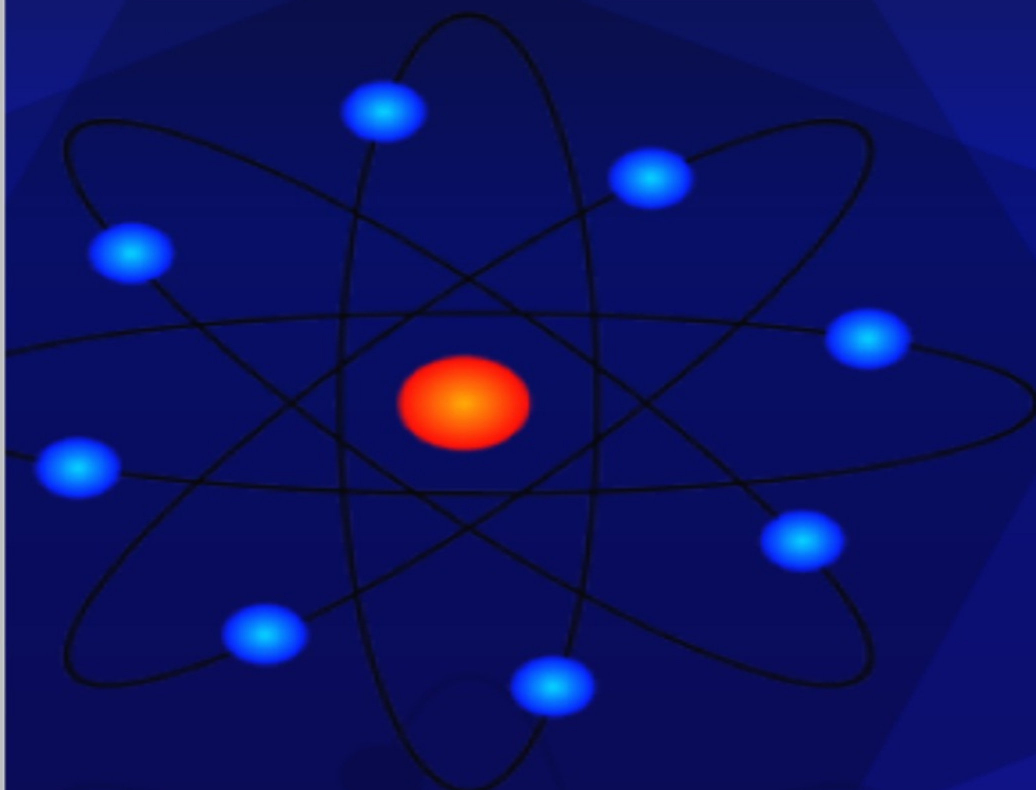
Atomic Structure



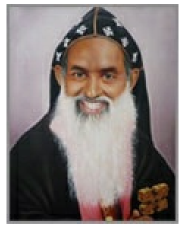
Sabarimuthu V

ATOMIC STRUCTURE

V. Sabarimuthu

This book is dedicated

to



Archbishop Benedict Mar Gregorios

Contents

Preface

This book is to show the beautiful interior of the atom.

The book starts with Democritus, proceeds chronologically through plum pudding model, ‘soft’ atom model, planetary model, ’hard’ atom model. Heisenberg and Schrödinger atom models, Dirac atom model and ends with Hofstadter and Gell Mann.

The meaning of Planck constant, similarity between matrix mechanics and wave mechanics, symmetry of the orbital and the reason for the stability of the octet configuration are given.

The experiment conducted by David Pritchard from the Massachysetts Institute of Technology to isolate an atom and the Experiment of Stephen Chn to trap atom are given.

The experiment conducted by Daniel Walls at the University of Auckland (1991) to demolish the argument of Einstein, Podolsky and Rosen is given.

The quarks, leptons and the structure of the nucleon are vividly discussed. The limitation of the standard model is also discussed.

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Matter → atom

Democritus – a philosopher of Abdera (Greek)- 2320 years ago said that matter is made of atoms (the word atoms in Greek means indivisible).

Dalton (1803) believed that atoms interact in the simplest way.

Zeeman (1896) spectroscopic ally showed the splitting of the energy levels in a strong magnetic field.

In 1990, the scientists began to consider new models for the structure of the atom.

J.J. Thomson and his team (1903) at the Cavendish laboratory, Cambridge, indicated for the first time that atoms are not the indivisible constituent units of matter.

J.J. Thomson envisaged that ***the atom consisted of positively charged matter with negatively charged electrons embedded in it, as are plums in a pudding.*** Thus, J.J. Thomson broke the thitherto structure-less atom and gave it a structure. His atom model is called ***plum pudding model.***

This atom model is now known as 'soft' atom model.

Atom → nucleus

In 1904, Hantano Nagaoka, a Japanese physicist, rejected the plum pudding model and proposed an alternative ***planetary model.*** In his model, a positively charged nucleus is surrounded by a number of revolving electrons, similar to the planets orbiting the sun.

It was the spectral lines that, further, aroused the curiosity of the scientists to probe into the structure of the atom. In fact, by the end of the 19th century, there was a large mass of spectroscopic data waiting theoretical interpretation. The burning question at that time was how an atom is able to give spectral lines at all.

Obviously, various theories about the structure of the atom are closely linked with the various theories of light.

In 1900, Rubens and Kurlbaum showed the contradiction between the experimentally observed energy distribution patterns in black-body radiation and the prediction of classical physics.

Max Karal Ernst Planck a German theoretical physicist, on 19 Oct. 1900, gave an empirical formula to explain the black-body radiation. As all attempts to derive his formula using classical theories failed, “as an-act of desperation", Planck assumed (December 14.1900) that energy exchanges between matter and electro-magnetic radiation take place only in the form of certain discrete packages (called quanta).The energy content of each package, according to him, is directly proportional to the corresponding frequency, the constant of proportionality being known as Planck constant. *h*.

Planck constant indicates, how much the (true) quantum description of a dynamical system deviates from the (approximate) classical description.

His idea was that ***the electro-magnetic radiation is like butter, which can be bought from or returned to the grocery store only in packages, although the butter as such can exist in any desired quantity'.*** This marked the advent of quantum theory.

Planck's idea of quanta triggered an explosion of knowledge. Thus: (1) Einstein's explanation of photoelectric effect,

(2) Bohr's interpretation of hydrogen spectrum.

(3) Peter Debye's explanation of the behavior of the specific heats of certain solids at very low temperatures,

(4) Interpretation of Compton Effect

(5) Louis de Broglie's explanation of matter-wave duality

(6) Werner Heisenberg's uncertainty principle.

(7) Schrödinger's wave equation

(8) Dirac's equation and numerous other interpretations use Planck's idea of quanta in one way or other.

Till the end of the 19th century, most of the experimental evidences, the phenomenon of interference included, supported the wave theory of radiation.

Shattering the wave theory, photoelectric effect (1887) suggested that the electro-magnetic radiation is corpuscular in nature.

In fact, since 1887 the wave theory of light was losing grounds to interpret the interaction between matter and radiation.

P. Lenard, in 1903, conducted an experiment with the cathode rays. In that experiment, the cathode rays penetrated a thin aluminum window but he left the matter there.

At that time, Planck's concept of 'quanta' was totally astonishing to the laws of classical physics. Planck himself said that packages of energy were involved only during emission and absorption of radiation and not during its propagation,

But Einstein was quick to realize the importance of Planck's theory and said (1905) that in order to explain the photoelectric effect it must be assumed that electromagnetic radiation is propagated in quantized bundles.

In 1907 Conway, however, concluded that an atom produces spectral lines, one at a time and that a complete spectrum results from an extremely enormous number of atoms, each of which has to be in an excited state.

In 1909, Einstein predicted that 'the next phase of the development of theoretical physics will bring us a theory of light that can be interpreted as a kind of fusion of the wave and particle theories'.

Earnest Rutherford, a student of J.J.Thomson and New Zealand born British chemist and physicist, and his team at the University of Manchester, developed a theory for the structure of the atom largely based on their experiment with **α** particles and thin metal foils.

When thin metal foils were bombarded with **α** particles, most of the particles passed the metal foils straight through. But, some particles suffered some deflection. Deflection of a few particles was as high as 180 degree. That is, the particles bounced back to the source although the calculations based on the theory of probability show that such deflections through more than 90 degree must be vanishingly small.

The above observation was quite incredible to Rutherford (1906). He wrote, ***'It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you had fired a 15 inch shell at a piece of tissue paper and it came back and hit you"***.

In the above experiment, Rutherford was assisted by Geiger and Marsden. They found that about one in 20,000 **α** particles was deflected through 90 degree or more in passing through a thin gold foil. In contrast, a 'soft' model predicted about one in 10^{3500}!

Rutherford, in 19I1, based on the above experiments, inferred that the atom consisted of an extremely minute nucleus (which caused the reflection of α particles) carrying positive charge, surrounded by electrons carrying negative charge. He could not consider these electrons to remain stationary because the electrons and the nucleus would attract each other and come together.

Hence, he assumed that the electrons revolved round the nucleus with great speed and were kept away from it by centrifugal force. He called ***the path followed by the electron around the nucleus, orbit***.

As the atom, on the whole, is electrically neutral, he predicted that the number of extra-nuclear electrons must be equal to the charge carried by the nucleus. The mass of the electron being extremely small, he said that practically the whole mass of the atom must be concentrated in the small nucleus.

The nucleus is, indeed, very small. It is even smaller than the electron. But, several elections could be ejected from the nucleus. ***It was compared to the formation of a big soap bubble on the nozzle of a pipe through which it is blown.***

At this stage of the development of the structure of the atom, the atom was compared to a football ground. ***The nucleus was compared to a football placed at the centre of the ground and the electrons were compared to the players running round the ground.***

As Rutherford atom model recognized a hard constituent in the atom, his atom model (hitherto called planetary model) is now called 'hard' atom model.

The remarkable achievement of Rutherford was that he could obtain the famous $\mathbf{sin^{-4}\ \Phi/2}$ law where Φ is the scattering angle. Using this law, he could calculate the angular distribution expected from his model.

Two years later (1913) Geiger and Marsden published a paper giving the other important features of scattering. In it, they went to the extent of recording the observed scintillations versus angle in the form of a table but chose not to plot a graph of their angular distribution.

It must be pointed out that Rutherford formula for charged particles assumed that both the **α** particle and the nucleus were point-like. Point-like means structure-less.

Rutherford atom model could not be accepted due to the following reason.

If the electrons were pictured as moving around the nucleus, they are subject to centripetal attraction. According to the principles of electro-magnetic theory, such electrons should give out energy, spiral down and eventually collapse into the nucleus. But the electrons fail to fall into the nucleus.

As the scientists had to choose either the classical electro-magnetic theory or the planetary model of the atom, they were in a great dilemma. Actually, neither could they accept Rutherford's planetary model nor could they reject classical electro-magnetic theory.

The confusion that prevailed at that time (1922) may he compared to the one prevailing now (2017) regarding the concept of leptons and quarks or that of black hole. Einstein, even while working on Planck's light quanta concept, remarked, “It was exactly as if the ground was slipping away from under our feet and we had no firm soil that we could build on”.

In continuation of the work of Conway and Rutherford, Niels Bohr, a Danish physicist, in 1913, suggested that an atom consists of a small positively charged nucleus orbited by negatively charged electrons.

He said that the gravitational force of the solar system is mathematically akin to the Coulomb (electrical) force between the positively-charged nucleus and the negatively-charged electrons.

However, making use of the quantum theory of Max Planck, he, further, suggested that the electron in an atom is **restricted** to move in a particular stable orbit only. The electron will neither radiate nor absorb energy as long as it remains in this orbit.

Is it possible to physically observe the orbit?

Yes. It can be physically observed in the form of spectral lines..

The electrons in an atom, when they do not absorb or radiate energy, could move only in certain selected orbits (or allowed states). Such orbits are called *stationary states*.

Each stationary state corresponds to certain energy. The energy of the orbit is related to its size. The lowest energy is found in the smallest orbit. Thus the orbits have a set size and energy.

Bohr postulated that when an electron jumps from a higher energy state to a lower energy state, a quantum of radiation is emitted with an energy equivalent to the energy difference of the two states.

Bohr assumed that the electron moves in a circular orbit (through the surface of an imaginary sphere) and its angular momentum is an integral multiple of $h/2\pi$ where h is the Planck constant. This integer is designated as n. the principal Quantum Number. n indicated the path followed by the electron and hence its distance from the nucleus. In other words, when n increases the radius of the orbit increases.

Thus, the first quantum number was introduced by Bohr

Though Bohr, at that time, could not say why ***n*** is an integer, he succeeded in giving an explanation for the spectroscopy of hydrogen, as it was then known.

It must be noted that till Bohr promulgated his theory, *t**he atomic spectral lines and the empirical rules to determine their frequencies were regarded in the same light as the lovely patters on the wings of butterflies; their beauty can be admired: but they are not supposed to reveal any fundamental laws"***.

Thanks to Bohr's theory, these lovely patterns of atomic spectroscopy became, for the first time, amenable to theoretical under-sanding. In fact, not only the characteristics of the atomic hydrogen emission spectrum fitted dramatically with the result derived from Bohr's theory but also Bohr could successfully calculate the radius of the electron orbit of the hydrogen atom (it is usually called Bohr's orbit).

Arnold Johannes Wilhelm Sommerfeld, a German theoretical physicist, introduced the second quantum number. It is designated by the letter, l.

He said that for a given value of *n* there can be a circular path or a variety of elliptical paths. Whereas, only the angle of revolution, **θ**, varies, in the case of circular orbits, the radius, **r,** and angle, **θ** (ie azimuth angle- note the origin of azimuthal quantum number) varies in the case of elliptical orbits.

It may be, further, pointed out that an electron moving around the nucleus of an atom in an elliptical orbit does not travel with uniform velocity. The velocity of the electron must be greater when it is close to the nucleus.

According to the theory of relativity, the effective mass of an electron must change with velocity when it moves through an elliptical orbit.

But for the above relativistic change, according to Sommerfeld, the energy state of a system with two or more degrees of freedom would have been degenerate. The change in mass must produce a corresponding, although very small, change in the coulomb force operating between the electron and the nucleus. Because of these changes in velocity, effective mass and effective force of attraction, the electron must make a precessional movement around the nucleus.

Because of the above precessional movement, the major axis of the eclipse must change its position in space and the actual path of the electron must be a succession of slightly changing orbits that must appear as a rosette pattern.

What is the basis for the conclusion of Sommerfeld that there are elliptical orbits besides the circular orbit for a given value of $\boldsymbol{n}$?

The basis for his conclusion is that the spectroscopes of high resolving power showed that what had been thought to be single lines were really a collection of several lines very close together.

It is clear that Bohr-Sommerfeld quantum theory, which is now known as old quantum theory, made use of classical mechanics to describe the motion of an electron around the atomic nucleus after introducing the concept of allowed states.

Thus, the important merits of the Bohr-Sommerfeld theory were:

(I) It provided a good approximation to explain the frequencies of the spectral lines of the hydrogen atom and

(2) It was considered as a crucial step in the development of the atomic theory.

However, this theory suffered from certain defects. The most important of them were:

(1) It's failure to deal with more complicated atomic problems. It could not, in fact, explain even the spectral lines of helium atom. All attempts to understand the basis of the periodic system in terms of this theory also ended in failure.

(2) It's ad-hoc way of imposing quantum conditions. This is because it remained conceptually and logically incomprehensible as to why only certain electronic orbits should be allowed in the atom and

(3) It remained as an unsatisfactory and almost unacceptable hybrid of quantum concepts grafted on classical mechanics.

It can be seen that the spectral lines split even more in the presence of the magnetic field (Zeeman Effect). This experimental observation necessitated one more explanation.

An electron in space actually needs three co-ordinates to describe its position.

Thus, besides radius and azimuthal angle, an electron requires a spatial reference. Without this spatial reference the arrangement of the orbital plane of the electron would be out and out arbitrary. This third degree of freedom, unlike radius and azimuthal angle - the other two degrees of freedom,- is degenerate. An external field, obviously, will remove this degeneracy because the electron in the presence of an external field will be able to precess only in the direction of the field (and hence it will no longer appear as a rosette pattern).

It is clear that we go on introducing one degree of freedom (often called quantum number) after another only to explain the experimental observations.

At the end of the 19th century many scientists, mainly based on the phenomenon of interference, firmly believed that electro-magnetic radiation has wave character.

But, many experiments conducted since 1900 indicated that electro-magnetic radiation has particulate properties.

Einstein in 1905, making use Planck's idea of quanta, explained Hertz's (1887) observation of photoelectric effect quite satisfactorily. He assumed that the electro-magnetic radiation consists of particles.

According to him, light is a particle. The mass of this particle depends on its velocity. He said that light quanta have properties of matter-momentum included.

Compton Effect (1923) reinforced the view that the electro-magnetic radiation is particulate in nature.

Thus, the phenomenon of interference supported the wave theory of radiation and the photoelectric effect supported the corpuscular theory of radiation.

Though the scientists could not explain how the wave nature of radiation is 'associated' with its particle nature, there was little doubt that electromagnetic radiation has dual nature. However, we are unable to experience the dual nature as a single nature.

In 1923 Louis de Broglie suggested that this duality of particle as well as wave nature - or field aspect - should apply not only to radiant energy but also to matter itself.

His conviction was that if radiation that appeared as a continuous wave had the graininess of quanta, then matter that appeared granular must behave as a wave. Thus, he predicted the wave nature of electron.

According to him, any particle of mass ***m*** and velocity ***v***, will have a wavelength, **λ**. This is often referred as de Broglie wavelength. It can be calculated using the equation **λ = h/mv.**

It is evident that **λ** will be significant only when ***m*** is very small.

Since the mass of the electron is very small, de Broglie applied this theory to the electron moving about the nucleus of the atom and said that the moving electron has associated wave properties.

This concept (wave mechanics) thus could explain why only certain electronic orbits are stable. ***Only those orbits that can accommodate a whole number of waves are stable***.

It must be noted that he gave an explanation for the restricted motion of the electron without any experimental evidence.

According to Bohr atom model, the electron is a moving point mass confined to an orbit at a certain distance from the nucleus. But, according to de Broglie's concept, the electron can be visualized as a standing 'spherical' wave (these waves are similar to water waves only in their mathematical behavior) existing around the nucleus in a circular form with integral number of wavelengths.

Is there any substantial difference in the meaning of the orbit when we incorporate de Broglie's concept?

The answer is that there is not much difference except the one pointed out above because both the theories move with the precinct that the path followed by the electron around the nucleus can be followed and the position of the electron pin pointed either as a point mass or as a wave.

However, it must be admitted that the concept of matter wave led to the important realization that it is impossible to construct a 'deterministic' model.

The classical mechanics presupposes that exact simultaneous values can be assigned to all physical quantities. But Werner Heisenberg , a student of Sommerfeld, in 1926, denied this possibility.

Thus, the concept that the electron is moving about the nucleus in an orbit whether as a point mass or as a standing wave had to be finally changed lock, stock and barrel, thanks to Heisenberg’s uncertainty principle (1926).

This principle is even now recognized as one of the corner-stones of the conceptual structure of quantum mechanics. His leading idea was that only those quantities that are in principle observable should play a role in the theory, and that all attempts to form a picture of what goes on inside the atom should be avoided.

It is said that Wernar Heisenberg visited the University of Berlin in 1926 and drew the attention of Einstein to his principle for the formulation of quantum mechanics. Einstein had said that a physical theory must deal only with directly observable entities.

He asked Einstein: ‘Isn't that precisely what you have done with relativity? You argued that it is impermissible to speak of absolute time, simply because absolute time cannot be observed'.

Einstein surprised Heisenberg by replying 'Possibly I did use this kind of reasoning, but it is nonsense all the same. Perhaps I could put it more diplomatically by saying that it may be heuristically useful to keep in mind what one has actually observed. But on principle, it is quite wrong to try founding a theory on observable quantities alone. It is the theory that decides what we can observe”.

It was the last remark of Einstein that stimulated the thinking of Heisenberg to find an answer to the question whether quantum mechanical theory implies any constraint on the measurability of physical quantities and this culminated in the discovery of uncertainty principle.

Uncertainty principle states that it is impossible to determine the momentum and position - the complementary properties of particles- of the electron at the same time with cent per cent certainty. This means that there is a limit to the precision to which position and momentum of a particle may be determined simultaneously.

In other words, we can speak only of its probability of being found in various regions of space.

This interpretation, in fact, shakes the foundations of classical physics because it annihilates the classical concept of a precise trajectory or path.

Then, can we find out any one of these with cent percent accuracy?

Theoretically, if the momentum is precisely specified the position will be totally uncertain.

In fact, the uncertainties in the determination of these two quantities vary inversely. This means that if any one of these quantities is determined fairly accurately, the other must be correspondingly inaccurate.

If the position is known to within δq the momentum will be uncertain to an extent δp. It is said that it is not due to any defect in the measuring instrument but an inherent limit of nature**.**

The immediate consequence of the uncertainty principle is that we cannot pin point the position of the electron in an atom. In other words, the particle states at the atomic level cannot be described in terms of well defined orbits.

Hence the concept that the electron is revolving about the nucleus in definite orbits either as a point mass or as a wave cannot be accepted.

If it is accepted, it amounts to locating the exact position of the electron.

It is clear that in order to describe the atomic and sub atomic particles, a radically different mathematical framework was needed. The mathematical description of their behavior is provided by the quantum mechanics.

Thus, 'quantum mechanics is a systematic physical theory of atomic and subatomic phenomena based on a set of self consistent mathematical rules supplemented by appropriate physical interpretations'.

On the other hand, the quantum number is the basic unit of electromagnetic energy. It characterizes the wave properties of electrons as distinct from their particulate properties. It is related to the degree of freedom required to describe the electron of an atom

In simple terms, quantum mechanics may be defined as the theories evolved to describe the motion and interaction of micro particles.

If there is a way for measuring the position and momentum of an atomic or subatomic particle at any instant with accuracy exceeding the limit envisaged by the uncertainty principle, the quantum mechanics would be invalidated, for the important precepts of quantum mechanics are (1) wave properties of the electron and (2) uncertainty principle.

Thus, it is said that the uncertainty principle protects quantum mechanics.

As there is a solid theoretical backing to the uncertainty principle, classical mechanics was forced to abdicate its position in favour of the probabilistic interpretation of quantum mechanics to explain the position of the electron moving about the nucleus.

It is explained that it is possible for an electron in an atom to remain anywhere around the nucleus - quite near to the nucleus or away from it. But, there is a region along which there is maximum probability (about 95%) of finding the electron. This region is called *orbital*.

In other words, ‘***orbital is the region (space) where the probability of electron presence is the greatest***’.

What goes on in an atom is not exactly known. But the orbitals could be physically observed in the form of spectral lines.

It is said that in May. 1925, Heisenberg succeeded in deriving correct energy expressions for harmonic and inharmonic oscillators and a simple rotating system.

However, he was disturbed by the fact that the algebra he used implied that the multiplication of two qualities, ‘a x b’, is not necessarily equal to ‘b x a’ (this is technically known as 'non-commutative algebra').

But thanks to the encouragement given by his 'invaluable critic friend', Pauli, he continued his work and 'constructed a dynamical scheme that directly dealt only with observable frequencies and amplitudes of radiation emitted or absorbed by an atom while making a transition between pairs of allowed states of the atom.

Thus, the two-dimensional arrays of frequencies and amplitude were operated as the relevant dynamical variables. With suitable rules of adding and multiplying these arrays Heisenberg obtained very encouraging results.

He submitted the paper to his supervisor Born.

Born realized that Heisenberg's multiplication rule as one pertaining to multiplication of two matrices and this led to the realization that in this scheme, observable quantities are represented by matrices.

Since Born himself was not proficient in matrices, while travelling in a train, he confessed his difficulties in handling matrices to one of his colleagues. A fellow passenger, Pascual Jordan, a bright research student proficient in matrices, overheard it. He came forward to assist Born.

It is said that it was the genesis of the fruitful collaboration between Born, Heisenberg and Jordan. Their concerted efforts gave rise to matrix mechanics version of quantum mechanics.

The above work was immediately followed by the works of Pauli. Schrödinger and Dirac.

Pauli, born in Vienna, pointed out that the energy spectrum of hydrogen atom can be explained by invoking the rules of the matrix mechanics version of the quantum mechanics.

Erwin Schrödinger, an Austrian physicist, from the University of Zurich (in the early half of 1926) rejected the quantum condition in Bohr orbit theory. He said that the atomic spectra should really be determined by some kind of ***eigen*** value problem. Further, he rejected the views of Einsten.

What is the actual difference between the views of Einstein's and Schrödinger?.

Einstein says that what we observe is not real.

Schrödinger says that what we observe is real and that we need not bother about what we do not observe. In my view, this is the crux of the matter.

Schrödinger connected the quantum with the familiar differential equation of physics. At the same time, he showed a mathematical way for calculating the quantum energy levels of a system like hydrogen atom.

It is an entirely different version of quantum mechanics (known as wave mechanics) but is equivalent to matrix mechanics. The difference is that whereas Heisenberg's method uses non-commuting operators (algebraic), Schrödinger's method uses a differential equation.

Because of the mathematical equivalence of the two mechanics, George Gamon, a well known physicist, remarked that 'the discovery of two different formulations of quantum mechanics ***is like as if America was discovered by Columbus sailing westward across the Atlantic Ocean and by some equally daring Japanese sailing eastward across the Pacific Ocean.***

However, it must be pointed out that though both the treatments are equivalent, Schrödinger's Scheme is said to be more tractable.

The connection between continuity (smoothness) and discreteness (graininess) had been known in mathematics (refer back de Broglie's concept).

Instead of considering a three dimensional body), if an infinite dimensional space (a wave tends to dissipate itself throughout space) is considered, one can deal only with 'eigen values' or proper values, A special example of such a space is given by (complex) functions whose (absolute) value squarred integrated is always finite.

Schrödinger - by intuition - indicated that this mathematical connection between eigen values and transformations of wave functions,'Ψ', could be utilized to connect the discrete quantum and the continuous wave.

It is said that Schrödinger's wave equation in an inspired postulate (it has no derivation) that permits the calculation of the wave function just like Newton's equations that enabled him to calculate the trajectory of particles.

The wave equation is dependent only on the space co-ordinates of the system and not on time.

In Bohr-Sommerfeld theory, there is a quantum number for each degree of freedom. Here quantization occurs as a 'natural consequence of mathematics'.

However, when the variables, radial, Φ and θ, are separated, the equation gives three independent equations, each containing only one of the variables. On solving the radial, Φ and θ, equations, it is extremely interesting to note, the analogues n, l and m of Bohr-Sommerfeld theory are obtained.

Born then gave the interpretation of a probability amplitude to the wave function obeying Schrödinger's wave equation. This equation strives to give a mathematical picture, rather than a physical picture, to the structure of the atom.

Thus, mathematically, for example, ***orbital is the value of the square of the wave function of the wave equation.***

The square of the wave function can be real or imaginary. This is because Schrödinger's wave equation is a second order differential equation and it has infinite number of solutions.

All mathematically possible values of **Ψ** are not physically acceptable as **Ψ** contains the imaginary quantity, i, the square root of -1. Hence the product **Ψ Ψ** * is taken. This value will be always real.

'1*s*' orbital is spherical in shape. This means, say, if an electron has the energy corresponding to the '**1s**' level, it will be most probably found in a spherically shaped region represented by the **1*s*** orbital.

Further, calculations show that the *s* orbital has a **+**sign everywhere and hence it is symmetrical with respect to the sign of the wave function.

p orbital is dum bell in shape. One lobe of the *p* orbital has **+** sign and the other lobe has **-** sign. Hence the ***p*** orbital is unsymmetrical with respect to the sign of the wave function.

There are three ***p*** orbitals and they lie along the three mutually perpendicular ***x, y*** and ***z*** (arbitrarily taken) axes. Though the three orbitals have different orientations in space, all the three orbitals are energetically and directionally equivalent.

The ***d*** orbitals are rosette in shape. There are five ***d*** orbitals.

Three ***d*** orbitals - ***dxy, dxz*** and ***dyz-*** have four petals each and are symmetrical with respect to the sign of the wave function.

The petals of these three orbitals extend along the bisectors of the angles. The $dx^2- y^2$ orbital lies along the **x** and **y** axes. dz^2 orbital (again arbitrarily named. There will be no difference even if it is designated as dx^2 or dy^2 orbital) is doughnut in shape and is concentrated along the **z** axis.

It is clear that though all the five ***d*** orbitals are energetically equivalent, unlike the ***p*** orbitals, they are all not directionally equivalent because the various ***d*** orbitals have different spatial distribution of electron density relative to the atomic nucleus. The ***f*** orbitals have still complicated structures.

The superposition of two ***p*** orbitals does not give a rosette shaped charge distribution like a ***d*** orbital but a ring shaped charge distribution only. The third ***p*** orbital fits into this so well that the superposition of all the three ***p*** orbitals gives a spherical charge distribution. **It is this spherical symmetry that is, in part, responsible for the special stability of the half filled and the fully filled *p* sub shells.**

A. Unsold proved that the sum of the squares of the wave functions of a subshell such as the three p orbitals is independent of θ and Φ and hence spherically symmetric

The position is more complicated for the ***d*** orbitals.

The three ***d*** orbitals - ***dxy, dxz*** and ***dyz***- do not add up to a spherically symmetrical charge distribution since in each case the individual distributions have nodes along their co-ordinate axes.

However, the three ***d*** orbitals - namely - ***dxy, dxz*** and ***dyz*** orbitals together with $d_{x^2-y^2}$ and d_{z^2} orbitals give a spherical charge distribution. Thus, **the special stability of the half filled and the fully filled *d* sub shell is also associated with the spherically symmetrical charge distribution of the *d* electrons.**

At this stage of the development of the structure of the atom, the nucleus was compared to ***a nest at the centre of a large tree and the orbitals were compared to the regions where a mother bird (electron) occupied most of the time.*** It may be noted that the mother bird may come very close to the nest to feed its young ones and, at times, it may move away from the tree. But it will occupy only various positions in the tree most of the time.

In contrast, ***the 'orbit' was compared to the path followed by a bee around a flower***.

Coming back, the Schrödinger wave equation assumes that:

(1) energy is quantized
(2) matter has wave as well as particle nature and
(3) the position and the momentum of any particle cannot be known simultaneously with cent percent accuracy.

However, though this equation describes the behaviour of a sub- atomic particle in the same way as the classical mechanics describes the macroscopic particles and though this equation is considered as one of the basic equations of the atomic physics and the quantum mechanics, this equation does not take into account Einstein's theory of relativity.

Further, this equation does not explain satisfactorily how an electron in a *p* or *d* orbital passes through the nodel planes within which the electron density is zero.

Further, the quantum numbers ***n, l*** and ***m*** are not adequate to explain all the spectral features. The proposal of Pauli that the “two valued-ness of electron" is associated with one more quantum number too appeared mystic.

However, it occurred to Kronig (1925) that the 'two valued-ness of the electron’ could be associated with its spin motion. He went to the extent of working out a formula for the fine structure of the atom but chose not to publish his idea. Mainly, based on this Sommerfeld introduced spin quantum number.

A few months later, two scientists-Uhlenbeck and Goudsmit-emphasized this rather abstract notion and arrived at the same fine structure formula that Kronig had derived. The beauty is that the spin angular momentum is not the integral multiple of $\frac{h}{2\pi}$ but $1/2\left(\frac{h}{2\pi}\right)$ only.

In the same year (1925) Pauli attributed the hyperfine structure of the spectral lines to the intrinsic angular momentum of the nucleus.

In July 1925, Heisenberg conducted a seminar at Cambridge on his work. Fowler immediately requested Heisenberg to send him the proof sheets of his paper.

On receiving the proof sheets in September, he transmitted those papers to Paul Dirac, a student of Sommerfeld and English physicist, for a closer study.

Within a month - in November 1925- Dirac came out with a very general scheme of the new quantum dynamics underlying Heisenberg's proposal. However, he presented his ‘glorious’ doctoral dissertation entitled 'Quantum Mechanics’ to the University of Cambridge only in May 1926.

In this connection, it must be pointed out that the three formulations- one due to Dirac, another due to Born, Jordan and Heisenberg and the third one due to Schrödinger - were not only different ways of looking at the same theory but also they were all propounded about the same time.

Again it must be noted that all these formulations did not take into account Einstein's principle of special relativity.

The real success of Dirac was that he, in 1928, ‘in a rare flash of reflection’ published a relativistic wave equation that conformed to the principles of quantum theory and the principle of special relativity.

According to Dirac, the description of the movement of an electron needs not one, but four Ψ functions and the probability of finding an electron in the volume ΔV is given by the function

$$(\Psi 1^2 + \Psi 2^2 + \Psi 3^2 + \Psi 4^2)\ \Delta V$$

A set of four **Ψ** functions, at all times, contains simultaneously *some* ***s*** and ***p*** or some ***s, p*** and ***d*** or some ***p, d, f*** character. As a result, there are no nodes, either radial or angular. Instead, there will be only constrictions in the electron clouds. In the constrictions, the electron density becomes very small.

The above model gives twice as many orbitals as the simple one. Thus, in the place of the spherically symmetrical ***Is*** electron cloud there will be two axially distorted, approximately spherical electron clouds.

However, these two electron clouds supplement each other to give an ideal spherical distribution. It considers the treatment of spin-orbit interactions as an artificial one and explains that the electrons of given value of **‘l’** are not exactly degenerate but differ slightly in energy.

Further, the above model combines the Einstein’s theory of relativity and the spin in one equation and explains how the electron spreads out into a field of matter or electron clouds.

Another aspect of this model is that though this equation takes into account Einstein's principles of special relativity and the principles of quantum theory, it not only gives solutions corresponding to positive values of energy but also it admits many solutions corresponding to negative values of energy.

According to Dirac, at energies higher than its mass of 0.5 MeV, the motion of the electron is governed by the theory of relativity and hence the electron energy is not just **E = p2/2m** where the momentum is **p**, but becomes related to the velocity of light, c, through the relativistic equation $\mathbf{tz^2 = p^2c^2 + m^2\, c^4}$**.** The energy can therefore have two values, one of which is negative.

But, according to quantum theory, transitions arc possible from a positive energy state to any of the negative energy states making a normal electron with positive energy unstable.

In order to overcome the above difficulty, Dirac –with great courage-postulated that states with negative energy exist but they are occupied by electrons and as such a normal positive energy electron is forbidden from falling into the negative energy states.

If an electron in the negative energy 'sea' is given enough energy by some means, the electron jumps out of this sea of negative energy leaving "a hole, if there were one would be a new kind of particle, unknown to experimental physics having the same mass and opposite charge to an electron. We may call such a particle an anti-electron".

Oppenheimer suggested to Dirac that the hole should be thought of as a new hitherto unknown particle. Dirac, then, named the new particle the anti-electron.

On the night of 2, August 1932 Carl Anderson quite accidentally discovered this new anti-particle. This was the first time that a theoretically predicted particle was discovered later in an experiment. Thus, Dirac's work introduced the concept of "anti-particle and anti-matter.

Above all, this equation not only explains all the relativistic particles like quark and leptons but also answers several other unanswered questions.

Perhaps due to mathematical simplicity all discussions in quantum mechanics are still in non-relativistic terms only.

Until the discovery of anti-electron, though it is a digression, the entire universe was built up of just two particles - electron and proton. The proton was positively charged, 1837 times heavier than the electron Thus nature, at that time, appeared asymmetric-a light negative charge balanced by a massive positive charge. After the discovery of anti-electron this was proved wrong.

However, it has again (1991) been established that matter preponderates over anti-matter. According to the present thinking (2017) the matter was biased in favour of the former at the beginning of the universe.

In 1930, Robert Andrews Millikan, an American experimental physicist, took Anderson as his post-doctoral research fellow.

In order to measure the energy of the cosmic rays directly, Millikan and Anderson redesigned Wilson cloud chamber to be vertical and set it in the field of a powerful electro-magnet.

The cloud chamber was fired at random and luckily they found a meaningful tract in one of the several pictures that were taken. That picture showed two tracks curving in opposite directions, one much denser than the other.

Millikan interpreted this as an electron and proton knocked out of an atom by a cosmic particle of the then stupendous energy of 250 MeV.

Anderson then measured the energy lost by a cosmic ray particle in going through matter by inserting a six milli-metre lead plate in the cloud chamber.

To his surprise a historic photograph resulted.

Anderson found that a particle of 63 MeV with the mass of an electron had curved upward and after losing its energy in the lead plate continued with 23 MeV.

Such a thin track was exactly characteristic of an electron of this energy and the track was at least ten times the possible length of a proton track of that curvature. The nature of the curve indicated that it was a positively charged particle.

Anderson checked his calculations several times and concluded that it was a positive electron and named it positron.

After obtaining further evidences, he published his discovery in 1932.

Yet for months, after his publication, he thought that positron was a rare particle.

However, the reexamination of the pictures proved that positron was as frequent as the electron, in cosmic ray events.

3

Nucleus $\rightarrow$ nucleon

In 1930, Bothe and Becker noticed the emission of a new particle by beryllium but they chose not to give a name to it. In 1932, Chadwick discovered neutron while striking beryllium with **α** particles.

The discovery of neutron not only indicated that the nucleus has a structure (thitherto point like or structure-less) but also it prompted scientists to believe that a novel force must be operating over a range of nuclear dimensions to bind the nucleons in the nuclei. They thought that this energy must be very much stronger than the electromagnetic force.

In this context it was found that Schrödinger's wave equation not only failed to describe relativistic particles as encountered in cosmic ray experiments but also it could not handle the creation and annihilation of particles as observed in neutron decay.

Though a theory called quantum electrodynamics incorporating the above features emerged to describe the electromagnetic interactions of electrons and photons, its potentialities were not realized.

But, later it became the prototype of relativistic quantum field theory.

The above theory is even now (2017) standing as the calculation framework of particle physics. In fact, it remains as the simplest example for 'gauge' theories that describe the strong and weak interactions of quarks and leptons.

In 1935 HidekiYukawa, a Japanese theoretical physicist, predicted *mesons* as the quantum of the short-range nuclear force field and the *pion* was eventually discovered in 1947.

In this connection, it is disturbing to note that Einstein, Podolsky and Rosen (EPR) claimed in 1935 that quantum theory was flawed because of an outrageous prediction ‘that photons could be somehow linked to a 'spooky' long-range interaction’.

According to EPR, the quantum theory predicted that a change to a photon in one place could instantaneously produce a corresponding ‘spooky’ change in another photon far away and hence they suggested that a more straight-forward theory is needed to account for the probabilistic nature.

Einstein in particular stoutly opposed the uncertainty principle and hence the probabilistic concept till the end of his life saying that it does not provide a square description of an individual micro-object, although in his later days he once remarked ***'of course I might have been wrong, but perhaps I have earned the right to make my mistakes'***.

Even while Planck, Heisenberg and hosts of other scientists were making rapid strides in the field of quantum physics, again though it is a digression, Hermann Weyl (1929), a German mathematician, was puzzled by the stability of the proton.

According to him, what prevented the electron and proton in an atom of hydrogen from merging and annihilating each other resulting in a shower of photons is neither centripetal and centrifugal forces nor any quantum condition but due to the simple fact that the proton and the electron possess two different kinds of charges that are always conserved.

In later years, American physicists K.C.G. Stueckelberg (1938) and Hungarian- American theoretical physicist Eugene P.Wigner (1949) proposed that the proton, neutron and hyperons carry their own signature called baryon number that must be conserved under all transformations. These particles were assigned a baryon number 1. This number is assumed to remain unchanged in any particle interaction.

The other lighter particles - the photon, electron, positron, graviton, muon, neutrino, mesons - were assigned a baryon number zero.

However, the argument of the Dutch physicist General I' Hooft (1971) is that according to grand unified field theory there are certain subtle effects that could not be represented by finite emission and absorption of elementary particles and hence the baryon number need not be conserved.

According to Andrei Sakharov and Steven Weinberg the preponderance of matter over anti-matter and absence of forces due to baryon concentrations in matter - it is being still studied- indicate that baryon numbers need not be conserved.

In 1980, a nuclear scientist in California reported that *'the atom changes its shape constantly. At one time it looks like an egg that is oval in shape and* *at another time it looks like an omelette that is flat'*

Coming back, the success of the quantum theory is that the experimental results of interaction of radiation with all known micro systems are in agreement with the results of the quantum mechanical calculations. It enables the scientists to have a conceptual vision of the beautiful interior of the atom.

Further, it has been found that quantum mechanics is absolutely essential to account for the behavior of macro systems such as superconductors, super-fluids, lasers.

However, whether quantum mechanical principles are universally valid for micro systems at sufficiently high energies or not is not clear till date.

In 1991, Daniel Walls and his colleagues at the University of Auckland conducted an experiment. Their experiment demolished the argument of EPR.

In their experiment, they made a photon to strike a half silvered minor. For half the time the minor will reflect the particles at right angles, the rest of the time, it will allow the particles to pass straight through. There are detectors at the ends of both routes.

They say that three things can happen in this experimental set up; the photon can be reflected to one detector, it can pass straight through the mirror to the other detector, or it can do both. In this case, both detectors will click at the same time: in other words, the photon is hitting both detectors simultaneously- a possibility allowed only by quantum theory. "That is really the mystery of quantum mechanics' Walls says.

In fact, a real experiment will have to be more complex than this because quantum theory - if correct- also makes it impossible for both detectors to pick up the photon directly. Instead, they will have to detect the effect of the photon through its interference with photons in another beam of light, also shown into the mirror.

In 1986, a research team led by David Pritchard from the Massachusetts Institute of Technology (MIT), succeeded through a new system, in isolating an atom to study its nature.

The system suspends an atom between two coinciding laser beams of different frequencies exploiting the fact that when the photons hit an object they give it a push. The relationship between the frequency of the light and the resonance of natural vibration of the atoms, determines the strength of the push.

A magnetic field changes the resonance of the atom. During such changes, the atom becomes susceptible to the frequency of a laser beam. Hence, the laser beam pushes the atom back if it tends to stray off a fixed path. By manipulating the laser beams and the magnetic field, scientists in the MIT were able to trap atoms".

"Stephen Chn and his colleagues developed another technique to trap atoms.

Their technique depends on the property of light that it exerts pressure on the objects that it strikes. This radiation pressure is very small when compared to gravity or air pressure. However, in a vacuum, radiation pressure is an important means of moving matter.

Mainly based on this principle they captured about 500 sodium atoms by vaporizing a pellet of sodium metal in a stainless steel chamber. The apparatus was connected to video cameras and measuring instruments that aided observation. Six laser beams from different direction and appropriate radiation pressure were focused on a cubic centi-metre of space within the vacuum chamber. The crisscrossed beams created an effect called 'optical molasses" by the Bell scientists.

In this environment the atoms are brought to a very slow random crawl. A seventh laser beam tuned to a different frequency was also focused into this space. It exerted a different kind of light force.

The light force attracted the atoms and so in effect created a tiny 'well' into which the atoms fell.

The above discovery offers an opportunity to observe atoms for a very long lime. Hence, this discovery may enable the scientists to probe the deep questions of atomic reality and we might see the atoms in the TV screen in the near future.

In 1962, Leon M. Lederman and Melvin Schwartz of the USA and Jack Steinberger of Switzerland developed techniques to capture neutrinos and use them to discover other particles in the sub-atomic world. Their work opened new opportunities for research into the innermost structure and dynamics of matter.

If we want to see a thing, it must be shown to us. Further, in order to see a thing, the light must fall on it and shine it. Then only we can see a thing. Naturally, we cannot see anything under darkness.

If a thing is smaller than the wavelength of light, the light will not fall on it and, therefore, the light will not shine it. Naturally, we cannot see it.

Therefore, when a thing becomes smaller and smaller, the wavelength of the particle that causes it to shine also must become shorter and shorter.

As the wavelength is inversely proportional to frequency, the frequency increases when the wavelength decreases.

When the frequency increases, the energy of the light particles increases.

Therefore, in order to probe small particles, we need radiations of higher energy.

As the nucleon is smaller than the atom, we need particles of higher energy - or higher frequency- for scattering experiments.

According to the uncertainty principle, the uncertainty in distance is inversely proportional to the uncertainty in momentum. It follows that if charged particles with a lot more energy than the **α** particles are utilized for the scattering experiment, it is possible to probe still shorter distances.

High energy particles required for this experiment are obtained using giant accelerators.

Accelerator experiments have shown that there are hundreds of fundamental particles.

If there is life in any other outer world, in nineteen eighties, one would have imagined that there would be a periodic table similar to the one on earth. It is now difficult to think so because it has been found that the protons and the neutrons are not fundamental particles and hence not structure-less particles but are 'elementary particles' composed of still smaller entities or point like (structure-less) particles called quarks.

Now it is believed that all matter is made of two types of particles or matter units. One kind is called ‘quarks’ and the other is called 'leptons'. It is believed that there are six quarks and six leptons.

Murry Gell-Mann, a Jewish- American physicist, in 1964 first proposed the concept of quarks. Three basic types of quarks in different combinations make up the heavy elementary particle, baryons, This reminded him of a line from ‘Finnegans Wake’ by James Joyce that reads, “ Three quarks for Musther Mark” and hence the name quarks.

All the six leptons and five of the six quarks have already been discovered. These are all included in the theories that deal with matter units and the forces associated with them. They are called Standard Model.

The six quarks are *up, down, strange, charm, bottom* and *top*.

The six leptons are the *electron, muon, tau* and the *three neutrinos* associated with each of these.

All these fanciful words have specific meanings to the particle physics and are of help in making mathematical models to explain quarks and how they combine to form elementary particles.

What are leptons?

Leptons arc one of the two structure-less matter units. They are the direct generalizations -or the general conclusion drawn- of the electrons.

The term lepton denotes particles that, if charged, interact both weakly and electro-magnetically and always weakly if neutral.

What are quarks?

Quarks are one of the two structure-less fermionic constituents of hadrons (Protons, neutrons and mesons).

Hence, quarks belong to the nuclei.

Quarks interact via strong, weak and electromagnetic interactions.

This indicates that the quarks and the leptons are analogous to the electron.

The important distinction is that whereas the quarks are capable of strong, weak and electro-magnetic interactions, the leptons are capable of weak and electro-magnetic interactions only.

Even the above distinction might disappear eventually if we can make it possible to unify the three types of forces mentioned above.

Pending this, we must be contented with the fact that the strong interactions of quarks arc described by quantum chromo-dynamics (QCD). Here, the quarks are permanently confined by forces coming from the exchange of ‘gluons’.

The weak and the electro-magnetic interactions of both quarks and the leptons are described by quantum electrodynamics (QED) or the electro-weak theory.

With the development of accelerator technology, scientists began to use electron beams instead of **α** particles. This eliminated the complications arising out of the poorly understood strong interactions between the **α** particles and the nuclei. Pioneers in this field are Hofstadter and collaborators.

They - in 1950s - found that the angular distribution of electrons scattered elastically from gold at energy of 126 MeV fell below the 'point nucleus' prediction of Rutherford. It is attributed to the wave mechanical diffraction effects over the finite volume of the nucleus.

In the above experiment, the angular distribution obtained is the product of the distribution corresponding to scattering from single point like target and the 'form factor'.

The ‘form factor’ is characteristic of the spatial extension of the target's (here nucleus's) charge density.

The finite spatial extension of the nucleus indicated that it has a structure.

In fact, when an electron beam with incident energy of 150 MeV was scattered at 90 degree from carbon, a nuclear spectrum similar to the atomic spectrum was obtained. This spectrum showed three peaks at 4.4 MeV, 7.7 MeV and 9.6MeV corresponding to the first three excited states of the carbon nuclei.

It is clear that the internal quantized motions of the constituents of the nuclei led to the observed nuclear spectra involving energy differences of the order of a few MeV.

Further, it is abundantly clear that when the nuclei are excited by appropriately higher energy beams they readily reveal their internal structure.

However, during chemical reactions, the nucleus appears as an inert core because energy released is not sufficient for its excitation.

Thus the nuclear degrees of freedom remain ‘ frozen’ on the scale of atomic physics.

Nucleon → quark

With the further development of accelerator technology (in 1960s), scientists began to use electron beams of still higher energy to probe still shorter distances.

When electrons of incident energy of 4.879 GeV (The rest energy of a proton is roughly equal to 1 GeV) is scattered at 10 degree from protons, an energy spectrum was obtained. This nucleon spectrum showed the normal large elastic peak besides the other small peaks presumably corresponding to the excitation of the recoiling system.

The detailed deciphering of the nucleon spectrum revealed that it is similar to the spectrum obtained for nuclei (nuclear spectrum) and for atoms (atomic spectrum).

It is clear that the internal quantized motions of the constituents of the nucleon led to the observed nucleon spectra involving energy difference of the order of a few GeV.

Thus, just as the nuclear degrees of freedom remain 'frozen' in atomic physics, the hadronic degrees of freedom remain frozen in nuclear physics.

Whether the quarks been isolated?

The answer is 'no'.

Truly, the quarks have not been observed as free isolated particles.

Free quarks are not formed even when hadrons of highest energy available are smashed into each other. However, during such smashing, the hard scattered quarks get converted into two almost straight jets of hadrons.

Hence, it appears that they remain only as clusters confined to hadronic volumes. This is because the energies currently available are not sufficient to overcome the very strong inter-quark force (QED).

The inter-quark force is very much stronger but similar to the electromagnetic forces.

Then what are the evidences that imply the existence of quarks?

Surely, nucleon spectroscopy can be interpreted as due to the internal motions of the constituents of the nucleons.

The fact that the constituents are charged is inferred from a Rutherford type experiment. In that experiment, the existence of a nucleus in the atom was inferred from the deflections and reflections of the **α** particles directed towards a gold foil.

Here, when a negatively charged electron beam of sufficient energy (around 5 GeV) was scattered from protons, some of the electrons bounced back to the source.

Obviously, it must be due to the negatively charged constituent in the proton.

It must be pointed out that nucleon spectroscopy is complicated by the presence of gluons (the photon of strong forces).

However, the inelastic scattering experiment of electrons from nucleons by Hofstadter and co-workers in 1960s showed that the proton has a spatial extension.

They found that in proton there is an approximately exponential distribution of charge with a root mean square radius of about 0.8 fm.

The magnetic moment distributions of nucleons have been measured down to distances of the order of 0.04 fm and this also shows that the magnetic moments of nucleons have a spatial distribution.

Based on the above and several other fragmentary evidences, Gell Mann (1964) and Zweig (1964) independently concluded that nucleon - like states are composed of three, spin **– ½,** constituents called quarks.

As some of the electrons of the electron beam bounced back after hitting the proton, they concluded that there must be a negative centre in the proton.

As the proton has unit positive charge, they concluded that the quarks must have fractional charges and the combined charges of the quarks of a proton would be one positive charge. The most economical arrangement, according to them would be then **2/3** charges for two constituents and **– 1/3** charge for one constituent, thus making a total charge of one **(2/3+2/3 – 1/3 = 1)**.

The quarks with **2/3** charges are called 'up' quarts (symbol u).And the quarks with **-1/3** charges are called down (symbol d) quarks.

Thus, the proton is a uud system and the neutron is a udd system.

The ▪ ++ particle is a baryon discovered by Fermi and his team in 1951. This particle is **uuu.** The π^{+} meson is **ud** etc d = down anti-quark). The forces between the up and the down quarks, however, do not depend on the charge they carry.

In spite of several evidences, many physicists in the 1960s and 1970s refused to accept quarks as a physical entity. At best, they considered quarks as a useful means for systematizing a huge mass of nucleonic spectroscopic data.

In fact, Gell Mann, in 1964, finished his paper with the statement ‘A search for a stable quarks of charge **1/3** or **+2/3** and /or stable di-quarks of charge **2/3 or +1/3 or +4/3** at the highest energy accelerators would help to reassure us of the non-existence of real quark'.

But many deep inelastic scattering experiments conducted in 1980s do confirm **-1/2** spin hadronic constituents. These constituents appear point like down to the currently probed distances and possess the other attributes of quarks.

The total spin, **J,** of each nucleon is **+1/2**. The spin, **J**, of each quark also is **+1/2** . Since there are three quarks in, say, proton, we get the total spin **½** for proton by following the conventional rules of addition of angular momenta.

→The particle ▪ ++ (π^{+} + **p** ▪ ++) has spin **J = 3/2.** It can be explained only by assuming that ▪ ++ is formed by combining three identical **J = 1/2**u quarks in their ground state **ie uuu.**

But, the basic doctrine of Fermi statistics is that no two particles in a system of fermions can have all the quantum numbers the same. Further, they are characterized by half integer spin and hence they tend to spread out in different states.

Thus, when the fermions are found in large numbers, they do not form clusters.

It is evident that uuu configuration for ▪ $^{++}$ **must** be forbidden by Fermi statistics.

The scientists have solved this problem by introducing a new quantum number or property called the 'colour’.

According to them, the quarks come in three different colours: red, green and blue. Their symbols are **R, G** and **B** respectively. The analogy is that all the real colours are made of three primary colours.

It is clear that the quark wave function for ▪ $^{++}$ is now **uRuGuB** and the three quarks are now different with respect to their colour quantum numbers. In this way the scientists have solved the statistical problem.

But, in the above method, it can be seen, though there is only one proton, there can be several different states such as **uRuGdB, uRuGdG,uRuGdg** for it.

In order to avoid this complication, whenever colour quantum number is utilized, proliferation of the number of states is avoided.

The basis for this is that all particle states observed in nature are 'colourless' or 'white'.

The anti-quarks arc called anti-red (symbol $\bar{R}$. anti-green ($\bar{G}$) and anti-blue ($\bar{B}$).

Anti-quarks have actuality been assigned the complementary colours of quarks. They are cyan ($\bar{R}$) megenta ($\bar{G}$) and yellow ($\bar{B}$).

The colour is not related to the colour of everyday life. One must study the colour theory to understand it better.

The quarks and the leptons interact through certain forces. Four forces have been identified. They are I) strong nuclear forces (2) weak nuclear forces (3) electo-magnetic force and (4) gravitational force.

All the constituents of the universe, from the smallest atomic nucleus to the largest galaxy, are held together by these forces.

All the above forces of nature are a result of particle exchange.

These particles are called bosons.

Even Newton believed that all forces of nature must be a result of particle exchange. In his letter to Bentley, Newton wrote as follows.

'That gravity should be innate. inherent and essential to matter, so that one body can act upon another at a distance through vacuum, without the mediation of anything else, by and through which action and force may be conveyed from one to the other is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it”

Thus it is clear that the bosons are the 'conveyors' of force or the medium of interaction. They are exchanged during interactions.

Unlike the fermions, they have no restriction on their quantum states and can condense to the same lowest energy state.

The strong nuclear forces are responsible for holding the quarks together in a nucleon. They are also responsible for the nuclear force between the nucleons that holds them together in an atomic nucleus.

It has already been indicated that there are three **'u'** quarks with same charge in the ▪$^{++}$ particle.

Naturally, there must be a strong force to bind these quarks into ▪$^{++}$ particle (the doubly charged ▪$^{++}$ lives for about **10^{-23}**sec only before decaying back into a π^+ and a proton).

The above force must overcome the electro-magnetic repulsion of the three quarks also.

Just as the electromagnetic interactions bind positronium **(e- e+),** the colour field binds the quarks.

It is the 'colour charge' of the quarks that endows the quarks with this colour field.

The quantum of the colour field is called gluon.

It is a mass-less particle. It has no electric charge.

It is actually the gluons that bind the quarks in the nucleons and the nucleons in the nuclei.

When the quarks interact, they exchange colour.

The gluons also are a bi-coloured object, labeled $(B\bar{B})$

It is clear that the photons of the strong forces are nothing but gluons.

The weak nuclear force or the electroweak force mediates through weak field quanta**, W.** The weak field quanta or the intermediate vector bosons, unlike the photons and gluons, have electric charge. In fact, they exist with positive, **$W,^+$** negative, **W^-** and neutral, **Z^0**), electric charge.

They can be massive also. The novelty of the weak interaction is that it changes a **d** quark into a **u** quark and a muon into a neutrino.

It is said that the weak interactions change quark and leptons flavor'. Further, the muons interact electro-magnetically and weakly and the basic interaction strengths of a muon are identical to those of an electron. No convincing explanation has been offered so far (or this duplication.

Since W^+, W^- and Z^0 bosons can be up to hundred times heavier than a proton (other carriers of forces are mass-less), exchange of a particle of mass m means that its rest mass energy **$E= mc^2$** is suddenly created at emission and lost at the time of absorption. The uncertainty principle, allows such a temporary non-conservation of energy over a short time **span, $t = h/ mc^2$** or equivalently a very short range of force. But, all other forces have a long range.

The concept of boson has the following basis behind it.

When two charged particles interact with one another, the interaction happens because the photons are swapped between two particles. The photons carry the electro-magnetic force. So physicists theorized that the weak nuclear force must be carried by a particle. They named it weak boson even though nobody had detected such a ‘beast’.

They believed that the $\mathbf{W^+}$ and the $\mathbf{W^-}$ are necessary to carry charge and the third called, $\mathbf{Z^0}$, is necessary because charge is not always transferred in weak interactions. The $\mathbf{Z^0}$ is the weak force counterpart of the photon and the **W** particles are, in effect, charged photons.

In this connection, it is necessary to point out that the weak forces are not strong enough to produce any binding effects among the systems studied so far.

Electro-magnetic force acts through the exchange of photons. All particles carrying the electric charge, in fact, interact through the exchange of photons. This force is responsible for holding the nucleus and the electrons together in an atom. It has spin 1.

The gravitational interactions are mediated by gravitons. These are analogous to photons.

One of the predictions of Einstein's general theory of gravitation is that spinning asymmetric masses should radiate gravitational waves carrying energy and momentum just like the emission of electromagnetic radiation. Thus, gravitational waves may be considered as disturbances that propagate through vacuum, with the speed of light. Any material body that lies in its path would undergo acceleration. This acceleration is periodic and is transverse to the direction of propagation of the waves.

However, though it couples to all forms of matter, it is too weak to be easily detected and hence it has not much practical importance to the subatomic world. In fact, its effect is very many orders of magnitude weaker than even the weak force.

The above conclusion is valid at least until the inter particle separation reaches distances far smaller than the magnitude we would be probing at present.

Further, not only the gravitational wave has not so far been quantized but also none of the many experiments done in many parts of the world have led to any positive result (regarding gravitational wave).

However, the concept of graviton is gaining ground since the discovery of intermediate vector bosons **($\mathbf{W^+}$, $\mathbf{W^-}$** and **$\mathbf{Z^0}$)**.

The vital support for the concept of graviton comes from the graphical extrapolation of coupling constants of the various fundamental forces against the energy of interaction. The extrapolated graphs seem to meet at a point in the region of $\mathbf{10^{15}}$ GeV. These ranges are not attainable in the laboratory with the present day technology - the maximum attained is around 10 GeV).

At such tremendous energies, the forces must be indistinguishable from one another and only at lower energies do they show up their differences.

Theoretical considerations imply that the graviton mast be extremely massive if it exists. It will have spin 2.

Even though the gravitational force is a feeble force – about 10^{-39} times the electromagnetic force in strength - gravity holds the moon in its orbit around earth, earth and the other planets around the sun, and the sun and a hundred billion stars clustered together in our galaxy.

A fifth force also has been predicted.

The apparent stability of the proton suggests that not only the baryon number is conserved but also there exists a force dependent on the baryonic content of matter. (Proton; undergo decay is another matter).

Baryonic content indicated the composition of matter. Whether the constant of gravitation varied with the nature of material was investigated even by Galileo by his ‘free fall’ experiments.

Later, though the experiments of R.V. Eotvos *et all* (1922) pointed out to the possibility of a fifth force (This force must be feebler than gravity by a factor $\mathbf{10^{-5}}$), none of the many other experiments conducted all over the world indicated the possibility of the fifth force.

It is now more or less certain that the six quarks and six leptons interact via four forces. That the Standard Model by itself is inconsistent, it is no wonder that the scientists have discovered fundamental inconsistencies in the nature of forces.

Yet they strive to find out the forces that cause the particles to cluster together and cause them to react to make up the bigger structures that eventually one can see, touch and smell.

The picture appears to be too complicated for them.

They have not so far understood the nature of the massive particle in particular. They have also not understood why some forces arc long range and other forces short range.

They hope to find out the answer for these problems by looking at a certain regions of energy. That is why many scientists believe that they would get the answer from the Super Conducting Super Collider (SSC). As the USA has abandoned the SSC due to economic reasons, the scientists depend on the Large Hadron Collider (LHC) of the European Organization in the France-Switzerland border.

Just as the experiments of AA. Michaelson and Edward Morley disapproved the existence of ether-one of the fundamental tenets of classical physics and paved the way for the Einstein's Special Theory of Relativity, scientists believe that their experiments with the LHC would clear the mist before them and pave the way for a new theory that is out and out alien to the physics we know today.

Pending it, it must be pointed out that many scientists believe in a unified force, and a simpler regime.

Already scientists have succeeded in unifying electro-magnetic and weak interactions just as Maxwell had combined electricity and magnetism into one.

Feeble efforts are on to unify the first three forces (Grand unification) and even all the forces of nature into one mathematical description, one set of equations, a unified field theory (Super unification).

They continue to glimpse here and there for this.

This takes them to cosmology just as the quantum theory took the scientists to spectral lines in the early years of this century.

In fact, new theories from cosmology and micro-physics are illuminating each other to determine whether the physics we know today is a primeval one or not.

Just as in nineteen thirties, the physicists abandoned the classical concept of localized particles and replaced it with the idea that the position of the particle is distributed like the amplitude of wave, now they are willing to abandon the concept of conservation and other ideas foretold by symmetry in order to be replaced with the idea that the differences in the forces of nature are due to broken symmetries.

In the light of the new theories, scientists are looking for a decaying proton, a passing monopole (believed to have separated itself during the early microsecond of the universe), a massive neutrino and the mysterious fifth force.

Thus, the scientists are at the very exciting frontier from where they see a door. If they could open the door some new physics and all kinds of wonderful things might appear.

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Some conversion factors

$1\,\text{TeV} = 10^{3}\,\text{GeV} = 10^{6}\,\text{MeV} = 10^{9}\,\text{KeV} = 10^{12}\,\text{eV}$

$1\,\text{fermi} = 1\,\text{F} = 10^{-13}\,\text{cm} = 5.07\,\text{GeV}^{-1}$

$1\,\text{fm} = 10^{-15}\,\text{m}$