

# Hypothetical particles

ALFRED S GOLDHABER AND J SMITH

Institute for Theoretical Physics, State University of New York, Stony Brook, Long Island,  
New York 11794, USA

## Abstract

A review is given of the status of hypotheses about various undiscovered particles. Magnetic monopoles, intermediate bosons, heavy leptons, scalar particles, quarks, tachyons and gravitons are discussed, along with speculations about the newly discovered neutral mesons.

This review was completed in December 1974.

**Contents**

	Page
1. Introduction . . . . .	733
2. Recently discovered particles . . . . .	735
2.1. SU(3) families . . . . .	735
2.2. Regge families . . . . .	736
2.3. Dual models . . . . .	738
2.4. Exotic states . . . . .	738
2.5. The mu neutrino . . . . .	739
3. Magnetic monopoles . . . . .	739
3.1. Dirac's condition . . . . .	739
3.2. Spin approach . . . . .	740
3.3. Theoretical difficulties . . . . .	741
3.4. Extension of Dirac's theory . . . . .	742
3.5. Binding of monopoles . . . . .	743
3.6. Experimental searches . . . . .	745
3.7. Indirect evidence on monopoles . . . . .	746
4. New particles predicted in unified gauge field theories . . . . .	747
4.1. Intermediate vector bosons . . . . .	747
4.2. Gauge field theories . . . . .	749
4.3. Heavy leptons . . . . .	750
4.4. Scalar particles . . . . .	751
4.5. Neutral currents . . . . .	752
4.6. Charmed particles . . . . .	753
4.7. Miscellaneous . . . . .	754
5. Constituents of the hadrons . . . . .	755
5.1. Quarks . . . . .	755
5.2. Integrally charged triplets . . . . .	757
6. Tachyons, or particles faster than light . . . . .	757
6.1. General considerations . . . . .	757
6.2. Experimental searches . . . . .	758
7. Gravitons and dilatons . . . . .	760
8. The new particles . . . . .	761
9. Bibliography of recent related reviews . . . . .	762
Acknowledgments . . . . .	764
References . . . . .	764

## 1. Introduction

A method of prediction widely used at one time was described by Xenophon (371 BC). To determine, for example, the outcome of a battle if it were to be fought on a given day, animals would be sacrificed, and their entrails examined by an experienced diviner. Modern physics permits far more precise and reliable predictions of certain (ever-broadening) classes of phenomena. The physicist can apply beautiful and powerful ideas which have been discovered and confirmed through a delicate interplay between theory and experiment. Among these ideas, the concept of 'particle' is one of the most ancient and useful. It refers to an object, usually treated as indivisible, of definite mass, and characterized also by intrinsic properties, such as electric charge and angular momentum. In this review we wish to examine the status of a number of popular hypotheses about certain subnuclear or 'elementary' particles whose existence has yet to be shown. Unlike the solution of a well-defined physics problem, particle prediction may seem nearly as mystical as divination from entrails, but there have been some remarkable successes. To set the stage for examining current guesses, we exhibit in table 1 a partial listing of particles predicted and/or discovered in the past half century or so.

The table merits a number of comments:

(a) In the cases where families of particles are involved, we frequently indicate only the earliest discovered members or the crucial members required to verify the familial pattern. Thus cavalierly do we dismiss the antiproton, as well as the host of

**Table 1.** Predicted and discovered particles. For predicted particles the first date is the year of prediction. For discovered particles the last date is the year of discovery.

	<i>Predicted</i>	<i>Not predicted</i>
<i>Discovered</i>	Photon (1905, 1916) Neutron (1920, 1932) Antiparticles [positron (1930–1, 1932)] Neutrino (1930, 1953) Pi meson (1935, 1947) SU (2) families [ $\pi^0$ (1938, 1950)] Hadronic vector mesons (1957–9, 1961) Mu neutrino (1958, 1962) Regge families (1959, 1965) SU (3) families [ $\Omega^-$ (1961, 1964)] Regge daughters [ $\rho'$ (1967, 1972)]	Electron (1897) Proton (1911) Muon (1937) Strange particles [K, $\Lambda$ , $\Sigma$ , $\Xi$ (1947–53)] Resonant states [ $\frac{3}{2}^+$ , $\frac{3}{2}^-$ (1952)] Strange resonances [ $Y^*$ , $K^*$ (1960)]
<i>Not discovered</i>	Graviton (1930) Magnetic monopole (1931) W bosons (1957) Heavy leptons (1960) Tachyon (1962) Quarks (1964) Triplets (1965) Scalar bosons (1965) Neutral bosons (1967) Dilatons (1968) Veneziano families (1968) Lee–Wick anomaly (1970) Massless weakly interacting particles (1972)	Exotic particles (1964) (antipredicted)

other hadron antiparticles. This is not merely to express a point of view about the significance of the later discoveries, but mainly to present as modestly as possible the past successes of particle prediction, permitting what we hope would be conservative speculations about the chances that further predictions will succeed.

(b) One could argue that, on the average, the successful predictions were a bit more closely tied to known experimental results than the not-yet-successful. Also, success usually came within a few years of prediction. The longest gaps were for the electron neutrino (23 years) and the pi meson (12 years). In the former case, the long time lag was not so important because indirect arguments gave such strong evidence for the neutrino—basic conservation laws required it. Physicists who wish to speculate ‘by the charts’, as do some who follow the stock exchange, might conclude that prospects for the quark are the best, and for the newly suggested neutral bosons or leptons, second best. We do not advocate these as safe speculations!

(c) In looking back at a previous report in this journal on a related topic (Peierls *et al* 1955), one is struck by an enormous change in the pace of ‘particle discovery’. Only one additional lepton ( $\nu_\mu$ ) has been found since then, but literally hundreds of new unstable hadronic (strongly interacting) states have appeared (Particle Data Group 1974). These resonances are grouped into families, suggesting that the vast profusion of hadrons may be governed by a few simple principles, perhaps even that the hadrons are constituted of a few truly elementary particles.

(d) It is evident that families of particles are often ‘predicted’ only in the sense that a pattern is observed which permits prediction of some new members of the family. SU(3) is a prime example of this. Clearly the process is difficult to terminate, since at any time there may be some outstanding gaps in recognized families.

(e) It may never be possible to stop recording new particles, but there are some general trends which suggest new directions in the particle searches. For the strongly interacting particles, or hadrons, the only known obstacle to strong or electromagnetic decay is kinematics. A hadron will be ‘stable (mean life more than about  $10^{-22}$  s!)’ only if its mass is below the threshold for any multiparticle system having the same quantum numbers. This is the reason for the empirical rule that there is never more than one stable hadron with the same internal quantum numbers (charge, baryon number, isospin, strangeness). Perhaps the  $\Omega^-$  was the last stable hadron to be found (but see §8!). If this be so, then the concept of particle may lose its usefulness as a way of identifying fundamental components of the observed hadrons, since the unstable resonant states may be ever more difficult to identify at higher masses.

(f) Conversely, if constituents with anomalous quantum numbers, such as quarks, are useful in describing hadron structure, these objects may nevertheless be unable to appear as isolated particles. Therefore it is possible to argue in very different ways that strongly interacting elementary particles do not exist, and other concepts are needed to guide theoretical development.

(g) For students of electromagnetic and weak interactions, there are far more vivid hopes that a few more discoveries may complete some small families of truly elementary particles whose interactions could be described accurately by renormalized perturbation theory.

The remainder of this paper is planned as follows: In the next section we sketch briefly the discoveries of the last decade, referring where possible to previous reviews. In §3 we discuss the oldest surviving idea, that of the magnetic monopole. Section 4 is an exposition of the burgeoning array of vector, spinor and scalar particles which have been proposed in the effort to build a renormalizable unified theory of weak and

electromagnetic interactions. Section 5 presents suggestions about the possible interpretations of hypothetical sub-units of hadrons, including the properties of these objects if they could appear as free particles. Section 6 is devoted to tachyons, or particles moving faster than light, and §7 to gravitons and dilatons. Section 8 concerns the recently discovered narrow neutral states. In §9 we present a brief bibliography of recent reviews which may be of interest to the reader.

At this point we should enter several disclaimers, to protect the unwary student from false impressions, and ourselves from the indignation of colleagues. While we emphasize theoretical developments, there are surely some omissions even on theory; for these we apologize. The main reason that we do not dwell on experiments is that we feel poorly qualified to appraise them. Nevertheless, one should realise that discoveries summarized here in a sentence or a table entry were made in painstaking experiments, frequently requiring complex skills, great imagination and ingenuity, and an almost superhuman drive to wrest secrets from nature. To appreciate (as best one can from reading) the flavour of experimental physics, one would do well to peruse the following: *Foundations of Nuclear Physics* ed R T Beyer (1949); the series *Adventures in Experimental Physics* ed B C Maglič (1972 onwards); and the *Nobel Prize Lectures in Physics*. Beyond acknowledging the remarkable work of experimenters, we want to note a point which is obvious, but often overlooked: without experiments, none of the theoretical predictions discussed here would have been made, much less tested. To put it another way, the phrase 'physics is an experimental science' means: stopping theory would badly cripple development; stopping experiment would kill it. A final caution: those who look for a complete history of past particle discovery are sure to be disappointed in at least two respects. The classification in table 1 is our choice, and almost every entry could be debated. To give a full discussion would require an article in its own right, and we should be glad to hear from readers who have special knowledge relevant to such a discussion. In the next section we survey recent discoveries, not giving a history, but only presenting an outline of what is currently known (or believed) about particles and their classification, as a background for discussing the main topic of unconfirmed hypotheses.

## 2. Recently discovered particles

### 2.1. SU(3) families

In 1932, Heisenberg introduced the SU(2) symmetry of strong interactions now known as isospin invariance, in order to describe the similarities between the proton and the neutron. This symmetry was studied more fully by Kemmer (1938) (see also Kemmer 1971). Since then many SU(2) families of particles have been discovered, including  $(\pi^+, \pi^-, \pi^0)$ ,  $(\Sigma^+, \Sigma^-, \Sigma^0)$ ,  $(\Xi^-, \Xi^0)$ . All these families are characterized by unit spacing in electric charge. All the members of a given family have the same hypercharge  $Y \equiv S + B$ , obeying the Gell-Mann–Nishijima relation (Gell-Mann 1953, Nakano and Nishijima 1953)

$$Y = 2(Q - I_3) \quad (2.1)$$

where  $S$  is called strangeness<sup>†</sup>,  $Q$  is the electric charge in units of proton charge,  $B$  is

<sup>†</sup> A term derived from the unusual properties of strange ( $S \neq 0$ ) particles. They are produced strongly in high-energy collisions, but are stable against strong decay; conservation of  $S$  in strong interactions 'explains' why strange particles are produced in pairs.

the baryon number†, and  $I_3$  is the third component of the isospin operator. The masses of identified isospin multiplets range from hundreds to thousands of MeV, but the splitting between adjacent members of a multiplet is never much more than several MeV.

In the late 1950s many schemes were proposed for placing groups of SU(2) multiplets in larger 'supermultiplets'. The most successful scheme, that of Gell-Mann (1962) and Ne'eman (1961), treated the supermultiplets as representations of the group SU(3), the unitary unimodular group in three dimensions. This suggested the existence of an approximate SU(3) symmetry of strong interactions whose precise meaning is still a subject of debate.

The most publicized step in confirmation of the SU(3) classification scheme was the discovery of a stable (only weakly decaying) member in a supermultiplet whose other members are observable only as short-lived resonant states, since they have sufficient mass to decay strongly by pion emission to stable baryons of the same strangeness. The isosinglet  $\Omega^-$  completed the 10-dimensional multiplet whose members are the  $\Delta$  ( $I=\frac{3}{2}$ ,  $J=\frac{3}{2}^+$ ,  $S=0$ ) (Fermi *et al* 1952),  $\Sigma$  ( $I=1$ ,  $J=\frac{3}{2}^+$ ,  $S=-1$ ) (Alston *et al* 1960),  $\Xi$  ( $I=\frac{1}{2}$ ,  $J=\frac{3}{2}^+$ ,  $S=-2$ ) (Pjerrou *et al* 1962),  $\Omega^-$  ( $I=0$ ,  $J=?$ ,  $S=-3$ ) (Barnes *et al* 1964). The spin and parity have yet to be determined, but they must be  $\frac{3}{2}^+$  if the  $\Omega^-$  is really a triumph of SU(3) and not a bizarre accident.

Although the  $\Omega^-$  was discovered half a decade after the last previous weakly decaying particle  $\Xi^0$  (Alvarez *et al* 1959), there is older evidence for it, in papers by Eisenberg (1954) and Fry *et al* (1955a,b), recently evaluated by Alvarez (1973). The results of this retrospective examination suggest that, if there are any undiscovered stable particles with mass less than a few GeV, they are produced at very low rates compared with the rates of production of known particles.

Since the  $\Omega^-$ , there has been a steady growth in the number of resonances which have been grouped into full or nearly full SU(3) families. The remarkable feature of the families which are seen is that they could all be constructed out of the wavefunctions of hypothetical particles called 'quarks' (Gell-Mann 1964, Zweig 1965). Mesons (baryon number 0) are made of quark-antiquark pairs in 9 distinct states [(8+1)-dimensional representations of SU(3)]. Baryons (baryon number 1) are three-quark clusters lying in 1-, 8- or 10-dimensional representations of SU(3).

An even larger symmetry, corresponding to the case of nonrelativistic quarks interacting through spin—as well as SU(3)—independent forces, is the SU(6) of Gürsey and Radicati (1964). This symmetry would associate SU(3) families; eg an 8-dimensional spin- $\frac{1}{2}$  family together with a 10-dimensional spin- $\frac{3}{2}$  family forms a 56-dimensional representation of SU(6).

Even if the SU(3) scheme is right for very-high-mass systems, there may be at any time some incomplete SU(3) families. However, the internal quantum numbers (charge, strangeness, isospin) of the particles that are seen are restricted by the quark rules mentioned above. Any particle whose quantum numbers violate these restrictions is called 'exotic'; evidence about exotic particles will be discussed later.

## 2.2. Regge families

Yukawa's (1935) prediction of the  $\pi$  meson was based on the range of the force acting between nucleons. If this force were to be associated with the exchange of a

†  $B=1$  for n or p,  $B=0$  for  $\pi$ ;  $B$  may be absolutely conserved.

single particle, as in lowest-order relativistic perturbation theory, then the force would fall with separation  $r$  according to the form  $\exp(-\mu r)/r$ , where  $\mu$  is the particle mass in inverse length units. This implies a dependence on squared momentum transfer  $t$  of the nucleon-nucleon scattering amplitude

$$T(s, t) \propto 1/(\mu^2 - t) \quad (2.2)$$

where  $\mu$  is the pion mass, and  $s$  is equal to the square of the total energy in the centre-of-momentum frame.

Essentially the same idea in different language was used to predict the existence of the  $1^- \rho(I=1)$  and  $\omega(I=0)$  mesons from the electromagnetic form factors of the nucleon and the 'hard core' in the nuclear force (Frazer and Fulco 1959, Nambu 1957). These resonant states were found soon after (Erwin *et al* 1961, Maglič *et al* 1961).

Regge (1959) showed in nonrelativistic potential scattering theory that the high-energy, small-momentum-transfer scattering amplitude could take the form

$$T(s, t) \sim [1 \pm \exp(-i\pi\alpha(t))] s^{\alpha(t)} / \sin \pi\alpha(t). \quad (2.3)$$

If this is compared with equation (2.2) and its generalization to include exchange of higher-spin particles, one is led to consider  $\alpha(t)$  as an analytic function, the Regge trajectory function, which attains non-negative integer values  $J$  at values of  $t$  equal to the squared masses of physical particles with angular momentum  $J$  ( $t$  is negative when it plays the role of momentum transfer in a scattering process). In potential scattering, the signature factor  $1 \pm \exp(-i\pi\alpha)$  suppresses poles of the scattering amplitude at odd (even) values of  $J$ , since the presence of exchange forces produces two different trajectory functions  $\alpha_{\pm}(t)$ , one associated only with even  $J$ , the other only with odd  $J$ . Empirically, in the case of high-energy hadron-hadron scattering there seems to be an approximate identity between the function  $\alpha_+(t)$  and the function  $\alpha_-(t)$  corresponding to exchange of any given set of SU(3) quantum numbers different from those of the vacuum. This is called exchange degeneracy. Empirically also, these trajectory functions seem to be approximately linear in  $t$ . This implies the existence of an infinite family of 'Regge recurrences' of particles having the same internal quantum numbers, but squared masses increasing linearly with angular momentum  $J$ . The slope is nearly the same for all trajectories:

$$\alpha_i(t) \approx \alpha_i(0) + (1 \text{ GeV})^{-2}t. \quad (2.4)$$

Although the patterns in two-body scattering processes give strong evidence for the existence of Regge trajectories, in most cases there is firm evidence for one or at most two mesons on a trajectory of given quantum numbers, charge conjugation symmetry, and signature. Of the baryon (half-integer spin, baryon number 1) trajectories, more is known, since these states can be studied as resonances in meson-baryon scattering. Usually, at least one recurrence of the same signature (2 units higher in  $J$ ) and parity has been identified.

In summary, the hypothesis of infinitely rising (ie to infinite mass), linear, exchange-degenerate Regge trajectories has led to no contradictions with the observed particle spectrum. However, it is only well tested for meson or baryon masses below 2 GeV.

In 1967, Freedman and Wang used a detailed study of the symmetry and analyticity properties of scattering amplitudes in the neighbourhood of vanishing momentum transfer to argue that, for each Regge trajectory  $\alpha(t)$  with certain quantum numbers, there must be an infinite set of daughter trajectories, displaced downwards by integers from the parent trajectories at  $t=0$ . If the daughter and parent trajectories were

parallel, this would imply the existence of additional particles in the family associated with a given Regge trajectory. For example, on the  $\rho$ - $A_2$  trajectory, in addition to the  $J^P = 1^- \rho$  at squared mass about  $\frac{1}{2} \text{ GeV}^2$ , and the  $2^+ A_2$  at  $\frac{3}{2} \text{ GeV}^2$ , there should be a  $1^- \rho'$  at  $\frac{5}{2} \text{ GeV}^2$ . This example is especially useful because it can be studied in  $e^+e^-$  annihilation, since the intermediate virtual photon has  $J^P = 1^-$ . In addition, all the usual hadronic reactions are available to produce this state, albeit without the unique *a priori* indication of spin. Recent evidence confirms the existence of the  $\rho'$  (Bingham *et al* 1972, Bacci *et al* 1972, Barbarino *et al* 1972), and lends support to the notion that several 'generations' of particles with decreasing spin may be degenerate in mass.

Both for the  $\rho'$ , and for other daughters which are only seen in the conventional strong interactions, the main obstacle to clear identification is that the lower spin of daughters means a lower centrifugal barrier, hence greater widths than those of the parents of the same mass. This fact makes it very hard to look at meson-baryon scattering phase shift analyses and say that baryon daughters are not present.

We conclude that the hypothesis of Regge daughters is consistent with all available evidence for systems of mass below 2 GeV, and receives its strongest support from the existence of the  $\rho'$ .

### 2.3. Dual models

Veneziano (1968) created a model for two-particle scattering which was the ancestor of a whole class of theories called 'dual models'. These models violate unitarity, but maintain explicit crossing symmetry; that is, the dual amplitude for a reaction with a particle of four-momentum  $p_\mu$  going out is obtained from the amplitude for the antiparticle of four-momentum  $\bar{p}_\mu$  coming in by analytic continuation of the latter amplitude to the unphysical point  $\bar{p}_\mu = -p_\mu$ . The amplitude exhibits the linear Regge behaviour shown in equations (2.3) and (2.4), and also has poles at positive  $t$  corresponding to particles with unit spacing in squared mass. The dual models have even larger families of daughters than implied by the arguments of Freedman and Wang. In fact, these models suggest a density of states increasing exponentially with mass, as in the 'thermodynamic model' of Hagedorn (1965). Data for masses up to 2 GeV are compatible with such a pattern of resonant states, but are far from adequate proof. As mass goes up, the increasingly small branching ratio of particular states to particular two-body channels places a formidable obstacle in the way of confirming the exponential increase. Clearly, if confirmed, this would be the largest of all families of particles!

### 2.4. Exotic states

The converse of the quark model prediction of particular types of SU(3) families is the antiprediction of exotic states, baryons which cannot be made out of three quarks, or mesons which cannot be made of a quark and an antiquark. There are few cases which are candidates for the status of exotic resonances. Perhaps the best known is a positive strangeness bump in the KN cross section. However, there are good reasons to believe that this object is simply a threshold effect, no more elementary than the deuteron (Aaron *et al* 1971, 1973).

Arguments against all other exotic candidates are presented by the Particle Data Group (1974). The negative evidence on exotic states lends support to the quark model mentioned in the first part of this section.



### 2.5. The mu neutrino

While most particles discovered in the last decade have been unstable hadrons, or strong interaction resonances, there was one new lepton discovered at the beginning of the period. This was the mu neutrino,  $\nu_\mu$ , which had been predicted on the basis of such clues as the absence of the electromagnetic decay

$$\mu \rightarrow e + \gamma \quad (2.5)$$

(Feinberg 1958). The proof that  $\nu_\mu$  is different from the electron neutrino  $\nu_e$  came from a high-energy version (Danby *et al* 1962) of the inverse beta decay experiment (Reines and Cowan 1953) which confirmed  $\nu_e$  itself. A beam of  $\pi$ 's decaying in flight produced energetic neutrinos. These neutrinos in turn produced  $\mu$ 's but not  $e$ 's on interacting with matter (in a shielded target). There is still a technically open question whether muon number conservation is additive or multiplicative. If

$$N_\mu \equiv \text{number of } \mu + \text{number of } \nu_\mu - \text{number of } \bar{\mu} - \text{number of } \bar{\nu}_\mu$$

where the bar signifies antiparticles, then the data are consistent with

$$N_e, N_\mu = \text{constant} \quad \text{or} \quad (-1)^{N_\mu}, N_e + N_\mu = \text{constant}.$$

An experiment which could decide this point is to use  $\mu$  decay as a source of electron neutrinos. For additive conservation, only the decay

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

is allowed, while the multiplicative rule would permit

$$\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$$

with comparable strength. A target which can undergo inverse beta decay in response to  $\bar{\nu}_e$ , but not  $\nu_e$ , serves to determine whether the second mode occurs; one need but measure the absolute rate of inverse beta decay, as well as the relative rates, for  $\mu$  versus  $\bar{\mu}$  incident on the shielded target (Feinberg and Weinberg 1961).

If the multiplicative law should turn out to be the correct one, there would be a new and very unsettling situation for theory. In particular, theories with vector bosons mediating the weak interactions (discussed in §4) would be in difficulty, since such theories naturally accommodate additive  $\mu$  conservation, but not multiplicative. Fortunately present data favour the additive law (Wachsmuth 1973).

## 3. Magnetic monopoles

### 3.1. Dirac's condition

In 1931 Dirac wrote an article setting forth the condition to be satisfied if a particle bearing magnetic charge were to interact with ordinary matter in a way consistent with the laws of quantum mechanics. The condition is that the charge of the monopole must be an integral multiple of the unit

$$g_D = \hbar c / 2e \quad (3.1)$$

where  $-e$  is the charge of the electron. The essence of Dirac's argument comes in the recognition of the important role of the electromagnetic vector potential in quantum mechanics (as in classical Hamiltonian mechanics). If the vector potential is to be kept, the magnetic field must be divergence-free. Then the nearest thing to a magnetic

monopole is the end of a magnet of negligible thickness whose other end lies at spatial infinity. It turns out that, if the phase of a charged particle wavefunction is followed once around such a line of magnetic flux, the jump in phase is  $e\Phi/\hbar c$ , where  $\Phi$  is the enclosed magnetic flux and  $e$  is the particle charge. For a line with a pole at one end of strength  $g$ , the return flux to give a formally divergenceless magnetic field is

$$\Phi = 4\pi g. \quad (3.2)$$

Therefore the Dirac condition is simply the statement that the wavefunction has a continuous phase factor at the line and consequently need not vanish along it. This is enough to assure that the location of the line is unobservable by any physical measurement, so that the monopole may really be treated as an isolated particle. Dirac called the lines 'strings', and his condition means that, while particle degrees of freedom are observable, the continuously infinite degrees of freedom associated with the string are not observable.

In contrast to the positron, whose existence is required to assure a desirable property (locality) in the theory of quantum electrodynamics, the monopole is allowed, but not required. Dirac did give one argument favouring the existence of monopoles: equation (3.1) implies equally well the quantization of electric charge in multiples of a smallest unit, in full accord with experimental observation. This argument may have lost some of its force today, when other quantum numbers, such as baryon number, are recognized, albeit not associated with long-range forces.

Since Dirac's work, there have been many theoretical papers and many experimental searches for monopoles, but none has been found. We review these developments in the following subsections.

### 3.2. Spin approach

Almost immediately after Dirac's paper appeared, Tamm (1931) studied the solutions of the Schrödinger equation for nonrelativistic motion of a charge  $e$  in the presence of a fixed monopole  $g$ . A separation of variables occurs, analogous to that for a central potential. However, the angular functions which appear are the rotation functions  $d_{sm}^s(\theta, \phi)$  (with  $s = eg/\hbar c$ ) instead of the spherical harmonics  $Y_{lm}(\theta, \phi) \propto d_{lm}^0(\theta, \phi)$ . The polar axis for the angular coordinates is defined by the direction of the string, here chosen as a straight line.

A long series of authors have explored the question of the consistency of the equations of motion implied by Dirac's nonrelativistic Hamiltonian with a singular vector potential: Grönblom (1935), Jordan (1938), Fierz (1944), Peres (1968), Hurst (1968), Lipkin *et al* (1969). Beginning with Fierz, it has been recognized that rotational symmetry requires Dirac's condition as a necessary and sufficient criterion for an acceptable theory. Most of the papers mentioned deal explicitly with the wavefunctions, but Peres and (more fully and accurately) Lipkin *et al* formulate the problem in terms of the algebra of operators, so that the singular Dirac vector potential need not appear explicitly.

One is tempted to ask if a non-potential formulation of quantum electrodynamics might exist, in which the Dirac condition could be circumvented. A semiclassical argument was proposed independently by Saha (1936), Fierz (1944) and Wilson (1949). These authors noted that the electromagnetic field, in the presence of a pole  $g$  and a charge  $e$ , carries an angular momentum

$$\mathbf{S} = \int d^3r \, \mathbf{r} \times (\mathbf{E} \times \mathbf{B}) / 4\pi c = eg\hbar/c \quad (3.3)$$

where  $\hat{n}$  is a unit vector from charge to pole. The classical equations of motion of a charge moving past a fixed pole can be solved most easily using the fact that the total angular momentum

$$\mathbf{J} = \mathbf{L} + \mathbf{S} \quad (3.4)$$

(where  $\mathbf{L} = \mathbf{r} \times m\mathbf{v}$  is the usual orbital angular momentum) is conserved. If  $\mathbf{S} \cdot \hat{n}$  is quantized in units of  $\hbar/2$ , one obtains Dirac's condition equation (3.1).

Goldhaber (1965) attacked the problem of deriving Dirac's condition without depending on a specific formalism of quantum electrodynamics. By studying the small-angle scattering of quantum wave packets for a charge moving past a pole, he showed that Dirac's condition is required, provided that the Bohr correspondence principle holds (the classical limit gives correct classical trajectories) and that the cross section for a given scattering angle is independent of the orientation of the incident beam (which implies rotational invariance of the  $S$ -matrix). What he showed explicitly was that there must exist a conserved total angular momentum  $\mathbf{J} = \mathbf{L} + \mathbf{S}$ , with  $|eg/c| = S$ , where  $S$  is an integral multiple of  $\hbar/2$ . He also gave an explicit construction of the nonrelativistic quantum Hamiltonian in terms of the spin  $\mathbf{S}$ ; this removes the singular string of Dirac, in return for adding  $2S/\hbar$  redundant components of a spinor wavefunction. Rotating the spinor basis from a fixed  $\hat{z}$  axis to the  $\hat{n}$  axis diagonalizes the Hamiltonian in the spinor space, bringing it back to Dirac's form.

### 3.3. Theoretical difficulties

The results mentioned above confirm that Dirac's quantization is necessary for a consistent quantum theory with monopoles, and that the interaction of a charge with a fixed pole is indeed described consistently in Dirac's formulation. [The case of a 4-component relativistic electron wavefunction with a monopole field was solved by Banderet (1946).] However, there remain theoretical problems at several levels. In the classical (non-quantum) theory, Rosenbaum (1966) showed that a Lagrangian formulation of charge-pole interactions could be derived only if the constraint was added that trajectories of charge and pole could never intersect. The reason for this is easily seen in terms of the angular momentum  $\mathbf{J} = \mathbf{L} + \mathbf{S}$ . If the charge is aimed directly at the pole, then  $\mathbf{L}$  vanishes, and no force acts, so that the charge passes through the pole. At that moment,  $\mathbf{S}$  reverses direction, and therefore  $\mathbf{J}$  changes; total angular momentum is not conserved. To overcome this problem one could introduce an infinite repulsive potential at the overlap point. Then, instead of passing through, the charge would bounce back, and  $\mathbf{J}$  would not change.

In quantum theory, the overlap difficulty disappears because a constraint at a single point does not affect the wavefunction elsewhere. Indeed, as emphasized by Lipkin *et al* (1969), the wavefunctions obtained from Dirac's Hamiltonian do vanish at the origin of coordinates (location of the monopole). This is important, since in their formulation the Jacobi identity for the noncommuting generalized momenta reads

$$[\pi_x, [\pi_y, \pi_z]] + \text{cyclic permutations} = (-ieg/c) \delta(\mathbf{r}). \quad (3.5)$$

This is consistent provided the space of eigenstates of the Hamiltonian includes only wavefunctions vanishing at the origin.

The fully relativistic theory, in which particle creation and annihilation are allowed, is replete with difficulties. The first effort to write a field theory with charge

and pole was made by Cabibbo and Ferrari in 1962. They generalized the path-dependent formulation of quantum electrodynamics of Mandelstam (1962), in which noncommuting differentiation is defined. Schwinger (1966a) observed that the noncommuting derivatives appeared to violate the Jacobi identity. In particular, the identity for derivatives acting on the field  $\psi$  of electric charges implies  $\mathcal{J}_\mu \psi = 0$ , where  $\mathcal{J}_\mu$  is the monopole current density, and acting on the field  $\phi$  of the monopoles implies  $\mathcal{J}_\mu \phi = 0$ , where  $\mathcal{J}_\mu$  is the charge current density. One is tempted to repeat the argument of Lipkin *et al*, and speculate that these two conditions may be consistent with the field theory Hamiltonian; that is, if imposed at one time, they may be preserved.

Solving the field theory problem, even approximately, is difficult, precisely because of the strength of the monopole charge. Lowest-order perturbation theory gives a meaningless result (Weinberg 1965). This problem cannot be overcome by looking at the photon exchange pole in the charge-monopole scattering (Zwanziger 1965). If one attempts to isolate such a pole, the analytic structure of the residue function is abnormal. Both of these difficulties come from the extra angular momentum in the electromagnetic field. This cannot be realized at any finite order in perturbation theory (Rabl 1969). The extra spin also changes drastically the definition of the invariant amplitudes, and hence the analytic structure of their coefficients.

A most detailed study of field theory with monopoles was made by Schwinger (1966a,b,c). He argued, by using Dirac's procedure for certain singular cases (eg paths in a surface passing through the pole), that the unit of magnetic charge should be twice or even four times the Dirac value; this argument does not carry the same force as Dirac's (Wentzel 1966), since the singular cases might not influence the dynamics of the system. Schwinger also examined the question of renormalization, noting that both the renormalized ( $e, g$ ) and the bare ( $e_0, g_0$ ) charges must obey the quantization condition, as well as the condition

$$e/e_0 = g/g_0 < 1. \quad (3.6)$$

This implies that the renormalization factor is the square root of a rational number. It is conceivable that this constraint, or some other, may so overdetermine the field theory that there are no particles with nonvanishing renormalized magnetic charge.

We may summarize the current state of monopole theory by saying that no inconsistencies are known to arise from the existence of Dirac monopoles, but the consistency of field theory with monopoles is yet to be shown.

### 3.4. Extension of Dirac's theory

Classical electrodynamics is invariant under the transformation

$$\begin{aligned} \mathbf{E} &\rightarrow \cos \theta \mathbf{E} + \sin \theta \mathbf{B} \\ \mathbf{B} &\rightarrow -\sin \theta \mathbf{E} + \cos \theta \mathbf{B} \\ q &\rightarrow \cos \theta q + \sin \theta g \\ g &\rightarrow -\sin \theta q + \cos \theta g \end{aligned} \quad (3.7)$$

where  $q$  and  $g$  are electric and magnetic charges respectively. In particular, this symmetry means that if all charged particles had the same nonvanishing ratio  $g/q$ , then a redefinition would be possible, yielding a new purely electric charge

$$q'_i = \pm (q_i^2 + g_i^2)^{1/2}. \quad (3.8)$$

Implications of this symmetry for theories with particles possessing both electric and magnetic charge have been explored by Eliezer and Roy (1962), Schwinger (1968, 1969), Zwanziger (1968), Berrondo and McIntosh (1970), Kerner (1970), Bialynicki-Birula and Bialynicki-Birula (1971) and Han and Biedenharn (1971).

The main point is that if the monopole bears both magnetic and electric charge, then its magnetic charge must be quantized but its electric charge is unconstrained. This encourages speculation on the possibility that hadrons may be constituted of objects which have magnetic as well as electric charge, even though known hadrons are all magnetically neutral. Schwinger (1969) introduced the term 'dyons' for such constituents of hadrons. If two dyons could be observed in isolation, they would have to obey the condition

$$e_1 g_2 - e_2 g_1 = n\hbar c/2 \quad (3.9)$$

with  $n$  an integer.

Fierz (1964) and Goldhaber and Nieto (1971) considered another possible extension of Dirac's theory, to accommodate a nonvanishing photon mass. They noted that quantization of magnetic charge is no longer sufficient to assure an acceptable theory. In the Dirac formulation the string direction becomes observable. The classical field angular momentum  $S$  decreases continuously with increasing separation of charge and pole, so that the  $S \cdot \hat{r}$  cannot be quantized. In the quantum spin formulation, the condition  $S \cdot \hat{r} = \text{constant}$  is no longer maintained, so that the direction of  $S$  depends on the history of the motion. None of these approaches gives an acceptable theory of monopoles, so that nonvanishing photon mass and nonvanishing monopole charge seem to be mutually exclusive.

### 3.5. Binding of monopoles

The enormous size of the Dirac magnetic charge leads to severe difficulties in computing, or even making qualitative guesses about, anything except the exactly soluble charge-monopole interactions. An example of this difficulty, with important experimental implications, is the issue of binding of monopoles in ordinary matter. For an electron-monopole system there are no bound states (Banderet 1946, Harish-Chandra 1948). What about a monopole interacting with an association of charges in relative motion? Now the analysis becomes much more subtle, and even the slightest extra complication leads to controversial conclusions. For example, we may ask what happens when a monopole interacts with an atomic nucleus possessing a magnetic moment. If the magnetic moment were due to a classical current loop, we might say that the pole would be strongly attracted, plunge through the loop, and then be strongly repelled. This suggests no binding. However, the electromotive force from the pole passing through the loop would tend to reverse the current, and hence to make the pole once again attracted on the far side of the loop, thus bound to the magnetic moment.

In nonrelativistic quantum mechanics for a very massive pole interacting with a point nucleus possessing a sufficiently large anomalous magnetic moment, there is a state with infinite binding energy. Malkus (1951) ignored this state, apparently rejecting it as unphysical. Sivers (1970), on the other hand, suggested adding a short-range repulsive potential, in which case the binding becomes finite, but of the order keV or bigger. One may argue with the detailed steps in Sivers' procedure, but his qualitative reasoning appears to us quite convincing.

Previous authors have ignored another phenomenon which could lead to binding of monopoles to most nuclei; that is, the magnetic polarizability of the nucleon. A plausible estimate of this polarizability is (Bernabeu *et al* 1974)

$$\chi = d\mu/dB \approx 0.1e^2 \text{ fm}^3. \quad (3.10)$$

This implies an effective pole nucleus potential at the nuclear surface

$$V = -\frac{1}{2}A\chi g^2/r^4 \approx -1.7A^{-1/3} \text{ MeV} \quad (3.11)$$

where  $A$  is the nuclear mass number. We neglect any coherent magnetic polarizability of the nucleus as a whole. The latter is probably small and negative (diamagnetic). This potential has to compete with a quasi-centrifugal repulsion due to the charge-pole interaction,

$$V_{\text{cent}} \geq Zeg/2\mu r^2 \quad (3.12)$$

where  $\mu$  is the reduced mass. At the nuclear surface this becomes

$$V_{\text{cent}} \geq [Z(A+m)/24mA] 200/A^{2/3} = 8Z(A+m)/mA^{5/3} \text{ MeV} \approx 4A^{-2/3} \text{ MeV}. \quad (3.13)$$

Here  $m$  is the ratio of the monopole mass to the nucleon mass. This competition would still permit binding of massive monopoles, comparable with binding of nucleons to nuclei, for mass number  $A$  greater than 10 or so. Larger monopole charge, such as the Schwinger value, could make the binding almost universal. This binding will be relevant to some of the experimental techniques of monopole hunters discussed below.

What we have presented so far refers only to binding of the monopole to a nucleus. Malkus (1951) presented cogent arguments that atomic diamagnetism would tend to keep a slowly moving monopole away from the centre of an atom. He concluded that binding to atoms or molecules would be at most as strong as typical binding of electrons, since it would come as an indirect effect (that is, a byproduct of the atomic or molecular rearrangement produced by the pole).

Goto *et al* (1963) have discussed macroscopic binding of monopoles to ferromagnetic material. The effect is precisely analogous to binding of an electric charge to a dielectric medium, but much stronger than for most ions because of the large monopole charge.

The most profound binding problem of all is that of the mutual attraction of a pole-antipole pair (Dirac 1931, 1948). The superstrong coupling  $g^2/\hbar c \geq 137/4$  implies that such a pair would have very strong binding, so that a monopole mass substantially bigger than a GeV would be required to make the vacuum stable against spontaneous generation of pairs (Ruderman and Zwanziger 1969). This strong coupling to electromagnetism also implies that a pair flying apart would need a very large escape energy; even then, collapse and reannihilation could be almost inevitable (Newmeyer and Trefil 1971). Ruderman and Zwanziger suggested that such a process might account for some anomalous events in which emulsions exposed to cosmic rays reveal a collection of several energetic  $\gamma$  rays, highly collimated in the forward direction, with no related charged primary particles. They proposed that an incident photon of about  $10^4$  GeV, itself produced by  $\pi^0$  decay, might have generated the  $\gamma$ 's through monopole pair production during peripheral interaction with an emulsion nucleus. Collins *et al* (1973) have reviewed these cosmic ray events, and argued convincingly that an incident proton of  $\approx 100$  GeV might have produced them, since this is the total energy of the final multiphoton system. Accordingly, G B Collins *et al* (1974, private communication) are investigating multiphoton events produced

by a 300 GeV incident proton beam at the Fermi National Accelerator Laboratory, in order to study such processes with much higher statistics. If they duplicate the cosmic ray events, at least some revision in the reasoning of Ruderman and Zwanziger would be required, since an intermediate monopole-antimonopole pair would have to be highly virtual to contribute at these energies; its mass would be much less than twice the monopole mass.

### 3.6. Experimental searches

Efforts to discover Dirac poles are all based on their enormous strength. A relativistic monopole passing through matter should ionize at a rate  $(1/2\alpha)^2$  greater than a minimum ionizing electron, while the ionization would decrease at the end of the track because of the factor  $v/c$  in the force law between pole and charge (Cole 1951, Bauer 1951). A monopole under the influence of a magnetic field of  $10^5$  G would feel a force of  $20 \text{ eV } \text{\AA}^{-1}$ , strong enough to pull the pole out of matter, even if the pole were attached to a large group of atoms (Purcell *et al* 1963, Goto *et al* 1963). Evidently the same force would be enough to accelerate the pole to relativistic velocities in  $M$  cm, where  $M$  is the mass in GeV. A pole passing through a conducting loop would produce an electromotive force such that the potential  $V(t)$  around the loop would not average to zero, giving instead

$$\int dt V(t) = 2\pi Ne/\alpha c = 4 \cdot 1 N \times 10^{-15} \text{ V s} \quad (3.14)$$

where  $N$  is the number of times the pole passes through the loop in the same direction (Alvarez *et al* 1970). The passage of a pole through a loop changes the flux through the loop by  $h/e$  or enough to change the variation of phase of the macroscopic wavefunction around a superconducting ring by  $4\pi$  (Tassie 1965). The large charge would also amplify other characteristic phenomena associated with passage through matter, such as Cherenkov radiation (Frank 1952, Tompkins 1965) and transition radiation (Dooher 1971).

Most of the above effects have been exploited singly or in combination to search for monopoles. The searchers have looked for poles produced by or already present in cosmic rays, produced at accelerators, or stored in materials. Interpretation of the last group of experiments is based on the absolute conservation of magnetic charge, which must hold if monopoles are to fit into quantum mechanics, not to mention showing symmetry with electric charges. However, there do not seem to have been any serious efforts to estimate the effect of recombination of monopole pairs.

Cosmic ray searches began with Malkus (1951) and were made by Carithers *et al* (1966), Erlykin and Yakovlev (1969) and Fleischer *et al* (1969b, 1971). Of these, the first two looked for monopoles which were produced near the top of the atmosphere, thermalized, combined with large molecular complexes, and then drifted down along geomagnetic field lines to a solenoid collector-accelerator, finally leaving heavy tracks in emulsion. The latter two experiments looked for very-high-energy monopoles striking a detector. For Fleischer *et al* (1969b), that detector was naturally occurring rock of a type which would preserve tracks of heavily ionizing particles. For all such experiments there are ambiguities in the analysis required to extract production cross section limits. In particular, the limit depends on monopole mass, which determines the threshold energy for pair production, since cosmic ray flux falls steeply with energy. For a monopole mass less than 10 GeV, the experiment of Fleischer *et al* (1969b) gives a cross section upper limit for pp collisions of  $\sigma \leq 10^{-36} \text{ cm}^2$ .

Accelerator searches have been made at the Berkeley Bevatron (Bradner and Isbell 1959), the CERN PS (Fidecaro *et al* 1961, Amaldi *et al* 1963), the Brookhaven AGS (Purcell *et al* 1963), the Serpukhov IPHE (Gurevich *et al* 1972) and the Fermi Lab accelerator FNAL with 300 GeV protons (Carrigan *et al* 1973). The last experiment uses a common technique—putative monopoles are thermalized by passage through matter, trapped in ferromagnetic material, extracted and accelerated by a strong pulsed field, and finally detected by their large ionization. The production cross section upper limit obtained was  $6 \times 10^{-42} \text{ cm}^2$  at the 95% confidence level. Carrigan *et al* (1974) have carried out experiments with 400 GeV protons at FNAL, and with 26 on 26 GeV colliding beams at the CERN ISR (F A Nezrick 1974, private communication). Their preliminary results give  $\sigma < 10^{-41} \text{ cm}^2$  for a pole mass less than 14 GeV (FNAL) and  $\sigma \lesssim 10^{-35} \text{ cm}^2$  for a mass less than 25 GeV (ISR). The techniques used were similar to those of Carrigan *et al* (1973).

Finally, experimenters have searched for monopoles stored in matter. The poles were sought either by extraction with pulsed fields, or by passing a matter sample through a coil to detect the net magnetic charge in the sample. Experiments in this class were reported by Goto *et al* (1963), Petukhov and Yakimenko (1963), Vant-Hull (1968), Fleischer *et al* (1969a,c), Alvarez *et al* (1970, extended in Eberhard *et al* 1971 and Ross *et al* 1973) and Kolm *et al* (1971). In order, these searches sampled magnetic outcrops on the earth, meteorites, commercial copper, manganese nodules on the ocean floor, ferromanganese deposits in the ocean floor, moon rocks, and ocean sediments. Here again the production cross section, or even the monopole flux, is hard to extract from such data. For a mass less than 10 GeV, an upper limit of  $\sigma \lesssim 10^{-41} \text{ cm}^2$  seems indicated.

Despite all the uncertainties in these analyses, it seems safe to say that, if monopoles exist, either they are exceedingly massive or their production cross section is much smaller than straightforward estimates would suggest (Newmeyer and Trefil 1972).

### 3.7. Indirect evidence on monopoles

We have already seen that high-energy collisions producing highly collimated multiphoton states might be signs of virtual monopole pairs. There are two other indirect lines of argument. Porter (1960, 1968) suggested that monopoles might comprise a small component of cosmic rays, and that this could explain some apparent anomalies about cosmic rays. However, in addition to the stringent limits on monopole flux, implied by the experiments reviewed above, there is indirect evidence against monopoles in cosmic rays. Osborne (1970) has argued that such monopoles would produce high-energy photons by scattering on the  $3^\circ$  universal photon background. These high-energy photons would lead to muon-poor air showers, but very few such have been seen. An indication of monopole constituents in hadrons has been proposed by Sawada (1973, 1974a,b). He suggests that low-energy nucleon-nucleon scattering phase shifts show the presence of an extra, long-range, potential comparable in strength to  $2\pi$  exchange, but best fitted by a Van der Waals  $C/r^7$  potential. It appears that Sawada's definition of  $2\pi$  exchange allows only nucleons in the intermediate states in the NN channel. How much this restriction affects his conclusion is unclear. The matter deserves further examination. Also, it would be good to know the quantitative implications for nucleon magnetic polarizability of the existence of such a Van der Waals potential, which must arise from simultaneous magnetic polarization fluctuations in the two nucleons.



## 4. New particles predicted in unified gauge field theories

This section deals with new particles which are required in theories which synthesize weak and electromagnetic interactions. We discuss several varieties of heavy intermediate bosons, both neutral and charged, as well as schemes including heavy leptons. Also we mention briefly the properties of the scalar particles, charmed particles, and other new particles which have been postulated in attempts to build a completely renormalized theory of strong, weak and electromagnetic phenomena.

### 4.1. Intermediate vector bosons

The idea that the weak interaction in beta decay is mediated by a charged boson was stated in the original paper of Yukawa (1935). However, it soon became clear that this boson was not the same boson required to mediate the strong interactions. Moreover, confusion existed for many years as to whether the weak current transformed under Lorentz transformations as a scalar (S), pseudoscalar (P), vector (V), axial vector (A) or tensor (T). It was thought for a long time that the correct combination was a mixture of S, T and P, so the vector boson idea was sadly neglected. When the historic breakdown of parity conservation was discovered in the late 1950s (Lee and Yang 1956, Wu *et al* 1957), the form of the weak interactions in leptonic processes was clarified in a series of beautiful experiments. The interaction was shown to be V-A (see Goldhaber 1958), and the idea of a charged, weakly interacting vector boson was revived in analogy with the photon in quantum electrodynamics (Feynman and Gell-Mann 1958, Sudarshan and Marshak 1958, Schwinger 1957, Lee and Yang 1960).

Although it was already clear from the local nature of the weak interactions at low energies that the vector boson (W boson) had to be quite massive, several theorists tried to set some limits on its mass. Usually these calculations consisted of estimates of radiative corrections to weak decays or higher-order weak decays, where the boson mass was used as a cut-off parameter, and values above  $1 \text{ GeV}/c^2$  were indicated. As the theory was not renormalizable, it was difficult to trust in these estimates (Ioffe and Shabalin 1967).

The idea of actually using neutrino beams to produce the W boson and to investigate other properties of weak interactions was conceived independently by Pontecorvo (1959) and by Schwartz (1960). Calculations were performed by several authors for the reaction  $\nu_\mu + Z \rightarrow \mu^- + W^+ + Z$ , which seemed the most promising way to produce the W boson. The search for the W actually began with the BNL-Columbia experiment (Burns *et al* 1965) and continued at CERN (Bernardini *et al* 1965). Unfortunately no potential candidates were found, and these experiments only succeeded in placing a lower limit on the mass of the W particle,  $M_W \geq 2.8 \text{ GeV}/c^2$ . For a review of these experiments see the articles by Schwartz (1965) and Lederman (1967a). Since the lifetime of the W was expected to be around  $10^{-22} \text{ s}$ , it would not be seen directly. The signal sought in these experiments was therefore the detection of two muons (one coming from the decay mode  $W^+ \rightarrow \mu^+ + \nu_\mu$ ). Überall (1964) discussed polarization effects on the spectra of the two leptons. Other possible decay modes into strongly interacting particles, for example  $W^+ \rightarrow \pi^+ \pi^0$ , do not give a clear signal. Estimates for hadronic decay rates have been given by Yamaguchi (1966).

Obviously the reaction  $\nu + Z \rightarrow \mu^- + W^+ + Z$  is not the only way to produce W bosons. Calculations were performed by several authors on the muon production reaction  $\mu^- + Z \rightarrow \bar{\nu} + W^- + Z$ , the photoproduction reaction  $\gamma + P \rightarrow W^+ + N$ , and

the production of W pairs  $\gamma + Z \rightarrow W^+ + W^- + Z$ , to mention but a few. However, as it became increasingly obvious that the boson is rather massive, and the pair production threshold correspondingly high, not to mention the large backgrounds in alternate processes, primary interest continued to focus on the neutrino production reaction. Those readers interested in the latest theoretical cross sections should consult the articles by Brown and Smith (1971), Brown *et al* (1971), Fearing *et al* (1972), Smith (1972) and Kompaniets and Folomeshkin (1968).

Another chapter in the search for the W opened up recently at much higher energies. The neutrino beams available at the Fermi National Accelerator Laboratory (FNAL) are so energetic that the production of bosons with masses up to  $15 \text{ GeV}/c^2$  is actually possible. Indirect or virtual boson effects can be searched for up to masses of  $20 \text{ GeV}/c^2$ , although their interpretation, if seen, might be ambiguous. So far two groups (Barish *et al* 1973, Benvenuti *et al* 1974a) have performed experiments with the hope of detecting the W production reaction, but have seen no positive signal. From the linearity of the total cross sections, the limit for the mass is now  $M_W \gtrsim 10 \text{ GeV}/c^2$ , while the highest neutrino energy used in these searches was approximately 160 GeV.

No discussion of W boson searches would be complete without some discussion of cosmic ray measurements. An introduction to the subject of cosmic ray intensities deep underground is given by Menon and Ramana Murthy (1967) describing experiments to measure muon intensity curves deep underground; under the assumption that the muons are produced by neutrinos, one tries to detect some small difference between the sum total of the expected cross sections and the experimental measurements for the reactions  $\nu + n \rightarrow \mu^- + p$ ,  $\nu + p \rightarrow \mu^- + \Delta^{++}$ , and  $\nu + p \rightarrow \mu^- + X$ . The cross sections for the various reactions have been measured experimentally at lower energies, so there is no reason to rely entirely on theoretical calculations. Recent results have been given by Cowsik and Pal (1970), Chen *et al* (1971) and Bergeson *et al* (1973) indicating limits which are compatible with the recent accelerator searches, namely that  $M_W \gtrsim 10 \text{ GeV}/c^2$ .

If the mass of the charged vector boson is really so large, what chances do we have of ever producing such a particle? The pessimist would just say that we are chasing the tail of a rainbow, but recent advances make the continued search for the W boson very important. To understand these arguments we have to give a brief introduction to gauge field models of weak and electromagnetic interactions. Before doing so we would like to mention some alternative schemes.

Several theories of weak interactions have been presented, which are not based on a local gauge principle. For instance, the theory of Lee (1970) requires a negative metric scalar boson  $W_0^\pm$ . Another theory of Lee and Wick (1970) requires a similar spin-one boson  $B^0$  to mediate electromagnetic interactions. Calculations of the cross sections for the production of such objects by neutrinos and electrons (muons) have been made by Linsker (1972) and by Turner and Barish (1972). There have not been any experimental results given for the scalar  $W_0$  mass; however, they can be expected quite soon. The limit on the mass of the  $B^0$  comes from experiments designed to detect muon pairs in proton-proton or proton-nucleus collisions. Christenson *et al* (1973) have conducted such an experiment using proton-uranium collisions. Preliminary results from this experiment were used by Lederman and Pope (1971) to set limits on the  $W^\pm$  mass. A similar experiment was performed by Wanderer *et al* (1969). The production of high-energy electron pairs at the ISR has been used to set a limit  $M_{B^0} > 25 \text{ GeV}/c^2$  (Büsser *et al* 1974).

An alternative approach by Kummer and Segré (1965) and by Christ (1968) is to postulate the existence of several scalar particles. A weak interaction theory based on scalar meson exchange is renormalizable, but there is no experimental evidence for it. See also Segré (1974).

#### 4.2. Gauge field theories

A vector particle mediating weak interactions is analogous to the photon mediating electrodynamics. In fact, Fermi (1934) based his theory of beta decay directly on this analogy. One obvious difficulty with such an approach is that the photon is massless and quantum electrodynamics is a renormalizable theory, whereas the  $W$  boson is massive and the Fermi interaction is not renormalizable. Attempts to make a unified theory of both interactions have had to overcome this obstacle (Schwinger 1957, Glashow 1961). The idea behind a successful unification of the two interactions required considerable theoretical work in understanding whether Yang–Mills (1954) field theory was renormalizable, and studying complications involved in theories with spontaneous symmetry breakdown. Although the general theory was still incomplete, Weinberg (1967) and, independently, Salam (1968) proposed that both the photon and the  $W$  boson should be the quanta of the Yang–Mills vector fields associated with some exact local invariance of nature. Such theories were suspected to be renormalizable. Due to a spontaneous breakdown of the gauge symmetry, normally referred to nowadays as the Higgs–Kibble mechanism (Higgs 1964a,b, 1966, Englert and Brout 1964, Guralnik *et al* 1964, Kibble 1967), the  $W$  boson would acquire a mass while the photon remained massless. In Weinberg's original model another neutral vector boson, the  $Z^0$  particle, was also required. Basically each generator of the symmetry group is associated with a gauge boson and, because Weinberg chose a model incorporating the group  $SU(2) \times U(1)$  with four generators, there are four vector bosons: the photon, two charged vector bosons  $W^\pm$ , and a neutral massive boson  $Z^0$ .

The masses of the  $W^\pm$  and  $Z^0$  are generally required to be very large, because the Fermi coupling constant  $G_F$  is now related to the electric charge  $e$  (hence the unification). Typically  $G_F \simeq e^2/M_W^2$ , which means  $M_W > 30 \text{ GeV}/c^2$ . The  $Z$  particle mass is at least as large. Unfortunately such massive particles cannot be produced with the neutrino beams now available in the laboratory. This theory was not really appreciated until 1971 because it was not clear that it was renormalizable. However, 't Hooft (1971a) gave a proof that massless Yang–Mills gauge field theories were actually renormalizable. This work was extended by 't Hooft (1971b), Lee and Zinn-Justin (1972), and 't Hooft and Veltman (1972), and opened a new era in the study of relativistic quantum field theory (see also Slavnov 1972, Fadde'ev and Popov 1969, Fradkin and Tyutin 1969).

The reason why these theories need hosts of new particles can be understood in a rather simple way. If we accept the fact that charged  $W$  bosons are necessary to any theory of weak interactions, then we can study (theoretically, at least) the elastic scattering of neutrinos by antineutrinos. One possible intermediate state in such a reaction is  $\nu + \bar{\nu} \rightarrow W^+ + W^-$ . If we calculate the scattering amplitude for this reaction based on the Fermi theory with the Born terms given by the one-electron exchange diagram, then for centre-of-momentum energy  $\sqrt{s}$  the scattering amplitude grows like  $s^2$ . This leads to uncontrollable divergence problems in calculating the dispersive part of the elastic neutrino interaction  $\nu + \bar{\nu} \rightarrow \nu + \bar{\nu}$ . This phenomenon is known as the violation of the unitarity bound, and weak interactions would no longer conserve probability

at energies beyond 300 GeV in the centre-of-momentum frame. An attractive way to damp this high-energy behaviour of the  $\nu + \bar{\nu} \rightarrow W^+ + W^-$  amplitude is to introduce new particles which contribute some new Born diagrams. Then the coupling constants of these new particles are adjusted to cancel the dangerous behaviour of the scattering amplitude at high energies so that the unitarity bound is not violated (Bell 1973, Cornwall *et al* 1973, Llewellyn Smith 1973). There are two obvious possibilities. One is to introduce a new heavy lepton, the  $E^+$ , which is exchanged in a Born diagram analogous to the  $e^-$ . Another way is to introduce a neutral boson which couples to the two neutrinos, allowing the reaction  $\nu + \bar{\nu} \rightarrow Z^0 \rightarrow W^+ + W^-$ . It is possible that nature actually uses both mechanisms. The model of Weinberg incorporates the  $Z^0$ , which mediates a neutral current, ie couples to  $\nu \bar{\nu}$ ,  $e^+e^-$ , etc. Other models such as the Georgi-Glashow (1972) model use a heavy lepton and are constructed so that the only neutral gauge field which survives is the photon.

Even though the introduction of heavy leptons and/or neutral spin-one bosons is sufficient to remove some of the divergence difficulties in weak interactions, we still need other particles. In particular the Higgs-Kibble mechanism requires the introduction of a set of scalar fields. Many of these fields become unphysical after the spontaneous symmetry breakdown. However, some inevitably remain as real physical particles and are actually necessary for a renormalizable theory (Lee 1972). As there is very little evidence for  $0^+$  particles, the masses of these objects are then made sufficiently large so that they would have escaped detection up to now. This state of affairs is very unsatisfactory and has led authors to propose other dynamical mechanisms for giving masses to the quanta of the local Yang-Mills fields (Jackiw and Johnson 1973, Cornwall and Norton 1973). We now review the present status of the searches for heavy leptons and scalar bosons.

### 4.3. Heavy leptons

The search for heavy leptons is not a new phenomenon. For many years there have been speculations about new partners for the electron and the muon. The advent of gauge theories only adds importance to the search for such objects. Although it seems that present-day accelerators do not have sufficient energy to produce the heavy gauge bosons associated with gauge theories, the situation with respect to the leptons is more hopeful. In some cases their masses are constrained from above by the fantastic agreement between theory and experiment in the realm of quantum electrodynamics. If we add weak interactions to the calculation of the  $g-2$  value for the muon, for instance, then the effects are bounded by the experimental value. Hence there is hope that the heavy leptons are relatively light and can be produced directly. The only experiment which supplies a reasonable limit on the mass of such leptons is that of the Cal. Tech. group at FNAL (Barish *et al* 1974a). They tried to detect heavy, positively charged leptons which decay to a muon and neutrino. Normally, in observed weak interactions, muon-type neutrinos only produce negative muons, as implied by conservation of muon number. If heavy, positively charged leptons could be produced, then they could decay into positive muons, providing a signal in a neutrino beam experiment. Out of 1530 candidates only 8 were found, but they could all be accounted for by the presence of some antineutrino contamination in the neutrino beam. This experiment sets the lower limit on the mass of such a particle to be around  $8 \text{ GeV}/c^2$ , depending upon assumptions about its decay branching ratios into leptons and hadrons.

The FNAL result is consistent with that from the Gargamelle group at CERN (Eichten *et al* 1973), who looked for interactions of the type  $\nu_\mu + N \rightarrow M^+ + \text{hadrons}$ , followed by the heavy lepton decay  $M^+ \rightarrow e^+ + \nu_e + \nu_\mu$ . Finding none, they set a lower limit on the  $M^+$  mass of  $2.4 \text{ GeV}/c^2$ .

There is also the theoretical possibility that a heavy muon exists with the same lepton number as the usual muon. Such muons would be produced in the reaction  $\nu_\mu + N \rightarrow \mu'^- + \text{hadrons}$ , and the  $\mu'$  would probably decay into regular leptons. An analysis of the Gargamelle data by Asratyan *et al* (1974) has set the lower limit on the mass of this particle at  $1.8 \text{ GeV}/c^2$ .

Theoretical cross sections for heavy lepton production via neutrino beams have been given by Albright (1973) and Soni (1975). The present limits plus the restriction that the masses should not be too large are almost sufficient to rule out such theories. The other alternative, ie neutral currents, seems more promising and will be discussed later.

Before leaving the subject of heavy leptons we must mention searches at  $e^+e^-$  storage rings. As the heavy leptons are charged, they must couple to the electromagnetic field and be photoproduced in pairs. The reaction  $e^+e^- \rightarrow H^+H^-$ , where  $H$  is a heavy lepton, has been analysed theoretically by Tsai (1971a,b). The branching ratios for these heavy leptons were also estimated by Thacker and Sakurai (1971). The most recent experimental search was made at Frascati by Orito *et al* (1974), who set a lower limit of  $1.15 \text{ GeV}/c^2$  on the mass of a heavy lepton. There are also experiments on the production of heavy leptons in pp collisions. One of the latest results was given by Lebedev (1972). Unfortunately the theoretical aspects of the problem are obscure, so all conclusions concerning limits in hadronic interactions are very model-dependent.

Most of the searches mentioned above assumed that the spin of the heavy lepton was one-half. Theoretical speculations on the existence of heavy leptons with high spin values have been published by Gershtein *et al* (1972), but no searches for such objects have yet been made.

In §4.5 we will review the experimental evidence for the existence of neutral currents in neutrino interactions. It is appropriate to mention here that these neutral events could possibly be due to the production of a heavy lepton followed by its decay into hadronic channels (together with a neutrino). However, there is one argument against this interpretation of the data. The fact that the CERN events are seen at low energies would require a lepton of rather small mass, since the lepton is produced as a real particle. Hence one should expect that the FNAL experiments at high energy would produce such particles copiously. The data from FNAL indicate roughly the same ratio of neutral to charged amplitude as at CERN, and are therefore inconsistent with the heavy lepton interpretation, but more information on the composition of the final states is required before the idea can be rejected completely. The production of a heavy lepton would also produce an anomalous bump in the data when plotted in the  $q^2$  versus  $\nu$  plane.

#### 4.4. Scalar particles

Unified gauge theory models are constructed in a very special way. The gauge bosons acquire a mass from the Higgs-Kibble mechanism, and in order to invoke this method, all models need to start out with a set of scalar fields. After the spontaneous symmetry breakdown, some of the scalar fields become the longitudinal components

of the massive gauge fields, but others are left over. The scalar particles couple very weakly to fermions because they have an explicit factor of the mass of the electron in their coupling, so they will be very difficult to detect experimentally. This has discouraged searches for these particles.

One possible place where a light scalar particle may be needed is to patch up the present disagreement between theory and experiment in the bound-state energy levels of  $\mu$  mesic atoms. There are small discrepancies between the results of pure quantum electrodynamics and the latest experimental results for the energy spacings between rather high levels (Dixit *et al* 1971, Walter *et al* 1972). Such phenomena have existed in the past, but usually violations of pure quantum electrodynamics have not withstood the test of time. Some authors have added the exchange of a very light meson to the theoretical predictions based upon pure quantum electrodynamics (Resnick *et al* 1973). They then adjust the coupling constant to make the disagreement between theory and experiment disappear. For a mass of  $16 \text{ MeV}/c^2$  and an interaction of the type  $g\bar{N}\phi N$ , the coupling constant  $g$  is given by  $g^2/4\pi \simeq 1 \times 10^{-6}$ . Further experimentation is obviously needed to see whether this is the correct explanation. Recently new theoretical calculations have reduced the discrepancy (Brown *et al* 1974a, Arafune 1974), but it still exists at the two-standard-deviation level. Calculations made by Chen (1975) of high-order electrodynamic corrections suggest that this remaining discrepancy can also be removed. Adler *et al* (1974) also claim that the introduction of a light scalar particle is inconsistent with other experimental data.

#### 4.5. Neutral currents

Although the search for direct production of heavy leptons, charged vector bosons and scalar bosons has not been successful, there is another experimental test of these new theories: the mere existence of the  $Z^0$  particle, even in the limit where it is extremely massive, means that neutral currents as well as charged currents exist. We can test for these neutral currents by measuring deviations from the results of a theory based purely on the existence of charged currents. At the time of writing there are six possible experimental verifications of the existence of neutral currents. These experiments involve different signatures and different experimental groups, making them hard to dismiss as a statistical fluctuation. The reactions involved are the purely leptonic scattering process  $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$  (Hasert *et al* 1973a), weak pion production by neutrinos  $\nu + n \rightarrow \nu + \pi^- + p$  (Barish *et al* 1974c), and deep inelastic scattering  $\nu + p \rightarrow \nu + X$  (Hasert *et al* 1973b, 1974, Aubert *et al* 1974a,b, Benvenuti *et al* 1974b, Barish *et al* 1974b, Lee *et al* 1974).

The first reaction  $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$  is not allowed in a theory with charged currents which only couple to  $e^- \bar{\nu}_e$  and  $\mu^- \bar{\nu}_\mu$  respectively. What is required is a new neutral current like the exchange of a  $Z^0$  between the neutrino and electron lines. There are now three possible candidate events for this reaction at CERN (Hasert *et al* 1973a). They were found in a search of almost one million bubble chamber pictures, and three events is too large to be accounted for by the known contamination of electron-type neutrinos in the muon-type beam.

Weak pion production via neutral currents, ie where no  $\mu^-$  is detected in the final state, has been seen by the Argonne group (Barish *et al* 1974c). This is a very difficult experiment, and the statistics are poor. However, there are approximately 10 events which are compatible with the signal of the reaction and survive the cuts made to eliminate possible backgrounds.

Neutral currents have also been seen by the same Gargamelle collaboration (Hasert *et al* 1973b, 1974), who have reported three candidates for the purely leptonic interaction. Their evidence here is really overwhelming. The heavy liquid bubble chamber is so large that not only primary interactions are visible but also secondary interactions. Stray neutrons, which are the principal source of background, can actually be studied in this way. The main conclusion of the experiment is that far too many anomalous events are seen in the chamber to be accounted for by the possible backgrounds. In the neutrino runs the ratio of neutral to charged candidates is approximately 20%, whereas this number is 40% for the runs with antineutrinos.

The Harvard-Pennsylvania-Wisconsin neutrino experiment at FNAL (Aubert *et al* 1974a,b, Benvenuti *et al* 1974b) also has evidence for neutral currents. This is a counter experiment in a mixed beam of neutrinos and antineutrinos in which the number of muonless events exceeds that expected from the analysis of possible backgrounds. At the time of writing, the ratio of neutral current events to charged current events in the mixed beam is quoted as 20%, with a large error. Hence this result is compatible with that from CERN, in spite of the difference in beam energies (mean energy  $\sim 70$  GeV compared with  $\sim 2$  GeV at CERN).

At the London Conference on Elementary Particle Physics two other groups reported preliminary evidence for neutral currents. The Cal. Tech. group (Barish *et al* 1974b) have seen neutral current events in the deep inelastic neutrino interaction  $\nu + N \rightarrow \nu + X$  at FNAL. Also the Columbia group at BNL (Lee *et al* 1974) have some data pertaining to neutral currents.

The result of all this work indicates that neutral currents do exist, supporting that synthesis of weak and electromagnetic interactions which includes them (as opposed to heavy leptons). However, a word of warning may be appropriate at this point. The fact that neutral currents exist may have nothing to do with unified gauge theories, and may not even imply a neutral spin-one particle. It has been stressed by Kayser *et al* (1974) and Kingsley *et al* (1974) that further experimentation is necessary to clarify the space-time transformation properties of the neutral weak current, its isospin properties, etc; in fact, if the neutral current is scalar or pseudoscalar, right-handed neutrinos must exist. Searches for the  $Z^0$  analogous to those for the  $W^\pm$  have already been discussed (Jaffe and Primack 1973, Brown *et al* 1974b).

#### 4.6. Charmed particles

One real stumbling block in the formulation of gauge theories which involve hadrons is what to do with strange particles. All experiments with kaons are compatible with a very small  $\Delta S=1$  neutral current, where  $\Delta S$  is the change of strangeness of the hadron system. The present results on the branching ratio of the decay  $K_L^0 \rightarrow \mu^+\mu^-$  are compatible with a second-order electrodynamic process where the kaon decays first into two photons which then produce a muon pair (Carithers *et al* 1973). The experimental results on neutral currents so far apply only to  $\Delta S=0$  processes involving nucleons and pions. If the 20% neutral current seen in the neutrino experiments were  $\Delta S=1$ , one would see a decay rate for  $K_L^0 \rightarrow \mu^+\mu^-$  similar to that for  $K^+ \rightarrow \mu^+\nu_\mu$ . However, the experimental rate for  $K_L^0 \rightarrow \mu^+\mu^-$  is  $10^6$  times too small. Hence it seems a fact of nature that there are no first-order  $\Delta S=1$  neutral currents (and perhaps no  $\Delta S=1$  neutral currents at all).

Whenever we try to build models for hadronic processes involving kaons, it is difficult to avoid the introduction of neutral currents. We always start from a theory

with charged currents, and the commutator of two charged currents yields a neutral current. How are we then to explain the fact that a relatively large  $\Delta S=0$  neutral current exists while there is strong evidence that a  $\Delta S=1$  neutral current does not exist?

The usual way to avoid this difficulty is again to introduce more new particles. This time they are quarks (or hadrons) with a new quantum number called charm (Bjorken and Glashow 1964, Gell-Mann 1964, Hara 1964, Glashow *et al* 1970). The extra charmed proton quark is then incorporated with the three regular p, n and  $\lambda$  quarks in an SU(4) group, so that the neutral  $\Delta S=1$  current is exactly cancelled by the neutral current generated by the charmed particle. An alternative (nonquark) approach, involving new vector and axial vector multiplets, has been proposed by Schwinger (1973).

The charmed particle mechanism is rather contrived but allows the complete absence of first-order  $\Delta S=1$  neutral currents. Second-order effects still exist, and they are often embarrassingly large. The wealth of experimental data on K meson decays, in particular the limits on the unobserved process  $K \rightarrow \pi \nu \bar{\nu}$ , sets constraints on the masses of these charmed hadrons. Remember we are now working with renormalizable theories where physically significant quantities are necessarily calculable and finite. If the masses of the charmed particles were too large, some calculated K meson decay rates would violate known experimental bounds. Hence it looks as if the masses of these charmed particles cannot be larger than about  $10 \text{ GeV}/c^2$ , and, as such, they can be produced with the present accelerators. Here, however, the detection problem is severe. Presumably some rise in cross section occurs when we pass the threshold for the production of these particles. Perhaps the recent observation of dimuon events at FNAL indicates that charmed particles are produced in weak interactions (Benvenuti *et al* 1975).

#### 4.7. Miscellaneous

Almost all models which attempt to unify strong, weak and electromagnetic interactions predict even more new particles. An SU(2) version of the scheme proposed by Bars *et al* (1973) and by de Wit (1973) needs a new isoscalar pseudoscalar particle with negative charge conjugation (see Bardakci 1973, de Wit *et al* 1974). Presumably this particle decays mainly into a pion and rho meson. A judicious search among three-pion production data in the region around the  $A_1$  resonance may discover such an object (I Bars and M B Halpern 1974, private communication). Heavy pions with masses around 1 GeV also appear in such models.

The ultimate in gauge models is probably one which builds hadron quarks and leptons into a common representation. Then there is only one coupling constant, and the disparity in strengths between weak, electromagnetic and strong interactions in the range of accelerator energies is due to some dynamical symmetry breaking. A particular model by Georgi and Glashow (1974, see also Pati and Salam 1973) requires new intermediate bosons which carry both baryon and lepton number and mediate the semileptonic decays. These bosons are macroscopically massive and cannot possibly be produced as real particles. There is a potential difficulty in this type of model, namely that the proton is unstable. Any increase in the present limit on the lifetime of the proton would be instrumental in ruling out such models.

We should also mention the massless particles proposed by Bahcall *et al* (1972), which have various spin possibilities. Neutrinos leaving the sun could decay into



such particles before reaching the earth. This would explain why the flux of neutrinos at the surface of the earth is so small.

## 5. Constituents of the hadrons

### 5.1. Quarks

The quark model of hadrons was invented independently by Gell-Mann (1964) and Zweig (1965). Basically the model constructs all the hadrons out of three quarks,  $p$  (up),  $n$  (down) and  $\lambda$  (strange). The spin of the quark is  $\frac{1}{2}$ , its baryon number is  $\frac{1}{3}$  and the charges are  $\frac{2}{3}$ ,  $-\frac{1}{3}$  and  $-\frac{1}{3}$  respectively. All baryons then consist of three quarks, and the mesons are made from quark-antiquark pairs (with baryon number 0). Problems of statistics arise when higher spin resonances are included, because the quarks are fermions and we cannot put them in identical states. For example, consider the spin  $-\frac{3}{2}$   $\Delta^{++}$  (1236) resonance. If we construct this state from three proton quarks each having charge  $\frac{2}{3}$  and spin  $\frac{1}{2}$  then we need a symmetric spin wavefunction for zero orbital angular momentum. This violates the Pauli principle. It has therefore become fashionable to avoid this difficulty by assigning another property to the quarks, namely colour. Hence we have red, white and blue quarks so that the total number is nine rather than three, and the wavefunction can be antisymmetric in colour.

The basic idea that the hadronic particles are made up of simpler building blocks called quarks has led to considerable success in understanding many features of strong (and weak) interactions. In the past decade there have been a considerable number of experimental searches for such objects. Needless to say, no evidence for their existence has withstood the test of time, although several groups initially reported positive results. Before discussing the various experiments it is convenient to list some properties of these hypothetical particles. By now it is obvious that they must be rather massive (several GeV at least). One assumes that they are stable in isolation (or have a reasonable lifetime,  $\gtrsim 10^{-7}$  s), and also that the basic signal for positive identification is the discovery of a fractional charge.

The searches can be divided into three general classes. Let us call the first the physical-chemical search, which is based on the hope that the quarks exist in material on the earth and can be extracted if their concentration is not too low. Just how the quarks got there is really irrelevant. Various proposals include production in the cosmological big bang and production by cosmic rays. The second type of search is an accelerator search involving possible production in high-energy collisions (if the quark-antiquark threshold is passed) at CERN, BNL, IHEP, SLAC, and FNAL. The third type of search is based on the assumption that we do not yet have high enough energy in the laboratory and have therefore to use cosmic rays. Fractionally charged particles or time-delayed energetic particles are searched for in cosmic ray showers.

In the physical-chemical searches the fact that no quarks have been found gives limits on the magnitude of their concentration in various substances. The non-observation of quarks in accelerator and cosmic ray searches gives bounds on their production cross section. However, these limits invariably depend upon the theoretical model assumed for their production, and in consequence are not very stringent. For a review of some of the early experiments see Lederman (1967b) and Zichichi (1967).

The physical-chemical approach assumes that the quark should be bound to nuclei in stable Bohr orbits. The fractional charge then leads to strange chemical or physical properties of such atoms. By concentration the charged atoms are collected and subjected to some type of spectrometer analysis. Modifications of Millikan's oil drop experiment are also used so that larger droplets can be examined. Another experimental method employs magnetic levitation. Some of the latest references to these types of experiments are given in Morpurgo *et al* (1970), Hebard (1970) and Kim (1973), where specific limits on the concentration of quarks in various substances can be found.

The latest accelerator searches are those conducted at FNAL and ISR. In the experiment of Nash *et al* (1974) fractionally charged particles produced in proton-nucleus collisions at 200 and 300 GeV were searched for in a set of eight scintillation counters. Quarks of charge  $\frac{1}{3}e$  and  $\frac{2}{3}e$  should exhibit ionization losses respectively  $\frac{1}{9}$  and  $\frac{4}{9}$  of that for singly charged particles. The experiment was sensitive to quark masses below 11 GeV/ $c^2$ . Depending upon the mechanism, the upper limit on production of charge  $\frac{1}{3}e$  and  $\frac{2}{3}e$  quarks was given as a function of the mass of the quark. Another experiment at FNAL by Leipuner *et al* (1974) obtained similar limits for charges  $\frac{1}{3}e$  and  $\frac{2}{3}e$  and also quoted a limit on the production of charge  $\frac{4}{3}e$  quarks.

Similar searches at ISR have been made. The higher energy there means that one is checking the production of even higher masses (hypothetically as large as 25 GeV/ $c^2$ ). Bott-Bodenhausen *et al* (1972) found no quark candidates of charge  $\frac{1}{3}e$  or  $\frac{2}{3}e$  in  $6 \times 10^8$  interactions. For quark masses up to 22 GeV/ $c^2$  and charge  $\frac{1}{3}e$  they quote an upper limit for the total cross section as  $\sigma < 3 \times 10^{-33}$  cm<sup>2</sup>. Alper *et al* (1973) tried to detect particles with masses  $> 1.5$  GeV/ $c^2$  and charge  $\geq \frac{2}{3}e$ . However, no new stable particles were found among the  $7 \times 10^7$  charged particles entering their detector, and they quote  $\sigma < 2 \times 10^{-32}$  cm<sup>2</sup> for masses less than 25 GeV/ $c^2$ .

A search for photoproduced quarks was made with a photon beam at SLAC by Galik *et al* (1974), also with negative results. Several searches were made using the proton beams at CERN and IHEP. References to these experiments can be found in the papers of Allaby *et al* (1969) and Antipov *et al* (1969).

Finally we must describe the status of quark searches in cosmic ray physics. There was initially some apparent evidence for quarks in extensive air showers reported by McCusker and Cairns (1969), which was given an alternative interpretation by Adair and Kasha (1969); see also Kasha (1970). A repeat of the McCusker experiment by Clarke *et al* (1971), with some improvements designed to overcome some of the potential difficulties, failed to produce any quarks. A bubble chamber experiment by Chu *et al* (1970) appeared to show some evidence for quarks which was later refuted by Allison *et al* (1970). Other unsuccessful searches for fractionally charged quarks have been made in extensive air showers by Crouch *et al* (1972) and Ashton *et al* (1973). However, Tonwar *et al* (1972) found some delayed high-energy particles without knowing their charge. Dardo *et al* (1972) reported the observation of cosmic ray particles with charges between zero and  $e$  in magnitude which could be viewed as quark candidates. A different interpretation of the events has been given by Yock (1973), but with the conclusion that they are yet anomalous. Further investigation will be needed here.

In spite of the fact that there is no outstanding evidence for quarks at the present time, they may still exist with huge masses and/or having other properties which rule out the production mechanisms so far considered. Further searches are in progress at ISR and FNAL, but a disturbing aspect of the quark picture is coming more and

more into focus. No one doubts that the quark model has met with considerable success in explaining the low-energy properties of hadrons, yet scaling and other considerations seem to imply that the quark masses are not very large. One way out is to invent a model which allows a quark interpretation but does not allow quarks to be produced as real physical particles. Recent theoretical attempts to achieve quark containment have been made by Nielsen and Olesen (1974), Amati and Testa (1974), Wilson (1974), Kogut and Susskind (1974), Chodos *et al* (1974) and Bardeen *et al* (1975).

## 5.2. Integrally charged triplets

The quarks belonging to the triplet representation of  $SU(3)$  are unique in the sense that they possess fractional charge. It is possible to build hadrons out of quarks with integer charges if more than one basic triplet is used. The Han-Nambu (1965) model is one example of this kind of scheme. Three basic triplets are introduced (trions). Although there are certain theoretical reasons for favouring these models, the fact that the quarks do not possess some unique signature makes the experimental searches extremely difficult. A recent paper on the theoretical aspects of nine-quark models (quarks with colour) has been written by Nambu and Han (1974).

# 6. Tachyons, or particles faster than light

## 6.1. General considerations

To discuss such particles is to open Pandora's box and find it filled, not with evil attributes, but with a pile of paradoxes. The most elementary paradox is the apparent contradiction with the special theory of relativity, which is commonly supposed to rest on the postulate that no particle can move faster than light. Actually the theory requires that the speed of light is invariant under transformations between inertial coordinate systems, or frames, moving with different velocities, and, in consequence, that a particle moving more slowly than light in one frame moves more slowly than light in all frames. This leaves open the possibility that particles might exist which move faster than light, so long as their speed be superluminal in all frames.

The next level of difficulty is associated with the fact that the time order of events on a tachyon trajectory is not invariant under Lorentz transformations. This may be resolved as follows. We define the 4-momentum of a tachyon, just as for an ordinary particle, proportional to the 4-velocity. Then, if a positive energy tachyon is moving, say, to the right in one frame, there exist frames in which events further to the right occur at earlier times, and the tachyon has negative energy. We may reinterpret this negative energy tachyon 'moving backward in time' as a positive energy antitachyon moving forward in time; that is, an antitachyon travelling to the left (Bilaniuk *et al* 1962).

Under these assumptions, a single tachyon may never be used 'anticausally' to send a signal received at a time earlier than the time of emission. However, one may still ask if a sequence of tachyons emitted and absorbed by several different systems, each with high relative velocity, could form a loop in time. The answer again seems to be negative (Parmentola and Yee 1971).

Even ignoring these bizarre special cases, the issue whether a positive energy tachyon moving at some finite superluminal velocity can carry a signal (useful information) is exceedingly subtle. Since tachyon absorption does not depend only on the

observer (a tachyon must be incident before it can be observed!), and absorption in one frame is emission in another, perhaps spontaneous emission occurs, in which case a random tachyon background would always be present.

If one goes on to quantum field theory, the definition of a tachyon vacuum becomes difficult because tachyon destruction operators, which should annihilate the vacuum, become antitachyon creation operators in a different Lorentz frame (Feinberg 1967). Consequently, both at classical and quantum levels there are arguments for saying that, if tachyons exist, there must be a tachyon sea present, and all ordinary objects constantly absorb and emit tachyons.

Can charged tachyons exist, and what special behaviour would they have? There is a debate between those who say a charged tachyon would emit Cherenkov radiation *in vacuo* causing it to speed up (sic) (Bilaniuk *et al* 1962, Bartlett and Lahana 1972), and those who say it would not emit any radiation *in vacuo* (Mignani and Recami 1973, 1974). The latter view is based on the following reasoning: If there be radiation, there must be radiation reaction to conserve energy, but then even an isolated charged tachyon would not follow a straight line in Minkowski space, and in fact there would be a preferred frame in which the tachyon trajectory would have asymptotically infinite velocity. Thus the notion of a free particle as corresponding, in some sense, to a representation of the Poincaré group would be abandoned for charged tachyons. There are at least two ways to evade the dilemma. One is to assign the radiation reaction to the source of the tachyon so that the tachyon itself moves at constant velocity. In that case the Cherenkov radiation from the tachyon is easily computed, and infinite, unless some high-frequency cut-off is imposed. Such a theory is manifestly unsatisfactory, and, since a similar ultraviolet catastrophe would apply to gravitational Cherenkov radiation, tachyons would be ruled out altogether.

The second approach is to assume that, in a particular Lorentz frame, perhaps the rest frame of the emitter, the tachyon itself does suffer instantaneous radiation reaction, and there is a high-frequency cut-off given by  $\nu = E/h$ , where  $E$  is the tachyon energy and  $h$  is Planck's constant. This is the *ad hoc* procedure which led to the noncovariance criticized by Mignani and Recami, but G Feinberg (1975, private communication) has suggested a way out; if in the emitter rest frame one tachyon is emitted and slowly accelerates while losing energy, then in another frame there is a sea of tachyon-antitachyon pairs accompanying the 'original' tachyon. Evidently the same remark would apply for gravitational Cherenkov radiation, leading once again to the conclusion that even at the classical level there is no one-particle tachyon theory.

Feinberg (1967) has found that the quantum field theory of non-interacting spinless tachyons has unusual features. Single-particle states cannot be completely localized (even at one instant of time) if only oscillatory (as opposed to exponential) time dependence is allowed. In the explicit construction of the field theory, manifest Lorentz invariance imposed the assumption of Fermi-Dirac statistics. This in turn suggested that tachyons must be created or absorbed in pairs. These special properties may account for the failure, so far, to construct a manifestly Lorentz invariant theory of interacting tachyons. If no such theory existed, the discovery of tachyons would require a major revision in theoretical physics.

## 6.2. Experimental searches

The techniques for exposing tachyons are all implicit in our general discussion. Conservation of energy and momentum has been used to examine the total 4-momentum

of unobserved particles  $X$  in a reaction  $A + B \rightarrow C + X$ . By measuring the momenta of  $A$ ,  $B$  and  $C$  one may determine whether the 4-momentum of  $X$  is timelike ( $E_X > P_X c$ ) or spacelike ( $E_X < P_X c$ ). The latter case implies that at least one tachyon was present among the unobserved particles, unless an extraordinary collision occurred, in which an unobserved incident particle intercepted  $A$  and  $B$  at the same moment they collided with each other. Since the probability of such a three-body collision can be computed (and is very small), an experiment of this type can be used to set an upper limit on the cross section for producing a single tachyon  $X$ , as well as an order-of-magnitude limit on the cross section for any tachyons to be produced. The point here is that, if more than one particle is included in the unobserved  $X$ , the  $X$  may have a timelike 4-momentum, even if tachyons are present. Nevertheless, it is plausible that roughly half the time  $X$  would have spacelike 4-momentum. For an initial state consisting of  $K^-$  or  $\bar{p}$  and  $p$  at rest, Baltay *et al* (1970) found the ratio of tachyon production to  $\pi^0$  production, with no other unobserved particles, was roughly  $10^{-3}$  or less. For 2 GeV/ $c$   $K^-$  on  $p$ , Danburg *et al* (1971) found a cross section for charged tachyon pair production less than about  $10^{-31}$  cm<sup>2</sup>, assuming the tachyons left conventional tracks in the bubble chamber.

If tachyons could be emitted with negative energy (or, more sensibly, if there exists a tachyon sea whose members could give up energy), then the proton could be unstable. Moreover, a stationary proton could suddenly move. Danburg and Kalbfleisch (1972) set a lower limit on the lifetime for the second effect of more than  $10^{21}$  yr. As for the first effect, the lifetime of the proton is known to be  $> 2 \times 10^{28}$  yr (Gurr *et al* 1967). G. Feinberg (1975, private communication) has remarked that a sea of fermion tachyons and antitachyons filled to a certain level could collide with moving protons, causing them to lose energy while pushing tachyons above the Fermi level of the sea. The stability of beams at storage rings such as ISR would permit determination of an upper limit on such an effect. This combined with the proton lifetime limits would serve to give a very small upper limit on the value of the tachyon-proton coupling constant, of the order of that quoted by Danburg and Kalbfleisch for 'negative energy' tachyon emission.

Several experiments exploiting Cherenkov radiation *in vacuo* have set limits on low-energy (1 MeV) photoproduction cross sections for tachyons. Alväger and Kreisler (1965) and Davis *et al* (1969) set cross section limits first of  $10^{-30}$  cm<sup>2</sup>, then  $10^{-33}$  cm<sup>2</sup>, for a lead target. Bartlett and Lahana (1972) looked for bigger charges (monopole tachyons!) and obtained limits of about  $10^{-36}$  cm<sup>2</sup> for various targets. Finally, Ramana Murthy (1971) looked for correlations between interactions in a counter, and arrival of a cosmic ray shower some microseconds later. The interpretation would be that a cosmic ray collision in the upper atmosphere had produced a tachyon that arrived at the earth *before* the main shower, which travelled at  $v \lesssim c$ . Non-observance of a correlation implied that tachyon signals occur less than  $10^{-4}$  times as often as high-energy electrons are produced in such showers. However, recently Clay and Crouch (1974) have reported seeing a significant correlation in a similar experiment. Their approach was to store information about pulses in their counters during an interval of 128  $\mu$ s, which was continually advanced, so that, in principle, at any time the history of the previous 128  $\mu$ s would be available. When a cosmic ray shower triggered their apparatus, the history could be read out, and the correlation between advanced pulses and the shower studied. The experiment also differed from Ramana Murthy's in emphasizing more energetic showers ( $10^{15}$  eV). If this result indeed shows tachyons, it implies a very high cross section for tachyon production at high energies, of order

$10^{-26} \text{ cm}^2$ . However, M E Crouch and G Tanahashi (1975, private communication) have performed a similar experiment which did not show a significant correlation of advanced pulses with showers, and which puts a limit of  $6 \times 10^{-4}$  on the tachyon-electron ratio for  $10^{15} \text{ eV}$  showers. A conservative physicist could say that the existence of tachyons is not proved.

## 7. Gravitons and dilatons

As early as 1930, Léon Rosenfeld remarked that applying quantum theory to the gravitational field would require the existence of gravitons. In recent years, there have been many theoretical papers written on quantum gravitation, but the consistency and necessity of such a theory is not yet clear. Recent papers on this subject, which give references to earlier work, are by 't Hooft and Veltman (1974) and Deser and van Nieuwenhuizen (1974). These authors show that a quantized gravitational field (coupled to one or two other particular fields) does not yield a renormalizable theory. Their results, though distressing at first sight, actually revive the exciting possibility that gravitation will indeed, as Einstein hoped, supply the key to a unified field theory of the physical world: it may be that only for a unique choice of other fields and couplings could gravity be included in a renormalizable theory. However, such a theoretical 'discovery' of the graviton would be very far from an experimental observation. In fact, observation appears beyond the reach of present or foreseeable techniques. An indication of this difficulty is the report by Weber *et al* (1973) of detecting classical gravitational waves; this is hotly contested by others, eg Garwin and Levine (1973).

Until classical waves can be seen, observing individual quanta is hopeless. Even if the classical waves are detected, stout hearts may quail when faced with the small cross section for gravitational Compton scattering on a proton. In the Thomson limit, this must be of the order  $\pi(Gm_p/c^2)^2 \approx 10^{-103} \text{ cm}^2$ , while the smallest cross sections observed with beams of laboratory intensity are for neutrino scattering processes, and are more than 60 orders of magnitude bigger. Stated another way, the mean free path through matter of nuclear density is *far* larger than the radius of the universe! Therefore the graviton may or may not exist, but its existence has no foreseeable direct consequences.

A possible symmetry of the equations of motion governing the fundamental fields of nature (if such there be) is invariance under dilatation, or change in the scale of length and time by a common factor. There is no experimental evidence for this symmetry, which would lead to a world with only particles of zero mass or with a continuum of masses. If the symmetry nevertheless existed and were exact, its lack of visibility could be explained by the mechanism of Goldstone (1961) in which the vacuum is not invariant, and there is at least one massless particle in nature, the dilaton. It might have spin 2, and couple to the energy momentum tensor as the photon couples to the electric current (S Weinberg 1975, unpublished); it might have spin 0, and couple to the trace of the energy momentum tensor (Freund and Nambu 1968). The only apparent object exhibiting such features is the graviton. If the fundamental symmetry were only approximate, the dilaton could be massive (Mack 1968). Such mesons coupled to the energy momentum tensor and its trace were suggested by Gell-Mann (1962) as a natural extension of the analogy between photons and vector mesons introduced by Sakurai (1960). Even if they existed, they might be

difficult to identify because their couplings would vanish in some useful production reactions (Ellis 1970). Furthermore, recent developments in the concept of broken scale invariance suggest that the breaking would be likely to come from a cut-off energy required for renormalization, rather than from the Goldstone mechanism (Carruthers 1971, Gell-Mann 1971, Politzer 1974). In short, the dilaton is less plausible and no more detectable than the graviton.

## 8. The new particles

This article is being completed during the most sustained period of surprise and mystery in postwar high-energy physics. At this moment, at least two new, high-mass, exceedingly sharp particles have been established. These long-lived states have masses of 3.1 GeV (Aubert *et al* 1974c, Augustin *et al* 1974, Bacci *et al* 1974) and 3.7 GeV (Abrams *et al* 1974).

They are neutral, and decay to  $e^+e^-$ , to hadrons, and to  $\mu^+\mu^-$ , with total decay width  $\lesssim 1$  MeV and quite possibly  $< 100$  keV. This new and perhaps growing family of particles may revive interest in some narrow states in the neighbourhood of the nucleon-antinucleon threshold which have been widely ignored previously, even in the previous part of this article (Gray *et al* 1971, Carroll *et al* 1974, Kalogeropoulos 1974). The particular mass and width range of the new particles is especially tantalizing because it is compatible with two quite different kinds of hypothesis. The particles could be mediators of neutral current weak interactions, or they could be vector mesons which couple to leptons through an intermediate virtual photon. Needless to say, other possibilities could be proposed, but these are the two ways to fit them into existing models, especially those discussed in §§4 and 5. The weak boson idea would be confirmed immediately if some parity-violating effects were found, or if the state does not have  $J=1$ . Otherwise, it would be very difficult to establish this conclusively. Compelling evidence of hadron character for the 3.1 GeV state is the demonstration at FNAL (Knapp *et al* 1975) and at SLAC (Camerini *et al* 1975) that this object is produced on nuclear targets with cross sections bigger than 1 nb/nucleon. Further evidence might come from the discovery of new charged particles. Depending on the model, these charged relatives might be nearly degenerate in mass with the neutral ones, or simply in the same general, several GeV, region.

The quark model permits classification of guesses about the nature of such new hadrons. The first guess is that a new, charmed, quark exists, as mentioned in §5. The new quark could be used to explain the absence of strangeness-changing neutral currents, but also could explain (as a quark-antiquark threshold effect) the large cross section of  $e^+e^-$  into hadrons at centre-of-mass energies of 3–5 GeV (Richter 1974, Larsen 1974).

Appelquist and Politzer (1975) have studied this question in a semiquantitative way, and argued that very likely one or several bound states of charmed quarks, resembling levels in positronium, might be found at masses  $\lesssim 4$  GeV. If the  $e^+e^-$  cross section were to descend after 5 GeV, this analysis would be quite appealing. It would also imply the existence of particles carrying charm with masses between 2 and 4 GeV, decaying weakly to noncharmed states. An alternative scheme, which would have all the same merits except for the explanation of no  $\Delta Q=0$ ,  $\Delta S=1$  currents, would be to suppose that quarks are really Han-Nambu (1965) triplets, and that the new mesons are part of a colour SU(3) octet. This way, charged partners

should exist with very similar widths. Schwinger (1973, 1975) proposed a nonquark scheme in which lack of neutral  $\Delta S=1$  currents comes from mixing of well-known vector mesons with a higher-mass nonet; perhaps the new states belong to this nonet. Within the conventional fractionally charged quark picture, another possibility is suggested by the duality diagrams of Harari (1969) and Rosner (1969). In the process of baryon-antibaryon annihilation, these diagrams suggest that states made of two quarks and two antiquarks should be produced, some of which could have exotic (non-octet) quantum numbers (Rosner 1970). The decay widths and photon couplings of such objects are hard to predict, but if the widths were small this could be a unified rationale for the new and old narrow states.

Finally, one may ask if these particles are not really unusual nuclei; that is, bound states or resonances of baryon and antibaryon, or, a little more generally, states with three quarks and three antiquarks (Dürr 1975, Goldhaber and Goldhaber 1975, Tow *et al* 1975). Here the main immediate objection is that nucleon-antinucleon total cross sections at low energy suggest substantially larger decay widths. In fact, Shapiro and colleagues (Dal'karov *et al* 1970, Shapiro 1973, Bogdanova *et al* 1974) have suggested such states as accounting for many broad bumps seen in multimeson channels between 1 and 2 GeV, and have argued that widths at the several MeV level or larger could easily be explained. Conversely, much smaller widths are hard to explain without invoking some extra mechanism in the baryon-antibaryon potential (such as a very small annihilation region and a centrifugal barrier maintained despite tensor forces), or some more complex character of the multiquark wavefunction. The nuclear model would have as a necessary consequence that quite often the hadronic decay products would include baryon pairs (accompanied by mesons), substantially more often than for neighbouring mass regions in  $e^+e^-$  annihilation.

Of course, it remains possible that so many new states will be found as to defeat all prefabricated schemes. [There are no ready-made explanations of a very broad, resonance-like bump in  $\sigma(e^+e^- \rightarrow \text{hadrons})$  at 4.1 GeV (Augustin *et al* 1975).] Nieh *et al* (1975) have raised the possibility that the new particles are hadrons which are produced weakly at low energies only because they carry a new quantum number, and so must be associated with other particles (in analogy to the case of strangeness). In any case, the promise is great that a new and powerful constraint on theory is being uncovered, and should be thoroughly exploited by the time of the next review article on the topic of hypothetical particles.

## 9. Bibliography of recent related reviews

The following can provide useful additional information. We have borrowed freely from these sources in writing this article.

### 9.1

1. *The Present Position and Future Prospects for the Discovery of New Particles* Adair 1972
2. *Status Report on Elusive Particles* Ramana Murthy 1972
3. *Les Particules Introuvables* Bilaniuk and Boccio 1973
4. *Review of Particle Properties* Particle Data Group 1974
5. *Present Trends in Particle Physics* Fubini 1974
6. *The Missing Particles* Adair 1974



## 9.2

1. *The Quark Model* Kokkedee 1969
2. *Dual Resonance Theory* Schwarz 1973
3. *The Classification and Decays of Resonant Particles* Rosner 1974
4. *Dual Resonance Models* Mandelstam 1974
5. *Symmetries of Currents as seen by Hadrons* Gilman 1974
6. *Meson Spectroscopy and the Phenomenology of High-Energy Collisions* Quigg 1974

## 9.3

1. *Recent Developments in the Theory of Magnetically Charged Particles* Zumino 1966
2. *On the Dirac Magnetic Poles* Amaldi and Cabibbo 1972
3. *The Classical Problem of Charge and Pole* Carter and Cohen 1972
4. *Magnetic Monopoles: An Updated Bibliography* Stevens 1973

## 9.4

1. *Neutrino Reactions at Accelerator Energies* Llewellyn Smith 1972
2. *Gauge Theories* Abers and Lee 1973
3. *Gauge Field Theory* Veltman 1973
4. *Spontaneous Symmetry Breaking, Gauge Theories, the Higgs Mechanism, and All That* Bernstein 1974
5. *Search for Charm* Gaillard et al 1975
6. *Asymptotic Freedom; An Approach to Strong Interactions* Politzer 1974

## 9.5

1. *Unitary Symmetry* Charap et al 1967
2. *The Hunting of the Quark* Lederman 1967b
3. *Lectures on the Quark Model* Morpurgo 1969
4. *A Short Guide to the Quark Model* Morpurgo 1970
5. *Multiple Production of Hadrons at Cosmic Ray Energies* Feinberg 1972
6. *The Continuing Search for Quarks* Jones 1973
7. *Quarks for Pedestrians* Lipkin 1973
8. *The Structure of the Proton* Feynman 1974

## 9.6

1. *Are there Faster-Than-Light Particles?* Kreisler 1973
2. *Classical Theory of Tachyons* Recami and Mignani 1974

## 9.7

1. *Gravitational Waves—Progress Report* Logan 1973
2. *Sources of Gravity Waves* Sejnowski 1974

## Acknowledgments

We should like to thank our many colleagues at Stony Brook and elsewhere who have made helpful comments and suggestions, especially R W Brown for a critical reading of the draft, and L W Alvarez, G Feinberg and M Goldhaber for detailed comments on particular aspects. J Smith would like to thank Los Alamos Scientific Laboratory for hospitality during August 1974 when a substantial part of this manuscript was prepared. The work was supported in part by National Science Foundation Grant No. GP-32998X.

## References

- AARON R, AMADO RD and SILBAR RR 1971 *Phys. Rev. Lett.* **26** 407-10  
 AARON R, RICH M, HOGAN WL and SRIVASTAVA YN 1973 *Phys. Rev. D* **7** 1401-6  
 ABERS ES and LEE BW 1973 *Phys. Rep.* **9** 1-141  
 ABRAMS GS *et al* 1974 *Phys. Rev. Lett.* **33** 1453-5  
 ADAIR RK 1972 *Proc. 16th Int. Conf. on High Energy Physics* ed J D Jackson and A Roberts (Batavia, Illinois: NAL) pp307-18  
 — 1974 *Yale University Preprint* (50pp)  
 ADAIR RK and KASHA H 1969 *Phys. Rev. Lett.* **23** 1355-8  
 ADLER SL, DUSHEN RF and TREIMAN SB 1974 *Phys. Rev. D* **10** 3728-35  
 ALBRIGHT C 1973 *Phys. Rev. D* **7** 63-74  
 ALLABY JV *et al* 1969 *Nuovo Cim.* **64A** 75-94  
 ALLISON WWM, DERRICK M, HUNT GP, SIMPSON JD and VOJVODIC L 1970 *Phys. Rev. Lett.* **25** 550-3  
 ALPER B *et al* 1973 *Phys. Lett.* **46B** 265-8  
 ALSTON M *et al* 1960 *Phys. Rev. Lett.* **5** 520-4  
 ALVÄGER T and KREISLER MN 1965 *Phys. Rev.* **183** 1132-3  
 ALVAREZ L W 1973 *Phys. Rev. D* **8** 702-11  
 ALVAREZ L W, EBERHARD PH and ROSS RR 1970 *Science*, NY **167** 701  
 ALVAREZ L W *et al* 1959 *Phys. Rev. Lett.* **2** 215-9  
 AMALDI E and CABIBBO N 1972 *Aspects of Quantum Theory* ed A Salam and E P Wigner (London: Cambridge UP) pp183-212  
 AMALDI E *et al* 1963 *Nuovo Cim.* **28** 773-93  
 AMATI D and TESTA TM 1974 *Phys. Lett.* **48B** 227-31  
 ANTIPOV YU M *et al* 1969 *Phys. Lett.* **29B** 245-8  
 APPELQUIST T and POLITZER HD 1975 *Phys. Rev. Lett.* **34** 43-5  
 ARAFUNE J 1974 *Phys. Rev. Lett.* **32** 560-1  
 ASHTON F, COOPER DA, PARVARESH A and SALEH AJ 1973 *J. Phys. A: Math., Nucl. Gen.* **6** 577-81  
 ASRATYAN A E *et al* 1974 *Phys. Lett.* **49B** 488-90  
 AUBERT B *et al* 1974a *Phys. Rev. Lett.* **32** 1454-7  
 — 1974b *Phys. Rev. Lett.* **32** 1457-60  
 AUBERT JJ *et al* 1974c *Phys. Rev. Lett.* **33** 1404-6  
 AUGUSTIN J-E *et al* 1974 *Phys. Rev. Lett.* **33** 1406-8  
 — 1975 *Phys. Rev. Lett.* **34** 764-7  
 BACCI C *et al* 1972 *Phys. Lett.* **38B** 551-4  
 — 1974 *Phys. Rev. Lett.* **33** 1408-10  
 BAHCALL JN, CABIBBO N and YAHIL A 1972 *Phys. Rev. Lett.* **28** 316-8  
 BALTAY C, FEINBERG G, YEH N and LINSKER R 1970 *Phys. Rev. D* **1** 759-70  
 BANDERET PP 1946 *Helv. Phys. Acta* **19** 503-22  
 BARBARINO G *et al* 1972 *Lett. Nuovo Cim.* **3** 689-92  
 BARDAKCI K 1973 *Nucl. Phys.* **B51** 174-88  
 BARDEEN WA *et al* 1975 *Phys. Rev. D* **11** 1094-136  
 BARISH BC *et al* 1973 *Phys. Rev. Lett.* **31** 180-3  
 — 1974a *Phys. Rev. Lett.* **32** 1387-90

- BARISH B C *et al* 1974b *Proc. 17th Int. Conf. on High Energy Physics* vol IV, ed J R Smith (Chilton: Rutherford Laboratory) pp111-3
- BARISH S *et al* 1974c *Proc. 17th Int. Conf. on High Energy Physics* vol IV, ed J R Smith (Chilton: Rutherford Laboratory) pp123-5
- BARNES V E *et al* 1964 *Phys. Rev. Lett.* **12** 204-6
- BARS I, HALPERN M B and YOSHIMURA M 1973 *Phys. Rev. D* **7** 1233-51
- BARTLETT D F and LAHANA M D 1972 *Phys. Rev. D* **6** 1817-23
- BAUER E 1951 *Proc. Camb. Phil. Soc.* **47** 777-89
- BELL J S 1973 *Nucl. Phys.* **B60** 427-32
- BENVENUTI A *et al* 1974a *Phys. Rev. Lett.* **32** 125-8
- 1974b *Phys. Rev. Lett.* **32** 800-3
- 1975 *Phys. Rev. Lett.* **34** 419-22
- BERGESON H E, CASSIDAY G L and HENDRICKS M B 1973 *Phys. Rev. Lett.* **31** 66-70
- BERNABEU J, ERICSON T E O and FERRO FONTAN C 1974 *Phys. Lett.* **49B** 381-4
- BERNARDINI G *et al* 1965 *Nuovo Cim.* **38** 608-23
- BERNSTEIN J 1974 *Rev. Mod. Phys.* **46** 7-48
- BERRONDO M and MCINTOSH H V 1970 *J. Math. Phys.* **11** 125-41
- BEYER R T (ed) 1949 *Foundations of Nuclear Physics* (New York: Dover)
- BIALYNICKI-BIRULA I and BIALYNICKI-BIRULA Z 1971 *Phys. Rev. D* **3** 2410-2
- BILANIUK O M and BOCCIO J R 1973 *La Recherche* **40** 1037-47
- BILANIUK O M, DESHPANDE V K and SUDARSHAN E C G 1962 *Am. J. Phys.* **30** 718-23
- BINGHAM H H *et al* 1972 *Phys. Lett.* **41B** 635-8
- BJORKEN J D and GLASHOW S L 1964 *Phys. Lett.* **11** 255-7
- BOGDANOVA L N, DAL'KAROV O D and SHAPIRO I S 1974 *Ann. Phys., NY* **84** 261-84
- BOTT-BODENHAUSEN M *et al* 1972 *Phys. Lett.* **40B** 693-8
- BRADNER H and ISBELL W M 1959 *Phys. Rev.* **114** 603-4
- BROWN L S, CAHN R N and McLERRAN L D 1974a *Phys. Rev. Lett.* **32** 562-5
- BROWN R W, GORDON L B and MIKAELIAN K O 1974b *Phys. Rev. Lett.* **33** 1119-21
- BROWN R W, HOBBS R H and SMITH J 1971 *Phys. Rev. D* **4** 794-813
- BROWN R W and SMITH J 1971 *Phys. Rev. D* **3** 207-23
- BURNS R *et al* 1965 *Phys. Rev. Lett.* **15** 42-5
- BÜSSER F W *et al* 1974 *Phys. Lett.* **48B** 377-9
- CABIBBO N and FERRARI E 1962 *Nuovo Cim.* **23** 1146-54
- CARITHERS W C, STEFANSKI R and ADAIR R K 1966 *Phys. Rev.* **149** 1070-7
- CARITHERS W C *et al* 1973 *Phys. Rev. Lett.* **31** 1025-8
- CARRIGAN R A Jr, NEZRICK F A and STRAUSS B P 1973 *Phys. Rev. D* **8** 3717-20
- 1974 *Phys. Rev. D* **10** 3867-8
- CARROLL A S *et al* 1974 *Phys. Rev. Lett.* **32** 247-50
- CARRUTHERS P 1971 *Phys. Rep.* **1** 1-30
- CARTER E F and COHEN H A 1973 *Am. J. Phys.* **41** 994-1006
- CHARAP J M, JONES R B and WILLIAMS P G 1967 *Rep. Prog. Phys.* **30** 227-84
- CHEN H H, KROPP W R, SOBEL H W and REINES F 1971 *Phys. Rev. D* **4** 99-121
- CHEN M-Y 1975 *Phys. Rev. Lett.* **34** 341-4
- CHODOS A, JAFFE R L, JOHNSON K, THORN C B and WEISSKOPF V F 1974 *Phys. Rev. D* **9** 3471-95
- CHRIST N 1968 *Phys. Rev.* **176** 2086-100
- CHRISTENSON J H *et al* 1973 *Phys. Rev. D* **8** 2016-34
- CHU W T, KIM Y S, BEAM W J and KWAK N 1970 *Phys. Rev. Lett.* **24** 917-23
- CLARK A F *et al* 1971 *Phys. Rev. Lett.* **27** 51-5
- CLAY R W and CROUCH P C 1974 *Nature, Lond.* **248** 28-30
- COLE H J D 1951 *Proc. Camb. Phil. Soc.* **47** 196-206
- COLLINS G B, FICENEC J R, STEVENS D M, TROWER W P and FISCHER J 1973 *Phys. Rev. D* **8** 982-3
- CORNWALL J M, LEVIN D N and TIKTOPOULOS G 1973 *Phys. Rev. Lett.* **30** 1268-70
- CORNWALL J M and NORTON R E 1973 *Phys. Rev. D* **8** 3338-46
- COWSIK R and PAL Y 1970 *Acta Phys. Acad. Sci. Hung.* **29** (Suppl. 4) 367-70
- CROUCH M F, MORI K and SMITH G R 1972 *Phys. Rev. D* **5** 2667-76
- DAKIN J J *et al* 1975 *Phys. Lett.* to be published
- DAL'KAROV O D, MANDEL'TSWEIG V B and SHAPIRO I S 1970 *Nucl. Phys.* **B21** 88-92

- DANBURG JS and KALBFLEISCH GR 1972 *Phys. Rev. D* **5** 1575-82
- DANBURG JS *et al* 1971 *Phys. Rev. D* **4** 53-65
- DANBY G *et al* 1962 *Phys. Rev. Lett.* **9** 36-44
- DARDO M, NAVARRA G and PENENGO P 1972 *Nuovo Cim.* **9A** 319-39
- DAVIS MB, KREISLER MN and ALVÄGER T 1969 *Phys. Rev.* **183** 1132-3
- DESER S and VAN NIEUWENHUIZEN P 1974 *Phys. Rev. Lett.* **32** 245-7
- DIRAC PAM 1931 *Proc. R. Soc. A* **133** 60-72
- 1948 *Phys. Rev.* **74** 817-30
- DIXIT MS *et al* 1971 *Phys. Rev. Lett.* **27** 878-81
- DOOHER J 1971 *Phys. Rev. D* **3** 2652-60
- DÜRR HP 1975 *Phys. Rev. Lett.* **34** 422-6, 616-9
- EBERHARD PH, ROSS RR, ALVAREZ LW and WATT RD 1971 *Phys. Rev. D* **4** 3260-72
- EICHTEIN T *et al* 1973 *Phys. Lett.* **46B** 281-4
- EISENBERG Y 1954 *Phys. Rev.* **96** 541-3
- ELIEZER CJ and ROY SK 1962 *Proc. Camb. Phil. Soc.* **58** 401-4
- ELLIS J 1970 *Nucl. Phys.* **B26** 537-46
- ENGLERT F and BROUT R 1964 *Phys. Rev. Lett.* **13** 321-3
- ERLYKIN AD and YAKOVLEV VI 1969 *Sov. Phys.-JETP* **29** 992-3
- ERWIN AR, MARCH R, WALKER WD and WEST E 1961 *Phys. Rev. Lett.* **6** 628-30
- FADDE'EV LD and POPOV VN 1969 *Phys. Lett.* **25B** 29-30
- FEARING HW, PRATAP M and SMITH J 1972 *Phys. Rev. D* **5** 177-8
- FEINBERG EL 1972 *Phys. Rep.* **5** 295-6
- FEINBERG G 1958 *Phys. Rev.* **110** 1482-3
- 1967 *Phys. Rev.* **169** 1089-105
- FEINBERG G and WEINBERG S 1961 *Phys. Rev. Lett.* **6** 381-3
- FERMI E 1934 *Z. Phys.* **88** 161-78
- FERMI E *et al* 1952 *Phys. Rev.* **85** 935-6
- FEYNMAN RP 1974 *Science, NY* **183** 601-10
- FEYNMAN RP and GELL-MANN M 1958 *Phys. Rev.* **109** 193-8
- FIDECARO M, FINOCCHIARO G and GIACOMELLI G 1961 *Nuovo Cim.* **22** 657-60
- FIERZ M 1944 *Helv. Phys. Acta* **17** 27-34
- 1964 *Helv. Phys. Acta* **37** 663-6
- FLEISCHER RL, JACOBS IS, SCHWARZ WM, PRICE PB and GOODELL HG 1969a *Phys. Rev.* **177** 2029-35
- FLEISCHER RL, PRICE PB and WOODS RT 1969b *Phys. Rev.* **184** 1398-401
- 1971 *Phys. Rev. D* **4** 24-7
- FLEISCHER RL *et al* 1969c *Phys. Rev.* **184** 1393-7
- FRADKIN ES and TYUTIN IV 1969 *Phys. Lett.* **30B** 562-3; *Phys. Rev. D* **2** 2841-57
- FRANK IM 1952 *Vavilov Memorial Symp., USSR* (Moscow: Academy of Sciences)
- FRAZER WR and FULCO JR 1959 *Phys. Rev. Lett.* **2** 365-8
- FREEDMAN DZ and WANG J-M 1967 *Phys. Rev.* **153** 1596-609
- FREUND PGO and NAMBU Y 1968 *Phys. Rev.* **174** 1741-3
- FRY WF, SCHNEPS J and SWAMI MS 1955a *Phys. Rev.* **97** 1189-90
- 1955b *Nuovo Cim.* **2** 346-7
- FUBINI S 1974 *Proc. 17th Int. Conf. on High Energy Physics* vol VI, ed J R Smith (Chilton: Rutherford Laboratory) pp1-16
- GAILLARD MK, LEE BW and ROSENER JL 1975 *Rev. Mod. Phys.* **47** 277-310
- GALIK R *et al* 1974 *Phys. Rev. D* **9** 1856-64
- GARWIN RL and LEVINE JL 1973 *Phys. Rev. Lett.* **31** 176-80
- GELL-MANN M 1953 *Phys. Rev.* **92** 833-4
- 1962 *Phys. Rev.* **125** 1067-84
- 1964 *Phys. Lett.* **8** 214-5
- 1971 *Broken Scale Invariance and the Light Cone* ed M Dal Cin, G J Iversen and A Perlmutter (New York: Gordon and Breach) p42
- GEORGI H and GLASHOW SL 1972 *Phys. Rev. Lett.* **28** 1494-7
- 1974 *Phys. Rev. Lett.* **32** 438-41
- GERSHTEIN SS, LANDSBERG LG and FOLOMESHKIN VN 1972 *Yad. Fiz.* **15** 345-50 (1973 *Sov. J. Nucl. Phys.* **15** 195-7)
- GILMAN F 1974 *Proc. 4th Conf. on Experimental Meson Spectroscopy* (New York: AIP) pp369-85

- GLASHOW S L 1961 *Nucl. Phys.* **22** 579–88  
 GLASHOW S L, ILIOPOULOS J and MAIANI L 1970 *Phys. Rev. D* **2** 1285–92  
 GOLDBABER A S 1965 *Phys. Rev.* **140** 1407–14  
 GOLDBABER A S and GOLDBABER M 1975 *Phys. Rev. Lett.* **34** 36–7  
 GOLDBABER A S and NIETO M M 1971 *Rev. Mod. Phys.* **43** 277–96  
 GOLDBABER M 1958 *Proc. Int. Conf. on High Energy Physics* ed B Ferretti (Geneva: CERN) pp233–50  
 GOLDSTONE J S 1961 *Nuovo Cim.* **19** 154–64  
 GOTO E, KOLM H H and FORD K W 1963 *Phys. Rev.* **132** 387–96  
 GRAY L, HAGERTY P and KALOGEROPOULOS T 1971 *Phys. Rev. Lett.* **26** 1491–4  
 GRÖNBLOM B O 1935 *Z. Phys.* **98** 283–5  
 GURALNIK G S, HAGEN C R and KIBBLE T W B 1964 *Phys. Rev. Lett.* **31** 585–7  
 GUREVICH I I *et al* 1972 *Phys. Lett.* **38B** 549–50  
 GURR H S *et al* 1967 *Phys. Rev.* **158** 1321–30  
 GÜRSEY F and RADICATI L A 1964 *Phys. Rev. Lett.* **13** 173–5  
 HAGEDORN R 1965 *Nuovo Cim. (Suppl.)* **3** 147–86  
 HAN Y N and BIEDENHARN L C 1971 *Nuovo Cim.* **2A** 544–56  
 HAN Y N and NAMBU Y 1965 *Phys. Rev.* **139** 1006–10  
 HARA Y 1964 *Phys. Rev.* **134B** 701–4  
 HARARI H 1969 *Phys. Rev. Lett.* **22** 562–5  
 HARISH-CHANDRA 1948 *Phys. Rev.* **74** 883–7  
 HASERT F J *et al* 1973a *Phys. Lett.* **46B** 138–40  
 ——— 1973b *Phys. Lett.* **46B** 121–4  
 ——— 1974 *Nucl. Phys.* **B73** 1–22  
 HEBARD A F 1970 *PhD Thesis* Stanford University  
 HEISENBERG W 1932 *Z. Phys.* **77** 1–11  
 HIGGS P W 1964a *Phys. Lett.* **12** 132–3  
 ——— 1964b *Phys. Rev. Lett.* **13** 508–9  
 ——— 1966 *Phys. Rev.* **145** 1156–63  
 'T HOOFT G 1971a *Nucl. Phys.* **B33** 173–99  
 ——— 1971b *Nucl. Phys.* **B35** 167–88  
 'T HOOFT G and VELTMAN M 1972 *Nucl. Phys.* **B44** 189–213  
 ——— 1974 *Ann. Inst. Henri Poincaré* **20** 69–94  
 HURST C A 1968 *Ann. Phys.*, NY **50** 51–75  
 IOFFE B L and SHABALIN E P 1967 *Yad. Fiz.* **6** 828–39 (1968 *Sov. J. Nucl. Phys.* **6** 603–10)  
 JACKIW R and JOHNSON K 1973 *Phys. Rev. D* **8** 2386–98  
 JAFFE R L and PRIMACK J R 1973 *Nucl. Phys.* **B61** 317–32  
 JONES L W 1973 *Physics Today* **26** 30–7  
 JORDAN P 1938 *Ann. Phys. Chem.* **32** 66–70  
 KALOGEROPOULOS T 1974 *Proc. 4th Conf. on Experimental Meson Spectroscopy* (New York: AIP) pp97–123  
 KASHA H 1970 *Comm. Nucl. Particle Phys.* **4** 135–9  
 KAYSER B *et al* 1974 *Phys. Lett.* **52B** 385–8  
 KEMMER N 1938 *Proc. Camb. Phil. Soc.* **34** 354–64  
 ——— 1971 *Hadronic Interactions of Electrons and Photons* ed J Cumming and H Osborn (London: Academic) pp1–16  
 KERNER E H 1970 *J. Math. Phys.* **11** 39–46  
 KIBBLE T W B 1967 *Phys. Rev.* **155** 1554–61  
 KIM Y S 1973 *Contemp. Phys.* **14** 289–318  
 KINGSLEY R L, WILCZEK F and ZEE A 1974 *Phys. Rev. D* **10** 2216–8  
 KNAPP B *et al* 1975 *Phys. Rev. Lett.* **34** 1040–3  
 KOGUT J and SUSSKIND L 1974 *Phys. Rev. D* **9** 3501–12  
 KOKKEDEE J J J 1969 *The Quark Model* (New York, Amsterdam: Benjamin)  
 KOLM H H, VILLA F and ODIAN A 1971 *Phys. Rev. D* **4** 1285–96  
 KOMPANIETS V G and FOLOMBESHKIN V N 1968 *Yad. Fiz.* **8** 966–70 (1969 *Sov. J. Nucl. Phys.* **8** 561–3)  
 KREISLER M N 1973 *Am. Scient.* **61** 201–8  
 KUMMER W and SEGRÉ G 1965 *Nucl. Phys.* **64** 585–92  
 LARSEN R R 1974 *Particles and Fields Williamsburg Meeting* (New York: AIP) pp395–408

- LEBEDEV V 1972 *Proc. 16th Int. Conf. on High Energy Physics* ed J D Jackson and A Roberts (Batavia, Illinois: NAL) pp321-7
- LEDERMAN L 1967a *High Energy Physics* ed E H S Burhop (New York, London: Academic) pp304-64
- 1967b *Comm. Nucl. Particle Phys.* **1** 155-9
- LEDERMAN L and POPE B G 1971 *Phys. Rev. Lett.* **26** 765-8
- LEE B W 1972 *Proc. 16th Int. Conf. on High Energy Physics* ed J D Jackson and A Roberts (Batavia, Illinois: NAL) pp209-304
- LEE B W and ZINN-JUSTIN J 1972 *Phys. Rev. D* **5** 3121-37, 3137-55, 3155-60
- LEE T D 1970 *Phys. Rev. Lett.* **25** 1144-7
- LEE T D and WICK J C 1970 *Phys. Rev. D* **2** 1033-48
- LEE T D and YANG C N 1956 *Phys. Rev.* **104** 254-8
- 1960 *Phys. Rev.* **119** 1410-9
- LEE Y-Y *et al* 1974 *Proc. 17th Int. Conf. on High Energy Physics* vol IV, ed J R Smith (Chilton: Rutherford Laboratory) pp127-9
- LEIPUNER L B *et al* 1974 *Phys. Rev. Lett.* **31** 1226-9
- LINSKER R 1972 *Phys. Rev. D* **5** 1709-23
- LIPKIN H J 1973 *Phys. Rep.* **8** 173-268
- LIPKIN H J, WEISBERGER W I and PESHKIN M 1969 *Ann. Phys., NY* **53** 203-14
- LLEWELLYN SMITH C H 1972 *Phys. Rep.* **3** 261-379
- 1973 *Phys. Lett.* **46B** 233-6
- LOGAN J L 1973 *Physics Today* **26** (No. 3) 44-52
- MCCUSKER C B A and CAIRNS I 1969 *Phys. Rev. Lett.* **23** 658-9
- MACK G 1968 *Nucl. Phys.* **B51** 499-507
- MAGLIČ B C (ed) 1972 *Adventures in Experimental Physics* (Princeton, NJ: World Science Education)
- MAGLIČ B C, KALBFLEISCH G R and STEVENSON M L 1961 *Phys. Rev. Lett.* **7** 178-82
- MALKUS W V R 1951 *Phys. Rev.* **83** 899-905
- MANDELSTAM S 1962 *Ann. Phys., NY* **19** 1-24
- 1974 *Phys. Rep.* **13** 259-353
- MENON M G K and RAMANA MURTHY P V 1967 *Prog. Elementary Particle and Cosmic Ray Phys.* **9** 163-239
- MIGNANI R and RECAMI E 1973 *Lett. Nuovo Cim.* **7** 388-90
- 1974 *Lett. Nuovo Cim.* **9** 362-6
- MORPURGO G 1969 *Theory and Phenomenology in Particle Physics* ed A Zichichi (New York, London: Academic) pp84-200
- 1970 *Ann. Rev. Nucl. Sci.* **20** 105-46
- MORPURGO G, GALLINARO G and PALMIERI G 1970 *Nucl. Instrum. Meth.* **79** 95-124
- NAKANO T and NISHIJIMA K 1953 *Prog. Theor. Phys.* **10** 581-2
- NAMBU Y 1957 *Phys. Rev.* **106** 1366-7
- NAMBU Y and HAN Y N 1974 *Phys. Rev. D* **10** 674-82
- NASH T, YAMANOUCHI T, NEASE D and SCULLI J 1974 *Phys. Rev. Lett.* **32** 858-62
- NE'EMAN Y 1961 *Nucl. Phys.* **26** 222-9
- NEWMAYER J L and TREFIL J S 1971 *Phys. Rev. Lett.* **26** 1509-12
- 1972 *Phys. Lett.* **38B** 524-6
- NIEH H T, WU T T and YANG C N 1975 *Phys. Rev. Lett.* **34** 49-52
- NIELSEN H B and OLESEN P 1974 *Nucl. Phys.* **B61** 45-61
- ORITO S *et al* 1974 *Phys. Lett.* **48B** 165-8
- OSBORNE W Z 1970 *Phys. Rev. Lett.* **24** 1441-5; **25** 324 (erratum)
- PAMENTOLA J A and YEE D D H 1971 *Phys. Rev. D* **4** 1912-5
- PARTICLE DATA GROUP 1974 *Phys. Lett.* **50B** 1-198
- PATI J C and SALAM A 1973 *Phys. Rev. D* **8** 1240-51
- PEIERLS R E, SALAM A, MATTHEWS P T and FELDMAN G 1955 *Rep. Prog. Phys.* **18** 423-77
- PERES A 1968 *Phys. Rev.* **167** 1449
- PETUKHOV V A and YAKIMENKO M N 1963 *Nucl. Phys.* **49** 87-9
- PJERROU G M *et al* 1962 *Phys. Rev. Lett.* **9** 114-7
- POLITZER H D 1974 *Phys. Rep.* **14** 129-80
- PONTECORVO B 1959 *J. Exp. Theor. Phys.* **37** 1751-7
- PORTER N A 1960 *Nuovo Cim.* **16** 958-9

- PORTER NA 1968 *Nature, Lond.* **217** 329-31
- PURCELL EM, COLLINS GB, TADAO FUJII, HORNBOSTEL J and TURKOT F 1963 *Phys. Rev.* **129** 2326-36
- QUIGG C 1974 *Proc. 4th Conf. on Experimental Meson Spectroscopy* (New York: AIP) pp297-320
- RABL A 1969 *Phys. Rev.* **179** 1363-70
- RAMANA MURTHY PV 1971 *Lett. Nuovo Cim.* **1** 908-12
- 1972 *Proc. 1st Symp. on High Energy Physics* (Bombay: Indian Institute of Technology) pp 187-205
- RECAMI E and MIGNANI R 1974 *Riv. Nuovo Cim.* **4** 209-90
- REGGE T 1959 *Nuovo Cim.* **14** 951-76
- REINES F and COWAN CL 1953 *Phys. Rev.* **92** 830-1
- RESNICK L, SANDARESAN MK and WATSON PJS 1973 *Phys. Rev. D* **8** 172-8
- RICHTER B 1974 *Proc. 17th Int. Conf. on High Energy Physics* vol IV, ed J R Smith (Chilton: Rutherford Laboratory) pp37-55
- ROSENBAUM D 1966 *Phys. Rev.* **147** 891-5
- ROSENFELD L 1930 *Z. Phys.* **65** 589-99
- ROSNER JL 1969 *Phys. Rev. Lett.* **22** 689-92
- 1970 *Phys. Lett.* **33B** 477-80
- 1974 *Phys. Rep.* **11** 189-326
- ROSS RR, EBERHARD PH, ALVAREZ LW and WATT RD 1973 *Phys. Rev. D* **8** 698-702
- RUDERMAN MA and ZWANZIGER D 1969 *Phys. Rev. Lett.* **22** 146-8
- SAHA MN 1936 *Indian J. Phys.* **10** 145-50 (1949 *Phys. Rev.* **75** 1968)
- SAKURAI JJ 1960 *Ann. Phys., NY* **11** 1-48
- SALAM A 1968 *Elementary Particle Theory* ed N Svartholm (Stockholm: Almqvist and Wiksell) pp367-75
- SAWADA T 1973 *Phys. Lett.* **43B** 517-20
- 1974a *Nucl. Phys.* **B71** 82-92
- 1974b *Phys. Lett.* **52B** 67-70
- SCHWARTZ M 1960 *Phys. Rev. Lett.* **4** 306-11
- 1965 *Rep. Prog. Phys.* **27** 407-68
- SCHWARZ JH 1973 *Phys. Rep.* **8** 269-335
- SCHWINGER J 1957 *Ann. Phys., NY* **2** 407-34
- 1966a *Phys. Rev.* **144** 1087-93
- 1966b *Phys. Rev.* **151** 1048-54
- 1966c *Phys. Rev.* **151** 1055-7
- 1968 *Phys. Rev.* **173** 1536-44
- 1969 *Science, NY* **165** 757-9
- 1973 *Phys. Rev. D* **8** 960-4
- 1975 *Phys. Rev. Lett.* **34** 37-8
- SEGRÉ G 1974 *Phys. Rev. Lett.* **33** 1244-8
- SEJNOWSKI TJ 1974 *Physics Today* **27** (No. 1) 40-8
- SHAPIRO IS 1973 *Usp. Fiz. Nauk* **108** 431-54 (*Sov. Phys.-Usp* **16** 172-84)
- SIVERS D 1970 *Phys. Rev. D* **2** 2048-54
- SLAVNOV A 1972 *Teor. Math. Fiz.* **10** 153-61 (*Theor. Math. Phys.* **10** 99-104)
- SMITH J 1972 *Proc. 16th Int. Conf. on High Energy Physics* ed JD Jackson and A Roberts (Batavia, Illinois: NAL) pp239-49
- SONI A 1975 *Phys. Rev. D* **11** 624-32
- STEVENS DM 1973 *Magnetic Monopoles: An Updated Bibliography, Preprint Virginia Polytechnic Inst. VPI-EPP-73-5*
- SUDARSHAN ECG and MARSHAK RE 1958 *Phys. Rev.* **109** 1860-2
- TAMM I 1931 *Z. Phys.* **71** 141-50
- TASSIE LJ 1965 *Nuovo Cim.* **38** 1935-8
- THACKER HB and SAKURAI JJ 1971 *Phys. Lett.* **36B** 103-5
- TOMPKINS DR 1965 *Phys. Rev.* **138B** 248-50; **140B** 443-5
- TONWAR SC, NARANAN S and SREEKANTAN B V 1972 *J. Phys. A: Math., Nucl. Gen.* **5** 569-83
- TOW DM, TAN C-I, KANG K and FRIED HM 1975 *Phys. Rev. Lett.* **34** 499-501
- TSAI Y-S 1971a *Phys. Rev. D* **4** 2821-37
- 1971b *Lett. Nuovo Cim.* **2** 949-52
- TURNER MS and BARISH BC 1972 *Phys. Rev. D* **5** 638-61

- ÜBERALL H 1964 *Phys. Rev.* **133B** 444–53
- VANT-HULL L L 1968 *Phys. Rev.* **173** 1412–3
- VELTMAN M 1973 *Int. Symp. on Electron and Photon Interactions at High Energies, Bonn* ed H Rollnik and W Pfeil (Amsterdam: North-Holland) pp429–45
- VENEZIANO G 1968 *Nuovo Cim.* **57A** 190–7
- WACHSMUTH H 1973 *Proc. Summer Inst. on Particle Physics, SLAC Rep. No. 167*, pp235–49
- WALTER H K *et al* 1972 *Phys. Lett.* **40B** 197–9
- WANDERER P J *et al* 1969 *Phys. Rev. Lett.* **23** 729–34
- WEBER J *et al* 1973 *Phys. Rev. Lett.* **31** 779–83
- WEINBERG S 1965 *Phys. Rev.* **138B** 988–1002
- 1967 *Phys. Rev. Lett.* **19** 1264–6
- WENTZEL G 1966 *Suppl. Prog. Theor. Phys.* **37–38** 163–74
- WILSON H A 1949 *Phys. Rev.* **75** 309
- WILSON K 1974 *Phys. Rev. D* **10** 2445–9
- DE WIT B 1973 *Nucl. Phys.* **B51** 237–54
- DE WIT B, PI S-Y and SMITH J 1974 *Phys. Rev. D* **10** 4278–96
- WU C S, AMBLER E, HAYWARD R W, HOPPES D D and HUDSON R P 1957 *Phys. Rev.* **105** 1413–5
- XENOPHON 371 BC *Anabasis* [Translation: Rouse W H D 1958 *The March Up Country* (Ann Arbor: University of Michigan Press) pp154–7 and *passim*]
- YAMAGUCHI Y 1966 *Strong and Weak Interactions—Present Problems* ed A Zichichi (New York, London: Academic) pp691–710
- YANG C N and MILLS R L 1954 *Phys. Rev.* **96** 191–5
- YOCK P C M 1973 *Lett. Nuovo Cim.* **7** 470–2
- YUKAWA H 1935 *Proc. Phys. Math. Soc. Japan* **17** 48–57 (The early papers on meson theory are reprinted in 1955 *Suppl. Prog. Theor. Phys.* **1** 1–251)
- ZICHICHI A 1967 *Proc. Heidelberg Conf. on Elementary Particles* ed H Filthuth (Amsterdam: North-Holland) pp268–70
- ZUMINO B 1966 *Strong and Weak Interactions—Present Problems* ed A Zichichi (New York, London: Academic) pp711–30
- ZWANZIGER D 1965 *Phys. Rev.* **137B** 647–8
- 1968 *Phys. Rev.* **176** 1489–95
- ZWEIG G 1965 *Symmetries in Elementary Particle Physics* ed A Zichichi (New York: Academic) pp192–234