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ELEMENTARY PARTICLES

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Most of my scientific interest throughout my life was devoted to the problems of elementary particles. I will not present here a list of any personal contributions to physics which were but small building blocks in a great edifice, but I will try to give a short account of the development of the concept of elementary particles during this century.

The idea that matter consists of some simple and unchanging elementary constituents is deeply ingrained in our way of thinking. We observe that matter appears in enormous varieties of differents realizations, qualities, shapes and forms, transforming and changing from one into others. In these changes, however, we observe many recurrent properties, many features that remain unchanged, or if changed, return under similar conditions. We find constancies and regularities in the flow of events; we recognize materials with well-defined properties, as water, metals, rocks, or living species; we conclude that there must be something unchanging in nature

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which causes these recurrent phenomena. This is the origin of the idea of elementary particles.

Such elementary units were in fact discovered during the 18th and 19th centuries, when the chemists found that all matter is made up of 92 different species of "atoms" a term which is the Greek equivalent of indivisible.

The problem took a quite different turn, however, when in 1911 Rutherford took the atom apart and showed that the atom consisted of electrons and a nucleus. The ever-recurring, specific and unchanging properties of the atom had to be explained in view of the fact that it can be changed and taken apart. A solution to this problem was given by the discovery of the role of the quantum of action in the behavior of matter in the small. One of the consequences is the fact that a system of particles can be found only in a number of discrete quantum states. In each of these states the energy and many other properties are well defined and fully determined by the nature of the system, its forces and symmetries. The recurring, specific features of the atoms are explained by the existence of these quantum states: whenever the object assumes one of these states — in particular the state of lowest energy, the ground state — it will have the same identical properties associated with this state.

The energy threshold Δ between the lowest state and the first excited state is of special significance. Here an important relation holds: In general, the smaller the structure, the higher is the threshold Δ. For example, it is of the order electron volts in atoms and of the order of millions electron volts in the atomic nucleus. This important energy-size relation is the basis to a new interpretation of the concept of elementary particle: *Conditional elementarity.* As long as the energy transfers and exchanges occuring in regions of the universe are less than the threshold Δ of certain structures, these structures behave and act like elementary particles: they have well-defined fixed properties which cannot change because the structures remain in their ground state. The internal composition of this structure never gets into play, it is never excited and the internal dynamics remains dormant under these conditions. If the prevalent energy exchanges are raised above the threshold Δ of these structures, their inner dynamics comes into play, they become excited and sometimes decomposed into their constituents. Those constituents, being smaller, possess a higher threshold and act as elementary particles until, if ever, their own threshold is reached.

Thus we may consider molecules as elementary particles in a gas like air at room temperature; we may consider atoms as elementary in all processes with energy exchanges of less than about 1 eV. The next step is a much higher one: Up to energy transfers of several 10^5 eV we may consider electrons and atomic nuclei as the elementary particles of matter. That energy range includes almost all chemical and physical process in our terrestrial environment including the phenomena of life. However, when that threshold is surpassed and when energy exchanges occur of the order of 0.1 to 100 million electron volts, the atomic nuclei get excited and exhibit their internal dynamics. It was discovered that they are structures composed of neutrons and protons ("nucleons") held together by a new agent: the nuclear force. This is by no means the end. In the last 30 years it was shown that the protons and neutrons themselves are not elementary but that they can be excited to higher quantum states when energies of the order of several 10^8 eV are applied. It is not yet clear what the internal structure of those particles is based upon, but there seems to exist strong evidence that the nucleons consist of subparticles called "quarks". So far it was not possible to decompose a nucleon into separate quarks. It may perhaps turn out that such decomposition is impossible in principle. More about this later.

Each new step on this "Quantum ladder" opens up a new and rather distinct realm of natural phenomena. Let us start by looking at the phenomena which occur when the energy exchanges are held below the threshold of excitation of atomic nuclei. This is what I would like to call the atomic realm. Here the role of elementary particles is played by the different atomic nuclei and the electrons. The dominant interaction between them is the electro-magnetic force, in particular, the electrostatic Coulomb force between electrons and nuclei. Perhaps it is advisable, therefore, to add the quantum of the electromagnetic field, the photon, to the list of elementary particles in this realm, since photons are emitted, scattered and absorbed freely by atomic structures. Indeed, the electric interactions of very small, heavy and positively charged atomic nuclei with negatively charged electrons are the basis of our understanding, at least in principle, of all atomic phenomena, their aggregations to molecules, to liquids and solids of all kinds. The most important insight for this understanding was the discovery of quantum mechanics which explains the peculiar stability and variety of atomic systems and aggregates. Quantum mechanics and electricity serve also as a basis, in principle, to the understanding of the existence of macro-molecules and of the phenomena of life.

In this connection we should be aware of the important role played by the large mass difference between electrons and atomic nuclei. The latter are many thousand times heavier than the former. This is the reason for the existence of a definite molecular structure: the atomic nuclei form a more or less fixed skeleton, held together by the extended electron clouds which give it shape and rigidity. This molecular architecture underlies not only all chemistry but it also is the basis of the existence of macromolecules which are essential to life such as the double-helix of nucleic acids. This is why it is of utmost importance for the understanding of our world to find out what goes on within the nucleus and what causes the nuclear mass to be so much larger than the electron mass.

The next step of the quantum ladder brings us to the nuclear realm. Energy transfers of millions of electron volts are needed in order to excite nuclear phenomena which remain dormant under terrestrial conditions where the energy transfers never exceed a few hundred electron volts. We do find a few natural radioactive elements on earth but they are nothing but the long-lived remnants of a time when terrestrial matter was exposed to those higher energies in some previous cataclysmic star explosion. In this new realm, we observe excited nuclei and recognize the nuclei as being composed of protons and neutrons, held together by an altogether new and strong force, the nuclear force. Nuclear reactions take place, fusions and fissions, and, aside from light emissions on a much higher energy scale (γ-rays), we also observe a new kind of radiation — radioactivity — in which a nucleus emits an electron and a neutrino. The nuclear phenomena are active in the center of stars, where they produce the energy necessary to keep the star radiant for billions of years. On earth, they can only be induced in our laboratories by using particle accelerators which provide the necessary energy transfers, except for the few reactions that are induced by cosmic rays.

We now come to the next rung of the quantum ladder, the subnuclear realm. In the last 30 years it was technically possible to construct accelerators of extremely high power, which allowed energy transfers up to several hundred billions electron-volts. It then turned out that also the nucleons (protons and neutrons) are only conditionally elementary. Fermi and his collaborators found in 1952 that there exists an excited state of the proton. Many more excited states have been found after that. Today we have a well-developed spectroscopy of excited states of the nucleon; they are referred to as "baryon states".

As usual, whenever a new rung of the quantum ladder is opened up, the corresponding realm of phenomena turned out to be far richer than expected. This is true in particular of the subnuclear realm. A new feature appears here which I would like to comment upon. The energy transfers in the subnuclear realm are of the order of billions of electron volts. According to the famous Einstein relation — $E = m_c^2$ — these energies are of the order of the mass-energy of the particles involved. For example, the mass-energy of a proton is 0.94 billion electron volts. Hence, when such energy transfers take place, energy is directly transmuted into matter; not only do we see excited entities, but new particles are created during the processes. This is not so in the atomic realm (if one does not interpret the emission of a light quantum as the creation of new particles), and it is to a large extent not so in the nuclear realm although the radioactive emission of an electron neutrino pair could be interpreted as a creation process, but it is a weak and rare process.

In the subnuclear world the creation of new particles comes to its full validity. It is connected with the existence of antimatter and its properties. The existence of antimatter was predicted by purely theoretical reasoning. P.A.M. Dirac concluded from Quantum mechanics and Relativity theory that the electric assymetry in atoms (positive nuclei, negative electrons) should be only apparent. The opposite entities must also be possible in nature. Indeed a positive electron was found shortly after Dirac's prediction. The most interesting part of this story, however, is the fact that those opposite particles (antimatter) can be realized only together with their ordinary partners; they are created in pairs, when sufficient energy is available. Conversely, when an antiparticle impinges on a particle the pair disappears and their masses are transformed into other forms of energy such as for example, light quanta. This is referred to as an annihilation process. Therefore antimatter must be created together with matter, but it is not stable in an environment of ordinary matter. In the subnuclear realm the creation and annihilation of matter and antimatter is a common phenomenon.

Another new feature of this realm is the appearance of "mesons". When a nucleon is brought into an excited state, for example, by energy transfer through collision with a high-energy beam, the nucleon returns to the ground state by the emission of light quanta just as atoms do. More often than not, however, the return to the ground state is accompanied by the emission of "mesons". There are many types of mesons, some are electrically charged, others are not; they are "energy packages" as it were, and they are all ephemeral entities in the sense that they have a short lifetime after which they decay into more stable forms of energy such as light quanta or electron-neutrino pairs. A good part of modern particle physics is the systematic discovery and ordering of the many types of mesons. The recent discovery of a new type of rather heavy and relatively long-lived mesons by S. Ting and B. Richter was of special significance and has been awarded the distinction of a Nobel prize.

A further unexpected phenomenon in the subnuclear realm was the appearance of a new type of electron. Whenever conditions were such that electrons of high energies are created, another type of electron was observed which differs from the ordinary electron only by its mass: it is about 200 times heavier. In all other respects it is the same except that it has a finite existence. After about a millionth of a second it decays into an ordinary electron and two neutrinos.

The creation of new particles and antiparticles as well as the production of mesons of all sorts in high energy collisions make it so hard to find out about the internal constituents of the nucleon. Usually the constituent of an entity can be discovered from what emerges after a powerful collision of that entity. In the subnuclear realm, however, so many new particles are created in a collision process that it is hard to discover what were the original constituents.

Nevertheless a substructure of the nucleon and the meson has become apparent during the last decade. The investigations of the spectrum of excited nucleons and of the mesons made it more and more plausible that the constituents of those structures are a new kind of particles: the "quarks". It emerged from a growing body of facts that the nucleon consists of three quarks and that the meson is a combination of a quark and its antiparticle: the antiquark. What is the quark? It is a new kind of particle that seems to exist in four varieties, which differ in certain properties, such as charge, mass and other intrinsic qualities. The four varieties are referred to today by a certain nomenclature: We speak of the u-, d-, s- and c-quark. The u- and d-quark form a pair of rather similar properties, apart from the charge which is +2/3 for the u-quark and -1/3 for the d-quark, in units of the electronic charge e. Most of the ordinary particles, like the proton, the neutron, and the so-called π-mesons consist of u- and d-quarks. For example, the proton is supposed to be the combination u u d, giving the charge +1, the neutron is ddn, giving zero charge. The π-mesons are combinations of the type ud, du, dd, etc., where the bar means "antiquark" which carries opposite charge. Thus we get π-mesons of charge +1, -1,0 as observed. The s- and c-quarks are quarks with special properties named "strangeness" and "charm". This terminology refers to certain observed properties of excited nucleons and mesons which distinguishes them from other nucleons and mesons and which can be transmitted from one to the other in collision processes. So, for example, there is an excited nucleon state: dds, which carries "strangeness", or ddc which carries "charm". The electric charge of the s- and c-quark is supposed to be -1/3 and +2/3 respectively.

This is not the place to enter into any detailed discussion of these combinations. Suffice it to say that most, if not all, transformations and creations of particles observed so far are relatively easily interpreted when this picture of the nucleon- and meson-structure is used. Furthermore, definite evidence for the quark-structure of the proton and neutron was found when the electron-scattering at high energies was analyzed. In a M.I.T.-Stanford collaboration an experiment was performed several years ago which is similar to the Rutherford's experiment in 1911 when he found the structure of the atom. Rutherford bombarded the atoms of a metal foil with α-particles (charged helium nuclei) and found they suffered from time to time abnormally large angular deviations. Rutherford interpreted these events as a scattering by a small charge concentration within the atom and thus discovered the atomic nucleus. The M.I.T.-Stanford group also found abnormally large angular deviations when electrons of much higher energy were scattered by protons or neutrons. They also concluded that there must be small charged units within those bodies — probably the quarks — much smaller than the measured size of the nucleon.

What are the forces of nature that keep the quarks within the nucleons and mesons, the nucleons with the nucleus, the nucleus and the electrons within the atom, and the atoms within the molecules, and the molecules within a piece of matter, and the matter within a planet or star, and the star within a galaxy?

We know that the last two effects are due to the all-pervading force of Gravity. Actually, it is a very weak force but gravitational attraction increases with the mass of the objects; it is completely negligible on the scale of elementary particles but, of course, plays a decisive role on the scale of extremely massive astronomical entities.

Quantum theory requires that any force field is quantized, in the sense that the field is able to propagate in free space in form of field quanta. They are emitted or absorbed by the sources of the field, which, in the case of gravity, are all massive entities. Therefore "gravitons" should exist, the field quanta of the gravitational field, but they have not been discovered yet because of the extreme weakness of the coupling between the sources and the field.

We already discussed before the dominant role of the electric forces in the structure of atoms and molecules. Indeed they are the forces responsible, not only for keeping the negative electrons close to the positive atomic nuclei, but also for the somewhat weaker interatomic and intermolecular attractions (the chemical forces) which cause the formation of molecules and of solid matter. These chemical forces are a kind of spill-over of the strong electric attractions within the atom, in the sense that the electrons of one atom are also drawn to the nucleus of a neighboring atom.

It was recognized early in the 19th century that electric and magnetic phenomena are related. Indeed, the magnetic field is a necessary corollary of the electric field; they are both components of one and the same field, the electromagnetic one which is produced by electric charges. The corresponding field quantum is the photon, which is emitted and absorbed by any system of charged particles, such as atoms or molecules.

The nucleons are held together within the nucleus by the nuclear force, a short ranged but powerful agent that force the nucleons to stay with the confines of the nucleus. The nature of that force is still somewhat obscure today but it is most probable that, in analogy to the chemical forces, it is a spillover of the more fundamental force which keeps the quarks within the nucleons. Now we have reached the limit of real knowledge and enter the realm of speculations and hypotheses. We know little about the forces between quarks which are generally called: strong interactions. We infer from certain observations that they are relatively weak when the quarks are close together within the nucleon or meson. They become very much stronger when the distance between the quarks become larger than the dimensions of nucleons or mesons (about 10^{-13} cm). The attraction then may grow so steeply and steadily that it may be quite impossible to separate a quark from those entities; perhaps quarks exist only in groups of three within nucleons or in groups of quark-antiquark pairs within mesons and never as isolated units. There are many speculations about force-fields that indeed have properties of that sort. Whatever the outcome of this intellectual struggle may be, some kind of force field must be responsible for the interactions within and between nucleons and mesons, and for other manifestations of strong interactions such as the nuclear force. The quanta of this field are aptly called "gluons". They are still hypothetical particles which, like the quarks, may not exist as isolated entities.

There is a fourth force of nature besides gravity, electromagnetism and the strong interactions. It is called the "weak" interaction. It is so weak that it cannot hold particles together and form new entities as do the other forces. It manifests itself in different ways. Fast neutrinos are weakly scattered by nucleons and, sometimes, in the process, transformed into electrons. This effect exists probably also for other particles but it is so weak that it can only be observed with neutrinos since they do not respond to any other force but the weak interaction. It also is responsible for the transformation of some particles into others. For example, a neutron transforms itself into a proton with the emission of an electron and a neutrino. However, it takes the incredibly long time of 12 minutes to do so. (The time scale for other processes within the nucleons is of the order of 10^{-22} sec). Indeed there is a large number of such decay process known among nuclei, nucleons, and mesons, one of them is the previously mentioned decay of the heavy electron into an ordinary one and two neutrinos. Naturally one assumes that some special force field is responsible for these interactions, whose field quanta are usually referred to as "intermediate bosons" or "W-particles". They were not yet observed because of two reasons: the weakness of the interaction makes their appearance rather rare, and the very short range of the weak interactions (the neutrino has to pass closely by the proton to be deviated, the electron-neutrino pair is emitted very close to the neutron) points to a very high mass (50 to 100 proton masses) for the field quantum. Indeed, the weakness of the weak interactions may be due to the enormous mass of the field quantum. Weak processes at very high energies, comparable to the mass-energy of the quantum (10^{11} electron volt) may turn out to be as strong as the electromagnetic processes. Indeed, that possibility has stimulated some theories asserting that weak and electromagnetic forces are related in the sense that they are the components of a more general field. Those theories represent the first step towards a unification of the different forces that act between elementary particles. This unification must be the aim of any consistent theory of elementary particles. Today we are very far from this aim in respect to the strong and gravitational interactions. The former are still hidden behind a veil of ignorance about the nature and significance of what we call quarks today, and no connection has yet been found between gravity and the nature of elementary particles.

The efforts of the physicists during the last decades have yielded much progress in the field of particle physics. A large number of important new phenomena were discovered and some order was perceived in the subnuclear realm pointing towards another deeper level of elementary particles which we describe today in terms of quarks. In spite of this progress, we are still far from a fundamental understanding of this realm of phenomena which must contain the answers to some of the basic problems of the natural world, such as reasons for the existence of a unique electric charge of the electron and its particular size, and the reasons for the large mass difference between nucleons and electrons. There are two examples from the list of unanswered fundamental questions which are decisive for the understanding of the character of our environment. Finally the question arises whether we ever will reach the final level of elementarity in our search for the fundamental laws of nature or whether new, unexpected realms of phenomena will appear whenever we prod deeper into the structure of matter. Only further experimentation can decide this question.

Elementary Particles 1976

Quarks	type	charge
"up"	u	$2/3$
"down"	d	$-1/3$
"strange"	S	$-1/3$
"charm"	C	$2/3$

subject to:
strong interaction, weak interaction,
electro-mag. interaction

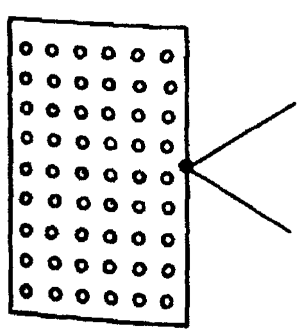
Leptons	type	charge
electron	e	-1
e-neutrino	ν	0
heavy electron	μ	-1
μ-neutrino	ν'	0

subject to:
weak interaction, electro-mag. interaction

Interactions

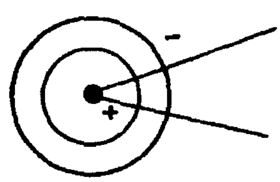
kind	transmitted by	source
gravity	graviton	mass
electro-magnetic	photon	charge
weak interactions	W-meson	weak charge
strong interactions	gluon	some new property of quarks

Matter
consists of
Atoms



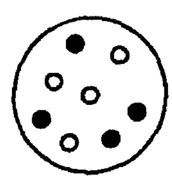
held together
by
Chemical Force

Atom
consists of
Electrons
Nucleus



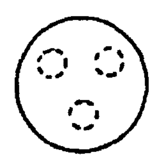
held together
by
Electric Force

Nucleus
consists of
Protons
Neutrons



held together
by
Nuclear Force

Nucleon
consists of
Quarks



held together
by
Strong Interaction