experimentally it has been found that the coupling constant is roughly equal along all the legs of the tetrahedron, although vector and axial vector couplings appear to be opposite in sign, but N.Cabibbo has lately proposed a method of accounting for this. It is not yet known if the vertices of the tetrahedron are linked to themselves, either in their own tetrahedron or the charge-conjugate of it, but the reaction $e^+ + e^- \longrightarrow v_e + \bar{v}_e$ is thought to assist in star-cooling (see chapter 4).

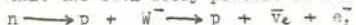
In 1973 the NAL 500 GeV accelerator was put into operation at Batavia, U.S.A. Among other experiments performed there, the first-ever high-energy neutrino interactions were studied. The 500 GeV protons from the main synchrotron were directed at a target, producing a shower of kaons and pions. These were allowed to decay in a 400 m decay tube, and the decay products were filtered by 1 km of earth. According to the Fermi theory of the weak interaction, the effective cross-section of neutrino interactions should increase linearly with neutrino energy in the c.m.s., but results showed that at 300 GeV the weak interaction was not nearly as strong as Fermi had predicted. They also found the disturbing result that the cross-section for antineutrino reactions was only about a third of that for neutrino reactions, when it should have been equal. However, these results are very new and it is possible that they are due to some experimental inaccuracy. The 'damping' of the weak interaction could be explained by the existence of a massive quantum of the weak force, and the NAL experiments have set a lower limit of 2000 MeV on its mass.

For many years, the search for the weak vector boson or W particle, the quantum of the weak force, has been going on, and from experimental facts about the weak interaction, we may deduce some of the properties of the W particle. To account for the six coupling in the Puppi tetrahedron and their charge conjugates, there must be both a W⁺ and a W⁻ particle. A W⁰ particle need not exist, and it seems likely that it does not, because of the low occurrence of decays like



which would require a neutral intermediate particle. The W particle may decay into any of the vertices of the Puppi tetrahedron, since it is coupled to all of them. The upper limit on the lifetime of the W, from theoretical considerations, appears to be 10^{-17} s, and so it would not be observable directly in a bubble chamber. We assume

that the beta decay process of the neutron is



and thus the spin of the W is 1. It is therefore a vector particle, because its three spin projections can be thought of as three-dimensional vectors. According to the Fermi theory of weak interactions, particles should interact at a point, even at high energies, but the experiments at NAL in 1973 showed that they did not. Theoretically, if there is a W , then the point interaction theory should fail at distances below $\hbar/m_W c$.

Although the W could theoretically be found in any of the reactions it mediates, it is very unlikely that it should become free in one of these, and so it was necessary to think of another reaction in which the W was produced in order to set up formation experiments. The best reaction, with the highest theoretical cross-section was found to be:



In about 1966 high-energy neutrino experiments were set up in CERN and Brookhaven, and in 1973 one was set up at NAL, Batavia, but all these have so far been unsuccessful, and a lower limit of 2 GeV has thus been set on the W mass. In 1964 various eminent theorists proposed that, like a strange particle, the W could take part in strong reactions when it was in a pair, and only weak ones when it was on its own. In 1965 P.Kabir and A.Kamal showed that this theory could not be reconciled with the low muon flux they found in gold mines unless the mass of the W was greater than 10 GeV. In 1967 J.Keufell and H.Bergeson started experiments on the cosmic ray muon flux in a 2000' deep silver mine in Utah. According to the conventional theory that the muons were due to pion and kaon decay in the atmosphere or rocks, there should have been more muons at lower angles where the atmosphere is not so tenuous, and the primary cosmic ray protons have a higher probability of interacting. However, the Utah physicists showed that there was roughly equal cosmic ray flux from all directions, and Bjorken attributed this to the W particle. He suggested that W particles were created in the atmosphere by cosmic ray collisions, and that the W decay muons, which were roughly isotropic, had their spin axes predominantly in one direction, while those resulting from pion and kaon decay had them mostly in the other direction. The muons from W decay were thought to be more likely to be absorbed in the rocks, and thus, as detectors are placed deeper and deeper in the Earth's crust, the muon distribution should become more and more non-isotropic. By 1971, the Utah physicists had obtained some 200 000 results, and from these they calculated that the W mass was about 36 proton masses. In the same year experiments were started in England by Wolfendale, in the 220 to 5000 GeV range, which should soon confirm or refute the findings at Utah.

However, in August 1973, a new massive particle perhaps corresponding to the W particles was found in cosmic rays. Since no momentum-analysing magnets strong enough to be used on cosmic rays of energies around 1 TeV currently exist, the only method of obtaining an absolute measure of cosmic ray particle energies is to use an ionisation calorimeter. This consists of a large piece of iron, carbon, or lead in which incident high-energy particles produce electron-photon showers whose energies can be measured by conventional proportional counters and so on. In 1969, W.Kellermann, G.Brooke, and J.Baruch built a single interaction ionisation calorimeter (SINC) in which only the first of the electron-photon cascades was monitored, instead of all of them, as in conventional detectors of this type, thus significantly decreasing both the cost and the size of the device. They installed their equipment at the main British cosmic ray research centre at Haverah Park, 800' above sea level. On average, their 4 m² detector found 3 cosmic ray events with an energy of more than 1 TeV per

day. They plotted the intensity of cosmic ray flux to energy on a graph and found that, unlike measurements made in space or on high mountains, theirs showed a distinct kink. For four years they attempted to find a flaw in their calculations or equipment, and they exposed the SINC to artificial particle beams from accelerators and monitored its reaction, but they could find no obvious way to account for the kink. In March 1973 the team reluctantly suggested the solution that they had found a new particle. The three possible candidates appeared to be the quark, the magnetic monopole, and the W particle. The magnetic monopole is a particle with only one magnetic pole, analogous to the electron, which has only one electrical pole. The team decided to name the new particle the 'mandela' after two South African political prisoners. From about 200 events in which the new particle is thought to have participated, its mass has been estimated at between 40 and 70 proton masses, and its lifetime to be greater than about 200 ns. The currently favoured suggestion is that the mandela is the W particle, because Weinberg's theory of weak and electromagnetic interactions postulates its mass as 38 proton masses, which is roughly the same as the Leeds team's findings. Already various other experiments have been started all over the world to hunt for mandelas, notably at Michigan and Leeds by W.Hazen and L.Hodson, and at Nottingham by P.Blake. The original team is also building a new Mark II detector, which should produce decisive results by mid-1974.

In chapter 4 we mentioned the discovery of two distinct decay modes for the K^0 meson, one with two pions, the other with three. Recalling the quantum number of parity, we see that if this is to be conserved in weak interactions, then the K^0 particle must have two distinct parities, which is impossible. Thus, in 1956, Lee and Wu suggested that parity was violated in weak reactions. We know that the momentum vector, p , changes sign under the parity operator, P , but the angular momentum vector, L , does not change sign because it is the product of the position and momentum vectors, both of which change their signs. In 1957, Wu, Ambler, Hayward, Hoppes, and Hudson set out to reveal non-conservation of parity in the beta decay of aligned cobalt-60 nuclei. If we apply the parity operator to the situation in which electrons are emitted in the same direction as the nuclear spin, then the new emission distribution should be a precise mirror image of the first. Wu et al. aligned their cobalt-60 source by putting it in a crystal of cerium magnesium nitrate, which exerts a strong internal magnetic field, and cooling the whole system to about 0.01 K by passing liquid helium around it. A magnetic field was then applied to the ^{60}Co nuclei. The reaction $^{60}\text{Co} \longrightarrow ^{60}\text{Ni} + e^-(0.312 \text{ MeV}) + \gamma(1.19 \text{ MeV}) + \gamma(1.32 \text{ MeV})$ was observed, and the angular distribution of decay electrons was ascertained by means of an anthracene scintillation counter. The counting rate was then graphed for nuclei with their spins up and with them down against time, and a clear anisotropy was revealed. Thus the law of parity conservation was broken. Within about six months of Wu's experiment, a group at the University of Columbia conducted a similar one on the distribution of electrons in muon decay, and found analogous results.

This caused them to suggest that the parity violation was due to the fact that the neutrino was biased towards a certain direction, and the antineutrino towards the other direction. They proposed the assignment of a new quantum number, helicity, H , or polarisation, P , to leptons and photons. They defined it by $H = (D^+ - D^-)/(D^+ + D^-) = \alpha v/c$, where D^+ and D^- represent the numbers of particles with their spin orientated along and against their direction of motion respectively. In the case of massless particles, such as the photon and the neutrino, $v/c = 1$, and hence H is a constant. For the

photon, $\alpha = +1$, and for the antiphoton $\alpha = -1$. Since the photon is its own antiparticle, or
 $C|\gamma\rangle = |\gamma\rangle$,

we should have an equal number of right- and left-handed photons in nature, since the electromagnetic interaction conserves parity. No indication of parity violation has been found in the electromagnetic interaction, except where its Hamiltonian mixes with that of the weak force. In 1957 and 1958, Frauenfelder, Cavanagh, and De Shalit independently found that $\alpha = 1$ for the e^+ , and $\alpha = -1$ for the e^- . The situation for the zero mass neutrino is analogous to that for the photon, so that the neutrino must be fully polarised. However, the neutrino is not an eigenstate of the C operator, and thus the neutrino must have some preference for its spin direction. In 1958 Goldhaber used an interesting experimental technique to ascertain the helicity of the neutrino. The europium isotope ^{152}Eu was made to capture an electron from its K shell, thus forming the excited state $^{152}\text{Sm}^*$. In order to preserve spin, the excited samarium isotope must have its spin antiparallel to that of the neutrino emitted. When the isotope returns to its ground state, it emits a 960 keV gamma ray. If the latter is emitted in a forward direction, it will have the same polarisation as the original neutrino, and if backwards opposite sense. Only the 'forward' gamma rays, with the same helicity as the neutrino are able to produce resonant scattering in samarium. The next task is then to determine the sense of the gamma rays emitted in $^{152}\text{Sm}^*$ decay. If the photons are made to pass through magnetised iron, then their polarisation will be reversed if the iron electrons have opposite sense by so-called 'spin-flip', but will remain unchanged if the spins are parallel. Having passed through a layer of magnetised iron, gamma rays were then made to hit a ring of Sr_2O_3 , and those which produced resonant scattering were detected by an NaI scintillation counter. By reversing the polarity of the iron's magnetic field, and watching the corresponding change in counting-rate, it was deduced that the neutrino had $\alpha = -1$, and was hence left-handed, and the antineutrino was right-handed. According to Dirac's theory for $J = \frac{1}{2}$ particles, their wave functions must be spinors, in four parts, corresponding to

- 1) the particle with spin up,
- 2) the particle with spin down,
- 3) the antiparticle with spin up,
- 4) the antiparticle with spin down.

However, because the neutrino has a definite helicity, only states (2) and (3) are available to it, and so its wave function has only two components. But in 1957 Eisler et al. found that parity was also violated in the decay

$$\Lambda^0 \rightarrow p + \pi^-$$

which does not contain a neutrino. The lambda particles, which were formed in the process

$$\pi^- + p \rightarrow \Lambda^0$$

were polarised, but with incident pion energies ranging from 910 to 1300 Mev, it was observed that 158 π^- 's in Λ^0 decay were emitted with their spins up, and 105 with their spins down, thus indicating a definite violation of parity. It has been found that in every weak process known parity is not conserved, and thus we must conclude that this is a permanent feature of the weak interaction.

In 1953 Schwinger produced a theorem which he called the CPT theorem. This was improved over the next two years by Lüders and Pauli, and now bears the name of the Lüders-Pauli theorem. It states that under the combined transformations, C, P, and T,

all properties of a particle system are invariant. This implies the existence of a corresponding antiparticle for every particle, and the equality of masses, lifetimes, and magnetic moments of antiparticles and particles. The only theories assumed by CPT are Lorentz invariance and microscopic causality, which states that no signal can travel, even over microscopic distances, faster than the velocity of light in vacuo. The equality of lifetimes for particles and antiparticles has been checked with muons, pions, and kaons to between 0.1 and 1% accuracy. By various means which we shall discuss later, the K^0 and \bar{K}^0 masses are known to be equal to one part in 10^{14} . We know that the muon and antimuon anomalous magnetic moments are equal to an accuracy of 0.001%, and in 1972 Fox et al., using the Brookhaven synchrotron, showed that the magnetic moment of the antiproton was roughly correct. The researchers trapped about a third of the screened antiprotons from the accelerator in uranium and lead targets. They then studied the fine-structure of a particular x-ray transition, and thus deduced the magnetic moment of the antiproton as -2.83 ± 0.10 nuclear magnetons.

An obvious test for C violation in the strong interaction would be to replace all particles by their antiparticles, and see, for example, if the cross-section for $p - \pi^+$ scattering was the same as that for $\bar{p} - \pi^-$ scattering. Unfortunately, this reaction is experimentally unobtainable, and so we must compare the rates of the reactions:

$$p + \bar{p} \rightarrow \pi^+ + \dots,$$

$$p + \bar{p} \rightarrow \pi^- + \dots.$$

By this method, the upper-limit to the C violating amplitude, f , in strong reactions has been established as 0.01. This has been confirmed by studies of $p\bar{p}$ annihilations into kaons and so on.

During the last decade, the search for C violation in electromagnetic reactions has been intense. There are basically three methods for checking C invariance in the electromagnetic interaction. The best one is concerned with the possibility of the existence of an electric dipole moment (EDM) for the neutron, but we shall discuss this later, since it involves T symmetry, which we have not yet considered. The other two methods both involve the electromagnetic decay of the η^0 particle. We may define a C parity for any particle. Due to the following argument we see that it must either be +1 or -1. If we apply the C operator to the π^0 wave, we have

$$C|\pi^0\rangle = k|\pi^0\rangle,$$

where k is a constant. If we now apply C a second time, we have

$$CC|\pi^0\rangle = +|\pi^0\rangle,$$

since the π^0 is its own antiparticle. Thus we see that

$$k = \sqrt{1} = \pm 1.$$

This proof can be extrapolated to other particles. For a particle which is invariant under C, i.e. is its own antiparticle, $C = +1$, and for other particles $C = -1$. The decay

$$\eta^0 \rightarrow \pi^0 e^+ e^-$$

is forbidden only by C-parity conservation, though even if C-parity were preserved in electromagnetic interactions, it could occur as a second-order process, but its branching ratio would be in the order of 10^{-5} . The $\pi^0 e^+ e^-$ decay mode has not been observed to date, and since $10^4 \eta^0$ decays have been observed altogether, this sets an upper limit of 10^{-4} on the branching ratio for this decay. However, this does not imply that the C-violating amplitude for the electromagnetic interaction $< 10^{-4}$, since the $\pi^0 e^+ e^-$ decay mode would be suppressed for reasons other than C-violation.

If there is a C-violating component in the electromagnetic interaction, then we

should expect some asymmetry in the c.m.s. energies of the charged pions in the decay $\eta^0 \longrightarrow \pi^+ + \pi^0 + \pi^-$.

In order to detect this asymmetry, we could either look for it in a relative energy or Dalitz plot of the pion energies, or we could define a parameter P such that $P = (N_+ - N_-)/(N_+ + N_-)$,

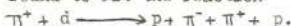
where N_+ is the number of events in which the c.m.s. energy of the π^+ was greater than that of the π^- , and N_- is the number of events in which the opposite is the case, and look for a non-zero value of it. In 1966 Chops et al. set up an experiment to study eta decay at CERN, Zurich, and Saclay. They used 713 MeV π^- 's in the process



to produce their η^0 particles, and detected the recoil neutrons by means of a circular array of 14 counters. Using a series of counters in anticoincidence, they ensured that no interaction besides η^0 formation had occurred in their hydrogen target, and that all the η^0 decay products entered their spark chamber. In order to compensate for the magnetic field applied to the spark chamber, they placed a magnet in front of the target. A total of 10 665 events were observed in this experiment, establishing a value of $0.3 \pm 1.1\%$ for P. Later in 1966, Larribe et al. conducted a slightly more accurate test. They produced η^0 's by the interaction of 820 MeV π^+ 's with a deuterium-filled bubble chamber in the process



Altogether 21 000 events were observed, of which, by kinematic analysis, 17 000 were found to fit the reaction



A few other events were discarded because of possible malfunctions in equipment, and the final value for P obtained was $-0.048 \pm 0.036\%$. In 1967, Baltay et al. and Fowler et al., using a similar experimental set-up to Larribe's, obtained values of $7.2 \pm 2.8\%$ and $4.1 \pm 4.1\%$ for P respectively. The latest value for P was obtained by Gormley et al. using Chops' method in 1968. They analysed a total of 38 518 events, which yielded the value of $1.5 \pm 0.5\%$. By looking at all the results obtained, we may conclude that any C-violating amplitude in the electromagnetic interaction is below 1%.

In 1939 Wigner introduced the time reversal operator T. If T symmetry is not violated, then any reaction can take place in either direction, and all physical laws are invariant with respect to the reversal of time or the interchange of signs for the t variable. We can see that in, for example, Newton's law,

$$F(x) = m \frac{d^2x}{dt^2},$$

nothing is altered by making t negative, because our expression is dependent on t^2 , not t. It would seem at first that time, and hence velocity, reversal for a stone falling and hitting the ground violated the law of gravity. However, if it were possible to reverse the directions of all the air molecules which were thrown outwards by the shock wave and so on, then we would produce exactly the right amount of energy, in the right direction, to make the stone rise again to its starting-point.

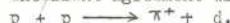
Although this event is allowed by physical laws, it was shown near the end of the nineteenth century, that it was disallowed by statistical ones. The second law of thermodynamics states that statistically a hot system always tries to become colder. Thus we may deduce that the entropy (S) of any system increases with time, and that therefore time reversal is statistically unacceptable for a macrocosmic system.

If the complete symmetry, CPT, is valid, then we should be able to produce an antiparticle by reversing the time variable for a given particle. It is on this principle that a positron is represented as travelling backwards in time on a Feynman

diagram. By finding a reaction which violates CP, we know that this reaction must also violate T correspondingly, in order to validate CPT. Assuming the validity of T symmetry, it is possible to prove the detailed balance theorem, which connects the cross-section of a given reaction and its T image. Since it does not require perturbation theory to prove, the detailed balance theorem must also hold good in electromagnetic and weak interactions as well as strong ones. The detailed balance theorem is

$$\frac{6(A \rightarrow B)}{\sigma(B \rightarrow A)} = \frac{p_x^*(2s_x + 1)(2s_y + 1)}{p_x^*(2s_x + 1)(2s_y + 1)},$$

where p_x is the momentum of the particle x, and s_x is its spin. Experimentally, excellent agreement with the theorem has been found by studying the reactions



T invariance in the strong interactions has been confirmed to an accuracy of 0.3% by observing the reaction



and comparing the results with the predictions of the detailed balance theorem.

Let us now return to the question of the enigmatic K^0 particle. Using complex field theory it is possible to prove that for a particle with odd C parity, its wave function must be of the form

$$\Psi = \Psi_1 + i\Psi_2,$$

where Ψ_1 and Ψ_2 are real. Using the continuity equations, we find that the wave function of the antiparticle of our initial particle must be

$$\Psi^* = \Psi_1 - i\Psi_2.$$

Since

$$C\Psi = \Psi^*,$$

we know that

$$C\Psi_1 = +\Psi_1,$$

$$C\Psi_2 = -\Psi_2.$$

For particles with even C-parities, such as the photon, $\Psi_1 = 0$. Since the K^0 and the \bar{K}^0 are distinct particles, because they can be shown to have opposite strangeness, they must both have $\Psi_2 \neq 0$. For charged particles, virtual transitions between particles and their antiparticles are forbidden by charge conservation, and similarly for baryons by baryon number conservation, but for K^0 - \bar{K}^0 virtual transitions, the only conservation law which must be broken is that of strangeness. Thus, as Gell-Mann and Pais predicted in 1955, mixing occurs between the K^0 and the \bar{K}^0 via the weak interaction. Since we have an equal probability of finding the K^0 and the \bar{K}^0 , we may write

$$\Psi_{K^0} = (1/\sqrt{2})(\Psi_1 + i\Psi_2),$$

$$\Psi_{\bar{K}^0} = (1/\sqrt{2})(\Psi_1 - i\Psi_2).$$

Since the K^0 and the \bar{K}^0 are obviously not eigenstates of the CP operator, Pais and Gell-Mann proposed the mixed wave functions

$$\Psi_{K_1^0} = (1/\sqrt{2})(\Psi_{K^0} + i\Psi_{\bar{K}^0}),$$

$$\Psi_{K_2^0} = -(i/\sqrt{2})(\Psi_{K^0} - i\Psi_{\bar{K}^0}).$$

We find that the K_1^0 has even CP-parity while the K_2^0 has odd CP-parity. It has been found that due to their differing CP-parities, the K_1^0 - K_2^0 mass difference is 3.55×10^{-6} eV, or about 10^{-4} m K^0 .

Let us now examine the CP-parities of the decay modes of the K^0 meson. As we mentioned in chapter 4, P-parity is defined by

$$P = (-1)^L,$$

where L is the orbital momentum of our system. Similarly, C-parity is defined by

$$C = (-1)^L,$$

and thus CP-parity is defined by

$$CP = (-1)^{L+1}.$$

Since the two pion system has $L=0$, its CP-parity is even. Thus, if CP-parity is conserved, the K^0 may only decay in the 2π mode, and the K_L^0 may not decay in this mode. By a similar method we may show that the 3π system has odd CP-parity, and thus only the K_L^0 may decay into a 3π channel. Since the 2π mode has a much larger kinetic energy of separation, Q , than the 3π one, Pais and Gell-Mann predicted that the K_L^0 would have a lifetime about a thousand times longer than that of the K^0 , and this was found to be the case. Due to this difference in lifetimes, the K^0 is sometimes represented as K_S^0 , and the K_L^0 as K_L^0 . An interesting property of a K^0 beam is a process known as regeneration. A beam produced in a reaction such as



should have an equal number of K^0 and K_L^0 particles in it initially. Using a xenon-filled bubble chamber, it has been shown that 0.53 ± 0.05 of all K^0 's decay by the 2π mode, so our hypothesis is correct. If we leave the beam for about 100 K^0 lifetimes, our beam should be pure K_L^0 's with wave

$$\Psi_{K_L^0} = (1/\sqrt{2})(\Psi_{K^0} - \Psi_{K^0}).$$

Thus it should be able to act both as an $S=1$, and as an $S=-1$ beam, and this was verified by Fry et al. in 1956, by observing hyperon production. However, if our beam passes through a target, the K^0 's and the K_L^0 's in it will be absorbed at different rates, since the K^0 particles can only undergo elastic charge exchange, whereas the K_L^0 's can interact to form hyperons as in



Thus, because it has more strong channels open, the \bar{K}^0 is absorbed more strongly than the K^0 . We have a K^0 amplitude $a\Psi_{K^0}$, and a \bar{K}^0 amplitude $\bar{a}\Psi_{K^0}$, and $\bar{a} < a < 1$.

With respect to decay, we may write that the beam is

$$(1/\sqrt{2})(a\Psi_{K^0} - \bar{a}\Psi_{K^0}) = \frac{1}{2}(a+\bar{a})\Psi_{K_L^0} + \frac{1}{2}(a-\bar{a})\Psi_{K^0}.$$

Since we know that $a \neq \bar{a}$, we must have regenerated a number of K^0 's, and this has been confirmed by experiment.

In 1964, while studying regeneration phenomena, Christenson, Cronin, Fitch, and Turlay, and independently Abashian et al. found a very small CP violating component in K_L^0 decay. Christenson et al. placed their detection apparatus 18 m from the target of the Brookhaven AGS, having filtered out gamma rays with a 4 cm layer of lead, so that they received a pure K_L^0 beam. The K_L^0 's then decayed in a large helium-filled bag, and the particles produced were detected by a pair of symmetrically-placed spark chamber spectrometers. Each of these spectrometers consisted of two spark chambers separated by a magnet and triggered by scintillation and Cerenkov counters.



decays were detected when two oppositely-charged particles entered the spectrometers simultaneously, and had typical pion momenta. It was calculated that regeneration phenomena in the helium bag could not account for the number of 2π decays observed. The ratio of $\pi^+\pi^-$ decay to all other charged decay modes was found to be about $(2.0 \pm 0.4) \times 10^{-3}$. By averaging the results of Christenson (1964), Galbraith (1965), Fitch (1967) and de Bouard (1967), we obtain the average value of $(1.90 \pm 0.05) \times 10^{-3}$

for our decay ratio. It is obvious to ask if we can also observe the decay
 $K^{\circ} \rightarrow \pi^+ \pi^-$.

In 1967 the gamma rays from this decay were made to materialise in thick plates at CERN; however, it was difficult to tell whether the decay mode was a 3π one with only two of the gamma rays materialising, or whether it was a true 2π one. But, by the so-called 'Monte Carlo' computer calculation, which compensated for unformed virtual pairs, a value of $(4.3 \pm 1.1) \times 10^{-3}$ was obtained for the ratio of $\pi^+ \pi^-$ decay to all other uncharged decays. The next year a similar experiment was carried out at Princeton, but here the c.m.s. energies of the gamma rays were measured by means of a spark chamber magnetic spectrometer. The $\pi^+ \pi^-$ decay is the only one in which gamma rays with energies greater than 165 MeV are produced. The Princeton group obtained the ratio $(4.9 \pm 0.5) \times 10^{-3}$ for $\pi^+ \pi^-$ decay. Around 1970, CP violations were also found in the decays

$$K^{\circ} \rightarrow \pi^{\pm} + \mu^{\mp} + \bar{\nu}_{\mu},$$

$$K^{\circ} \rightarrow \pi^{\pm} + e^{\mp} + \bar{\nu}_e,$$

by observing charge asymmetries.

Various theories, including some very far-fetched ones, were soon advanced to account for this violation of CP symmetry. One of these was that there exists a new long-range galactic field in which the potential energies of the \bar{K}^0 and the K^0 would be slightly different, thus making the K^0 and the \bar{K}^0 a mixture of CP-eigenstates in any region where there exists more matter than antimatter or vice-versa. However, this predicted that the rate for the 2π decay would be proportional to γ^{2J} , where J is the spin of the new field's quantum, and γ is the Lorentz factor, defined

$$\gamma = \sqrt{(1-v^2/c^2)},$$

and the rate was found to be independent of γ , and hence the velocity of the kaon beam. Another theory was that the Bose-Einstein statistics necessary to show that the $\pi^+ \pi^-$ state has even CP-parity were in error, but this was invalidated when $K^{\circ} \rightarrow 2\pi^0$.

was observed. Various suggestions concerning new particles produced in decay were discounted because they would prevent the degree of mixing observed between states. In 1965, Bernstein, Feinberg, and Lee suggested that the CP-violation in K^0 decay was caused by the violation of CP symmetry in the electromagnetic interaction, and they pointed out that the CP-violating component was $\sim \infty$. However, as we have already seen, this theory was found to be erroneous. The most popular theory at present is the superweak force theory proposed by Wolfenstein in 1964, and later by Bell, Perring, Bernstein, Cabibbo, and Lee. By comparing anomalous decay rates, we can deduce that the strength of this new coupling need only be 10^{-2} of that of the weak force to account for observed effects. The force would violate CP and T symmetry, but not CPT symmetry, and would allow strangeness transitions of 2 units, thus permitting $K^0 - \bar{K}^0$ mixing to occur. Unfortunately there appear to be no other precise tests of CP than the K^0 system, and so, for the foreseeable future, it seems likely that nothing more will be discovered about the superweak interaction.

As we have mentioned before, one of the most sensitive tests of CP and hence T invariance is the measurement of a possible electric dipole moment for the neutron. This would exist if there were any asymmetries in the neutron's charge distribution. The best results have been obtained by Ramsey et al. in 1968. They used thermal neutrons from a reactor core, which they cooled by passing them through a highly-polished narrow bent nickel tube. The emergent beam of low-energy neutrons was then made to strike a magnetised mirror of cobalt-iron alloy. This transversely spin-polarised

about 70% of the neutrons. After traversing a spectrometer these were then reflected from a spin-analysing Co- β e magnetic mirror, and recorded in a ${}^6\text{Li}$ -loaded glass scintillation counter. The transmitted neutron intensity, I , is maximal when the incident neutrons are not depolarised in the spectrometer. The spectrometer consists of a magnetic field of strength B which causes the neutrons to precess through the Larmor frequency, $\mu_n B/h$, and an RF field of frequency v . When $v = v_L$, the Larmor frequency, spin-flips occur, and the beam is partially depolarised, thus decreasing I . Using two coils the RF frequency can be varied around resonance. A reversible electric field is applied to whole spectrometer. Ramey et al. selected an RF frequency at which the ratio dI/dv was large, and then reversed the electric field. This caused no noticeable change in I , and so they concluded that the EDM of the neutron, if it existed, was smaller than $3 \times 10^{-22} \text{ e cm}$. Thus CP symmetry was once again validated.

Since the Hamiltonians or interaction functions of all the forces are interconnected, then it is not surprising that even in the strong interaction, we should detect some P violation caused by the influence of the weak Hamiltonian on the strong one. In 1965 physicists all over the world began to look for parity-violating components of the nuclear force, and in 1970 some of these were found, but none had very large amplitudes. In 1971 Krane, Olson, Sites, and Steyerl polarised metastable hafnium-180 nuclei and looked for asymmetries in the spatial distribution of their decay gamma rays. A positive result demonstrated parity violation, which appears to be about a hundred times as intense as in other parity-violating parts of the nuclear force. Assuming absolute CPT invariance, we can deduce CP invariance to 10^{-4} in the strong hamiltonian, 10^{-2} in the electromagnetic one, and 10^{-9} in the non-leptonic part of the the weak one from the equality of K^0 and \bar{K}^0 masses.

Let us now reconsider the dynamics of the weak interaction. We shall discuss the beta decay of the neutron, since it is probably the simplest and most common of the weak reactions among particles. In 1934, Fermi initiated his preliminary theory of beta decay, in which he assumed that the matrix element would contain a linear combination of the four-component (spinor) wave functions of the four particles taking part in the reaction, and perhaps also some operator, A . By analogy with electromagnetic interactions, Fermi proposed that this operator should be a vector one. He assumed that weakly-interacting particles reacted at a point, and thus he avoided the difficulty encountered in describing the Coulomb field, of having to integrate his results over all space.

In nuclear beta decay, there are two types of transitions in which the resultant electron and neutrino have zero orbital angular momentum. In one of these, their spins are parallel, and hence they have a total angular momentum of 1 (Gamow-Teller transition), and in the other, they are anti-parallel, giving the whole system zero angular momentum (Fermi transition). In the Gamow-Teller transition, the nucleon spin is 'flipped over', but in the Fermi one, it is left unaltered. Prior to the discovery of parity violation in 1956, Fermi's vector operator was excellent for describing Fermi transitions, but was unable to describe Gamow-Teller ones, since it could not produce a nucleon 'spin-flip'. While still maintaining Lorentz invariance in weak interactions, we find that the operator A can take any one of five forms, corresponding to the different possible combinations of the gamma matrices: scalar (S), vector (V), tensor (T), axial vector (A), and pseudoscalar (P). We find that the S and V operators produce Fermi transitions, while the T and A ones produce Gamow-Teller ones. P is unimportant in beta-decay, since it couples to the velocity-dependant component of the decay particles' spinors, which is practically zero in beta-decay.

By symmetry, we may deduce that the S interaction must produce leptons of the same helicity, while the V one must produce leptons of opposite helicity. Similarly, in Gamow-Teller transitions the T and A interactions must produce leptons of the same and different helicities respectively. By studying lepton helicities in experiments (see above), it has been deduced that only the V and A interactions would produce observed helicities and other phenomena. A pure V-A interaction would imply parity conservation, but we know that parity is not conserved in weak interactions. Thus we add another pseudoscalar factor, which gives us two possible matrix elements, one for left- and one for right-handed neutrinos. Since we know the neutrino to be left-handed, we obtain a unique expression for the matrix element. This is called the two-component neutrino theory, and was first proposed by Lee, Yang, Landau, and Salam. It predicts correct helicities for the other leptons, which is important (see above). We find a term C_A/C_V in our expression for the weak matrix element, where C_A is the axial vector coupling, and C_V is the vector one, whose magnitude we must determine. By means of a series of experiments on decay directions from polarized neutron beams, notably at Chalk River in 1958, Argonne in 1960, and Moscow in 1968, it has been ascertained that

$$C_A/C_V = -0.86$$

In 1958, Feynman, Gell-Mann, Marshak, and Sudarshan suggested that the slight departure from

$$C_A = -C_V$$

could be caused by a strong component of the weak interaction's Hamiltonian.

In most calculations concerning the weak interaction, we assume that the electron and muon coupling constants are equal, and this is known as electron-muon universality. In electron-proton scattering, by the electromagnetic interaction, it is sometimes useful to consider the reaction as one between two currents rather than between two particles. We see that each current carries exactly the same amount of electric charge, and this is conserved. We find that the electromagnetic current is conserved in strong interactions, since they themselves are charge-independant. Let us now consider weak interactions in terms of currents. We say that each particle has a so-called 'weak charge' of \sqrt{G} , where G is the weak coupling constant. As we see from the Puppi tetrahedron (see above), the weak currents are electric charge conservation violating. They are also composed of two components, an axial vector one and a vector one, whereas electromagnetic currents are pure vectors. By measuring the

$$(\pi \rightarrow e)/(\pi \rightarrow \mu)$$

branching ratio, it was deduced that the electron and muon carried the same weak charge. At one point, it was thought possible that all subatomic particles carried the same weak charge, and this was the basis for the name 'the Universal Interaction'. However, by observing the decay

$$^{14}_O \rightarrow ^{14}_N^* \rightarrow e^+ + v$$

it was found that the weak charge differed between the proton and electron by a factor of 2%. The comparative smallness of this discrepancy led to the proposal that vector current was conserved by the strong interaction (GVC hypothesis). Using the so-called 'Sargent rule' we find that this hypothesis gives us excellent agreement when calculating various pion decay branching ratios. Axial vector current, however, is not conserved in strong interactions, and it has been suggested that this is due to the strong process of single pion exchange.

In chapter 4 we mentioned that the conservation of linear and angular momentum was due to invariance under translation and rotation of the Lagrangian equations of motion.

We consider an isolated system of n particles. Each particle is described by six co-ordinates. By analogy with phase space, we may regard three of these as position co-ordinates, and the other three as momentum ones. Let p be any space co-ordinate, and let q be any momentum one. Thus

$$q = m dp/dt = m\dot{q},$$

in Newton's fluxion notation. The Lagrangian or Hamiltonian equations of motion describing our system are

$$\dot{q} = -\partial H/\partial p,$$

$$\dot{p} = \partial H/\partial q,$$

where H , the so-called 'Hamiltonian', equals the total kinetic and potential energy of the system. We find that if we now make an infinitely small space translation, then the Hamiltonian remains unchanged, and thus we may deduce that the momentum is also invariant under motion. Remembering that a finite translation may be compounded from a series of infinitesimal ones, we see that, because translation does not alter H , momentum is conserved. By choosing time and energy as the quantities represented by the co-ordinates, we find that energy is also conserved under time translations.

In quantum mechanics, we may produce a similar proof of momentum conservation. The Heisenberg equation of motion is

$$dD/dt = i/\hbar [H, D],$$

where D is an operator acting on the system described, and $[H, D]$ is the so-called 'commutator'

$$HD-DH.$$

If D commutes with the Hamiltonian, then

$$HD-DH = 0,$$

and H must be invariant under the D operator. If we take D to be a generator of infinitesimal space translations, then we may demonstrate that it commutes with H and that therefore momentum is conserved. By taking D as a rotation generator, we may show that angular momentum is similarly conserved.

Let us now consider the so-called 'gauge transformations', which may be used to prove the conservation of currents. In classical electromagnetic theory, the field components E and B were considered as represented by the derivatives of the vector and scalar potentials A and ϕ . If we add appropriate constants to these potentials, then we find that, because the field components are only dependent on the derivatives of the potentials, we thus effected no change in them. We may deduce that this implies that the scale of an electrostatic potential measurement is always purely arbitrary. Wigner has shown that this is only consistent with energy conservation if electric charge is also conserved. He says that, if the potential scale is arbitrary, then no physical process must be dependent on its absolute potential. An amount of work W is performed in order to create a charge Q in a region of electrostatic potential V . By moving our charge to a region where we have chosen to say that the potential is V' , we have gained $Q(V-V')$ of energy. If we now destroy the charge, we recover our initial energy W and we are left with a net energy gain of $Q(V-V')$, which violates energy conservation. Thus, if energy is conserved, we may not destroy our charge, and so charge must be a conserved quantity. In field theory, we describe particles by the complex field function ϕ . If we apply the gauge operator to this, we obtain

$$\phi \exp(i\Theta),$$

where Θ is arbitrary, and thus we have altered the phase of the field function. However, any interaction depends on $\phi \phi^*$, where ϕ^* is the complex conjugate of ϕ , and thus it must be independent of the phase factor $\exp(i\Theta)$. It is possible to show that this invariance is the cause of baryon and lepton current conservation and CVC.

To end, we shall make a brief review of the large and expanding subject of field theory. In so-called 'axiomatic field theory', we assume that all particles are scalar (i.e. they have zero spin) and are electrically neutral. The removal of these two basic axioms leads to so-called 'anaxiomatic field theory', and there is much research going on at present to produce, for example, a vector field. In 1943, Heisenberg invented an operator which he named the S-matrix. He considered primarily only the initial and final states in a reaction, at $t = -\infty$ and $t = \infty$ respectively, and assumed that these were far enough apart for them to be considered as completely independent systems. The S operator acts on the initial state in a reaction to produce all the possible final states. If we are interested in only one particular final state, then the matrix element S_{fi} represents the transition amplitude to it. We find that, if our initial state is normalized (see chapter 2), then the S matrix must be unitary, i.e.

$$S S^* = I,$$

where I is the identity element, and S^* is the complex conjugate transpose of S. Most operators and matrices in field theory are unitary because this implies a 'conservation of probability', which obviously should occur.

Let us now consider the so-called 'axioms' of axiomatic field theory. First, we assume that we may learn something about the interacting part of our field by considering the free fields at the initial and final states i and f . Thus we say that the matrix elements of $\phi^i(x)$ and $\phi^f(x)$ are the limits of those of $\phi(x)$ itself. This is known as the asymptotic condition axiom. The second axiom is that of Lorentz invariance. We assume that the interacting field transforms in the normal manner, like its limits, under the Poincaré transformation, which is compounded of a Lorentz transformation, Λ , and a translation. The third axiom is causality. The causality condition states that the measurements of the field at two separated points in space, a and b , commute, so long as $(a-b)^2 < 0$. In quantum electrodynamics, causality ensures the so-called 'measureability of the fields'. We find that it implies that there is no quantum mechanical interference between the two measurements. If there were, then this would necessitate a signal travelling faster than light.

Obviously, one of our major interests is in the S-matrix elements, which represent the scattering amplitudes in the interaction region. We have the Wightman functions, which are effectively field elements, but in order to translate these into scattering amplitudes, we must make use of the so-called 'reduction formula'. Axiomatic field theory then proves that the scattering amplitudes are analytic functions of momentum. The reduction formula contains the so-called Heaviside 'step function', which is one for $z^+ > 0$, and zero for $z^+ < 0$. It also contains a causality condition, which limits the regions where the commutator is nonzero. Thus we may deduce that the scattering amplitude is only nonzero in the so-called 'future cone', but that here it is an analytic function of momentum transfer. The fact that all physical states have positive or zero energy means that the Wightman functions are analytic functions of the differences between their arguments. The analyticity of the Wightman functions accounts for the CPT theorem and the connection between spin and statistics (see chapter 4), and that of the scattering amplitudes for crossing symmetry and dispersion relations.

In 1957 Jost proved CPT using axiomatic field theory. He showed that all the Wightman functions are invariant under CPT using their analyticity, and that thus the whole system was also invariant. In quantum electrodynamics, we ensure that the right particles obey the right statistics by saying that the particles' fields obey either a commutation or an anticommutation relation due to causality, depending

on their spins. We find that if we make the 'wrong' choice of statistics for our particles, then they and their fields cease to exist, since a half-integral spin field is multiplied by -1 by a half-turn rotation, whereas an integral spin one is not.

In 1956, Bogoliubov proved a number of dispersion relations using axiomatic field theory. A dispersion relation in a given variable indicates that the scattering amplitude is analytic in that variable. The reduction formula quickly yields a dispersion relation in the Mandelstam variable t (see chapter 5). However, dispersion relations in s and u have only been proved for pion-pion and pion-nucleon, but not for nucleon-nucleon scattering. This inability arises from the fact that only causality and the mass spectrum are assumed. However, no practical significance has been attached to this limitation. In 1965 the proof was extended somewhat by Martin, and he showed, by considering the fact that the imaginary component of any partial wave is always positive, that the scattering amplitude is analytic in both s and t simultaneously. Any further advance appears to necessitate the consideration of the scattering amplitude in a three-particle system, which is mathematically very involved. Assuming the dispersion relations, Bros, Epstein, and Glaser managed to produce a rigorous proof of crossing symmetry from field theory.

There is currently a considerable amount of disagreement between the proponents of the so-called 'analytic S-matrix theory' and those of ordinary field theory. While some suggest the complete abandonment of field theory, because of such problems as renormalisation, others calculate, for example, the properties of the hydrogen atom, including such quantum electrodynamical effects as the Lamb Shift, from it, without making use of the Schrödinger equation or its equivalents. We should expect that the probability that a free electron becomes a free electron after a time interval was unity, since the electron is stable. However, such processes as the emission and reabsorption of virtual photons tend to alter this probability. This means that the mass of the electron (like its magnetic moment, as we saw earlier) is altered. The Feynman rules, which are a direct consequence of quantum electrodynamics, however, give the electron transition amplitudes in terms of the bare electron mass, which is incorrect. Thus we must change mass variables, which we do through perturbation theory in a process known as mass renormalism.

CHAPTER EIGHT: THE DETECTION OF PARTICLES.

The simplest type of true radiation detector is the electroscope. The most efficient kind of these is the gold leaf electroscope. This consists of two gold leaves fixed to one end of a metal rod, at the other end of which there is a metal sphere. Usually, to avoid any movement due to wind and so on, the leaves are enclosed in a case with transparent windows so that their movements may be observed. When a charged object touches the metal sphere, its charge immediately travels down the metal rod, and the same charge is imparted to each of the leaves, causing them to diverge in proportion to the amount of charge on the object. In order to return the electroscope to its original uncharged state, an ionising radiation must be passed through the chamber containing the leaves. This will cause pairs of ions to be produced, and whatever charge that the electroscope has will be neutralised because it will attract the ions with the opposite charge to itself. The ion pairs will soon recombine in the chamber again to form ordinary atoms. One slightly more advanced type of electroscope is the Lauritsen electroscope invented in 1937. This uses leaves made of quartz fibre coated with a very thin layer of gold. These leaves are then placed so that one is kept rigid, while the other is free to move nearer or further from its partner according to their relative charges. There is a simple clip connected to a cell for charging the leaves. In order to detect the very slightest movement, a microscope and scale assembly is fitted above the chamber. One version of the quartz fibre electroscope in use today is the pocket dosimeter. This is used to detect personal dosages of x - and gamma rays. It is simply a pen-shaped quartz fibre electroscope which is first charged from an external charging unit, and then secured to the clothing of the person whose radiation dosage is being measured. It can be read by holding it up to the light and noting the position of one of the leaves of the electroscope relative to the scale. Usually dosages of up to about 0.5 röntgens can be measured to quite a high accuracy, although, like all electroscopes, the pocket dosimeter can not detect the passage of a single ionising particle through it.

The ionization chamber, proportional counter, and Geiger counter all work on very much the same principle as radiation-sensing electroscopes. Ionization chambers use the principle that ionising particles produce electrons whose energies and numbers are dependent on their own charge, and therefore power of ionisation, which can then be attracted to discharge electroscopes or equivalent. An ionization chamber consists of two metal plates with a potential difference of about 100 V separated by a volume of some argon, krypton, or neon gas, such that the charge gradient is about 1 kV m^{-1} . The walls of the chamber are made of some material which does not stop alpha and other soft radiations, such as mica, nylon, or pliofilm. An ionising particle, when it passes through an ionization chamber, will produce a shower of ion pairs, the threshold energy for such being only about 50 eV in inert gases, which then travel at differing rates towards the cathode and anode. The nuclei usually travel about a hundred times slower than the electrons, thus making one pulse from the anode and one from the cathode discharge discernable. Of course, as currents of only about 1 pA are produced by single particles, it is necessary to have electronic amplifiers with linear gains of about 10 000, which are very difficult to construct. Another disadvantage of the ionization chamber is the large leakage current from it, which can be partially stopped by fitting an earthed guard ring to the chamber. But when the signals have been amplified enough, they can be fed into three basic types of electronic

device: scalers, which record the total number of particles passing through the chamber; counting rate meters, which record the rate at which particles pass through it; and pulse-height analysers, which calculate the degree of ionisation and therefore type of each particle. Practically any kind of particle can be detected in an ionisation chamber. If, for example, we wished to detect thermal neutrons, all we need do is to introduce boron trifluoride into the gas in the chamber.

A much superior type of radiation detector to the ionization chamber is the proportional counter. This consists of a cylinder containing inert gas at low pressure, with a highly charged wire strung through its axis of rotational symmetry. The outside of the cylinder is connected to the opposite terminal of a high-tension battery from the central wire. A typical set of dimensions for a cylindrical tube of this type would be: diameter 20 cm, height 200 cm, diameter of central wire 10 μm . The basic difference between a proportional counter and an ionization chamber lies in the fact that the pulse height of a given particle is no longer independent of the potential difference applied between the central wire and the outside of the cylinder. On a graph of applied voltage to ionisation current, there are primarily four regions. First the ionization chamber region, where the ionisation current is constant and independent of the applied voltage; second the proportional counter region, in which the current increases roughly with the square of the voltage; and third the Geiger-Müller counter region, in which the ionisation current increases to some extent and then levels off. The last region is useless for counters, because even after an ionising event has finished, a current is produced, so that any counter turns into a continuous discharge tube. The proportional region extends between about 500 and 800 V, so this is the potential difference between the two sections in a proportional counter. Proportional counters can detect pulses as short as 100 ns, and thus this is said to be their 'recovery time'.

The Geiger-Müller counter was invented in 1908 by Rutherford, in order to ease the detection of alpha rays, and was developed in 1913 by Geiger, whose name it now carries. Geiger counters operate in the Geiger region, which extends from 800 to 1500 V. The only major difference between the construction of a Geiger and a proportional counter is that the former, instead of having a wire which is stretched right across the cylinder has one which is only connected, with an insulator, at one end. In operation, Geiger counters produce much more intense pulses than proportional ones. This is because the electron from the ion pairs has a much greater energy, and thus can produce secondary as well as primary pulses by collision with gas atoms, which produces new electrons. The recovery time of a Geiger counter is about 100 μs . This is the time necessary for the positive ions to move away from the central wire to the outer cathode, during which time none of the electron avalanche produced by an ionising event can reach the central wire. When this positive ion sheath reaches the outer cathode, it often releases a few electrons from the latter, thus causing a continuous discharge and recycling the counter. This fault can be overcome by quenching techniques. These involve the addition of a few percent of some polyatomic hydrocarbon, such as methane, ethane, or ethyl alcohol to the argon gas in the tube. Thus, when an ionised argon atom touches an ordinary ethane molecule, the latter becomes ionised and the former returns to its initial state by the exchange of electrons. This means that by the time the sheath of ionised argon has expanded almost to the outside of the tube, it is solely composed of ionised ethane. When this approaches within 100 nm of the wall, it captures an electron from it and splits into two smaller molecules. The disadvantage of this method of quenching is that after about a thousand million pulses,

all the molecules have been broken up into smaller ones, thus rendering them useless. Geiger counters are very versatile, and can be used for detecting practically any ionising radiation. They have the great advantage, because about 10 million electrons are incident on the central wire per ionising event, of producing pulse voltages in the order of 10 V, which can be run through electronic equipment without preliminary amplification.

Scintillation counters consist primarily of three sections. First the scintillator itself, a solid, liquid, or gas which emits light when a charged particle passes through it. Second the photomultiplier, which transforms light pulses from the scintillator into electrical pulses which may be passed through electronic equipment. And third, light pipes, which carry the light from the scintillator to the photomultiplier tube. The light pipes are usually made of a plastic called Lucite, can be any shape, as they still totally internally reflect light pulses from the scintillator. The intensity of these is proportional to the ionisation of the radiation detected. When choosing a scintillator to detect a certain type of radiation, there are four criteria which need to be borne in mind. First, the sensitivity of the scintillator to the radiation being detected; second, the amount of light produced by a given particle energy, or the light yield; third, the time necessary for a light pulse to die out, or the speed of the scintillator; and fourth, the practical questions of cost, ease of manufacture, density, inflammability, and so on. There are a very great number of scintillators in common use today, but we shall only consider a few of the better-known ones here. The very first scintillator was zinc sulphide, used by Regener in 1908 to detect alpha particles (see chapter 1). In 1947 Kallman found that naphthalene ($C_{10}H_8$) was a good scintillator, and in the early 1950's, the scintillator sodium iodide (NaI) activated with thallium was discovered. This is useful in detecting gamma rays, because, due to its high density (3700 kg/m^3), it absorbs those with an energy of less than about 1 MeV, and scintillates proportionately to their energy. The main disadvantage of NaI as a scintillator is that it has the comparatively long decay time of $1\mu\text{s}$. A decay time is defined as the time taken for the light pulse in a scintillator to fall to $1/e$ (~ 0.36788) of its initial intensity. Examples of other inorganic crystal scintillators are caesium iodide (CsI) and potassium iodide (KI), both activated with thallium, zinc sulphide, activated with silver, and diamond. Another important group of scintillators are the inert gases: helium, neon, argon, krypton, xenon, radon. These are important because of their almost perfect linearity, which means that the intensity of their light pulses are directly proportional to the energies of the incident particles. Organic scintillators, either as crystals or liquids, form another large group of scintillators. The most common of these are probably transilrene ($C_{16}H_{12}$), p-terphenyl ($C_{16}H_{12}$), and anthracene ($C_{16}H_{10}$). However, they are only linear for electrons above 125 keV, and they have low densities of around 1200 kg/m^3 . Furthermore, they are very difficult to grow as crystals, and when they are grown, they are very fragile indeed. This led to the development of liquid organic scintillators, which, although they are very corrosive and inflammable, are often used. The first of these to be discovered were solutions of p-terphenyl in xylene and toluene. Liquid scintillators all have very good light yields, and are nearly transparent, allowing large volumes to be used in a single scintillation counter. The best scintillators, however, are the plastic ones. These are usually combinations of liquid scintillators and plastics, such as p-terphenyl-in-polystyrene, and, like liquid scintillators, have short decay times and good light yields.

Let us now consider a new type of particle detector: the semiconductor detector.

In appearance, semiconductor particle detectors resemble scintillation counters, but in operation they more closely resemble ionization chambers. They work on the principle that when an ionising particle passes through a semiconductor crystal, it liberates electrons and positrons. These can be swept out of the crystal by means of a small magnetic field, and will then produce a pip on an oscilloscope. Naturally, this type of detector can be made very small, and the time necessary for clearance is only about 10 ns, which is shorter than for most gaseous detectors. But crystal counters have been unsuccessful, because of 'dark' current, background radio and electrical noise emanating from a semiconductor crystal, and polarisation, which reduces the strength of the electric signals considerably. These two drawbacks can be minimised by doping a silicon crystal with phosphorus and gold, and this type of crystal detector works well, especially for low count experiments.

A much better type of detector, called the surface junction counter, has been invented, in which the effects which mar the operation of a crystal counter are negligible. In a pure silicon crystal, all the valency electrons are used up. But if some boron, for example, is incorporated in the silicon crystal's structure, then one new electron is needed per boron atom, because boron does not have enough valency electrons. Thus free electrons are easily trapped in these holes. Silicon doped with boron is known as a p-type semiconductor, because of the positive holes in the crystal lattice. If however, a silicon crystal is doped with phosphorus instead of boron, one extra valency electron from each phosphorus atom becomes free, making the whole crystal negatively charged or n-type. If, instead of doping a whole crystal with phosphorus, just one face of an otherwise p-type crystal is doped with it, this creates a junction. If an ionising particle passes through a junction in a semiconductor, it leaves behind a great many electrons and positrons which can be swept out of the crystal by a magnetic field and recorded electronically. This junction type of particle detector allows very high energy resolution, so that it can distinguish between particles with energy differences of 0.3% or less. But one difficulty of these ordinary detectors is that the depletion or junction layer is very thin, thus making it essentially two-dimensional, so that only particles in exactly the same plane as it are detected, and the pulses which they produce are very small. The depth of the depletion layer is proportional to the product of the square root of the magnetic field intensity applied to the junction and the purity of the crystal. However, even with the purest silicon currently available and a 400 V electric field, the depletion layer is only 1 mm thick.

One method of widening the depletion layer is to utilise an n-i-p version of the ordinary n-p junction counter. This is really a cross between the crystal and junction type of semiconductor particle detector. It consists of a slab of ultrapure silicon doped on opposite faces with boron and phosphorous, thus producing three distinct layers: a p-layer, an undoped or intrinsic layer, and an n-layer. This type of counter relies on the use of absolutely pure silicon, otherwise any impurities allow electric currents to flow from the charged into the neutral layer, giving false readings. Lately, the new method of lithium drift has been used to create crystals which act like ultrapure silicon. In this method, one face of a silicon crystal has lithium atoms diffused into it. These act as donor atoms, but do not, because of their chemical properties, become truly bonded into the crystal lattice, and remain interstitial and free to move about within the silicon crystal. When an electric current is applied to the crystal, the free lithium ions will be forced into the positive part of the crystal, and will there fall into an acceptor site or positive ion. This process of neutralisation is known as 'compensation', and after a short time, all the acceptor

sites in a silicon crystal can be compensated, thus making the crystal behave like ultrapure silicon. Using this method, junction counters with depletion layer depths of up to 6 mm have been produced, and it seems likely that n-i-p counters made by the lithium drift method will soon be produced commercially. However, while physicists have been trying to make junction counters with as large depletion layers as possible, they have also been trying to produce very thin wafer junctions, in which particles with almost identical energies, but with different rates of energy loss, will appear as different. Due to the extreme fragility of this silicon crystals, this has been difficult, although junctions with a depletion layer of only 10 μm have been produced. Naturally scintillation counters as well as semiconductor detectors, can be cut to any size and shape, but the formers' photomultipliers make them bulky and thus, unlike the latter, unusable in large arrays.

Before we may discuss Cerenkov counters, we must consider, as we have done briefly already in chapter 3, the nature and cause of Cerenkov radiation. It was discovered in 1934 by P. Cerenkov who noticed the bluish light issuing in a cone from water into which gamma rays had been directed. This radiation was investigated and accounted for by Frank and Tamm in 1937 in terms of the shock waves of electromagnetic radiation produced by particles travelling faster than the velocity of light in the medium in which they are going. The velocity of light in a given medium is given by the formula:

$$v_e = c/\mu,$$

where μ is the refractive index of the medium and c is the velocity of light in vacuo. The refractive index of the vacuum is arbitrarily taken as unity. All other refractive indices are, unless otherwise stated, the refractive indices of the transition between the vacuum and a substance. The refractive index of water is 1.332, of glass is between 1.5 and 1.7, and for diamond is 2.4173. We find that the angle at which Cerenkov radiation is produced is given by

$$\theta = \cos^{-1}(1/\beta\mu),$$

where

$$\beta = v/c,$$

and μ is the refractive index of the medium. Cerenkov counters utilise Cerenkov radiation, which is usually emitted in the form of dim flashes of light. These are amplified by photomultipliers and changed into electrical signals which are fed to various pieces of electronic equipment. There are basically two types of Cerenkov counter in use today: velocity threshold or differential counters, which record the passage of any particle going faster than the velocity of light in their media, and velocity selective counters. The former work by having some optically dense medium surrounded on all except one side by mirrors, and on the open side there is a Lucite light pipe running to a photomultiplier tube. Thus these counters act as ordinary particle detectors, and have recovery times of about 1 ns. The latter work by passing the Cerenkov radiation through a series of vanes or mirrors in order to filter out all but a very small angle, and therefore particle velocity, of radiation, and then recording the light which is left by means of a photomultiplier.

Obviously the simplest way to record the tracks of particles in reactions is to photograph them. One of the first methods for sensing the individual tracks of ionising particles was to utilise special photographic plates in which the passage of a particle was recorded by a colour difference on the developed plate. This method was first employed by Reinganum in 1919. Photographic plates used in particle research consist of ordinary silver bromide (AgBr) crystals suspended in gelatin, with about $\frac{1}{7}$ of the emulsion by weight consisting of AgBr : somewhat more than in normal plates.

Usually, photons passing through a photographic emulsion will sensitise one molecule of AgBr each, which, when exposed to various chemical processes will eject its silver atom to form a black spot on the negative. The same occurs with nuclear emulsions, except that these are sensitised by charged particles rather than photons. Before about 1947, nuclear emulsions were only sensitive to slow, low-energy particles, but they were then improved. As particles are very likely not to travel solely in the plane of a thin photographic plate, but often skew with respect to it, it is necessary to have the emulsion as thick as possible. In fact, nuclear emulsions as thick as 2 mm have been made, requiring many months to develop. Much the best thing to do with nuclear emulsions, however, is to put many plates of them together, thus making what is known as an emulsion stack, in which the progress of a charged particle may be followed from one plate to another. Because of the extreme smallness of particle tracks in nuclear emulsions, it is necessary to study these under a microscope, thus rendering statistical measurement very difficult. Furthermore it is impossible to shield nuclear emulsions from cosmic rays in any way, so that it is not possible to determine whether a given event occurred during or after the proper exposure time of the plate. This constitutes a serious drawback to nuclear emulsions as methods of particle track detection.

The first type of instantaneous track-forming detector to be invented was the cloud chamber. In 1880 and 1898 respectively, Aitken and C. Wilson noticed, while studying the mechanics of rain, that even when water was cooled much below its boiling or 'dew' point, it would not form condensation droplets unless it had suitable condensation nuclei, such as dust particles. In 1912 Wilson showed that ionising particles could, by ionising the air molecules in their path, make condensation droplets form in their wake. Thus the track of a subatomic particle could be seen by the water droplets it produced in a cloud-like chamber. A cloud chamber is operated by means of a piston or pump, which withdraws at a certain predetermined time, thus, by Boyle's Law, making the water or other vapour cool below its dew point, so that any condensation nuclei available are used. After the tracks formed by charged particles have been suitably photographed, they can be erased by the application of a small magnetic field to the chamber. Naturally the uses of a cloud chamber can be significantly increased if a magnetic field is applied to it while in operation as well as after, thus making it possible to calculate the charge on a particle by seeing in which direction it travels with respect to the magnetic field. If a uniform magnetic field is applied to the chamber, then any charged particles move in circles or helices, the radii of which are proportional to the momenta of the particles which form them. Cloud chambers are very good for accurate measurements of particle momenta, because the low density of the gas makes collisions between particles and gas molecules uncommon. But this low density also has its disadvantages: it means that very few reactions except for decays can be observed in cloud chambers. Naturally, the introduction of metal plates somewhat overcomes this problem, but no cloud chambers are as good as bubble chambers for observing particle reactions. Furthermore, cloud chambers can not be used in high-speed, multiple, types of observations, as anything between 15 and 60 s is required to re-establish correct conditions within a cloud chamber. One method of slightly improving cloud chambers is to place counters a suitable distance from them, so that they trigger the latter at a time when they will produce the tracks of the radiation which activated the counter. A great advance in cloud chambers was the invention of the continuously-operating diffusion cloud chamber. This utilises the principle that a warm gas can hold more vapour than a cool one, so that a

reduction in the temperature of the gas holding some water vapour will result in the formation of water droplets on any suitable condensation nuclei, such as ions produced by the passage of a charged particle. In a diffusion cloud chamber, the top of the chamber is heated, and vapour is produced there, while the bottom of the chamber is cooled to about the freezing point of carbon dioxide (-78.5°C). This causes the vapour to diffuse downwards through the chamber, and as it does so, to cool below its dew point, thus producing particle tracks. The part of the chamber where tracks may be observed is brightly illuminated, and photographs can be taken of any tracks through the glass at the top of the chamber. Unfortunately, although diffusion cloud chambers eliminate the very long recovery time necessary with expansion chambers, they can only be used in a horizontal position, rendering them useless for cosmic ray research. Initially only argon and air at atmospheric pressure were used in cloud chambers, but in 1957 it was found that high-pressure hydrogen could be used instead, thus allowing the observation of reactions between particles and hydrogen nuclei.

The bubble chamber arose out of research by D.Glaser in 1952, aimed at producing a track-forming detector which combined the good characteristics of the cloud chamber and nuclear emulsion. Chemists had known for some time that an ultrapure liquid in a smooth-walled chamber may be heated above its boiling point without boiling. However, if 'boiling stones' are dropped into a superheated liquid, the latter will begin to boil around these trigger points. Glaser realised that the ions produced by the passage of a charged particles could act as trigger points and produce bubbles along their tracks. In his prototype bubble chamber, Glaser connected two small glass bulbs by a capillary tube. Both of these bulbs were filled almost entirely with ether. One was heated up to about 140°C while the other was maintained at a temperature of 160°C. Liquid was forced into the cooler bulb from the hotter one, thus causing the ether in the cooler bulb, which was subjected to a pressure of about 20 bars, to become superheated, but not to boil. Glaser found that the superheated ether could remain, in its normal state, without boiling for a few minutes, but when some radioactive cobalt was brought near to it, it began to boil violently. The next thing was to find out if at any point a single track was formed by the passing charged particle. By taking 3000 exposure per second ciné films, it was established that good tracks were produced, and that bubble chambers were sensitive to even the very slight ionisation produced by the passage of a low-energy muon. Glaser fitted a bubble chamber so that it was shielded on each side by lead, with Geiger counters above and below it. These were connected to a coincidence circuit, which, when it recorded a pulse from each of the Geiger counters, activated a xenon flash discharge lamp. The camera which had been left with its shutter open in the same room as the bubble chamber, then photographed the cosmic ray tracks. By delaying the operation of the flash tube after the event had been registered by the coincidence circuit, the bubbles could be photographed at practically any stage in their growth, from having a diameter of about 100 microns after a few microseconds, to filling the whole chamber after about a second.

But ether was not the only liquid used in bubble chambers. In 1953 Mildebrand et al. filled a bubble chamber with liquid pentane, thus producing interesting pictures of nuclei-pion collisions when it was placed near the emergent beam of the Chicago synchrocyclotron. However, when larger bubble chambers, suitable for use in the laboratory, were built, the superheated liquids would boil very quickly due to the roughness of the inside of a metal bubble chamber, with glass windows. Luckily it was discovered that for about 7 ms after the retraction of the pneumatically-operated piston, the liquid would only boil around the tracks of charged particles, and so,

during this short time, worthwhile particle track photography could be carried out. Bubble chambers have grown considerably in size since Glaser built his 1" one. There now exists as 72" liquid hydrogen bubble chamber at Brookhaven. Unfortunately, bubble chambers take about 50 ms for a complete cycle of expansion, recompression, and recovery, thus somewhat limiting their uses in fast statistical particle experiments. But in 1969, this problem was overcome by the invention of high-speed bubble chambers whose internal pressure was controlled by ultrasonic sound waves. In this type of bubble chamber liquid hydrogen, helium, or some heavier liquid, is held just above its boiling point continuously, while high-frequency sound waves are sent through it, producing alternate regions of compression and expansion. Although only discontinuous tracks can be produced in this type of chamber, this slight disadvantage is amply compensated for by the very fast recycling times available. The first ultrasonic bubble chamber was constructed by C.Ramm at CERN. Sound waves with a frequency of 110 kHz were produced in liquid helium by two piezoelectric transducers each 7 cm in diameter, spaced between 5 and 25 cm apart. The standing wave nodes are about 2 mm apart, and already very promising pictures of pion reactions have been obtained. Ramm suggests the use of triggering devices for his new type of detector, though it is obvious that much more research must be done on the detector itself before such ideas become feasible.

In the late 1940's, J.Kaufel built a number of spark counters, consisting of parallel highly-polished metal plates maintained at a high potential. Often a spark would jump between two neighbouring plates preferentially along the path of an ionising cosmic ray particle. In 1955 M.Conversi and A.Gozzini constructed a hodoscope chamber, which consisted of a stack of neon discharge tubes fixed between two parallel metal plates. When a charged particle was detected by two counters in coincidence, a high potential was created between the two plates, causing discharge to occur in the tubes traversed by the particle. The chief defect of the hodoscope was that it only revealed a two dimensional image of a particle's three-dimensional trajectory. In 1957 the British physicists, T.Cranshaw and J.de Beer invented a new type of detector in which both the triggering technique of the hodoscope and the spatial resolution of the spark counter were incorporated. They made a spark chamber with many parallel plates 6 cm apart, and introduced the clearing field method in which a small magnetic field was applied continuously to the chamber, thus erasing any tracks older than a few microseconds. Unfortunately the Cranshaw-de Beer chamber had air between its plates, thus making it impossible for more than one track to be produced in each spark gap, because of the extreme electro-positivity of oxygen. But in 1959 S.Fukui and S.Miyamoto built a successful neon-filled spark chamber. Within a matter of months, work built a six-gap spark chamber and exposed it to the beam of the Lawrence Radiation Laboratory 6 Gev accelerator, and found that excellent tracks were produced. It was discovered that about 300 or 500 ns were necessary to trigger and spark chamber, and the chamber had a dead time of only about 10 ms, which is very good for a track-forming detector. There are currently two basic types of spark chamber: narrow-gap or track-sampling ones, and wide gap ones. narrow-gap chamber plates are separated by distances of about 0.2 to 1 cm, and a high-voltage pulse is applied to alternate plates, producing a field of about 10^6 Vm⁻¹. A modern method of quick digitisation of particle tracks is the sonic spark chamber. A clock is started when the chamber is triggered, and microphones, usually in the form of piezoelectric crystals or capacity transducers, using sonic ranging immediately locate the spark and record it on magnetic tape. In wide-gap chambers, the plates are usually about 30 or 40 cm apart, and fields of around 400 kVm⁻¹

are applied to the chambers, using a Marx pulse generator. Sparks can be produced at up to 45° from the normal, but after 20° , their intensity tends to diminish. Sometimes projection chambers are used, which are similar to spark chambers, but one of their plates has been replaced by a wire-mesh grid. Thus sparks are viewed as sheets of discharge, but the light emission from these is low, which necessitates very large lens apertures. A new type of track-forming detector is the streamer chamber. This is basically a wide-gap spark chamber, for which very short high-voltage pulses are used, thus not allowing the sparks produced to grow very long. The lengths of these streamers are directly proportional to the pulse-lengths, and a pulse of about 50 ns is needed to obtain streamers a few millimetres long in a field of 10^4 kVm $^{-1}$. Streamer chambers may be viewed by means of 90° stereo cameras, and have very short recovery times in the order of 40 ms. The fact that streamer chambers can be selectively triggered gives them some advantage over bubble chambers, but this is rather offset by the disadvantage of not providing identical reaction and detection media. In 1968 Charpak et al. constructed a wire proportional detector, in which one set of electrodes consisted of wires about $50 \mu\text{m}$ thick, spaced about 0.1 to 1 cm apart, and the other set of electrodes was an area of steel mesh. A typical applied voltage is 2000 V, and the gas filling is usually an argon/alcohol mixture at S.T.P. The spatial position of a particle may be obtained to within $\frac{1}{4}$ mm with 100% efficiency, using discharge pulses amplified about 5000 times.

CHAPTER NINE: THE ACCELERATION OF PARTICLES.

By 1930 it was well-known that some atomic nuclei produced high-energy radiations which could be used to induce artificial nuclear transmutations and to probe the interiors of atoms and nuclei. However, particles produced in radioactive decay did not have very much energy, and no protons could be made, which could probe nuclei much more effectively than electrons. Thus it was seen that high-energy particles must be produced artificially. Hence, in 1931, Van de Graaf invented a machine capable of producing very high voltages, which has come to be known as the Van de Graaf generator. It is obvious that the simplest method of accelerating particles is to make them fall through a large potential drop, and this is utilised in the Van de Graaf generator. The van de Graaf generator consists primarily of two electrodes, one of which is usually earthed. Between the electrodes runs a belt made of some insulating material, usually rubber. At the grounded electrode ions or electrons are supplied to the belt by means of corona discharge, which occurs when air is broken up by very high voltages. Inside the second electrode, which is usually hemispherical and made of metal, the charge is transferred from the belt to the electrode by means of brushes or combs. When the upper electrode has been raised to the desired voltage by the moving belt, an ion source within it can be started, and the ions accelerated by the potential drop to the earthed electrode. For a particle with Z times the charge of the electron, accelerated through a potential drop of V volts, we find that

$$E = ZV,$$

where E is in electron volts. It might be thought that so long as the belt continues to bring charge to the unearthing electrode, then the latter's charge should continue to increase. However, this is not the case, since leakages can occur by a variety of means. The beam itself removes some of the charge, and insulators are never perfect, so some charge may be earthed. Furthermore, corona discharge may occur at the regions of very high charge.

When Van de Graaf generators were first constructed, air at S.T.P. was used inside them, and they were usually housed in sheds with their auxiliary equipment. However, as higher and higher voltages became necessary, the size of Van de Graaf machines grew larger and larger until they were impractical. The solution to this problem was to use high pressure nitrogen, freon, or the like, or a mixture of these, instead of air. We know that as the pressure of a gas increases, so the average distance between molecules in it decreases, thus shortening the free path of an ion. The use of high pressure gases meant a size decrease by a factor of about seven. One would probably expect that the size of Van de Graaf generators would increase linearly with the voltage required. However, beyond 7 Mev, increases in the size of the accelerating tube, which was made of series of insulating rings joined by glass, did not cause any corresponding increase in energy. This is known as the 'total voltage effect'. It is thought that this is caused by high-energy particles hitting material in the accelerator, producing x-rays, which in turn ionise the gas within the accelerator, thus causing more charge leakage. As the energy of the particles increases, so also does the energy of the x-rays and hence the magnitude of the leakage. In 1962, this problem was solved by Van de Graaf, Rose, and Wittkower, by introducing a radial component to the accelerating field by means of inclined tubes.

In 1936 Bennett and Darby suggested the use of a two-stage method of acceleration,

but it was only in 1959 that Van de Graaf et al. built a two-stage 'tandem' generator at the Chalk River laboratories in Canada. The principle of this accelerator is that negative ions are produced at ground potential and are then accelerated towards a positive terminal, at which electrons are stripped off. The resulting positive ions are then again accelerated to ground potential. The negative ions are initially produced by making an intense 13 keV positive ion beam impinge on a charge-exchange gas canal, in which about 1% of the positive ions are converted into negative ones. Neutral and positive ions are removed from the beam by means of a magnet. In 1960 a 12 MeV tandem generator was installed in Canada, and later that year two were built at Harwell and Aldermaston, U.K. By 1964 over thirty tandem generators had been built or were under construction, and by now the number is easily in three figures. Lately a three-stage tandem generator has been developed, in which ions are first accelerated from a negative to a ground potential, before entry into a conventional two-stage accelerator. Tandem generators are especially useful for heavy ion acceleration.

In 1932, Cockcroft and Walton, at the Cavendish Laboratories, Cambridge, U.K., were the first to produce the artificial transmutation of atomic nuclei, in this case lithium ones. They used an accelerator known as the cascade generator or Cockcroft-Walton machine. It utilised Greinacher's method for 'stepping up' electric current. This consisted of two banks of condensers joined diagonally by rectifiers. A high-voltage A.C. current was applied to the condenser banks by means of a conventional transformer. The bottom condenser of one of the two banks was earthed. Thus, whenever its potential was greater than that of a condenser in the other bank, current would flow to the latter through a rectifier, but when the A.C. cycle was at another point, the rectifier would not allow current to flow back again. Hence, every time the A.C. current altered sign, an upward movement of current would take place throughout the cascade generator. In Cockcroft and Walton's first accelerator, an A.C. transformer produced about 400 000 V of current. Protons from a hydrogen source were accelerated in two steps of 200 000 V each in an evacuated tube, so that they were travelling at a velocity of about 8000 km/s when they were incident upon a lithium target. This produced alpha particles with speeds of about 19 000 km/s, the latter not varying appreciably with differing applied voltages. The current limit for Cockcroft-Walton machine energies is around 100 kV, since this is the maximum tolerance of selenium rectifiers, though in 1957, Lorrain et al. reported a 500 kV machine operating at a frequency of 32 kHz. Cockcroft-Walton machines are used in low-energy research, and have the common disadvantage of producing a discontinuous stream of particles, because of the ripple effect, which is present whenever A.C. is transformed into D.C.

As early as 1930 Wideroe had the idea of utilising many more than one accelerating tube in a particle accelerator, but it was not until 1947 that this idea was put to any practical use. Wideroe suggested the use of an alternating acceleration current, so that successive tubes would have opposite signs. However, he realised that when the A.C. wave was in an unfavourable position, the particle would be decelerated by the same amount as it had been accelerated when the wave was in a favourable position. He overcame this problem by using the fact that there is no electric field inside a hollow conductor, whatever voltage may be applied to it. Thus, a number of hollow drift tubes were used, between which there were accelerating gaps. Hence a particle would drift in these while conditions were unfavourable for its acceleration outside. But since the velocity of particles would increase along a linear accelerator of this type, the length of the drift tubes had to be increased correspondingly. In

1931 Sloan and Lawrence built a thirty-tube linear resonance accelerator, as it was called, which could produce 1.26 MeV mercury ions, but had a peak accelerating voltage of 42 kV.

In a resonance linear accelerator, it is obvious that many particles are lost, either at injection, because the electric field is unfavourable, or later. However, there are a few particles which stay in phase or resonance with the A.C. wave until the final energy has been attained. It is this principle which all modern accelerators make use of, in some way or another. The linear accelerators built in the 1930's were restricted to the acceleration of heavy ions, since no oscillators of more than 10 MHz were available at that time, and these are necessary for the acceleration of lighter particles such as electrons or protons. However, developments in Radar during the Second World War yielded magnetrons, klystrons, and so on, capable of producing radio frequency oscillations of around 1GHz. Another advance, perhaps even more important, was made on the theoretical side by Veksler in 1944, and independently by McMillan in the next year.

We know that the applied voltage between two electrodes in a resonance linear accelerator can be expressed as

$$V = V_{\max} \sin \omega t,$$

where ω is the angular frequency of the field oscillation, and t is the time passed since zero field. The phase, ϕ , of a particle can be described by

$$\phi = \omega t,$$

which varies between 0 and 2π , since ω is taken in radians. The time, t , is that at which the particle crosses an acceleration gap after the field has zero strength. Thus the extra energy, ΔE , imparted to a particle of charge Q due to a particular crossing is

$$\Delta E = QV_{\max} \sin \phi,$$

so that for optimum acceleration the particle's phase had to be near 90° and thus it crossed the gap when the field was at its favourable maximum. This arrangement was satisfactory for accelerators with a comparatively small number of accelerating gaps, but it became inadequate with a great many. Consider a particle which arrives slightly late at a given acceleration gap. When it reaches the next one it will be even later, and finally it will be lost from the beam. Similarly, an early particle, although it will finally attain a phase of 90° will, by that time, be travelling too slowly, and so will again be lost. Thus, when many drift tubes are used, the beam strength will quickly be significantly decreased. However, if the optimum phase is, for example, 45° , then satisfactory acceleration is achieved by all particles, regardless of lateness or earliness. Particles having a constant phase precisely equal to the optimum one are said to be synchronous. A particle which arrives later than the synchronous ones will encounter a larger field, and hence will be given more energy. But after a few acceleration pulses, the particle will be going too fast, and hence will arrive at the gaps early. Here it will find a smaller accelerating field, and so its speed will again decrease. Thus early or late particles' phases will oscillate about the synchronous phase, allowing them to be accelerated as normal. To alter the optimum phase, we simply have to alter the lengths of the drift tubes.

In the first linear proton accelerators, the electrodes, which were placed along the axis of an evacuated glass tube, were fed directly from an R.F. oscillator. However, this method is extremely wasteful of radio energy, and so a new one was devised. The drift tubes were suspended from the top of a highly conductive copper box, in which a standing electromagnetic wave was produced by an external R.F.

generator. The tank resonates at a well-defined frequency proportional to its dimensions. The electric field component of the standing wave is directed along the axis of the tank and hence provides an accelerating force for the protons. Since the overall process of acceleration takes many periods of the standing wave, drift tubes must be provided to shield particles when the wave is unfavourable. Synchronous particles must be inside a drift tube for a complete period of the wave, in order to keep their phase constant. We find that the separation between successive gaps is given by

$$S = \frac{c}{\lambda},$$

where

$$\beta = v/c,$$

and λ is the wavelength of the accelerating field in free space. In most proton linear accelerators (linacs), the actual accelerating tube is enclosed within a larger steel tank to avoid distortions due to pressure changes.

The first post-war proton linac was built at Stanford, and had an energy of 32 MeV. The particle beam was focused by distorting the electric field within it. This was achieved by placing very thin beryllium foils at the entrance to each drift tube. So that the protons would not encounter undue energy loss in the foils, a pre-accelerator accelerated them to 4 MeV before injecting them into the main machine. However, it was found that the foils were very easily damaged, especially by sparks during R.F. build-up, and so the design had to be abandoned. Tungsten grids were used instead, and these caused a slight loss of particles, but compensated for this disadvantage by having the advantage that low-energy injectors could be used. The Stanford injector was a 500 keV Cockcroft-Walton machine. At roughly the same time as the Stanford linac, two other proton linacs, with energies of 70 and 50 MeV respectively, were built at Minnesota and Harwell. These a method known as strong focusing, in which magnets are actually placed within drift tubes, and act as magnetic lenses. This method is more commonly used in circular accelerators, and it is with them that we shall discuss it. Linacs' energies can not be smoothly varied as with Cockcroft-Walton machines and other static accelerators, but by dividing them into sections, it is possible to obtain two or three distinct energies. The Harwell machine has three sections: in the first protons are accelerated to 10 MeV, in the second to 30 MeV, and in the third to 50 MeV. By de-energising various sections, a number of different energies are attainable. Heavy ions may be accelerated by similar methods as protons, except that the R.F. necessary is only about 70 MHz, and so the sizes of the drift tubes are correspondingly greater. Since drift-tube length for heavy ions is proportional to Q/m , which is roughly equal for all ions, a single accelerator can be used for a variety of different ions.

Since electrons are only about 1836 as massive as protons, they achieve relativistic velocities correspondingly quicker. After they have been accelerated to 1 MeV, there will be little further increase in velocity, only in mass. Hence all the drift tubes should be long but of the same length. They would be of roughly the same length as the free space wavelength of the R.F. wave, and thus they would be extremely uneconomical. It is possible to use a completely different method to accelerate electrons, which makes use of the fact that their velocity is nearly equal to that of an electromagnetic wave. A travelling wave is made to propagate along a metal cylinder known as a waveguide, carrying the electrons with it. Phase stability is used, though not in the same way as in proton linacs. No synchronous particles can exist, since these would have to travel at the velocity of light, and would hence have infinite mass. Neither are true phase oscillations possible, since no particles can travel

faster than light. Instead, the phase of the particles steadily decreases, the rate of decrease being inversely proportional to the speed of the electrons. Finally the phase will approach a limiting value, and the electrons will become locked onto the carrying wave. We find that, because no cosine is greater than one in absolute value, only a certain range of phases are available at injection. Any particles with phases out of the allowed region will not be accelerated, but those with phases in it will be, to some extent, focused.

The largest electron accelerator in the world is the Stanford Linear Accelerator (Centre), SLAC. This is nearly 3 km long and produces electrons with an energy of around 40 GeV. The internal diameter of the evacuated accelerating tube is 8.247 cm, and the wavelength of the travelling wave is 10.5 cm. If the inside of the tube were completely free from obstructions, then the velocity of the wave would be c , and no electrons would be permitted to follow it. Thus, irises, consisting of annular metal disks, are placed all along the waveguide to slow the travelling wave down to the desired velocity. This is known as the 'modular' method. Since all parts of the accelerator tube are identical, it is possible to construct an accelerator of out a large number of identical basic units. In the 40 Gev accelerator at Stanford, the basic unit consists of a section of tube containing two irises. Five of these joined together represent a section, and the whole accelerator has 240 sections. Each section is powered by its own 2956 MHz klystron. The complete accelerator is buried underground, and its conditions are rigourously controlled. Numerous important experiments, especially e-N scattering ones, have been carried out at SLAC. Despite SLAC's appearance, due to the Lorentz contraction, it only behaves as if it were about 38 cm long to an electron accelerated in it. The total energy output of the klystrons in SLAC is between 1.4 and 5.8 GW, more than for the whole of a small country. Most of this energy is transformed into heat, and to avoid overheating, the beam must be pulsed. A useful constant is known as an accelerator's duty cycle, and is the ratio between the time the beam is actually on, and the total time the machine is operating. For the SLAC, this is only about 1/100. In 1962 Dickson and Parkinson suggested the use of superconductors instead of copper for the resonant cavity. This would make continuous operation feasible. Lately, much work is being done on cryogenic accelerators, and it seems possible that they may soon be ready for use.

In California, at roughly the same time as Cockcroft and Walton were building their accelerator in Cambridge, Lawrence et al. were also working on the design of a linear accelerator. However, they realised that it would be possible to much decrease the size of accelerators by making particles pass over the same accelerating gap many times. Lawrence suggested the application of a magnetic field to the accelerating particles, which would keep these moving in a circular trajectory. He proposed that the accelerating gap should be created between two hollow 'D-shaped' electrodes (dees), and that an external electromagnet should be placed so as to keep the particles crossing the gap. Obviously, as the particles became more and more energetic, the external field, if its strength remained constant, would have less and less effect on their trajectories, so that they would move in a spiral. In 1932, Lawrence and Livingstone built the first so-called 'cyclotron'. It consisted of a brass box which contained hydrogen or helium at a low temperature and thus pressure. Mounted at the centre of the box was a hot filament which produced electrons. These were then accelerated by a voltage of about 100 V and ionized the atoms of gas immediately surrounding the filament. The ions described spiral as they were accelerated by an alternating potential difference of 4000 V. The equipment was arranged so that the

field in the dees was always favourable to particles entering them. Altogether the particles were accelerated as if they had fallen through a single potential difference of 1.2 MV. In 1932, Lawrence, Livingstone, and White succeeded in disintegrating lithium nuclei, and confirmed Cockcroft and Walton's results. Two years later, Lewis, Lawrence, and Livingstone managed to break up the nuclei of heavier elements by bombarding them with accelerated deuterons. It is obvious that the angular velocity of particles accelerated in a cyclotron remains constant, and thus the frequency of the A.C. current may also remain so. When the radius of the accelerated particles' trajectory reaches almost that of the cyclotron's casing, they will either be made to hit a target, thus producing a cascade of other particles, or simply be deflected out of the cyclotron by an electrostatic field to become an 'emergent' beam. Because of the relativistic mass increase in high-velocity particles, no more than 15 MeV particles can be produced with cyclotrons of the primitive Lawrence type. Up to this limit, it is found that the energies of accelerated particles are directly proportional to the squares of the radii of their cyclotrons. One advantage of this early type of accelerator was that, unlike later high-energy ones, a continuous stream of accelerated particles could be obtained. Between 1932 and 1945, a great number of useful experiments were performed using cyclotron beams, including the transmutation of gold into mercury.

In 1946 it was proposed that a much superior accelerator to the conventional cyclotron could be made by changing the frequency of the A.C. current according to the velocity of the accelerating particles. This new type of machine was soon constructed, and was named the synchro-cyclotron. Naturally, synchro-cyclotrons had the disadvantage of having to accelerate particles in $100 \mu\text{s}$ pulses, instead of continuously. The change in frequency in a synchro-cyclotron can be achieved simply by rotating or vibrating the circuit condenser for the radio frequency modulator (RFM). The largest FM synchro-cyclotron in operation at present (1974) is the 184' one at Berkeley, which produces protons with an energy of up to 730 MeV. A new method, which was suggested by Thomas as early as 1938, has allowed higher energies to be obtained in un-pulsed cyclotrons. The basic principle is to vary the magnetic field outside the accelerating chamber so that the particles within remain in isosynchronous orbits, and thus they arrive at the correct time for favourable acceleration by the dees however great their relativistic mass may become. This type of cyclotron is known as an 'azimuthal varying field' (AVF) device. The variations in magnetic field can be attained simply by shaping the pole-pieces of the external magnet in a correct manner. Theory predicts that up to about .9 GeV should be obtainable from AVF machines. A 50 MeV device of this type was built and demonstrated at the University of California in 1962, and by 1966, forty-two machines were either in operation or under construction. The Oak Ridge isosynchronous cyclotron (ORIC) is used, like many similar machines, primarily as a so-called 'meson factory'. Large currents of mesons are available from AVF machines for experimentation.

Soon after the invention of the synchro-cyclotron, Kerst proposed a device known as the betatron. This was able to accelerate electrons to practically any energy, using magnetic induction, as in a simple transformer. The electrons were kept in a single orbit by means of a continuously-varying magnetic field. This induced a corresponding electric field, which served to accelerate the particles, as Steinback had suggested in 1936. Theoretically, a single magnet could be employed both to keep the electrons on course and also to accelerate them. However the power necessary for this magnet would be far beyond any practical possibilities, and thus one magnet is

employed for each function. In actual betatrons, thermionically-produced electrons of about 50 keV are injected into the 'doughnut', as the torus-shaped acceleration tube is called, and are then accelerated to high velocities in circular paths. When the electrons have attained the desired energy, the guiding magnet is switched off, allowing them to follow a linear trajectory. This causes them to hit a tungsten (wolfram) target, producing a shower of high-energy gamma and x-rays and pions. The largest betatron currently in operation is that at the MIT, which produces an electron beam with an energy of between 6 and 7.5 GeV, and was built in 1962. However, for electron acceleration, it is almost certainly the case that linear accelerators serve much better, and consequently these are much more widely used.

Probably the most important type of accelerator currently in use is the proton synchrotron. This may trace its origins back to the so-called 'electron synchrotron'. The electron synchrotron is very similar to the betatron, in that it has a small beam, kept in place by guiding magnets whose strength rapidly increases with the beam's energy. However, like a linear accelerator, it has drift tubes in the form of resonant cavities in which electrons were boosted by oscillating electric fields. Primary electrons are injected into the device at about 100 keV, and are then accelerated to energies of around 2 MeV by the betatron-type method, at which point the soft iron flux bars of the magnets' poles become saturated, and the resonant cavities take over. The largest electron synchrotron in operation is that at DESY, Hamburg, with an energy of 6.5 GeV.

Protons which are injected into a proton synchrotron have usually been pre-accelerated by a linear accelerator, fed by a Cockcroft-Walton or Van de Graaf machine coupled to a source in which hydrogen has been thermally ionised. The proton synchrotron consists primarily of an evacuated torical tube into which protons are injected. When the number of protons in the tube is high enough, injection ceases. Around the torical chamber are placed a number of guiding electromagnets and resonant accelerating cavities. When the desired energy has been attained, the particle beam is made to hit a target which suddenly flips up in its path. The secondary or ejected beam may then be directed away to experimental areas. Sometimes the main beam is used, but this requires very high-power electromagnets and is dangerous, and it is consequently rare. At the end of each acceleration cycle, perhaps every 2 s or so, the magnetic field is reduced, and new protons are injected. The slowness of present-day proton synchrotrons is a major defect, but it is possible that it has been overcome at Princeton, using large banks of condensers. Usually synchrotrons are buried underground and surrounded by a thick layer of concrete as a protection against the heavy radiation which they produce.

The similarity between linear accelerators and synchrotrons allows us to apply again the principle of phase stability. We see that, because of relativistic mass gains, the frequency of the accelerating electric wave need only be increased by a factor of five in order to effect an energy increase of around five hundred times. However, due to Relativity, protons may not remain on the same part of the electric wave regardless of their velocity, since Relativity sets a limit on this. Thus, at the so-called 'transition energy' of around 4 GeV, the beam of protons jumps from a position at -60° on the wave to one at 60° . Luckily, 4 GeV was an energy far beyond those attainable with the very first proton synchrotrons.

It is obvious that, unless some sort of focusing was used, particles injected into a synchrotron would quickly diverge and be lost. However, the so-called 'guiding field' is used for this purpose. The earliest type of focusing employed was that of so-called

'weak focusing'. This uses the principle that, due to the slight convexity of the magnetic field produced by the guiding electromagnets, particles tend to occupy the median or halfway plane between the poles of the magnets. As there is no preference for any particular position on the optimum plane, particles will oscillate in so-called 'betatron oscillation' on it. A weak-focusing synchrotron will only accept those particles which are near or in the median plane at injection, and the others will be lost, and thus it is said to have a 'low acceptance'.

The method of weak focusing, however, necessitates large vacuum chambers and magnets, which are uneconomical. A much better method of focusing, known as 'strong focusing', was suggested by Thomas, Christofilos, Courant, and Livingstone and Snyder in 1938, 1950, and 1952 respectively. Strong focusing utilises the widely-used principle in optics of focusing, then de-focusing, and so on, a beam. The amount which a focusing magnetic field changes with distance from the desired orbit is known as the 'gradient' of that magnetic field. Thus the gradient of a weak-focusing magnet is extremely low. It is obvious that a high-gradient magnetic field will cause any particle not in the optimum trajectory to rush outwards at a high-velocity, and thus many will be lost. However, if we alternate the gradient of the focusing field, then particles in both the vertical and the horizontal planes will diverge then converge, and so on. Skew particles act according to the components of their vectors. The main advantage of alternating gradient (AG) focusing is that, while the acceptance of the accelerator is increased, the beam radius is decreased by a factor of about twenty. Thus, if the CERN 28 GeV proton synchrotron had had weak focusing, then its beam would have had a diameter of about 3 m, whereas with AG focusing, this is reduced to 15 cm, while still retaining the same acceptance.

A further type of focusing is known as zero gradient (ZG) focusing. This is utilised by the Argonne 12.5 GeV proton synchrotron constructed in 1963. Here, no effort is made to decrease the magnetic field with increasing radius, as in non-zero gradient machines. However, the magnetic field is deformed near to the actual magnet poles, and this deformity tends to keep particles away from this region, and concentrate them in a loose beam.

Physicists working at MURA spent many years attempting to find methods for building large unpulsed synchrotrons, and from their work, the idea of the fixed field and alternating gradient (FFAG) synchrotron was born. One of the first solutions found to the pulsing problem was to produce a magnetic field which increased considerably with radius, and then to inject particles into a low-radius orbit, and allow them to spiral outwards with increasing energy. However, any particles not in the optimum orbit are lost by this type of focusing, and thus it was abandoned. The next suggestion was that convex magnetic field sections should be used alternately each way up. A convex magnetic field would induce particles to move towards the centre of the accelerator ring when it was one way up, but to move outwards when it was the other way up. These oscillations would keep the particles in a tight beam. However, the diameter of an FFAG machine would have to be considerably greater than that of a normal synchrotron. Nevertheless, a prototype FFAG synchrotron, with 16 sectors, was built at MURA in 1956, and it was able to accelerate electrons to 400 keV in an unpulsed beam with the high intensity of 10^{14} particles/second. However, in the near future it appears that FFAG devices will be used more to research into the properties of magnetic fields than to effect practical particle acceleration.

A contemporary idea for the acceleration of protons to very high energies is that of the so-called 'smoke ring' accelerator. This was first proposed by Bennett in 1934,

and again by Budker and Veksler in 1956, but at neither of these times did it receive much attention. But in 1968, Sarentsev reported that a small smoke ring accelerator had been built at Dubna, and that tests on it were beginning. The principle of the smoke ring accelerator is to blow magnetically rings of electrons into which protons may be inserted and accelerated to extremely high energies. The first major difficulty was to establish stable rings or wells of electrons. The stability of a ring depends on the relative numbers of protons and electrons in it, and the speed at which the electrons orbit the protonic nucleus. It is obvious that as many protons as possible should be placed in a given ring, in order that more of them may be accelerated at once. However, the more protons there are in a ring, the more its structure is disrupted. Despite these difficulties, stable rings were formed at Dubna in injection boxes, where 1.5 MeV electrons were made into 50 cm diameter rings, containing about 10^{15} electrons each, by the application of transverse magnetic fields of 200 gauss. These magnetic fields quickly increased in strength to their maximum of 10 kG, thus squashing the electron rings until they had a diameter of only 10 cm. They then injected about 10^{11} protons, in the form of hydrogen gas, which quickly becomes ionised, into the electron rings. These were then extracted from the injection box by means of a weak magnetic field. They can be accelerated in one of two ways. First, the magnetic pressure on the rings may be removed, thus causing the transverse energy of the spinning electrons to be converted into about 15 MeV of longitudinal proton energy. Alternatively, normal synchrotron techniques may be used to accelerate the rings in one piece, while these are being alternately squashed and expanded by magnetic fields, giving their protons even higher velocities. The emergent beam of rings may be converted into a proton beam by the application of a relatively strong magnetic field. Already heavy ions have been accelerated to 5 GeV in rings using the latter method, and it is obvious that the potentialities of the smoke ring accelerator have been far from all exploited.

However, the best way to achieve high-energy particle reactions is not to use a high-velocity particle beam and a stationary target, but to collide beams together. But before particle beams may be collided, suitable methods for storing them must be devised. In 1956, physicists at MURA suggested the use of FFAG devices for both production and storage, but due to the vast size of machine necessary, this proposal was discarded. Soon after this, Brobeck, Lichtenberg and Newton, and independently Ross had the idea of building two synchrotron-like magnetic guide fields into two stadium-shaped storage rings. These would have one straight side in common, in which high-energy particle collisions would occur. The two rings would be fed from an accelerator, and the equipment would be arranged so that the beams in each ring would orbit in opposite directions.

The first difficulty to be encountered in the building of practical storage rings was the necessity of fast-acting magnets to bend the emergent beam from the main accelerator. This problem was overcome by Koreman and O'Neill in 1957, but soon a new difficulty presented itself: that of producing ultra-high vacua in the storage rings to avoid the loss of particles through collisions with gas molecules. When this problem was finally solved in 1965, the first electron-positron colliding beam experiment was set up. Electrons from the Stanford linac were directed into two intersecting storage rings (ISR) and held there until they could collide. In this experiment, two major problems were immediately shown up. The first of these was that, due to the Maxwell-Lorentz effect (see chapter 1), the circulating electrons radiated x-rays which liberated atoms from the chamber walls, thus decreasing the perfection of the vacuum. This difficulty was overcome by the installation of more pumps in the storage

rings. The second problem was that whenever any disturbance was encountered by the circulating beams, they began to oscillate, and if the oscillations were not precisely in phase at the collision point, then no successful collision would occur. But when the problem of oscillations had been suitably overcome, it became possible to collide .56 GeV electron beams together, and to observe the results with a spark chamber. Often a separate spark chamber was placed above the intersection point and shielded from it, to detect spurious cosmic ray events. In 1960, it was decided that a small storage ring for .25 GeV electrons and positrons should be built in Italy. Because electrons and positrons will circulate in different directions under the influence of the same magnetic field, the so-called 'Ada' apparatus was much smaller than the American electron-electron one. In 1962, Ada was transported to the Orsay accelerator in France, and here it disclosed the existence of the Touschek effect, whereby the more particles that are stored in a ring, the shorter their lifetimes become. Luckily, with energies beyond about .3 GeV this effect becomes negligible. In 1963, Ada was first used for experimental research, and two years later it was retired. At roughly the same time as the Stanford ring came into operation, a .4 GeV electron-positron ring was put into operation at Novosibirsk. Using these two rings, a number of new resonance particles have been discovered. Many other electron-positron and electron-electron rings have been projected or built, including perhaps one at NAL Batavia.

In 1958, having overcome the difficulty that protons are very 'stubborn' about accepting new situations, the proton storage ring finally seemed feasible. Soon after this, Collins suggested the use of multiply-intersecting rings with varying radii of curvature, and in early 1962, physicists at CERN began to design a giant ISR for their 28 GeV proton synchrotron. In 1971, this was completed, and a pressure of one nano-torr was maintained within it. It was 200 m from the main synchrotron, and itself 300 m across. The beam current in the storage rings can reach up to 20 A. The rings intercept a total of eight times, although collisions are often avoided by the application of a magnetic field at collision points. Research with the CERN ISR has just begun, and already interesting results have been obtained on high-energy proton-proton cross-sections, partons, and so on. At present, Budker is building a proton-antiproton storage ring at Novosibirsk, which should be ready in the near future. Plans are already going ahead to build equipment capable of maintaining a stored muon beam produced by the CERN synchrotron. Muons would survive for about 400 revolutions, and pions, kaons, and so on, for between $\frac{1}{4}$ and 4 or 5. The prospects for unstable particle collisions certainly seem exciting, and it is likely that much new information will be obtained using these in the near future.

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APPENDIX A: PROPERTIES OF PARTICLES AND FIELDS.

A.1 Properties of the quarks and antiquarks.

| Name | Q | I | I_3 | S | B | Y | T |
|---|------|-----|-------|----|------|------|------------------|
| A, p, Q ₁ | 2/3 | 1/2 | 1/2 | 0 | 1/3 | 1/3 | ~500 s |
| B, n, Q ₂ | -1/3 | 1/2 | -1/2 | 0 | 1/3 | 1/3 | ~500 s |
| C, Λ , Q ₃ | -1/3 | 0 | 0 | -1 | 1/3 | -2/3 | $\sim 10^{10}$ s |
| \bar{A} , \bar{p} , \bar{Q}_1 | -2/3 | 1/2 | -1/2 | 0 | -1/3 | -1/3 | ~500 s |
| \bar{B} , \bar{n} , \bar{Q}_2 | 1/3 | 1/2 | 1/2 | 0 | -1/3 | -1/3 | ~500 s |
| \bar{C} , $\bar{\Lambda}$, \bar{Q}_3 | 1/3 | 0 | 0 | 1 | -1/3 | 2/3 | $\sim 10^{10}$ s |

A.2 Properties of the stable particles.

| Name | Q | Q_{tot} | \bar{Q} | Y | B | L | e | μ |
|---------------|----|-----------|-----------|----|---|---|---|-------|
| γ | 0 | ND | ND | ND | 0 | 0 | 0 | 0 |
| ν_e | 0 | ND | ND | ND | 0 | 1 | 1 | 0 |
| ν_μ | 0 | ND | ND | ND | 0 | 1 | 0 | 1 |
| e^- | -1 | ND | ND | ND | 0 | 1 | 1 | 0 |
| μ^- | -1 | ND | ND | ND | 0 | 1 | 0 | 1 |
| π^- | -1 | -1 | -1 | -2 | 1 | 0 | 0 | 0 |
| Λ^0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Σ^0 | 0 | 1 | 1/2 | 1 | 1 | 0 | 0 | 0 |
| Ξ^0 | 1 | 1 | 1/2 | 1 | 1 | 0 | 0 | 0 |
| Ξ^+ | -1 | -1 | -1/2 | -1 | 1 | 0 | 0 | 0 |
| Ξ^+ | 0 | -1 | -1/2 | -1 | 1 | 0 | 0 | 0 |
| Σ^+ | -1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Ξ^+ | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Δ^- | -1 | 2 | 1/2 | 1 | 1 | 0 | 0 | 0 |
| Δ^0 | 0 | 2 | 1/2 | 1 | 1 | 0 | 0 | 0 |
| Δ^+ | 1 | 2 | 1/2 | 1 | 1 | 0 | 0 | 0 |
| Δ^{++} | 2 | 2 | 1/2 | 1 | 1 | 0 | 0 | 0 |
| η^0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| K^0 | 0 | 1 | 1/2 | 1 | 0 | 0 | 0 | 0 |
| K^+ | 1 | 1 | 1/2 | 1 | 0 | 0 | 0 | 0 |
| π^- | -1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| π^0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| π^+ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Name | M. | S | J | I | I_3 | U | P | G |
|---------------|----|----|-----|-----|-------|------|----|----|
| γ | ND | ND | 1 | ND | ND | ND | - | ND |
| ν_e | ND | ND | 1/2 | ND | ND | ND | ND | ND |
| ν_μ | ND | ND | 1/2 | ND | ND | ND | ND | ND |
| e^- | ND | ND | 1/2 | ND | ND | ND | ND | ND |
| μ^- | ND | ND | 1/2 | ND | ND | ND | ND | ND |
| Ω^- | 1 | -3 | 3/2 | 0 | 0 | 3/2 | + | ND |
| Λ^0 | 1 | -1 | 1/2 | 0 | 0 | 0 | + | ND |
| Σ^- | 2 | 0 | 1/2 | 1/2 | -1/2 | 1 | + | ND |
| Ξ^- | 2 | 0 | 1/2 | 1/2 | 1/2 | 1/2 | + | ND |
| Ξ^0 | 2 | -2 | 1/2 | 1/2 | -1/2 | -1/2 | + | ND |
| Σ^0 | 3 | -1 | 1/2 | 1 | 1 | -1 | + | ND |
| Σ^+ | 3 | -1 | 1/2 | 1 | 0 | 0 | + | ND |
| Δ^- | 3 | -1 | 1/2 | 1 | 1 | 1/2 | + | ND |
| Δ^0 | 4 | 0 | 3/2 | 3/2 | -3/2 | 3/2 | + | ND |
| Δ^+ | 4 | 0 | 3/2 | 3/2 | -1/2 | 1 | + | ND |
| Δ^{++} | 4 | 0 | 3/2 | 3/2 | 1/2 | 1/2 | + | ND |
| Δ^{++} | 4 | 0 | 3/2 | 3/2 | 3/2 | 0 | + | ND |
| Γ^0 | 1 | 0 | 0 | 0 | 0 | 0 | - | ND |
| K^0 | 2 | 1 | 0 | 1/2 | -1/2 | 1 | - | ND |
| K^+ | 2 | 1 | 0 | 1/2 | 1/2 | 1/2 | - | ND |
| π^- | 3 | 0 | 0 | 1 | -1 | -1/2 | - | - |
| π^0 | 3 | 0 | 0 | 1 | 0 | 0 | - | - |
| π^+ | 3 | 0 | 0 | 1 | 1 | 1/2 | - | - |

ND means Not Defined

Stable Particle Table

April 1973

Masses in MeV/c²; decay widths in keV; branching ratios in percent; charge + or - only.

| Particle | $(G_F)^2 \cdot C_0$ | Mass (MeV) m^2 (GeV/c ²) | Mean life (sec) τ_m (nm) | Partial decay mode | | $R \otimes$ Mode Fraction ^a | R_{\max} (MeV/c) |
|-----------|----------------------|---|--|--|--|--|-----------------------|
| | | | | Mode | Fraction ^b | | |
| γ | $0, 1(7)$ | $0 \leq 2.10^{22}$ | stable | stable | | | |
| ν | $\nu_{e, \mu, \tau}$ | $0 (V_L = V_R)$ | stable | stable | | | |
| e | $-$ | $-$ | stable | stable | | | |
| π^\pm | 1.10^{-1} | $0.511(0.5)$ ≈ 0.000001 | $= 2 \cdot 10^{21} \gamma$ | | | | |
| π^0 | 1.10^{-1} | 0.1994×10^{-6} ≈ 0.0006 $\pm 1.10^{-6}$ | $\pi^+ \pi^-$ $\approx 2.10^{-13}$ | π^0 | 100 | 10^{-5} | 53 |
| μ | 1.10^{-1} | 0.0003 $m^2 = 0.012$ $m_\mu - m_\tau = 2.47 \cdot 10^{-3}$ | $\pi^+ \pi^-$ $\approx 1.6 \times 10^{-12}$ | π^0 | < 1.6 | 10^{-5} | 43 |
| | | ≈ 0.006 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | π^0 | < 2.2 | 10^{-5} | 53 |
| π^\pm | 1.10^{-1} | $1.17 \cdot 5.68 \cdot 10^{-8}$ ≈ 0.054 $m^2 = 0.0195$ | $\pi^0 \pi^0$ $\approx 10^{-15}$ | $\pi^0 \pi^0$ | 100 | 10^{-5} | 50 |
| | | ≈ 0.054 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^0 \pi^0$ | < 2.4 | 10^{-5} | 70 |
| π^0 | 1.10^{-1} | $1.34 \cdot 9.65 \cdot 10^{-10}$ ≈ 0.074 $m_e + m_\mu + m_\tau = 3.40 \cdot 10^{-6}$ | $\pi^+ \pi^-$ $\approx 4.10^{-13}$ | $\pi^0 \pi^0$ | < 3.0 | 10^{-6} | 67 |
| | | ≈ 0.074 | $\pi^+ \pi^-$ $\approx 1.2 \cdot 10^{-12}$ | $\pi^0 \pi^0$ | < 3.6 | 10^{-6} | 67 |
| K^\pm | 1.10^{-1} | $4.93715 \cdot 1.2571 \times 10^{-8}$ ≈ 0.077 $m^2 = 0.244$ $m_K^2 - m_\pi^2 = 1.69 \cdot 10^{-5}$ $m_K + m_\pi = 3.99$ ≈ 0.13 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $63.52(0.19)\%$ $5(1.8) \times 10^{-5}$ | 236 | |
| | | ≈ 0.077 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $5.159(0.01)\%$ $5(1.8) \times 10^{-5}$ | 205 | |
| | | ≈ 0.244 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $3.24(0.10)\%$ $5(1.8) \times 10^{-5}$ | 193 | |
| | | ≈ 0.077 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $4.85(0.08)\%$ $5(1.8) \times 10^{-5}$ | 228 | |
| | | ≈ 0.244 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $5(1.8) \times 10^{-5}$ | 236 | |
| | | ≈ 0.077 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $5(1.8) \times 10^{-5}$ | 203 | |
| | | ≈ 0.077 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 5 | 10^{-7} | 203 |
| | | ≈ 0.077 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $< 9.40 \cdot 10^{-6}$ | 10^{-6} | 193 |
| | | ≈ 0.244 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $< 1.30 \cdot 10^{-5}$ | 10^{-6} | 247 |
| | | ≈ 0.077 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 7 | 10^{-6} | 247 |
| | | ≈ 0.244 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $< 1.54 \cdot 10^{-5}$ | 10^{-6} | 203 |
| | | ≈ 0.077 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 10 | 10^{-6} | 125 |
| K^0 | 1.10^{-1} | $4.977.1 \pm 0.11$ | $50\% K_{\text{short}} \cdot 50\% K_{\text{long}}$ | | | | |
| K_S^0 | 1.10^{-1} | $m^2 = 0.048$ | 0.422×10^{-10} ≈ 0.004 ≈ 2.45 | $\pi^+ \pi^-$ $\approx 10^{-12}$ | $6.81 \pm 0.29\%$ $5(1.8) \times 10^{-5}$ | 206 | |
| | | | $\pi^+ \pi^-$ $\approx 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $1.14 \pm 0.12\%$ $5(1.8) \times 10^{-5}$ | 220 | |
| | | | $\pi^+ \pi^-$ $\approx 10^{-12}$ | $\pi^+ \pi^-$ $\approx 10^{-12}$ | < 0.7 | 10^{-5} | 225 |
| | | | $\pi^+ \pi^-$ $\approx 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 1.5 | 10^{-5} | 249 |
| | | | $\pi^+ \pi^-$ $\approx 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $< 2.40 \cdot 10^{-4}$ | 10^{-4} | 249 |
| | | | $\pi^+ \pi^-$ $\approx 10^{-12}$ | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 0.7 | 10^{-3} | 249 |
| K_L^0 | 1.10^{-1} | 5.181×10^{-8} ≈ 0.044 ≈ 1.553 | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $21.5 \pm 0.8\%$ $5(1.8) \times 10^{-5}$ | 117 | |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $12.0 \pm 1.0\%$ $5(1.8) \times 10^{-5}$ | 133 | |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $1.5 \pm 0.4\%$ $5(1.8) \times 10^{-5}$ | 220 | |
| | | | $m_{K_L} - m_{K_S} = 0.546 \times 10^{-10} \text{ sec}^{-1}$ ≈ 0.0035 | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $38.8 \pm 0.6\%$ $5(1.8) \times 10^{-5}$ | 220 | |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 1.3 | 10^{-6} | 220 |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $< 0.04 \pm 0.19\%$ $5(1.8) \times 10^{-5}$ | 209 | |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 0.4 | 10^{-1} | 209 |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | $< 4.4 \pm 0.4$ | 10^{-8} | 251 |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 4 | 10^{-8} | 225 |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 1.5 | 10^{-8} | 236 |
| | | | | $\pi^+ \pi^-$ $\approx 1.2 \times 10^{-12}$ | < 1.6 | 10^{-8} | 249 |

| Particle | $ G_F ^2 \mu_{\text{eff}}$ | Mass (MeV) | Mean life (sec) | Partial decay mode | | | |
|------------|----------------------------|--|--|---|--|---|-----------------------------|
| | | | | Mode | Fraction ^a | $p_{\text{max}}^{\text{B}}$ | $p_{\text{max}}^{\text{B}}$ |
| | | | | | (MeV/c) | (MeV/c) | (MeV/c) |
| η' | $0^+(0^+)$ | 548.8 ± 0.6 ± 1.4 $m^2 = 0.301$ | $\Gamma = 12.4 \pm 0.58 \text{ keV}$ Neutral decays 21.1% | $\gamma\gamma$ $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$ $\mu^+\mu^-$ $\mu^+\mu^-\pi^0$ | { 38.0 ± 1.0 (% S=1.2) 3.1 ± 1.1 (% S=1.2) (3.0 ± 1.1 (% S=1.1) 3.3 ± 1.1 (% S=1.1) 5.0 ± 1.1 (% S=1.1) < 0.04 (% S=1.1) < 0.2 (% S=1.1) < 0.2 (% S=1.1) < 2.2 ± 0.8 (% 10 ⁻⁴) < 5 (% 10 ⁻⁴) | 274 258 180 173 236 258 236 236 236 236 211 | |
| | | | | Charged decays 28.9% | | | |
| ρ | $1(1^+)$ | 938.2592 ± 0.052 $m^2 = 0.803$ | stable $\Gamma = 2 \times 10^{-8} \text{ GeV}$ | | | | |
| η | $1(0^+)$ | 938.5527 ± 0.052 $m^2 = 0.8028$ $m_p - m_n = -1.29344$ $\Delta = 40.00007$ | $\Gamma = 0.016 \pm 0.014 \text{ MeV}$ $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\mu^+\mu^-$ $\mu^+\mu^-\pi^0$ | $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\mu^+\mu^-$ $\mu^+\mu^-\pi^0$ | 100 5 5 | 100 100 100 | |
| Λ | $0(1^+)$ | 1115.9 ± 0.05 ± 1.1 $m^2 = 1.245$ | 2.523×10^{-10} $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$ | $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$ | { 64.2 ± 0.5 (% S=1.2) 35.8 ± 0.5 (% S=1.2) (8.13 ± 2.91 (% 10 ⁻⁴) 1.24 ± 0.40 (% 10 ⁻⁴) 1.13 ± 0.40 (% 10 ⁻⁴) 1.24 ± 0.40 (% 10 ⁻⁴) < 2.1 (% 10 ⁻⁵) < 1.0 (% 10 ⁻⁵) < 1.0 (% 10 ⁻⁵) < 1.0 (% 10 ⁻⁵) | 100 100 100 100 100 100 100 100 100 | |
| Σ^+ | $1(1^+)$ | 1189.41 ± 0.07 ± 1.6 $m^2 = 1.315$ $m_{\Xi^0} - m_{\Xi^+} = -0.04$ $S = 0.08$ $m_{\Xi^0} - m_{\Xi^+} = -0.01$ $S = 1.2$ | 0.860×10^{-10} $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$ | $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$ | { 51.0 ± 0.7 (% S=1.2) 1.4 ± 0.7 (% S=1.2) 1.24 ± 0.18 (% 10 ⁻⁴) 1.31 ± 0.24 (% 10 ⁻⁴) 1.32 ± 0.24 (% 10 ⁻⁴) < 2.1 (% 10 ⁻⁵) < 1.0 (% 10 ⁻⁵) < 1.0 (% 10 ⁻⁵) < 1.0 (% 10 ⁻⁵) | 100 100 100 100 100 100 100 100 100 | |
| Σ^0 | $1(1^+)$ | 1192.48 ± 0.10 ± 1.1 $m^2 = 1.322$ | $< 1.0 \times 10^{-14}$ $\pi^+\pi^-$ $\pi^0\pi^0$ | $\pi^+\pi^-$ $\pi^0\pi^0$ | 100 5 $\pi_1: 5.4 \times 10^{-3}$ | 74 74 | |
| Σ^- | $1(1^+)$ | 1197.38 ± 0.07 ± 1.2 $m^2 = 1.434$ $m_{\Xi^0} - m_{\Xi^-} = -0.48$ $S = 0.00$ | 1.484×10^{-10} $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ | $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ | 100 5 $\pi_1: 0.450 \times 10^{-3}$ | 191 230 210 76 183 | |
| Ξ^0 | $1(1^+)$ | 1118.9 ± 0.05 ± 1.729 $m_{\Xi^+} - m_{\Xi^0} = +0.4$ $S = 2.6$ | 2.998×10^{-10} $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ | $\pi^+\pi^-$ $\pi^0\pi^0$ $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^+\pi^-\pi^+\pi^-\pi^0$ | 100 5 $\pi_1: 1.1 \times 10^{-3}$ $\pi_2: 1.1 \times 10^{-3}$ $\pi_3: 1.1 \times 10^{-3}$ $\pi_4: 1.1 \times 10^{-3}$ $\pi_5: 1.1 \times 10^{-3}$ | 135 299 123 118 112 84 84 84 | |
| Ξ^- | $1(1^+)$ | 1321.29 ± 0.14 ± 1.746 | 1.672×10^{-10} $\Lambda^-\pi^+$ $\Xi^0\pi^+$ $\Xi^-\pi^0$ | $\Lambda^-\pi^+$ $\Xi^0\pi^+$ $\Xi^-\pi^0$ | 100 5 $\pi_1: 0.10 \times 10^{-3}$ $\pi_2: 0.5 \times 10^{-3}$ $\pi_3: 1.1 \times 10^{-3}$ $\pi_4: 0.5 \times 10^{-3}$ $\pi_5: 1.1 \times 10^{-3}$ $\pi_6: 1.1 \times 10^{-3}$ | 139 190 121 118 70 303 327 | |
| Ω^- | $0(2^-)$ | 1672.58.5 ± 2.797 | $1.3^{+0.5}_{-0.5} \times 10^{-10}$ $\pi^+\pi^-$ $\pi^0\pi^0$ | $\pi^+\pi^-$ $\pi^0\pi^0$ | Total of 294 28 events seen | 294 290 211 | |

^a A scale factor = $\sqrt{N}/(\sqrt{N} + 1)$, where N is number of experiments. S should be < 1. If S > 1, we have enlarged the error of the mean. See, e.g., $\pi^+\pi^-$.

This convention is still inadequate, since if S > 1, the experiments are probably inconsistent, and therefore the real uncertainty is probably even greater than the one given by the standard deviation.

a. Quoted upper limits correspond to 90% confidence level.

b. In decays with more than two bodies, p_{max} is the maximum momentum that any body can have.

c. See Stable Particle Data Card Listings for energy limits used in this measurement.

d. Theoretical values: see also Stable Particle Data Card Listings.

e. See note in Stable Particle Data Card Listings.

f. $\Gamma = 2 \times 10^{-8} \text{ GeV}$ measured.

g. Assumes rate for $\Xi^- \rightarrow \Xi^- \pi^0$ is small compared with $\Xi^- \pi^-$.

h. The direct emission branching ratio is $(1.56 \pm 0.35) \times 10^{-3}$.

i. A contradictory unpublished result of $\pi^+\pi^-$ (with 6 events seen) has been reported by Garthwaite et al. See note in Stable Particle Data Card Listings.

ADDENDUM TO Stable Particle Table

| Magnetic moment | |
|--|---|
| e | $1.001 \pm 0.000 \pm 0.000 \pm 0.000 \pm 0.000$ |
| μ | $1.001 \pm 0.000 \pm 0.000 \pm 0.000 \pm 0.000$ |
| K² | |
| Mode: | Partial rate (sec^{-1}) |
| $\mu\bar{\nu}_\mu$ | $(31.3 \pm 0.15 \pm 0.09 \pm 0.12 \pm 0.01) \cdot 10^{10}$ |
| $\pi^+\pi^-$ | $(37.04 \pm 0.15 \pm 0.09 \pm 0.12 \pm 0.01) \cdot 10^{10}$ |
| $\pi^0\pi^0$ | $(4.54 \pm 0.02 \pm 0.00 \pm 0.11 \pm 0.01) \cdot 10^{10}$ |
| $\pi^+\pi^0$ | $(2.16 \pm 0.08 \pm 0.01 \pm 0.10 \pm 0.01) \cdot 10^{10}$ |
| $\pi^-\pi^+$ | $(2.16 \pm 0.08 \pm 0.01 \pm 0.10 \pm 0.01) \cdot 10^{10}$ |
| $\pi^0\eta$ | $(3.92 \pm 0.01 \pm 0.00 \pm 0.12 \pm 0.01) \cdot 10^{10}$ |
| K_S⁰ | |
| Mode: | Partial rate (sec^{-1}) |
| $\mu\bar{\nu}_\mu$ | $(0.769 \pm 0.02 \pm 0.01 \pm 0.01 \pm 0.01) \cdot 10^{10}$ |
| $\pi^+\pi^-$ | $(0.773 \pm 0.02 \pm 0.01 \pm 0.01 \pm 0.01) \cdot 10^{10}$ |
| K_L⁰ | |
| Mode: | Partial rate (sec^{-1}) |
| $\mu\bar{\nu}_\mu$ | $(1.15 \pm 0.14 \pm 0.05 \pm 0.13 \pm 0.01) \cdot 10^{10}$ |
| $\pi^+\pi^-$ | $(1.19 \pm 0.15 \pm 0.05 \pm 0.13 \pm 0.01) \cdot 10^{10}$ |
| $\pi^0\pi^0$ | $(1.19 \pm 0.12 \pm 0.05 \pm 0.13 \pm 0.01) \cdot 10^{10}$ |
| $\pi^+\pi^0$ | $(1.16 \pm 0.13 \pm 0.05 \pm 0.13 \pm 0.01) \cdot 10^{10}$ |
| $\pi^-\pi^+$ | $(1.08 \pm 0.10 \pm 0.05 \pm 0.13 \pm 0.01) \cdot 10^{10}$ |
| $\pi^0\eta$ | $(1.04 \pm 0.10 \pm 0.05 \pm 0.13 \pm 0.01) \cdot 10^{10}$ |
| η | |
| Mode: | Aximetry parameters |
| $\pi^+\pi^-$ | $\Delta = 0.24 \pm 0.04 \pm 0.12 \pm 0.01$ |
| $\pi^0\pi^0$ | $\Delta = 0.11 \pm 0.04 \pm 0.04 \pm 0.01$ |
| p | |
| Magnetic moment ($\text{eV}/2m_ec$) | Decay parameters ^b |
| 1.792782 ± 0.000017 | Measured Derived s_A/s_V ^b s_V/s_A ^b |
| π^- | $\pi^- \pi^-$ $\pi^- \pi^+$ $\pi^- \pi^0$ $\pi^- \pi^0$ |
| A | |
| Mode: | Decay parameters ^b |
| π^+ | $s_V^2 = 0.847 \pm 0.013$ $(-6.5 \pm 3.5)^{\circ}$ 0.76 $(7.6 \pm 4.1)^{\circ}$ |
| π_0 | $s_V^2 = 0.851 \pm 0.04$ $(-6.5 \pm 3.5)^{\circ}$ 0.76 $(7.6 \pm 4.1)^{\circ}$ |
| Σ | |
| Mode: | Decay parameters ^b |
| π^+ | $s_V^2 = -0.938 \pm 0.017$ $(22 \pm 9)^{\circ}$ 0.17 $(184 \pm 15)^{\circ}$ |
| π^0 | $s_V^2 = +0.666 \pm 0.016$ $(167 \pm 20)^{\circ}$ -0.97 $(-75 \pm 13)^{\circ}$ |
| Λ | $s_V^2 = -0.91 \pm .52$ $S = 1.1^{\circ}$ |
| Σ^- | |
| Mode: | Decay parameters ^b |
| π^+ | $s_V^2 = -0.069 \pm 0.00$ $(104 \pm 13)^{\circ}$ 0.98 $(249 \pm 12)^{\circ}$ |
| π^0 | $s_V^2 = +0.069 \pm 0.00$ $(249 \pm 13)^{\circ}$ 0.84 $(225 \pm 13)^{\circ}$ |
| Ξ^0 | |
| Mode: | Decay parameters ^b |
| Λ^+ | $s_V^2 = -0.39 \pm 0.09$ $(254 \pm 17)^{\circ}$ 0.84 $(225 \pm 17)^{\circ}$ |
| Ξ^- | $s_V^2 = +0.40 \pm 0.03$ $(-448 \pm 5)^{\circ}$ 0.91 $(170 \pm 17)^{\circ}$ |
| Ξ^- | |
| Mode: | Decay parameters ^b |
| Λ^+ | $s_V^2 = +0.40 \pm 0.03$ $(-448 \pm 5)^{\circ}$ 0.91 $(170 \pm 17)^{\circ}$ |

^a Scale factor. Quoted error includes scale factor; see footnote to main Stable Particle Table for definition.

^b s_A/s_V defined by

$$s_A^2 = |C_A|^2 + |C_V|^2, \quad s_V^2 = |C_A|^2 + |C_V|^2, \quad Z = \langle \bar{v} | \Gamma_1 | v \rangle / \langle \bar{v} | \Gamma_1 | C_V | v \rangle, \quad Z = \langle \bar{v} | \Gamma_1 | v \rangle / \langle \bar{v} | \Gamma_1 | C_V | v \rangle;$$

^c s_V^2 defined by $\cos \theta = -s_V^2(C_A^* C_V + C_A C_V^*)/s_A s_V$ [for more details, see text Section IV E].

b. The definition of three quantities is as follows [for more details on sign conventions, see text Section IV H]:

$$= \frac{2|z||p| \cos \Delta}{|z|^2 + |p|^2},$$

$$\rho = \sqrt{1 - z^2} \cos \Delta;$$

$$= \frac{2|z||p| \sin \Delta}{|z|^2 + |p|^2},$$

$$\gamma = \sqrt{1 - z^2} \sin \Delta,$$

s_A/s_V defined by $(S_f - S_i)(s_A/s_V - 1)/2$; Δ defined by $s_A/s_V = |s_A/s_V| e^{i\Delta}$.

c. The definition of the slope parameter of the Delta plot is as follows:

$$M^2 = 1 + \epsilon \left(\frac{s_2 - s_0}{m_{\pi}^2} \right).$$

d. The definition for the charge asymmetry is as follows: $\epsilon = \frac{\Gamma(K_L^0 \rightarrow \pi^+ \pi^-) - \Gamma(K_L^0 \rightarrow \pi^0 \pi^0)}{\Gamma(K_L^0 \rightarrow \pi^+ \pi^-) + \Gamma(K_L^0 \rightarrow \pi^0 \pi^0)}$

e. See note in Stable Particle Data Card Listings.

f. The quantity y^2 is defined as follows: $y^2 = \frac{\Gamma(K_L^0 \rightarrow \pi^+ \pi^-)}{\Gamma(K_L^0 \rightarrow \pi^+ \pi^- + \pi^0)}$
where CP is assumed valid.

A.3 Quark combinations to form stable hadrons.

| Quarks | Q | Y | S | I | M | Particle | J |
|------------------|----|----|----|-----|---|---------------|-----|
| AAA | 2 | 1 | 0 | 1/2 | 2 | - | 1/2 |
| | 2 | 1 | 0 | 3/2 | 4 | Δ^{++} | 3/2 |
| BBB | -1 | 1 | 0 | 1/2 | 2 | - | 1/2 |
| | -1 | 1 | 0 | 3/2 | 4 | Δ^- | 3/2 |
| AAB | 1 | 1 | 0 | 1/2 | 2 | p | 1/2 |
| | 1 | 1 | 0 | 3/2 | 4 | Δ^+ | 3/2 |
| ABB | 0 | 1 | 0 | 1/2 | 2 | n | 1/2 |
| | 0 | 1 | 0 | 3/2 | 4 | Δ^o | 3/2 |
| AAC | 1 | 0 | -1 | 0 | 1 | - | 1/2 |
| | 1 | 0 | 1 | 1 | 3 | Σ^+ | 1/2 |
| ABC | 0 | 0 | -1 | 0 | 1 | Λ^o | 1/2 |
| | 0 | 0 | -1 | 1 | 3 | Σ^- | 1/2 |
| BBC | -1 | 0 | -1 | 0 | 1 | - | 1/2 |
| | -1 | 0 | -1 | 1 | 3 | Ξ^- | 1/2 |
| ACC | 0 | -1 | -2 | 1/2 | 2 | Ξ^o | 1/2 |
| BCC | -1 | -1 | -2 | 1/2 | 2 | Ξ^- | 1/2 |
| CCC | -1 | -2 | -3 | 0 | 1 | Ω^- | 3/2 |
| $\bar{A}\bar{A}$ | 0 | 0 | 0 | 1 | 3 | π^o | 0 |
| $\bar{A}\bar{B}$ | -1 | 0 | 0 | 1 | 3 | π^- | 0 |
| $\bar{A}\bar{C}$ | 0 | 1 | 1 | 1/2 | 2 | K^o | 0 |
| $\bar{B}\bar{A}$ | 1 | 0 | 0 | 1 | 3 | π^+ | 0 |
| $\bar{B}\bar{B}$ | 0 | 0 | 0 | 0 | 1 | η^o | 0 |
| $\bar{B}\bar{C}$ | 1 | 1 | 1 | 1/2 | 2 | K^+ | 0 |
| $\bar{C}\bar{A}$ | 0 | -1 | -1 | 1/2 | 2 | K^- | 0 |
| $\bar{C}\bar{B}$ | -1 | -1 | -1 | 1/2 | 2 | \bar{K}^- | 0 |
| $\bar{C}\bar{C}$ | 0 | 0 | 0 | 1 | 0 | η^o | 0 |

A.4 Resonance particles

(From 'Particle Properties' (April 1973), Particle Data Group, CERN)

Baryon Table

April 1973

[See notes on N^{\pm} and Δ^{\pm} , on possible Z^{*+} , s_1 , and on Y^{+} 's at the beginning of those sections in the Baryon Data Card Listings; also see notes on individual resonances in the Baryon Data Card Listings.]

| Particle ^a | $I \quad (J^P)$ | $\Sigma \text{ or } K \text{ Decay}$ | Mass | Width | $\frac{1}{\Gamma} \text{ Width}$ | M^2 | Partial decay mode | $\frac{M}{M}$ | Fraction | $\frac{M}{M}$ |
|---------------------------|---------------------|---|-----------------|----------------|----------------------------------|--|--|--|---------------------------------|---------------|
| n | $t = \text{date}$ | $\Sigma(10^3)$ $p(\text{GeV}/c)$ $\sigma = 4 \pi R^2 (\text{mb})$ | [MeV] | [MeV] | [MeV] | [GeV 2] | Mode | % | Fraction | [MeV/c] |
| See Stable Particle Table | | | | | | | | | | |
| $N^*(1470)$ | $t/2(1/2^-) P_{11}$ | $T=0.51 \pm p$ $p=0.66$ $\sigma=27.8$ | 1470 300 | ~1470 ~0.41 | 938.3 935.6 | 0.880 0.883 | N^* N^*_w Δ^* Δ^*_w Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c | 6.0 4.0 5-10 % 20-30 % ~7 % 0.05 0.05 0.08 | 420 368 173 435 435 | |
| $N^*(1520)$ | $t/2(1/2^-) D_{13}$ | $T=0.61$ $p=0.74$ $\sigma=23.5$ | 1520 to 1540 | 105 to 150 | 2.31 ~0.18 | N^* N^*_w Δ^* Δ^*_w Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c | 50 ~50 ~0.2 % ~2.25 % ~15-40 % 0.2-1.4 % ~35 0.30 | 456 ~450 ~410 ~422 224 471 471 | | |
| $N^*(1535)$ | $t/2(1/2^-) S_{13}$ | $T=0.64$ $p=0.76$ $\sigma=22.5$ | 1500 to 1600 | 50 to 160 | 2.36 ~0.19 | N^* N^*_w Δ^* Δ^*_w Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c | 35 55 ~10 1-2 % 0.2-0.4 % 0.12 | 467 182 ~422 481 | | |
| $N^*(1670)^1$ | $t/2(1/2^-) D_{15}$ | $T=0.87$ $p=1.55$ $\sigma=15.6$ | 1670 to 1685 | 115 to 175 | 2.79 ~0.24 | N^* N^*_w Δ^* Δ^*_w Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c | 40 ~40 ~50-60 % ~1 % 200 368 ~0.01 ~0.02 | 560 525 ~370 200 372 231 368 ~0.01 ~0.02 | | |
| $N^*(1680)^1$ | $t/2(5/2^-) F_{15}$ | $T=0.90$ $p=1.03$ $\sigma=14.9$ | 1680 to 1690 | 105 to 180 | 2.85 ~0.23 | N^* N^*_w Δ^* Δ^*_w Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c | 6.0 4.0 12 % 15 % 13-19 % ~1 % 20-1 ~10-1 ~10-20 ~0.05-0.1 ~0.05 | 572 525 ~340 372 372 231 368 ~0.01 591 | | |
| $N^*(1700)^1$ | $t/2(1/2^-) S_{15}$ | $T=0.92$ $p=1.05$ $\sigma=14.3$ | 1665 to 1765 | 100 to 300 | 2.89 ~0.42 | N^* N^*_w Δ^* Δ^*_w Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c | 6.0 ~6.0 ~25-30 % ~10-20 % 5 ~5 ~5 0.05-0.1 ~0.05 | 580 547 ~355 ~355 250 348 ~0.01 591 | | |
| $N^*(1780)^1$ | $t/2(1/2^-) P_{11}$ | $T=1.07$ $p=1.20$ $\sigma=12.2$ | 1750 to 1860 | 90 to 350 | 3.17 ~0.51 | N^* N^*_w Δ^* Δ^*_w Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c | ~20 ~20 30-40 % 25-35 % ~5 ~5 ~5 0.05-0.1 ~0.05 | 631 603 ~440 ~353 353 476 476 ~0.01 643 | | |
| $N^*(1860)$ | $t/2(3/2^-) P_{13}$ | $T=1.22$ $p=1.36$ $\sigma=12.4$ | 1770 to 1860 | 180 to 330 | 3.46 ~0.57 | N^* N^*_w Δ^* Δ^*_w Δ^*_s Δ^*_d Δ^*_u Δ^*_c Δ^*_s Δ^*_d Δ^*_u Δ^*_c | 25 ~25 ~55-65 % ~55-65 % ~5 ~5 ~5 ~5 ~5 ~5 | 665 655 ~440 ~353 437 545 | | |
| $N^*(1900)$ | $t/2(7/2^-) G_{17}$ | $T=1.94$ $p=1.07$ $\sigma=6.21$ | 2000 to 2260 | 270 to 325 | 4.80 ~0.67 | N^* N^*_w | 25 ~25 | 888 888 | | |
| $N^*(2220)$ | $t/2(9/2^-) H_{19}$ | $T=2.00$ $p=1.14$ $\sigma=5.97$ | 2245 | 260 to 330 | 4.93 ~0.65 | N^* N^*_w | 45 ~45 | 905 887 | | |

| Fermion ^b | $I = 1^{\pm}$ ↓ mass. | π or K, Decay T(GeV) p(GeV/c) $\sigma = 4 \pi r^2 \cdot \text{fm}^2$ | | Mass MeV | Full Width Γ (MeV) | M^2 $\pm 1\text{ GeV}^2$ | Partial decay mode | | |
|---|---|---|-----------------------------------|--------------------|------------------------------------|----------------------------------|--|---|----------------------|
| | | Mode | Mode | | | | Mode | Fraction % | p or d (MeV/c) |
| N(2650) | $1/2(\text{-} 7^+)$ | T=1.12 p=1.12 $\sigma = 0.67$ | -2650 | -660 | 7.02 ± 0.95 | N ^c | $(J^{+}/2)_s$ $\pm 0.45^*$ | 1154 1140 | |
| N(3030) | $1/2(\text{-} 7^+)$ | T=1.17 p=1.11 $\sigma = 0.52$ | -3030 | -400 | 9.18 ± 1.21 | N ^c | $(J^{+}/2)_s$ $\pm 0.05^*$ | 1366 1358 | |
| $\Delta(6330)^{(\text{m})}$ | $3/2(1/2^+)$ P ₃₃ | T=0.195 (+1) 1230 to p=0.104 1236 $\sigma = 0.18$ | 110 to 122 | 1.53 ± 0.14 | N ^c N ^d | 92.4 0 | 231 90 | | |
| | | Pole position ^m : $M - i\Gamma/2 = (1211, 640, 7) \pm (45, 54, 8)$ | | | | | -0.6 | 263 | |
| $\Delta(1650)$ | $3/2(1/2^+)$ S ₃₁ | T=0.63 p=0.96 $\sigma = 0.18$ | 1655 to 1695 | 130 to 200 | 2.72 ± 0.28 | N ^c N ^d | 28 8.4% 26-32% N ^e | 547 511 340 558 | |
| $\Delta(1670)$ | $3/2(1/2^+)$ D ₃₃ | T=0.87 p=1.00 $\sigma = 1.56$ | 1650 to 1720 | 175 to 300 | 2.70 ± 0.40 | N ^c N ^d | 15 22-30% N ^e | 560 525 357 572 | |
| $\Delta(1890)$ | $3/2(1/2^+)$ F ₃₅ | T=1.36 p=1.42 $\sigma = 0.88$ | 1840 to 1920 | 200 to 350 | 3.57 ± 0.49 | N ^c N ^d | 17 55-70% N ^e | 704 677 403 712 | |
| $\Delta(1910)$ | $3/2(1/2^+)$ P ₃₁ | T=1.33 p=1.46 $\sigma = 0.54$ | 1780 to 1935 | 200 to 340 | 3.65 ± 0.55 | N ^c N ^d | 25 3-16% 14-16% N ^e | 716 691 429 541 0.03 725 | |
| $\Delta(1950)$ | $3/2(1/2^+)$ F ₃₇ | T=1.41 p=1.54 $\sigma = 0.80$ | 1930 to 1980 | 170 to 270 | 5.80 ± 0.44 | N ^c N ^d | 45 8-12% 14-19% N ^e | 741 716 471 571 | |
| $\Delta(2420)$ | $3/2(1/1^+)$ | T=2.50 p=2.55 $\sigma = 0.55$ | 2320 to 2450 | 270 to 350 | 5.86 ± 0.75 | N ^c N ^d | 11 22 | 1023 1006 | |
| $\Delta(2850)$ | $3/2(\text{-} 7^+)$ | T=3.71 p=3.85 $\sigma = 0.05$ | -2850 | -400 | 8.12 ± 1.14 | N ^c | $(J^{+}/2)_s$ $\pm 0.25^*$ | 1266 1254 | |
| $\Delta(3230)$ | $1/2(\text{-} 7^+)$ | T=4.94 p=4.98 $\sigma = 0.25$ | -3230 | -440 | 10.4 ± 1.4 | N ^c | $(J^{+}/2)_s$ $\pm 0.05^*$ | 1475 1464 | |
| Z^a Evidence for states with hypercharge Z is controversial. See the Baryon Data Card Listings for discussion and display of data. | | | | | | | | | |
| | $0(1/2^+)$ | | 1115.6 | | 1.24 | See Stable Particle Table | | | |
| Λ' | $0(1/2^+)$ | | | | | | | | |
| $\Lambda'(1405)$ | $0(1/2^+)$ S ₀₁ | p=0 K ⁻ p 1405 _n $\pm 10^{\circ}$ ± 0.05 | 40 _n | 1.97 | N ^c | 100 | 142 | | |
| $\Lambda'(1520)$ | $0(1/2^+)$ D ₀₃ | p=0.369 1518 _n $\pm 24.5^{\circ}$ ± 0.02 | 16 _n | 2.30 | N ^c | 44±1 | 234 | | |
| $\Lambda''(1670)$ | $0(1/2^+)$ S ₀₁ | p=0.74 $\pm 26.5^{\circ}$ | -1670 | 15 to 18 | 2.79 ± 0.04 | N ^c N _n | 15-35 15-25 30-50 | 140 | |
| $\Lambda''(1690)$ | $0(3/2^+)$ D ₀₃ | p=0.78 $\pm 26.1^{\circ}$ | -1690 | 27 to 45 | 2.86 ± 0.5 | N ^c N ^d | 20-30 40-70 | 429 | |
| $\Lambda''(1815)$ | $0(5/2^+)$ F ₀₅ | p=1.05 $\pm 14.7^{\circ}$ | 1820 | 64 to 140 | 3.30 ± 0.15 | N ^c N ^d | 61 22-35% 25-45% $\pm 25^*$ | 542 519 152 | |
| $\Lambda'(1830)$ | $0(5/2^+)$ D ₀₅ | p=1.09 $\pm 15.6^{\circ}$ | 1810 to 1840 | 60 to 150 | 3.33 ± 0.19 | N ^c N ^d | -10 20-60 | 554 519 536 | |
| $\Lambda(2100)$ | $0(7/2^+)$ G ₀₇ | p=1.68 $\pm 6.68^{\circ}$ | -2100 | 60 to 140 | 4.41 ± 0.22 | N ^c N _n | 28 5 6-11% 2-5% 4-8% 1-1% | 748 699 913 817 483 443 | |
| $\Lambda(2350)$ | $0(\text{-} 7^+)$ | p=2.29 $\pm 5.85^{\circ}$ | -2350 | 140 to 324 | 5.52 ± 0.55 | N ^c N _n | $(J^{+}/2)_s$ $\pm 0.7^*$ | 913 | |
| $\Delta(2585)$ | $0(\text{-} 7^+)$ | p=2.95 $\pm 9.4^{\circ}$ | -2585 | -300 | 6.66 ± 0.77 | N ^c | $(J^{+}/2)_s$ $\pm 1.0^*$ | 1058 | |
| Z^a See Stable Particle Table | | | | | | | | | |
| | $1(1/2^+)$ | | 1(11185.4 0(1192.5 -1197.3) | | 1.41 | See Stable Particle Table | | | |
| $\Sigma'(1185)$ | $1(3/2^+)$ P ₁₃ | p=0 K ⁻ p 1(1185.4 0(1192.5 -1197.3) | 1(1185.4 0(1192.5 -1197.3) | 1.92 ± 0.09 | N ^c | 89±2 | 204 | | |
| $\Xi'(1670)$ | $1(3/2^+)$ D ₁₃ | p=0.74 $\pm 28.5^{\circ}$ | -1670 | 35-65 | 2.79 ± 0.08 | N ^c | -8 -40 | 410 387 | |
| | Parameters here are obtained from partial wave analyses for the resonance. Production experiments suggest two such states; see footnotes k and the Baryon Data Card Listings. | | | | | | | | |
| $\Sigma'(1750)$ | $1(1/2^+)$ S ₁₁ | p=0.91 $\pm 10.7^{\circ}$ | 1700 to 1790 | 50 to 100 | 3.05 ± 0.13 | N ^c N _n | seen seen seen | 481 507 54 | |

| Particle ^a | J/ψ state | T or K Beam GeV/c | Mass MeV | Full Width Γ_D (MeV) | M^2 $\pi^+ \pi^-$ (GeV 2) | Partial decay mode | | |
|-----------------------|------------------------------|----------------------|--------------------------------|--------------------------------------|---------------------------------------|--|----------------|--------------------|
| | | | | | | Mode | Fraction % | p_{max} MeV/c |
| $\Xi(1765)$ | $1/2(1/2)^+$ D ₁₃ | $p=0.94$ $q=19.6$ | 1765 ₊₅₀ | -120 | 3.12 | $N\bar{K}$ | -41 | 496 |
| | | | | | +0.21 | $\Lambda^* \pi$ | -13 | 518 |
| | | | | | | $\Xi(1520)\pi$ | -15 | 537 |
| | | | | | | $\Xi(1385)\pi$ | -10 | 515 |
| | | | | | | $\Xi^+ \pi^-$ | -1 | 461 |
| $\Xi(1915)$ | $1/2(1/2)^+$ F ₁₅ | $p=1.25$ $q=11.0$ | 1900-1930 | 50-100 | 3.67 | $N\bar{K}$ | -14 | 612 |
| | | | | | +0.14 | $\Lambda^* \pi$ | -4 | 547 |
| | | | | | | $\Xi(1915)\pi$ | -6 | 558 |
| $\Xi'(1940)$ | $1/2(1/2)^+$ D ₁₃ | $p=1.32$ $q=12.0$ | -1940 | -220 | 3.77 | $N\bar{K}$ | seen | 678 |
| | | | | | +0.43 | $\Lambda^* \pi$ | seen | 680 |
| | | | | | | $\Xi^+ \pi^-$ | seen | 589 |
| $\Xi(2030)$ | $1/2(1/2)^+$ F ₁₃ | $p=1.52$ $q=9.93$ | -2030 | 100 to 170 | 4.12 +0.27 | $N\bar{K}$ | -20 | 700 |
| | | | | | | $\Lambda^* \pi$ | -20 | 700 |
| | | | | | | $\Xi^+ \pi^-$ | -4 | 652 |
| | | | | | | $\Xi \pi^+$ | -2 | 512 |
| $\Xi(2290)$ | $1/2(1/2)^+$ | $p=2.04$ $q=6.76$ | -2290 | 100 to 230 | 5.06 +0.37 | $N\bar{K}$ | $(J/\psi)/\pi$ | 845 |
| | | | | | | $\Lambda^* \pi$ | π^0/π^+ | 845 |
| $\Xi(2455)$ | $1/2(1/2)^+$ | $p=2.57$ $q=5.09$ | -2455 | -120 | 6.03 | $N\bar{K}$ | $(J/\psi)/\pi$ | 979 |
| | | | | | +0.29 | | π^0/π^+ | 979 |
| $\Xi(2620)$ | $1/2(1/2)^+$ | $p=2.95$ $q=4.30$ | -2620 | -175 | 6.88 | $N\bar{K}$ | $(J/\psi)/\pi$ | 1064 |
| | | | | | +0.35 | | π^0/π^+ | 1064 |
| Ξ^f | $1/2(1/2)^+$ | | (0)1314.9 (-)1121.3 | | 1.73 | See Stable Particle Table | | |
| $\Xi(1930)$ | $1/2(1/2)^+$ P ₁₃ | | (0)1931.6a, 4 (-)1935.6a, 6 | (0) 9, 14b, 5 (-) 12, 9e, 1 | 2.34 +0.01 | $\Xi^+ \pi^-$ | 100 | 144 |
| $\Xi(1820)$ | $1/2(1/2)^+$ | | | 1795 to 1870 | 4.20 +0.10 | $\Lambda^* \bar{K}$ | 398 | |
| | | | | | 99 | $\Xi^+ \pi^-$ | 413 | |
| | | | | | | $\Xi(1830)\pi$ | 244 | |
| | | | | | | $\Xi(1830)\pi$ | 306 | |
| $\Xi(1940)$ | $1/2(1/2)^+$ | | | 1894 to 1961 | 4.40 +0.18 | $\Xi^+ \pi^-$ | 499 | |
| | | | | | | $\Xi(1940)\pi$ | 318 | |
| | | | | | | Seen in both final states; not clear if one, or more, states present. | | |
| Ω^+ | $013/2(1/2)^+$ | | 1672.5 | | 2.60 | See Stable Particle Table | | |

- * Quoted error includes an 8% scale factor. See footnote to Stable Particle Table.
- An arrow to the left of the "T" table indicates a candidate that has been omitted because the evidence for it is not in the "T" table. The question of whether these particles are real is open to considerable question. For convenience all Baryon States for which information exists in the Baryon Data Card Listings are listed at the beginning of the Baryon Table. In the "T" table the omitted particles are those having been omitted from the Baryon Table; for additional information on such states, see the Baryon Data Card Listings.
- a. For the Baryon states, the name (such as $\Xi(1470)$) contains the mass, which may be different for each new analysis. The convention for using primes in the names is as follows: when there is more than one resonance on a given Argand diagram, the first has been designated with a prime, the second with a double prime, etc. The name (col. 1) is the name of the state as it appears in the Baryon Table.
- b. For M and Γ of most baryons we report here an interval instead of an average. Averages are appropriate if each result is based on independent measurements, but inappropriate where there is spread in parameters arises because different models or procedures have been applied to a single experiment. When the spread is large enough to cause only one experiment reports that state or because the various experiments averaged have taken into account the spread, we report the interval.
- c. For this column M is the rounded average which also appears in the same column. Γ is taken as the center of the interval given in the column labeled "T".
- d. For decay modes involving 3 particles p_{max} is the maximum momentum that any of the particles in the final state can have. The momenta have been calculated using the averaged center mass energy, after taking into account the isobar masses. For the $\Xi^+ \pi^-$ mode p_{max} is computed using the nominal isobar masses. If the isobar plus stable mass is less than the resonance mass, no value for p_{max} is given.
- e. Squared branching ratios are squared fractions of the previous untracked decay mode. Our estimates come from data in the Baryon Data Card Listings (where available) and from the isobar model Argand plots of HERNDON 72. See the Mini-Review preceding the N^0 Data Card Listings.
- f. This particle has been seen only in total cross sections. λ is not known, $\lambda = T_0/T$.
- g. The tabulated radiative fractions involve a sum over two helicities ($1/2, -1/2$). In the case of $1/2(1/2)^+$ resonances, there are two distinct isospin couplings, whence y_1 and y_2 . For further information and conventions, see the Mini-Review preceding the Baryon Data Card Listings.
- h. These values are particularly crude. Any naive estimate from the Argand plots of HERNDON 72 (see the Mini-Review preceding the Baryon Data Card Listings) yields branching fractions that are often greater than unity. The branching fractions have been downward to be consistent with the branching fractions from other (non-isobar) channels.
- i. Only information coming from partial-wave analyses has been used here. For the production experiments results are in the Baryon Data Card Listings.
- j. Values come in part from a partial-wave analysis which uses a t-channel-pole-plus-resonance parametrization. The values of the couplings obtained for the resonances may be affected by double counting.

- k. In this energy region the situation is still confused. In addition to the $D_{13}(1670)$, formation experiments have found evidence for fairly narrow ($\Gamma = 50$ MeV) S_{11} and/or P_{11} states near 1620 MeV. It is not clear how many such states really exist. No one has reported a strong coupling of any of these states to $\Lambda\bar{N}$, but there is much disagreement about branching ratios.
- l. Only $N(1530)$ is firmly established; information on the other states comes from experiments that have poor statistics due in the fact that the cross sections for $S=2$ states are very low. For H states, discussions of the angular distributions, and thus our knowledge of the radial quantum numbers of the states, are limited. Four-standard-deviation statistical significance and if they are seen by more than one group. So $Z(2030)$, with main decay mode $\Lambda\bar{K}$, reported as a 3.5-standard-deviation effect, is not tabulated. See the Baryon Data Card Listings for the other states.
- m. See note on $\Delta(1236)$ in the Baryon Data Card Listings. Values of mass and width are dependent upon resonance shape used to fit the data. The pole position appears to be much less dependent upon the particular relativistic model used.
- This is not an estimated process; the error given is larger than the error of the average of the published values (see the Baryon Data Card Listings for the latter).

Baryon States for which information can be found in the Data Card Listings. The name, the mass, the quantum numbers, and the status are shown. Those states with four or three stars can be found in the following Table; the others have been omitted because the evidence for the existence of the effect and/or for its interpretation is a chance is open to considerable question.

| | | | | | | | | | | | | | | |
|-----------|----------|------|----------------|--------|------|-----------|--------|------|-----------|--------|------|-----------|--------|------|
| $N(440)$ | P_{11} | **** | $\Delta(1236)$ | $P3$ | **** | $A(1325)$ | $P0_1$ | **** | $Z(1190)$ | $P11$ | **** | $Z(1320)$ | $P11$ | **** |
| $N(470)$ | P_{11} | *** | $\Delta(1650)$ | $P3$ | *** | $A(1325)$ | $P0_1$ | *** | $Z(1320)$ | $P11$ | *** | $Z(1430)$ | $P13$ | *** |
| $N(472)$ | D_{13} | *** | $\Delta(1670)$ | $D3$ | *** | $A(1405)$ | $S0_1$ | *** | $Z(1440)$ | $P6$ | Dead | $Z(1450)$ | $P13$ | *** |
| $N(473)$ | S_{11} | **** | $\Delta(1690)$ | $P3$ | * | $A(1520)$ | $D0_3$ | **** | $Z(1480)$ | $P7$ | * | $Z(1820)$ | | *** |
| $N(475)$ | D_{13} | *** | $\Delta(1700)$ | $S0_1$ | *** | $A(1520)$ | $D0_3$ | *** | $Z(1520)$ | $S11$ | *** | $Z(1940)$ | | *** |
| $N(476)$ | S_{11} | *** | $\Delta(1700)$ | $D3$ | *** | $A(1520)$ | $D0_3$ | *** | $Z(1520)$ | $S11$ | *** | $Z(1950)$ | | *** |
| $N(478)$ | $F35$ | *** | $\Delta(1700)$ | $P3$ | * | $A(1580)$ | $T0_3$ | *** | $Z(1620)$ | $P6$ | ** | $Z(2250)$ | | * |
| $N(479)$ | S_{11} | **** | $\Delta(1750)$ | $F37$ | **** | $A(1750)$ | $P0_1$ | ** | $Z(1620)$ | $P6$ | ** | $Z(2250)$ | | * |
| $N(480)$ | D_{13} | *** | $\Delta(1760)$ | $D3$ | * | $A(1815)$ | $F0_5$ | *** | $Z(1670)$ | $D1_3$ | **** | $Z(2500)$ | | * |
| $N(480)$ | P_{11} | *** | $\Delta(1760)$ | $S0_1$ | * | $A(1815)$ | $F0_5$ | *** | $Z(1670)$ | $D1_3$ | **** | $Z(2500)$ | | * |
| $N(480)$ | $P3$ | *** | $\Delta(2400)$ | $H31$ | *** | $A(1860)$ | $P0_3$ | ** | $Z(1690)$ | $P7$ | ** | | | |
| $N(490)$ | $F17$ | *** | $\Delta(2850)$ | | | $A(1870)$ | $S0_1$ | ** | $Z(1750)$ | $S11$ | *** | | | |
| $N(492)$ | S_{11} | *** | $\Delta(2850)$ | | | $A(1870)$ | $S0_1$ | ** | $Z(1750)$ | $S11$ | *** | | | |
| $N(500)$ | S_{11} | * | | | | $A(1870)$ | $S0_1$ | ** | $Z(1850)$ | $D1_3$ | **** | $G(1570)$ | $P0_3$ | *** |
| $N(500)$ | S_{11} | * | | | | $A(1870)$ | $S0_1$ | ** | $Z(1850)$ | $D1_3$ | **** | $G(1570)$ | $P0_3$ | *** |
| $N(500)$ | D_{13} | * | | | | $A(2020)$ | $F0_7$ | ** | $Z(1860)$ | $P11$ | ** | | | |
| $N(510)$ | S_{11} | * | | | | $A(2100)$ | $Q0_7$ | *** | $Z(1880)$ | $P11$ | ** | | | |
| $N(510)$ | D_{13} | * | | | | $A(2110)$ | | | $Z(1910)$ | $F15$ | *** | | | |
| $N(510)$ | S_{11} | * | | | | $A(2110)$ | | | $Z(1910)$ | $F15$ | *** | | | |
| $N(510)$ | $G17$ | *** | $Z(1780)$ | $P0_1$ | * | $A(2150)$ | $S0_1$ | *** | $Z(2000)$ | $S11$ | * | | | |
| $N(5220)$ | $H49$ | *** | $Z(1865)$ | $P3$ | * | $A(2585)$ | | *** | $Z(2000)$ | $S11$ | * | | | |
| $N(5230)$ | S_{11} | * | $Z(1890)$ | $F35$ | * | | | | $Z(2030)$ | $F17$ | *** | | | |
| $N(5330)$ | * | | $Z(1890)$ | | | | | | $Z(2050)$ | $P11$ | ** | | | |
| $N(5345)$ | * | | $Z(1890)$ | | | | | | $Z(2080)$ | $P13$ | ** | | | |
| $N(5390)$ | * | | $Z(1890)$ | | | | | | $Z(1900)$ | $G17$ | *** | | | |
| $N(5750)$ | * | | | | | | | | $Z(2250)$ | | | | | |
| | | | | | | | | | $Z(2450)$ | | | | | |
| | | | | | | | | | $Z(2620)$ | | | | | |
| | | | | | | | | | $Z(3000)$ | | | | | |

**** Good, clear, and unmistakable.
*** Needs confirmation.

** Good, but in need of clarification or not absolutely certain.
* Weak.

| Partial decay mode | | | | | | |
|---|--|--------------------------|----------------------------|---|--|--|
| $\frac{1}{2}(0^+)$ | $\frac{1}{2}(0^+)$ | Mass M [MeV] | Width Γ [MeV] | μ^2 [GeV] ² | Mode | Fraction (%) (Upper limits are in (%)) |
| $\omega(1675)$ | $0^+_1(\Lambda)$ formerly called $\pi(1675)$ | 1664 +13 -12 | 141 +17 -12 | 2.77 1.25 5n | π^+ K ⁺ K ⁻ | dominant possibly observed 10/10 |
| $\eta(1680)$ | $\frac{1}{2}^+(\Lambda')$ | 1680 +10 -10 | 161.5 +130 -127 | 2.82 1.27 5n | π^+ [incl. $\pi\eta, \pi\eta\pi, \pi\eta\pi\eta$] K ⁺ K ⁻ [incl. K ⁰] | ≈ 40 ~ 50 ~ 3 ~ 3 |
| | | | | | | (4) 617 |
| | | | | | | 617 |
| See note (1) for possible heavier states. | | | | | | |
| $\pi^+(494)$ | $\frac{1}{2}(0^+)$ | 493.71 | | 0.244 | See Stable Particle Table | |
| $\pi^+(498)$ | $\frac{1}{2}(0^+)$ | 497.71 | | 0.248 | | |
| $\pi^+(901)$ | $\frac{1}{2}(1^+)$ | 901.7 +10.5 -11 | 58.1 +1.1 -1.045 | 0.795 K ⁺ K ⁻ | π^+ K ⁺ K ⁻ | ~ 100 ~ 0.2 ~ 0.18 |
| | | | | | | 288 218 309 |
| (Charged mode; $m^+ - m^- = 6.11 \pm 1.5$ MeV) | | | | | | |
| π^+ | $\frac{1}{2}(0^+)$ | | | | | |
| | | | | | | |
| See note on π^+ S wave. | | | | | | |
| $\Xi_c(1240)$ | $\frac{1}{2}(1^+)$ | 1242 +10 -125 | 127 +1.6 | 1.54 | K ⁺ | only mode seen |
| or C | | | | | | [large] |
| | | | | | | |
| $\Xi_c(1280)$ | $\frac{1}{2}(1^+)$ | 1280 to 1400 | | | \bar{K}^0 | seen] |
| See note (n). | | | | | $\bar{K}^0 \pi^+$ | possibly seen] |
| | | | | | | |
| $\Xi_c(1420)$ | $\frac{1}{2}(2^+)$ | 1421.5 +5.5 -10.9 | 106.9 +10.9 | 2.07 +1.14 | K ⁺ K ⁻ | 55.0±3.1 29.5±2.7 |
| | | | | | | 415 |
| | | | | | | 319 |
| | | | | | | 234 |
| | | | | | | 432 |
| | | | | | | |
| $\Xi_c(1770)$ | $\frac{1}{2}(3^+)$ | 1765.5 +10.5 -15.5 | 140 +50 -25 | 3.11 +1.25 | K ⁺ K ⁻ | dominant seen |
| | | | | | | 788 |
| | | | | | | 757 |
| | | | | | | |
| $\bar{J}^P = 1^+$, favoured, 1^+ and 3^+ not excluded. | | | | | | |
| See note (1) for possible heavier states. | | | | | | |

* indicates an entry in Meson Data Card Listings not entered in the Meson Table. We do not regard these as established resonances.

† See Meson Data Card Listings.

‡ Quoted error includes scale factor $S = \sqrt{q^2/(q-1)}$. See footnote to Stable Particle Table.

§ Square brackets indicate a subtraction of the previous (unbracketed) decay mode(s).

¶ This is only an unquoted guess; the error given is larger than the error of the average of the published values. [See Meson Data Card Listings for the latter.]

(a) TM is approximately the half-width of the resonance when plotted against M^2 .

(b) For decay modes into 2 particles, p_{max} is the maximum momentum that any of the particle in the final state can have. The momenta have been calculated by using the averaged central mass values, without taking into account the widths of the resonances.

(c) From pole position ($M = 1772$), see also body, and §7 the pole is on Riemann Sheet 2.

(d) The $\pi^+\pi^-$ branching ratio from $\pi^+\pi^-$ experiments only. The total branching is then due to mixing only and is expected to be smaller than the value in Meson Data Card Listings. The $\pi^+\pi^-$ branching ratio is compiled from 3 experiments, each possibly with substantial $q\bar{q}$ interference. The error reflects this uncertainty, see notes in Meson Data Card Listings. If no universality holds, $(\sigma^{\pi^+\pi^-}) = (\sigma^{\pi^+\pi^-} + \sigma^{\pi^+\pi^-}) / \text{phase space correction}$.

(e) Empirical limits on fractions for other decay modes of $\pi(1675)$ are $\pi^+ < 0.51$, $\pi^- < 0.81$, $\pi^0 < 0.131$, $\pi^+\pi^- < 0.21$.

- (f) Note that experiments with final state $K_0 K_0 \pi^+ \pi^-$ at rest give $M_0 = 780.8 \pm 0.5^{\circ}$, $m\pi^+ \pi^- < 51$, $p_T \pi^+ < 15$, $\pi^+ \gamma < 254$, $2\pi^+ 2\pi^- \gamma < 95$.
- (g) Empirical limits on fractions for other decay modes of $\psi(3686)$ are $\pi^+ \pi^- < 55$, $\pi^+ \pi^0 < 15$, $n + n\bar{n} < 15$, $\pi^+ \pi^+ < 0.5\%$, $\pi^+ \pi^- < 0.5\%$.
- (h) Empirical limits on fractions for other decay modes of $\psi(3686)$: $\pi^+ \pi^- < 25$, $\pi^+ \pi^0 < 55$, $\pi^+ \pi^+ < 15$, $\pi^+ \pi^+ \pi^- \pi^+ < 15$, $\pi^+ \pi^- < 15$, $\pi^+ \pi^+ < 0.5\%$, $\pi^+ \pi^- < 0.5\%$.
- (i) Empirical limits on fractions for other decay modes of $\psi(1019)$ are $\pi^+ \pi^- < 0.05\%$, $\pi^+ \pi^0 < 45$, $m\pi^+ \pi^- < 25$, $p_T \pi^+ < 15$, $(\pi^+ \pi^-)^2 < 15$, $K_0 K_0 < 21$, $K_0 K_0 \pi^+ < 6\%$.
- (j) Empirical limits on fractions for other decay modes of $\psi(1019)$ are $\pi^+ \pi^- < 20\%$, $m\pi^+ \pi^- < 1.15$, $\pi^+ \pi^0 < 45$, $m\pi^+ \pi^- < 85$.
- (k) Empirical limits on fractions for other decay modes of $\psi(1019)$ are $\pi^+ \pi^- < 25$, $\pi^+ \pi^0 < 45$, $m\pi^+ \pi^- < 25$, $p_T \pi^+ < 15$, $(\pi^+ \pi^-)^2 < 25$, $K_0 K_0 < 21$, $K_0 K_0 \pi^+ < 6\%$.
- (l) Empirical limits on fractions for other decay modes of $\psi(1019)$ are $\pi^+ \pi^- < 20\%$, $m\pi^+ \pi^- < 1.15$, $\pi^+ \pi^0 < 45$, $m\pi^+ \pi^- < 85$.
- (m) We assume as a working hypothesis that peaks with $J^P = 1^+$ observed around 1.7 GeV all come from $\psi(1019)$. For indications to the contrary see **Meson Data Card Listings**.
- (n) See Q-region note in **Meson Data Card Listings**. Some investigators keep a broad enhancement in mass ($M_{\pi\pi}$) from 1250-1400 MeV (the Q -region), and others see structure. The K_0 , $K_0 \pi$, and $K\pi$ are less than a few percent.
- (o) The calculated mass of 1421 MeV comes only from charged $K_0(1420) \rightarrow K\pi$ measurements; the average of the neutral $K_0(1420)$ mass is 1423 MeV. $K\pi$ mode can be contaminated with diffractively produced $J^P = 1^+$.
- (p) Empirical limits on fractions for other decay modes of $\psi(1270)$ are $\pi^+ \pi^- < 15\%$; $K^0 \bar{K}^0 < c.c. < 6\%$.
- (q) The tiny partial width for $\pi^+ \pi^- \rightarrow \pi^+ \pi^-$ ($T < 2$ MeV) is based on an ONE model.¹
- (r) Empirical limits are $\pi^+ \pi^- < 20\%$, $K\pi < 8\%$.

Established Nonets, and octet-singlet mixing angles from Appendix II B, Eq. (21). Of the two isosinglets, the "mainly octet" one is written first, followed by a semi-colon.

| $J^P C_0$ | Nonet members | $\theta_{\text{lin.}}$ | $\theta_{\text{quadr.}}$ |
|--|---------------|------------------------|--------------------------|
| $(0)^+ -$, K_0 , n ; n^0 | $24 \pm 1^*$ | $10 \pm 1^*$ | |
| $(1)^+ -$, π , K^* , π^0 ; u | $36 \pm 1^*$ | $39 \pm 1^*$ | |
| $(2)^+ -$, A_0 , $K_0(1420)$, π^0 ; χ | $29 \pm 2^*$ | $31 \pm 2^*$ | |

(1) Contents of **Meson Data Card Listings**

| Non-strange ($ Y = 0$) | | | | Strange ($ Y = 1$) | | | |
|---------------------------|----------------------------|-------------------------------|---------------------------------------|----------------------------|-------------------------------|---------------------------|-------|
| entry | $J^P C_0$ | entry | $J^P C_0$ | entry | $J^P C_0$ | entry | J^P |
| * | $(100) \quad 1^+(0)^+$ | * | $\pi^+_N \quad (1080) \quad 0^+(N)^+$ | $A_1(1640) \quad 1^+(2^+)$ | | $K(494) \quad 1/2(0^+)$ | |
| n | $(140) \quad 0^+(0^+)$ | a | $A_1(1100) \quad 1^+(1^+)$ | $u(1875) \quad 0^+(0^+)$ | | $K^*(892) \quad 1/2(1^+)$ | |
| c | $(600) \quad 0^+(0^+)$ | - | $H(1250) \quad 1^+(1^+)$ | $g(1680) \quad 1^+(3^+)$ | x | $\times \quad 1/2(0^+)$ | |
| d | $(770) \quad 1^+(3^+)$ | - | $A_1(1417) \quad 1^+$ | x | $(1690) \quad -$ | $K_A(1175) \quad 3/2^-$ | |
| w | $(784) \quad 0(1^-)$ | b | $(1235) \quad 1^+(1^-)$ | x | $(1795) \quad 1^-$ | $\pi_A(1265) \quad 3/2^-$ | |
| +M | $(940) \quad -$ | f | $(1270) \quad 0^+(2^+)$ | $\phi(1880) \quad -$ | q | $1/2(1^+)$ | |
| +M | $(953) \quad -$ | d | $(1285) \quad 0^+(A^-)$ | $\omega(1890) \quad -$ | $\eta_0(1420) \quad 1/2(1^+)$ | | |
| n^0 | $(958) \quad 0^+(0^+)$ | a ₂ | $A_2(1310) \quad 1^+(2^+)$ | s | $(1930) \quad -$ | $\eta_0(1660) \quad 1/2$ | |
| δ | $(970) \quad 1^+(0^+)$ | e | $(1420) \quad 0^+(A^-)$ | p | $(2100) \quad 1^-$ | $\eta_0(1760) \quad 1/2$ | |
| -II | $(990) \quad 0^-(A^-)$ | x | $(1420) \quad 0$ | t | $(2200) \quad 1$ | $L(1770) \quad 1/2(0^-)$ | |
| S' | $(1000) \quad 0^+(0^+)$ | $\chi(1440) \quad 1$ | $\phi(2275) \quad 1^*$ | $\phi(1850)$ | | | |
| ψ | $(1019) \quad 0^+(1^+)$ | $\ell^*(1514) \quad n^*(2^*)$ | $U(2360) \quad 1$ | $\pi^*(2200)$ | | | |
| +M | $(1033) \quad 1^*$ | $a^*(1540) \quad 1(A)$ | $N(2375) \quad 0$ | $\pi^*(2400)$ | | | |
| $\pi_1(1040) \quad 1^*$ | $a^*(1600) \quad 1^*(1^+)$ | $X(2500-3600)$ | | | | | |

A.5 Conservation and invariance laws.

| Quantity | Strong | Electromagnetic | Weak |
|----------------|--------|-----------------|----------------------------|
| E | Y | Y | Y |
| p | Y | Y | Y |
| J | Y | Y | Y |
| Q | Y | Y | Y |
| b | Y | Y | Y |
| l | Y | Y | Y |
| e | - | Y | Y |
| μ | - | Y | Y |
| Vector current | N? | Y | Y |
| Gauge | Y | Y | Y |
| Y | Y | Y | N |
| S | Y | Y | $ \Delta S = 1$ |
| I | Y | N | $ \Delta I = \frac{1}{2}$ |
| I | Y | Y | N |
| P | Y? | Y | N |
| CP | Y? | Y | N |
| T | Y? | Y | N |
| CPT | Y | Y | Y |
| G-parity | Y | Y? | N |
| Weak charge | - | Y? | Y |

APPENDIX B: ABBREVIATIONS.

| | |
|----------------|---|
| a _s | First Bohr radius. |
| A | The 'A' quark. |
| A | Atomic mass. |
| A | Axial vector gamma matrix product. |
| A | Scattering amplitude. |
| A | Area. |
| A | Angle. |
| \AA | Angstrom unit. |
| AC | Alternating current. |
| AG | Alternating gradient. |
| AGS | Alternating gradient synchrotron. |
| AVF | Azimuthal Varying Field. |
| b | Barn. |
| b | Baryon number. |
| B | Baryon number. |
| B _T | SU(3) step operator. |
| B | The 'B' quark. |
| B | Bohr magneton. |
| c | The velocity of light in vacuo. |
| C | The 'C' quark. |
| C | Coupling. |
| C _T | SU(3) step operator. |
| C | C parity. |
| C | Charge conjugation operator/symmetry. |
| CBS | CERN Boson Spectrometer. |
| CERN | (European centre for nuclear research). |
| CVC | Conserved vector current. |
| d | The deuteron. |
| d | Diameter. |
| d | Distance. |
| D | Spin orientation in decay. |
| D | 2 $\frac{1}{2}$ orbital momentum. |
| DC | Direct current. |
| e | Electronic charge. |
| e | Euler's constant. |
| e | Electron/positron. |
| exp | Exponent of. |
| E | Energy. |
| E | Electron number. |
| f | Frequency. |
| f | Amplitude. |
| f | Scattering amplitude. |
| F | Electric form factor. |
| F | 3 $\frac{1}{2}$ orbital momentum. |

| | |
|---------|--------------------------------------|
| FFAG | Fixed field alternating gradient. |
| ζ | Acceleration due to gravity. |
| ζ | Interaction coupling constant. |
| ζ | Anomalous magnetic moment. |
| G | Magnetic form factor. |
| G | G parity/operator. |
| G | The Gravitational constant. |
| G | Weak charge. |
| G | $4 \sqrt{3}$ orbital momentum. |
| h | Planck's constant. |
| \hbar | Dirac's constant. |
| H | Hamiltonian. |
| H | Helicity. |
| H | $5 \sqrt{3}$ orbital momentum. |
| Hz | Hertz. |
| i | The square root of -1. |
| i | Intrinsic layer in a semiconductor. |
| i | Atomic energy level. |
| I | Beam flux. |
| I | Isospin. |
| I_3 | Third component of i -spin. |
| I_z | Third component of i -spin. |
| I | Total angular momentum of a nucleus. |
| ISR | Intersecting Storage Ring. |
| j | The square root of -1. |
| j | Total angular momentum. |
| J | Total angular momentum. |
| k | Atomic energy level. |
| k | The Stefan-Boltzmann constant. |
| K | Numerical constant. |
| K | Kaon. |
| K | The first atomic electron shell. |
| l | The orbital quantum number. |
| l | Orbital angular momentum. |
| L | Orbital angular momentum. |
| L | Lepton number. |
| L | The leptonic trion. |
| L | The second atomic electron shell. |
| m | Relativistic mass. |
| m | The magnetic quantum number. |
| m | Multiplicity. |
| m_0 | Rest mass. |
| m_e | Electronic rest mass. |
| m_e | Electronic mass. |
| m_n | Neutron mass. |
| m_π | Pion mass. |
| m_p | Proton mass. |

| | |
|------------------|--|
| M | Matrix element. |
| M | Multiplicity. |
| M | The third atomic electron shell. |
| MIT | Massachusetts Institute of Technology. |
| NMS | Missing-mass spectrometer. |
| n | Principal quantum number. |
| n | Neutron. |
| n | Refractive index. |
| n | The 'n' Sakaton. |
| n | 'n' layer in semiconductors. |
| N | Event number. |
| N | Nucleon. |
| N | Neutron number. |
| N _± | Charge asymmetry parameter. |
| NAL | National Accelerator Laboratory. |
| N _o | Avogadro's number. |
| ORIC | Oak Ridge Isosynchronous Cyclotron. |
| p | 'p' layer in semiconductors. |
| p | Proton. |
| p | The 'p' Sakaton. |
| P | Momentum. |
| P | Parity. |
| P | Parity symmetry. |
| P | Probability. |
| P | $l \neq$ orbital momentum. |
| P | Permutation operator. |
| P | Pseudoscalar gamma matrix product. |
| PS | Proton synchrotron. |
| Pz | Degree of polarization. |
| q | The four-momentum transfer. |
| Q | Charge. |
| Q | Dinintegration energy. |
| Q | Kinetic energy of separation. |
| Q̄ | Average charge. |
| Q _{tot} | Total charge. |
| r | Radius. |
| r | Roentgen. |
| r | Interaction range. |
| R | Transition rate. |
| R _∞ | Ryberg's constant. |
| Re | Real component of. |
| RF | Radio frequency. |
| RFM | Radio frequency modulator. |
| R(3) | SU(2) group. |
| s | The spin quantum number. |
| s | The first Mandelstam variable. |
| s | Time interval. |

| | |
|----------------|---|
| S | Scalar gamma matrix product. |
| S | Entropy. |
| S | 0 $\not\!\!$ orbital momentum. |
| S | Strangeness. |
| S | Hadronic trion. |
| STP | Standard temperature and pressure. |
| SLAC | Stanford Linear Accelerator Complex. |
| SU(2) | 2 quantum number group. |
| SU(3) | 3 quantum number group. |
| t | Time. |
| t | The second Mandelstam variable. |
| T | Kinetic energy. |
| T | Tensor gamma matrix product. |
| T | Time reversal symmetry/operator. |
| T | Isospin. |
| T _± | SU(3) step operator. |
| u | The third Mandelstam variable. |
| U | Potential energy. |
| U | Unitary spin. |
| v | Velocity. |
| V | 'V' spin. |
| V | 'V' particle. |
| V | Vector gamma matrix product. |
| V(r) | Yukawa potential. |
| W | The W particle. |
| W | Metallic correction factor. |
| x | Target thickness. |
| Y | Hypercharge. |
| Y | Hyperon. |
| z | Combination of Mandelstam variables. |
| Z | Atomic number. |
| ZGS | Zero Gradient Synchrotron. |
| ꝝ | Velocity independant component of helicity. |
| ꝝ | Continuous spin variable. |
| ꝝ | First type of Regge trajectory. |
| ꝝ | Fine structure constant. |
| ꝝ | Alpha particle |
| ꝝ | v/c |
| ꝝ | Second type of Regge trajectory. |
| ꝝ | Beta particle. |
| ꝝ | Photon. |
| ꝝ | Electrical units correction factor. |
| ꝝ | Gamma ray. |
| ꝝ | Third type of Regge trajectory. |

| | |
|----------------|----------------------------------|
| γ | A gamma matrix. |
| Γ | Bandwidth. |
| δ | Delta particle. |
| δ | Even-odd nucleon correction. |
| δ | Displacement. |
| δ | Differential operator. |
| δ | Fourth type of Regge trajectory. |
| Δ | The error in. |
| Δ | Difference. |
| Δ | Small increment of. |
| ϵ | Intrinsic parity. |
| ϵ_0 | The permittivity of free space. |
| η | Eta particle. |
| θ | Angle. |
| θ | Theta meson. |
| ϑ | Precession angle. |
| K | K meson. |
| λ | Wavelength. |
| λ_{cp} | Wavelength over two pi. |
| λ_{ce} | Compton wavelength of proton. |
| λ_{ce} | Compton wavelength of electron. |
| λ_{cp} | Compton wavelength of pion. |
| Λ | Lambda hyperon. |
| μ | Refractive index. |
| μ | Muon. |
| μ | Magnetic moment. |
| μ | Muon number. |
| μ | Exchanged quantum mass. |
| ν | Frequency. |
| ν_L | Larmor frequency. |
| ν | Neutrino. |
| ν_e | e-neutrino. |
| ν_μ | mu-neutrino. |
| N | Nucleon. |
| Ξ | Cascade (ξ) particle. |
| π | Pion. |
| π | Pi. |
| Π | Parity operator. |
| ρ | Density. |
| ρ | Radius of curvature. |
| $\rho(E_i)$ | Density of states. |
| σ | Cross-section. |
| σ_T | Total cross-section. |

| | |
|-----------------|--|
| σ_a | Elastic cross-section. |
| σ_{inel} | Inelastic cross-section. |
| σ | Pauli matrix. |
| Σ | Sigma hyperon. |
| T | Signature. |
| T | Mean lifetime. |
| T | Tau meson. |
| T | Time. |
| ϕ | Phase. |
| ϕ | Angle of deflection. |
| ϕ_e | Phase angle. |
| ϕ | Angle. |
| Ψ | The spatial wave function. |
| ω | Angular velocity. |
| Ω | Solid angle. |
| Ω | Omega particle. |
| ∇^2 | ('det') The Laplacian operator. |
| $ X\rangle$ | ('ket', 'bra') The state vector of X (Dirac notation). |
| ∂ | The partial differentiation operator. |

APPENDIX C: UNITS.

C.1 The SI prefixes.

| Exponent of ten | Prefix | Symbol |
|-----------------|--------|--------|
| 12 | tera | T |
| 9 | giga | G |
| 6 | mega | M |
| 3 | kilo | k |
| 2 | hecto | h |
| 1 | deca | da |
| -1 | deci | d |
| -2 | centi | c |
| -3 | milli | m |
| -6 | micro | μ |
| -9 | nano | n |
| -12 | pico | p |
| -15 | femto | f |
| -18 | atto | a |

C.2 The basic SI units.

(From 'Chambers 4-figure Mathematical Tables', L.J.Comrie, pp 65-66)

| Concept | Symbol | Unit | Unit symbol | Definition |
|---------------------------|--------|----------|-------------|--|
| Length | l | metre | m | 1 m = 1 650 763.73 wavelengths of the radiation ($2p_{10}$ - $5d_5$) of Kr-86. |
| Mass | m | kilogram | kg | International prototype kg. |
| Time | t | second | s | $1/31\ 556\ 925.974\ 7$ of the tropical year for 1900 Jan. 0, 12 h ephemeris time. |
| Electric current | I | ampere | A | An ampere in each of two infinitely long parallel conductors of negligible cross-section in vacuo will produce on each a force of 200 nN/m. |
| Thermodynamic temperature | K | kelvin | K | The kelvin is $1/273.16$ of the thermodynamic temperature of the triple point of water. |
| Luminous intensity | | candela | cd | The luminous intensity of a black body radiator at the temperature of freezing Pt at a pressure of 1 std. atm. viewed normal to the surface is 600 cd/m ² . |
| Amount of substance | | mole | mol | The amount of substance of a system which contains as many |

elementary units as there are atoms in 12 g of C-12. The elementary units must be specified.

C.3 Compound SI units used in this book.
(From 'Chambers 4-figure Mathematical Tables', L.J.Comrie, pp 65-66)

| Concept | Symbol | Unit | Unit symbol | Definition |
|-------------------------|----------------|--|----------------------------------|--|
| Plane angle | | radian | rad | A radian is equal to the angle subtended at the centre of a circle by an arc equal in length to the radius. |
| Solid angle | | steradian | sr | A steradian is equal to the 3-D angle subtended at the centre of a sphere by an area on the surface equal to the radius squared. |
| Area | A, a | square metre | m ² | a = 1° |
| Volume | V, v | cubic metre | m ³ | V = 1³ |
| Velocity | v, u | metre/second | ms ⁻¹ | v = dl/dt |
| Acceleration | a | metre/second ² | ms ⁻² | a = d ² l/dt ² |
| Density | ρ | kilogram/metre ³ | kgm ⁻³ | ρ = m/V |
| Momentum | p | kilogram metre /second | kgms ⁻¹ | p = mv |
| Angular momentum | Iω | kilogram metre ² /second | kgm ² s ⁻¹ | Iω = dI/dt |
| Kinetic energy | T | kilogram metre ² /second ² | kgm ² s ⁻² | T = $\frac{1}{2}mv^2$ |
| Force | F | newton | N | F = ma |
| Potential energy | U | newton metre | Nm | U = $\int Fdl$ |
| Permittivity of vacuum | ε ₀ | farad/metre | Fm ⁻¹ | ε ₀ = 1/(4π ₀ c ²) |
| Electric charge | Q | coulomb | C | Q = $\int Idt$ |
| Electric potential | V | volt | V | V = $\int_{\infty} \phi dl$ |
| Electric field strength | E | volt/metre | Vm ⁻¹ | E = dV/dl |
| Electric resistance | R | ohm | Ω | R = V/I |
| Electric flux density | D | coulomb/metre | Cm ⁻¹ | D = dQ/dA |
| Frequency | f | hertz | Hz | |
| Magnetic flux | Φ | weber | Wb | Φ = $\int B dl$ |
| Magnetic flux density | B | tesla | T | B = dΦ/dA |

C.4 Conversions of non-SI to SI units.

| Non-SI unit | Symbol | SI unit | Conversion factor (to SI) |
|------------------|--------|------------------|---------------------------------|
| Inch | " | cm | 2.54 |
| Foot | ' | m | 0.3048 |
| Mile | mi | km | 1.609344 |
| Minute | min | s | 60 |
| Hour | hr | s | 3600 |
| Day (mean solar) | day | s | 864000 |
| Year | yr | s | 31556925.9747 |
| Degree | ° | rad | 0.01745329 |
| Ton (force) | tonf | N | 9964.02 |
| Gauss | G | T | 0.0001 |
| Torr | torr | Nm ⁻² | 133.332 |
| Atmosphere | atm | Nm ⁻² | 10332.275 |
| Electron volt | eV | J | 1.602191770 x 10 ⁻¹⁹ |
| Barn | b | m ² | 10 ⁻²⁸ |

APPENDIX D:

THE GREEK ALPHABET.

Lower-case

Upper-case

Letter name.

ε δ ι μ ο ν ρ η ς υ π θ ο κ σ ι

Α Β Δ Ε Ζ Η Κ Ι Ο Λ Μ Ν Θ Ω Σ Τ

| | |
|---------|---------|
| Alpha | A |
| Beta | B |
| Gamma | G |
| Delta | D |
| Epsilon | E |
| Zeta | Z |
| Iota | I |
| Theta | T |
| Lambda | L |
| Nu | N |
| Xi | X |
| Ci | Ci |
| Pi | Pi |
| Rho | Rho |
| Sigma | Sigma |
| Tau | Tau |
| Upsilon | Upsilon |
| Phi | Phi |
| Omicron | Omicron |
| Psi | Psi |
| Ciomega | Ciomega |

APPENDIX E: PARTICLE ACCELERATORS.

(From 'Fundamentals of Elementary Particle Physics', M.J.Longo, p 22, and
 'Introduction to High Energy Physics', D.H.Perkins, p 45)

Proton accelerators:

| Location | Name | Energy (GeV) | Intensity 10^{12} parts. /pulse | Max. rep. rate /second |
|---------------------------|----------|-----------------|---|------------------------------|
| LBL, Berkeley, Calif. | Bevatron | 6.2 | 5 | 0.2 |
| ANL, Argonne, Ill. | ZGS | 12.5 | 3 | 0.4 |
| BNL, Upton, N.Y. | AGS | 33 | 10 | 1.0 |
| NAL, Batavia, Ill. | - | 200-500 | 50 | 0.35-0.12 |
| ITEP, Moscow, USSR | - | 7.5 | 0.6 | 0.25 |
| JINR, Dubna, USSR | - | 10 | 0.1 | 0.1 |
| IHEP, Serpukhov, USSR | - | 76 | 1 | 0.1 |
| CERN, Geneva, Switzerland | PS | 28 | 2 | 0.40 |
| RHUL, Harwell, UK | Nimrod | 8 | 3.5 | 0.5 |
| CENS, Saclay, France | Saturne | 3 | 1.2 | 0.35 |

Electron accelerators:

| | | | | |
|----------------------------|------|-----|------|-----|
| CEA, Cambridge, Mass. | CEA | 6 | 0.1 | 60 |
| Cornell Univ., Ithaca, NY | - | 12 | 0.1 | 60 |
| SLAC, Stanford, Calif. | SLAC | 21 | 0.8 | 360 |
| Phys. Inst., Bonn, Germany | - | 2.5 | 0.06 | 50 |
| DESY, Hamburg, Germany | DESY | 7.5 | 0.6 | 50 |
| LAL, Orsay, France | - | 2.3 | - | - |
| NFL, Daresbury, UK | NINA | 5 | 0.2 | 50 |
| Phys. Inst. Kharkov, USSR | LU-2 | 2 | 0.15 | 50 |
| Inst. Phys. Yerevan, USSR | - | 6 | 0.1 | 50 |

Storage rings:

| Location | Type | Energy (GeV) |
|---------------------------|---------------------------------|--------------|
| CERN, Geneva, Switzerland | p - p | 25 |
| Novosibirsk, USSR | e ⁺ - e ⁻ | 0.7 |
| Orsay, France | e ⁺ - e ⁻ | 0.55 |
| Frascati, Italy | e ⁺ - e ⁻ | 1.5 |

APPENDIX F: PHYSICAL CONSTANTS.

(From 'Particle Properties' (April 1973), CERN, p 35 and
'Chambers 4-figure Mathematical Tables', L.J.Comrie, p 64)

| Constant | Symbol | Value |
|--------------------------------|------------------|--|
| Pi | π | 3.1415926536 |
| Euler's constant | e | 2.7182818285 |
| Velocity of light in vacuo | c | 2.9979250(10) $\times 10^8$ m s ⁻¹ |
| Planck's constant | h | 6.626196(50) $\times 10^{-34}$ J s |
| Dirac's constant ($h/2\pi$) | \hbar | 1.0545919(80) $\times 10^{-34}$ J s |
| Electronic charge | e | 1.6021917(70) $\times 10^{-19}$ C |
| Permittivity of vacuum | ϵ_0 | 8.8541(8) $\times 10^{-12}$ F m ⁻¹ |
| Gravitational constant | G | 6.6732(31) $\times 10^{-11}$ N m ² kg ⁻² |
| Electron rest mass | m_e | 9.109558(54) $\times 10^{-31}$ kg |
| Electron charge/mass ratio | e/m _e | 1.758796(6) $\times 10^{11}$ C kg ⁻¹ |
| Proton rest mass | m_p | 1.67252(3) $\times 10^{-27}$ kg |
| Neutron rest mass | m_n | 1.67482(3) $\times 10^{-27}$ kg |
| Ryberg's constant | R _∞ | 1.0973731(1) $\times 10^7$ m ⁻¹ |
| Bohr radius | a ₀ | 5.2917715(81) $\times 10^{-11}$ m |
| Bohr magneton | μ_B | 9.2732(2) $\times 10^{-24}$ J T ⁻¹ |
| 1/fine structure constant | α^{-1} | 137.03602(21) |
| Boltzmann's constant | k | 1.380622(5) $\times 10^{-23}$ J K ⁻¹ |
| Avogadro's constant | N _A | 6.022169(40) $\times 10^{23}$ mol ⁻¹ |
| Compton wavelength of electron | λ_{ce} | 2.42621(2) $\times 10^{-12}$ m |
| Compton wavelength of proton | λ_{cp} | 1.321398(13) $\times 10^{-15}$ m |
| MeV | MeV | 1.6021917(70) $\times 10^{-19}$ J |
| Proton gyromagnetic ratio | γ | 2.675192(7) $\times 10^8$ rad s ⁻¹ T ⁻¹ |
| Mass unit | u | 1.66043(2) $\times 10^{-27}$ kg |
| Acceleration due to gravity | g | 9.80665 $m s^{-2}$ |
| - (at Greenwich) | g | 9.81883 $m s^{-2}$ |