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THE STRUCTURE OF MATTER SEVENTY YEARS AFTER THE BOHR-RUTHERFORD ATOM

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Structure of Matter Seventy years after the Bohr-Rutherford atom

Nineteenth century science appeared to have found the answer to the ancient question about the basic constituents of matter: all substances, it had been found, are composed of chemical elements and these elements are composed of atoms, the ultimate particles of matters. Then towards the end of that century, J.J. Thomson discovered the electron to indicate that the problem was far from solved and that the atom has constituent parts.

The intellectual breakthrough with which modern physics begins is the Rutherford's discovery that the atom, as Bohr put it, consists of a relatively heavy, "positively charged nucleus surrounded by a system of negatively charged electrons kept together by attractive forces from the nucleus." But according to classical electrodynamics, the system of electrons would lose energy continuously through radiation and eventually fall into the nucleus. To prevent continuous loss of energy by the electrons required a new principle in physics. As is well known, in 1913 Niels Bohr provided a solution by introducing in the laws of motion of the electrons Planck's principle of the quantum of action to limit the energy an electron can give out to fixed values. Quantum mechanics had provided a theoretical explanation of the stability of the atom. It is a composite system consisting of a nucleus and electrons. By 1932, the scene appeared ~~beguilingly~~ simple: the building blocks of matter were the four entities, the electron, the photon (the carrier of light), the proton and the neutron, the last two being the constituents of nucleus. The study of the structure of matter has a continuous history which is still going on today. Our aim here is to report on the progress made since Bohr's breakthrough but especially since these past two decades.

In the realm of classical physics, the proton and electron interact with each other through two of nature's basic forces, namely, the electromagnetic and the gravitational forces. Since the (attractive) gravitational force between two protons inside a nucleus is weaker than the corresponding (repulsive) electromagnetic force by the enormous factor of about 10^{36}, the amazing stability of the nuclear structure cannot be explained on the basis of these two forces alone. Clearly there is inside the nucleus a new fundamental force strong enough to overcome the enormous electrical forces tending to blow the nucleus apart. This is the strong nuclear force, an extremely short range force whose effects are felt over distances of only about 10^{-13} cm, the radius of a subatomic particle. It is so strong that it swamps the electromagnetic force by a factor of about one hundred.

The simple picture of the basic constituents of matter of the 1930s had since then been complicated by the discovery these past few decades of hundreds of related subatomic particles which respond to the strong force. Such particles are called <u>hadrons</u> and are subdivided into two classes. Those with integral spin are called <u>mesons</u> while those with half-odd-integral spin are called <u>baryons</u>, the proton and neutron being examples of baryons. The pion, the particle predicted by Hideki Yukawa as a carrier of the nuclear force,is a meson.

Hadrons are unstable and have a mean life of about 10^{-7} to 10^{-10} sec. (except the proton with a mean life af about 10^{31} yrs.) and decay spontaneously into other lighter particles. If the forces responsible for hadron decay were the same strong nuclear force then a simple calculation shows that their mean lives should be of the order of about 10^{-23} sec. To explain this discrepancy, a new nuclear force inside the hadrons responsible for their disintegration into lighter particle was proposed. This is the weak nuclear force which, like its partner, the strong nuclear force, is short range: two particles must approach to within 10^{-15} cm in order to feel it. It is extremely weak with a strength of only about 10^{-13} that of its partner. In contrast to the strong and electromagnetic interactions which are invariant under reflection, the weak nuclear force is not reflection-invariant, but shows a preference for "left-handedness". Also, associated with the weak nuclear force is another family of spin one-half particles, called leptons, which do not feel the strong force but appear through the weak interactions as decay products. The strong nuclear, the electromagnetic, the weak nuclear and the gravitational forces are the four basic forces in nature which account for the observed actions of matter.

Every subatomic particle, hadron or lepton, has associated with it certain intrinsic properties which are used to identify it uniquely. These are called its quantum numbers. Examples are its electric charge, baryon or lepton number, hypercharge, strangeness, etc. All particles also possess another property called statistics which can be applied to classify them into two broad types. There are those which prefer to exist together in the same quantum state. Such particles are said to obey the Bose-Einstein statistics and are called <u>bosons</u>. There are others which obey Pauli's exclusion principle according to which no two such particles can be in the same quantum state. These particles obey the Fermi-Dirac statistics and are called <u>fermions</u>. All particles with integral spins (such as the pion and the photon) are bosons and all those with half-odd-integral spins (such as the proton and neutron) are fermions. No other type of statistics has so far been discovered.

By combining special relativity and quantum mechanics, the two great discoveries of this century, Dirac proved the existence of anti-matter: to every particle there is an antiparticle whose quantum numbers are the additive inverses of the former. The electron's antiparticle is called the positron, but generally all others are identified by the prefix anti-, so that of the proton, for instance, is the anti-proton, a negatively charged particle. Some, like the photon and the neutral pion, are their own anti-particles. If a particle collides with an antiparticle, the two annihilate each other and are transformed into photons.

Order in the subnuclear world.

By 1960 so many hundreds of particles had been discovered that matter on the smallest scale appeared to be an arbitrary jumble of elementary particles. No simple and orderly relationship among the particles could be perceived and serious doubts were expressed as to whether these could be considered as the basic building blocks of matter. Such a plathora of fundamental objects of nature was felt to be intellectually unappealing. Could one find a structure in these subnuclear particles to bring order and beauty into this apparent chaos. The answer was provided by Gell-Mann and Ne'eman in 1961, using the mathematical discipline of the theory of groups which has now become the important tool of modern theoretical physics especially that branch invented by Sophus Lie in the nineteenth century and now known as Lie groups.

Heisenberg had earlier observed that because the proton and the neutron have the same spin and nearly the same mass, and also interact strongly with about the same strength, although electromagnetically they behave differently they could, for strong interaction purposes, be considered as the two states of a single object called the nucleon. To distinguish between these states the nucleon is, in analogy to ordinary spin, assigned an I-spin of $\frac{1}{2}$ (in units of $\hbar$) so that its third components of I-spin are $\pm \frac{1}{2}$, with the $+\frac{1}{2}$ assigned to the proton and the $-\frac{1}{2}$ to the neutron. This is the first known example of a multiplet, that is, a collection of particles with a number of common properties, which behave in an identical way with respect to some interactions of nature. When this concept is extended to all hadrons it is readily seen that they form I-spin multiplets consisting of one, two, three or four members called the singlet, doublet, triplet and quartet, respectively. These are representations of the SU(2) group of Sophus Lie, the term standing for the special unitary group of two-by-two matrices of determinant one. The I-spin concept requires that all hadrons should belong to multiplets corresponding to representations of the SU(2) group.

In 1961 Murray Gell-Mann and Yuval Ne'eman independently proposed an extension of the above idea by organizing all hadrons into multiplets corresponding to representations of the SU(3) group, the special unitary group of three-by-three matrices of determinant one. Of all the several representations of the SU(3) group, however, only

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those with one, eight or ten members called the singlet, the octet and the decuplet are favoured. That is a curious result which will lead us to an understanding of the structure of hadrons. As in the SU(2) representations members within each multiplet share a common spin angular momentum but are now distinguished from one another by two quantum numbers, I_z and hypercharge Y. If for each multiplet we plot the particles' I_z against their Y, the hadrons are found to form orderly arrays. Each of the spin-zero and spin-one mesons are organised into singlet and octet representations, with the singlet represented as a point at the origin and the octet as a hexagon with a particle at each vertex and two particles at the centre. The spin-half baryon octets are identically represented while the spin three-half baryons appear as a triangle with a particle at each vertex, two particles, equally spaced along the lines joining the vertices and one particle at the centre. In 1964, the correctness of the theory was confirmed when the Ω^- particle it predicted was discovered. Our picture of the hadrons has been transformed from chaos to a considerable degree of order by simple group-theoretical ideas.

COMPOSITION OF HADRONS AND THE COLOUR FORCE

Why is it that of the many possible representations of SU(3) only the three representations appear in nature ? Gell-Mann and Zweig independently proposed an explanation. Nature's choice of the singlet, octet and decuplet representations could be understood if we consider hadrons not as the ultimate constituents of matter, but as composite objects which are constructed from three basic particles called quarks, by Gell-Mann. The quarks are members of the fundamental representation of SU(3), have spin angular momentum of one-half but, unlike the hadrons, they carry fractional charges, hypercharges and baryon numbers. Gell-Mann designated the three quarks u , d and s and the corresponding antiquarks as $\bar{u}$, $\bar{d}$ and $\bar{s}$, with u and d forming an I-spin doublet of hypercharge $Y = \frac{1}{3}$ and s an I-spin singlet of hypercharge $Y = -\frac{2}{3}$ with a mass different from the other two quarks.

From this multiplet the three representations consisting of one, eight and ten members are obtained if mesons are constructed out of a quark and an antiquark and baryons constructed out of three quarks bound together. The quark-antiquark combination gives rise to the singlet and octet representations while the three quark combination yields the singlet, octet and decuplet representations. No other combination can exist as a hadron and the quantum numbers of all the hadrons observed at that time were all correctly accounted for.

Now since quarks are fermions they should obey the exclusion principle we referred to earlier, according to which no two such particles can be in the same quantum state. Quarks in a meson satisfy this principle because a quark and its antiquark cannot have identical quantum numbers. For baryons, however, the story is different because we can identify some baryons such as N^{*++}(uuu), N^{*-}(ddd) and Ω^{-}(sss) in which at least two of the three quarks can have identical quantum numbers. Pauli's principle is too entrenched in quantum mechanics to be so lightly abandoned. To ensure that the three quarks inside a baryon obey the principle therefore, a new quantum number with three possible values must be assigned to each quark. This quantum number is called <u>colour</u>; each triplet of quarks can appear in any one of the three colours - red, green and blue. Antiquarks will then possess the colours anti-red, anti-green and anti-blue. Baryons are now made up of three quarks all of which have different colour quantum numbers, and, as a result, the particles in a multiplet are colourless. Similarly, mesons consist of a quark of one colour and the antiquark of the corresponding anti-colour and the resulting particle is also neutral with respect to the colour quantum number. All hadrons are therefore colour singlets and particles with colour do not exist in a free state.

High-energy inelastic electron-proton scattering experiments conducted at the Standford Linear Accelerator Centre (SLAC) in the late 1960s provided persuasive evidence of the existence of small point-like particles within the proton which behave exactly in the way expected of quarks.

Thus another important advance towards our understanding of the structure of matter has been made: Hadrons are not the ultimate building blocks of matter but are composites of more fundamental particles called quarks. Each quark exists in three states, distinguished by a property called colour and all hadrons are colourless.

The SU(3) of Gell-Mann and Ne'eman is concerned with performing transformation on the three objects, u, d and s, so that a u-quark, for instance, can be transformed into a d-quark or a d-quark into an s-quark. Now that each quark exists in three colour states, a new SU(3) group enters the picture. Within this group, blue quarks are transformed into green quarks or green into red. The isotopic spin and strangeness quantum numbers possessed by the quarks are referred to collectively as flavour quantum numbers. Because the two groups are not identical, the original SU(3) is now known as flavour SU(3), or $SU_F(3)$, and the new one as colour SU(3) (or $SU_C(3)$). Unlike $SU_F(3)$, which is an approximate symmetry group, the $SU_C(3)$ group is exact. Blue, green and red d-quarks, for instance, have identical masses.

Considerations of symmetry have always been important in physics but with the advent of quantum mechanics, they have acquired special significance. In recent years, one particular type of symmetry known as gauge invariance has assumed a particularly unique role in particle physics. The basic forces of nature are due to the exchange of spin one particles and these forces, it has been discovered, are best understood through the use of gauge symmetries. Because of this, the carriers of the forces are called gauge particles.

As we have seen above, hadrons consist of coloured quarks bound together. It is natural to enquire about the force that binds them together. Through the gauge theory of colour SU(3) one finds that quarks are bound together by a strong nuclear (or colour) force which is transmitted by eight massless gauge particles which are supposed to glue the quarks together and so are called gluons. A quark emitting or absorbing a gluon has its colour changed, the flavour remaining unchanged. Thus, like the quarks, gluons are coloured and therefore do not exist in a free state but are permanently confined inside the hadron. The distribution of hadrons observed at the PETRA electron-positron collider strongly suggests the existence of these gauge particles.

Unifying the basic forces of nature

Remarkable progress has been made towards our understanding of the weak nuclear force. At present, only six leptons are known which feel the weak force as they approach each other. These are the electron (e^-), the muon (μ^-), the tau (τ^-) and the neutrinos associated with each : ν_e, ν_μ and ν_τ. The first three are massive and carry - 1 unit of electric charge while their neutrinos are massless and are electrically neutral. All the indications are that leptons have no internal structure and so are truly elementary. There are, however, important differences between quarks and leptons, the two kinds of basic particles we have identified so far. Firstly, whereas quarks are subject to the strong nuclear force leptons are not. Also quarks form aggregates of particles, the hadrons, but there are no composite structures consisting of leptons. Finally quarks do not exist in a free state whereas isolated leptons are in abundance. These differences arise from the fact that quarks have colour while leptons are "colourless"

Leptons participate in both the electromagnetic and weak forces and it was to find the carriers of the weak nuclear force, that Abdus Salam and Steven Weinberg proposed to unify these two interactions notwithstanding the fact that the former force conserves strangeness and is reflection-invariant, while the other respects neither and also that the two forces have different strengths. To take care of these differences, the charged leptons are split into right - and left-handed states, their neutrinos being already left-handed and the differences in the strength of these forces is assumed to be due to the fact that the carriers of the weak force are massive.

In this way an SU(2)x U(1) gauge theory of weak and electromagnetic interactions was constructed with the left-handed electron paired with the left-handed neutrino to form an SU(2) doublet and the right-handed electron placed all by itself in an SU(2) singlet. A similar pattern can also be constructed for the muon and its neutrino. We saw earlier that application of the gauge principle to SU(3) leads to massless gauge particles and this is also true when SU(2) x U(1) is gauged. And yet here we are requiring three of the four particles associated with the group to be massive. A way was found which kept the photon mass zero and gave the others their desired masses. The mechanism used , known as "spontaneous symmetry breaking", is unfortunately too technical for us to explain here. Suffice it to say that Salam and Weinberg were then able to show that the electromagnetic and weak nuclear forces are in fact different facets of a more basic short-range force now known as the electro-weak force, whose effects can be felt over distances of less than 10^{-15} cm. Of the four gauge particles one is the photon, the carrier of the electromagnetic interactions and the other three, the carriers of the weak force, are the massive $W^{\pm}$ and Z^{0} particles. These massive particles provide a link between quarks and leptons changing the quarks' flavour but not their colour during a scattering process and decaying into leptons. Discovery of these particles in 198 provided strong evidence that SU(2) x U(1) gauge theory provides an excellent description of the electromagnetic and weak interactions.

Hadrons can also be incorporated in the theory by splitting the quarks into left-handed doublets (consisting of left-handed u-quark and a combination of left-handed d-and s-quarks) and two right-handed singlets in analogy to the above pattern, except that since the quarks are massive, the right-handed partner must also be used. To cancel out so far unobserved and therefore unwanted "strangeness-changing neutral currents", a new quark with electric charge of $\frac{2}{3}$ and carrying a new flavour c, called charm, was proposed. The existence of charmed quarks was confirmed in 1972 by the discovery of the J/ψ , a spin one neutral particle shown to consist of a charmed quark c and charmed antiquark $\bar{c}$. The J/ψ has hidden charm! Several particles carrying non-zero charm have since been detected.

Also for certain technical reasons (cancellation of anomalies), quarks are believed to come in pairs, one with an electric charge $\frac{2}{3}$ and the other $-\frac{1}{3}$. And to each quark pair must be associated a lepton and its corresponding neutrino to form a family whose total electric charge is zero. The members of the first family are identified to be u, d, e^- and ν_e. They play the largest role in naturally occurring phenomena. The second family is also known and it consists of c, s, μ and ν_μ. The tau and its neutrino must therefore be part of a third family of quarks and leptons. To complete this family, another set of quarks, the top (or truth) and bottom (or beauty) quarks with $\frac{2}{3}$ and $-\frac{1}{3}$ charges respectively was therefore proposed. A heavy meson Υ discovered in 1977 was found to have the $b\bar{b}$ quark composition but top-flavoured hadrons are yet to be fully established. The second and third families are born chiefly in particle accelerators and have an ephemeral existence. They are responsible only for extremely subtle effects in ordinary matter.

Combining the $SU_C(3)$ gauge theory of the strong interactions with the $SU(2) \times U(1)$ gauge theory of the electroweak interactions leads to the "standard" model of elementary particles and their interactions, a theory of the strong, weak and electromagnetic interactions which successfully describes an enormous number of quantitative and qualitative features of elementary particle physics and has no known inconsistencies.

Thus according to the standard model the basic building blocks of matter on which nature's forces act are the three quark-lepton families

$$(u , d , e , \nu_e), \quad (c , s , \mu , \nu_\mu) \quad \text{and} \quad (t , b , \tau , \nu_\tau).$$

The quarks carry two types of internal quantum numbers, the flavour quantum numbers which represents all of the internal quantum numbers conserved by the strong interactions. Each flavour of quarks comes in three colour states and the resulting hadrons are neutral with respect to colour. Quarks do not exist as isolated states whereas the leptons exist in a free state. There are also the twelve gauge particles which are the transmitters of three of the fundamental forces of nature, these are the eight massless gluons which carry the strong force but which are confined inside the hadrons because they are coloured; the three massive $W^{\pm}$ and Z^{0} particles, the carriers of the weak force, and the photon which transmits the electromagnetic force. Are these the ultimate indivisible constituents of matter, the "atoms" of Democritus ? In spite of its attractive features, few physicists believe that the standard model is the ultimate theory of elementary particle interactions because it is too complicated and arbitrary. From the fact that $SU_C(3) \times SU(2) \times U(1)$, a direct product of three factors, with different coupling constants we deduce that the three forces are basically unrelated and independent of each other. There also does not appear to be any fundamental explanation for the repetition of the quark-lepton families or for the quark and lepton charges to be related by a simple factor of three or for the unsymmetrical left-right handedness assignment in the weak interactions but not in the strong interactions. Finally gravity is not incorporated in the standard model.

It was in an attempt to understand some of these arbitrary features in the model that grand unified theories in which the strong, weak and electromagnetic forces are embedded in a larger gauge theory with a single coupling constant were developed. Most of such theories certainly have several appealing features, most explain one or more of the arbitrariness that exist in the standard model and most predict proton decay and the existence of neutrinos with a small but non-zero mass and of course, new interactions the new gauge particles predicted should mediate. But they also have their shortcomings. The number of fermion families is still not predicted by the theories, and perhaps, most important of all, gravity has not yet been unified with the other interactions and particles of different spins are not related to each other. Are there then more complete theories that include the results of the standard model and also address all the above questions ? The supersymmetry and supergravity theories appear to give one the hope that the ultimate theory does exist but this is another story all together.