

Physics in the 20th Century

V. F. Weisskopf

But to sacrifice particle physics certainly does not mean that the resources will go into something equivalent. CERN and related Laboratories are a successful venture in physics, and they themselves represent just the tip of the iceberg in terms of their total effect on physics. The existence of their excellent experimental facilities and the high calibre of scientist that they attract has an effect which gives extra vitality, both directly and indirectly, to physics departments in Universities throughout Europe.

Also CERN is a successful venture in terms of the organization of large scale science. It is perhaps the most successful of all the efforts at European collaboration. When there is much that has not succeeded, it would be a pity to jeopardize that which has.

Despite the serious problems which individual countries seem to be confronting one after another, Europe still has colossal resources both materially and intellectually. Particle physics is a comparatively small but significant field where, at present, they are being successfully applied.

Professor Weisskopf spent several summer months at CERN working in the Theory Division. During his stay he has given three talks to the Summer Vacation Students under the title 'Fundamental Questions of Physics'. Some of the themes in his talks also appeared in the talk which he gave at the Inaugural Conference of the European Physical Society in April. The Proceedings will be published as a special issue of 'La Rivista del Nuovo Cimento' and can be purchased from Messrs. Editrice Compositori, Viale XII Giugno 1, 40124 Bologna, at an estimated cost of \$ 12.

Reviewing the development of physics in the 20th century is indeed a dazzling experience. Relativity, quantum theory, atomic physics, molecular physics, the physics of the solid state, nuclear physics, astrophysics, plasma physics, particle physics, all these new insights into nature are children of the 20th century.

There was a definite change in the character of physics at the turn of the century. The older physics was under the spell of two fundamental forces of nature: gravity and electromagnetism. The development of classical mechanics from Galileo and Newton to Lagrange and Hamilton had shown the validity of the same natural law, the law of gravity, on earth and in the universe. Electrodynamics, a child of the 19th century, reared by Faraday, Maxwell and Hertz, was the first extensive application of the field concept in physics; it revealed the importance of electric phenomena in matter. The discovery of the electromagnetic field as an independent entity in space, the spectrum of electromagnetic waves, the electromagnetic nature of light, are some of the greatest human insights into the natural world. But the properties of matter were not understood at that time, they were not deduced from more elementary concepts, they were measured and expressed in the form of specific constants of materials, such as elasticity, compressibility, specific heat, viscosity, conductivity of heat and electricity, dielectric and diamagnetic constants.

The physicists of the 19th century were not unaware of the importance of interatomic forces for the determination of material properties. But there was no way of telling what the origin of these interatomic forces was, and how to account for their strength or absence. The great variety among the properties of the different elements was not considered a topic

for physicists; it was the task of the chemists to analyze and systematize them, as was done so successfully a hundred years ago by Mendeleyev in his periodic system of elements. The specific features of the different species of atoms, their characteristics optical spectra, their chemical bounds, were known and catalogued by the chemists, but they were not considered a suitable subject for physicists.

The electron was already discovered before 1900 and it became obvious that electrons must be essential parts of the atomic structure, but classical physics could not give any clue as to the kind of structure one should expect within the atoms. The discovery of a quantum of electric charge, dominating all electric and optical phenomena was the beginning of a long development, in which deep insights into the essence of matter were gained. It behoves us to say, however, that the significance of this unit of charge is still a major riddle today, a hundred years after its discovery.

In physics, the 20th century truly begins in the year 1900. This date is not an accident, it is the year of publication of Max Planck's famous paper on the quantum of action, the birth year of quantum theory. It is impressive to contemplate the rate of progress in the first quarter of this century: Planck's quantum of action in 1900, Einstein's special relativity theory in 1905, Rutherford's discovery of atomic structure in 1911, Bohr's quantum orbits and explanation of the hydrogen spectrum in 1913, Einstein's general relativity in 1916, Rutherford's first nuclear transformation in 1917, Bohr's explanation of the periodic table of elements (Aufbauprinzip) in 1922, the discovery of quantum mechanics by de Broglie, Heisenberg, Schrödinger and Bohr in 1924-26, the exclusion principle by Pauli in 1925, the electron spin by Uhlenbeck and Goudsmit in 1927, the relativistic quantum mechanics by Dirac in 1928, Heitler-London's theory of the chemical bond in 1927, the theory of metallic conductivity by Bloch and Sommerfeld in 1930. Let us stop there, although the rate of progress by no means stopped in 1930; it went on for at least another ten years, before slowing down to the relatively slow pace of today.

Among the great systems of ideas which

were created in that period, relativity theory, special and general, has a place somewhat different from the others. It was born in the 20th century as the brain child of one towering personality. It is a new conceptual framework for the unification of mechanics, electrodynamics and gravity, which brought with it a new perception of space and time. This framework of ideas, in some ways, is the crowning and synthesis of 19th century physics, rather than a break with the classic tradition. Quantum theory, however, was such a break; it was a step into the unknown, into a world of phenomena that did not fit into the web of ideas of 19th century physics. New ways of formulation, new ways of thinking had to be created in order to gain insight into the world of atoms and molecules, with its discrete energy states and characteristic patterns of spectra and bonds.

These new ways of thinking were formulated and codified in the midst of the third decade of this century. The wave particle duality was proposed by de Broglie in 1924, the equation for particle-waves was conceived by Schrödinger in 1925. In these years the concepts of quantum mechanics were expressed and critically analyzed in Copenhagen under the leadership of Niels Bohr, with the help of ideas of Heisenberg, Kramers, Pauli and Born. The ink of these papers was hardly dry when the new way of thinking was applied successfully to explanations for almost all atomic phenomena that puzzled physicists since they had been discovered. The rules of quantization of Bohr and Sommerfeld, which seemed arbitrary when they were invented, turned out to be logical consequences of quantum mechanics; atomic spectroscopy became a deductive science; the semi-empirical Aufbauprinzip of Niels Bohr emerged logically from quantum mechanics, with the help of Pauli's exclusion principle. Mendeleev's periodic table was easily explained. A few years later, the chemical bond was understood as a quantum mechanical phenomenon, so was the structure of metals and of crystals. A variant of a famous Churchill statement can aptly be applied to this golden age of physics: *'Never before have so few done so much in such a short time'*.

Let me mention three characteristic

features which quantum mechanics has brought to our view of the atomic world. First, it has introduced a characteristic length and energy which dominate the atomic phenomena, endowing them with a scale and a measure. The combination of electrostatic attraction between the nucleus and the electron on the one hand, the typical quantum kinetic energy of a confined electron on the other hand, define a length: the Bohr radius, and an energy: the Rydberg unit. The size of the atoms is determined by the length which is the combination $\hbar^2/me^2$ of a few fundamental constants, the unit of charge e , the electron mass m , and the quantum of action $\hbar$. The Rydberg unit is given by the combination $me^4/\hbar^2$. Thus atomic sizes and energies are basically determined and explained.

Second, quantum mechanics introduces a 'morphic' trait, previously absent in physics. The electron wave functions represent special forms of patterns of simple symmetry, characteristic of the symmetry of the situation which the electron faces in the attractive field of the nucleus and of the other electrons. These patterns are the fundamental shapes of which all things in our environment are made. These shapes are directly determined from the fields of force which bind the electrons. Here quantum mechanics has created the concept of ideal identity. Two atoms are either in the same quantum state, then they are identical; or in different ones — then they are definitely non-identical. The continuous transition between identical, almost identical and different has disappeared.

The third feature is the use of quantum numbers for the characterization of quantum states. Quality is reduced to quantity: the number of electrons and the quantum numbers of a given state fully determine all properties of the atom in that state. Pythagorean ideas are reborn here: the spectrum of frequencies of an atom represents a characteristic series of values, the typical chord of that atom, as it were; the 'harmonies of the spheres' reappear in the world of atoms. Kepler's speculation of simple geometrical and numerical ratios between the sizes of planetary orbits in the solar system proved to be wrong, but it is reborn in the electron orbits of the

atom, as a direct consequence of quantum mechanics.

A fundamental problem of natural philosophy was solved by the discovery of laws which give rise to specific shapes and well-defined entities. Clearly, Nature is basically made of such entities, as our experience tells us every day; materials have characteristic properties, iron remains the same iron after evaporation and recondensation. The specific properties of matter were the subject of chemistry before and not of physics. Quantum mechanics explains these properties and thus has eliminated chemistry as a separate science.

The infinitely varied, but well defined, ways in which atoms aggregate to larger units are now accessible to a rational interpretation in quantum mechanical terms. A theory of the molecular bond came into being in which electron wave patterns keep atomic nuclei together in the right arrangement. Since one again deals here with the interaction of nuclear charges and electrons, the same sizes and energies must appear as in atoms, giving rise to interatomic distances of a few Bohr radii and binding energies of the order of electronvolts. Atomic aggregates consist of two kinds of particles, heavy nuclei and light electrons, which are bound to each other by mutual attraction. The interatomic distances are fixed by the size of the electron cloud, a length which also can be regarded as the amplitude of the zero point oscillation of the electron. Because of the much heavier mass, the zero point oscillations of the nuclei in a molecule are much smaller (the ratio is the square root of the mass ratio); hence the nuclei form a rather well localized skeleton in molecules and solids, a fact which introduces a structural feature into chemistry, and material science, with all its architectonic consequences. The quantum mechanical description of atomic aggregates leads to an understanding of all these material properties and material constants of which classical physics collected empirical information. In principle, all these constants that we mentioned above can be predicted and expressed in terms of the fundamental constants e , m , $\hbar$ and the nuclear masses.

The well-defined structure of the nuclear



Professor Weisskopf speaking at the Inaugural Conference of the European Physical Society in Florence.

(Photo Torrini)

framework in molecules is of special significance in macromolecules, which are long linear arrays of molecular groups. The enormous number of different orderings of these groups, each order being well defined and reasonably stable, is reflected in the numerous species of living systems in our flora and fauna, due to an intricate copying and reproduction process which has been unravelled during the last decade. So chemistry, material science and molecular biology are direct descendants of the quantum mechanics of electrons in the Coulomb field of atomic nuclei. The basic structures have a limited stability measured in fractions of the characteristic energy unit, the Rydberg. Perturbations of a strength of a few electronvolts would disrupt them. This is the tender world of chemistry and biology which is destroyed at temperatures higher than a few electronvolts as is the case in most stars. Matter, in the form in which we are accustomed to see it, is a rare phenomenon in the universe. There is more between heaven and earth.

The faint glow of radium in Mme Curie's hand was the first indication of the existence of other phenomena in matter. It was soon apparent from radioactive processes that there must be much higher energies than the Rydberg unit relevant in the atom. Rutherford made use of these energies in order to penetrate into the structure of atoms, when he discovered the atomic nucleus by anomalous scattering of alpha-rays in atoms. Incredible as it may seem, he used the same tool only six years later (1917) in order to study the composition of the nucleus and found that some of its constituents are protons. A new world of

phenomena was discovered. However, the composition of the nucleus was only disclosed fifteen years later in the great year of physics, 1932. In that year Chadwick discovered the neutron, Fermi published his theory of the radioactive beta-decay and Anderson and Neddermeyer discovered the positron. Each of these three discoveries had far-reaching significance.

The existence of the positron confirmed the validity and depth of Dirac's relativistic wave equation (1927), one of the most remarkable examples of the power of mathematical thinking. This equation — a marriage of quantum mechanics with relativity theory — demonstrated the necessity of the existence of an electron spin with its typical magnetic moment. In addition, it exhibits a fundamental symmetry corresponding to the existence of two types of matter, ordinary matter and antimatter with equal properties but opposite charges and other characteristic quantum numbers.

The discovery of the neutron as a constituent of the nucleus revealed the existence of a new force in Nature. It pointed towards a strong non-electric effect which keeps neutrons and protons tightly bound with the confines of the nucleus. Here a manifestation of something new was observed, a new force of nature without any analogue in macroscopic physics. The strong interactions were discovered.

Fermi's theory of the beta-decay demonstrated the existence of another interaction between elementary particles. A neutron can transform itself into a proton with the emission of a lepton pair — an electron and a neutrino. This is the so-called weak interaction which appears as a fourth interaction, besides the gravitational, electromagnetic and strong. It is so weak that the

time scale of its nuclear processes is of the order of seconds, days or years. Thus the year 1932 was the beginning of a new type of physics dealing with the structure of the nucleus and its constituents, and working with hitherto unknown forces and interactions.

Let us return to the force between neutron and proton. Scattering experiments have revealed a rather complicated structure of this force. It is short-ranged and attractive, except for small distances of less than a Fermi when it becomes repulsive. It is also strongly dependent on the relative spin orientation of the two particles and on the symmetry of the wave function. In this respect, as well as in respect to the repulsive nature at small distance, it resembles the chemical force between two atoms, an analogy to which we will return later. As an estimate of the strength of attraction, let us compare it with the electrostatic attraction which would be present if the neutron and the proton had opposite electric charges g and $-g$. It turns out that the nuclear attraction is roughly equivalent to an electric attraction between two opposite charges of a size $g \sim 3e$. This information allows us to estimate the approximate size and energy of simple nuclear systems by applying the same quantum mechanical principles as was done for the atom. All we have to do is to take the expressions for the Bohr radius and Rydberg unit and change e into g , and the electron mass into the nuclear mass. We then obtain the nuclear Bohr radius ($\hbar^2/mg^2$) of about 2×10^{-13} cm, and the nuclear Rydberg ($mg^4/\hbar^2$) of about 3 MeV. Nuclear systems are 10^{-5} times smaller than atomic systems and the relevant energies are in the million electronvolt region.

Once the nuclear force was established, quantum mechanics could be applied to the nucleus as a system of neutrons and protons. We find in nuclear physics a repeat performance of atomic quantum mechanics, but with a different scale of units. Nuclear energy level spectra presented a similar structure to atomic spectra, with the same kind of quantum numbers. One significant addition appeared however, the isotopic spin quantum number. It originates from the fact that the

nuclear force does not distinguish neutrons from protons so that one should consider the two particles as equivalent states of a single particle, the nucleon. Thus a formally similar situation arises as with the two ordinary spin states of a fermion, and this analogy led Heisenberg to the introduction of the important concept of isotopic spin and its quantum numbers.

The weak interactions provide a process of changing a neutron into a proton and vice versa, so that the spin analogy has also a dynamical sense. The nuclear system therefore is not an entity with fixed numbers of neutrons and protons; all that is fixed is the total number A of nucleons. All nuclei with equal A belong to the same quantum system and one finds approximate degeneracy and other typical relations between quantum states of nuclei with equal A , which differ only by the replacement of neutrons by protons.

There are many striking similarities between atomic and nuclear structure. One is the periodicity of properties as a function of the atomic number A , arising from a similar shell structure. The occupation numbers at which the shells are completed are slightly different because of the different nature of the average potential and because of the important role which spin orbit coupling plays in nuclei. The role of the noble gases, consisting of high stability and low reaction rates, is played in nuclear physics by those nuclei for which shells are completed.

The analogy between atoms and nuclei is perhaps not thoroughly justified. It is probably more correct to compare nuclei with molecules where the nucleons play the role of the atoms rather than the nuclei. Why? The force between nucleons is complicated, both in its dependence on distance and on other properties. That force is much more like the chemical force between atoms, with its repulsive character at small distances, its minimum of potential in between and its dependence on the symmetry of the wave function. It is tempting to assume that, in analogy to the chemical force, the nuclear force is not a fundamental force such as the electrostatic attraction; it may be a derived effect of a more basic phenomenon residing within the nucleon, a residue of something much

more powerful and simple, just as the chemical force is a residue of the Coulomb attraction between electrons and nuclei within the atom.

Modern particle physics has discovered much evidence for an internal structure of the nucleon but has not yet been able to interpret it. The most important evidence is the fact that the nucleon seemingly changes its state when bombarded with energetic particle beams. It can be excited to a large number of quantum states. These states form a level spectrum which represents a third spectroscopy in which excitation energies are measured in GeV and not in MeV as in nuclei, or eV as in atoms. This level spectrum shows similar regularities as the others, the same quantum numbers appear with addition of a new one introduced by Gell-Mann and Nishijima, the hypercharge or strangeness. Transitions between the states occur again with emission or absorption of light quanta and lepton pairs, but a new form of energy exchange was found: the absorption or emission of mesons. The search for the internal structure of the nucleon is one of the most challenging frontiers of modern physics.

The existence of excited states certainly points to some internal dynamics. The presently known spectrum of these states exhibits certain regularities which are vaguely related to those of a system consisting of three kinds of particles with half-integer spin, sometimes referred to as 'quarks' or 'stratons'. In addition, the regularities in the spectrum of mesons — they also have been observed in many quantum states forming a spectrum — point towards a structure of mesons being made up of a pair of a quark and its antiparticle. In this hypothetical picture, the mesons are the quantum states of a quark-antiquark system, in analogy to positronium, which is an electron-positron system.

The question of an internal structure of the electron has not yet been opened. The most puzzling aspect of this question is the existence of the heavy electron or muon, a particle which, seemingly, is in every respect identical with the electron, except that it is 200 times heavier. It may be that the four known leptons — electron, muon, two types of neutrinos — represent the beginning of a more compli-

cated lepton spectrum. Although today the electromagnetic interactions of the electron are extremely well described by the almost perfect theory of quantum electrodynamics, there remain grave questions regarding the nature of the electron: the reason for the apparent uniqueness of the elementary charge, the existence of the heavy electron, the source of the electron mass and, last but not least, the nature of weak interactions with their puzzling violations of established symmetries, such as right- and left-handedness and matter-antimatter symmetry.

Modern particle physics presents many challenging problems for the understanding of the numerous unexpected phenomena which were discovered. Theoretical understanding does not yet go very far, although theoretical physicists here contributed many ideas, models and analogies in order to correlate and systematize the wealth of experimental material. There is no Rutherford of particle physics yet, but neither has its Niels Bohr appeared. The lack of success is not caused by any lack of intellectual effort. The great insight into what goes on within a so-called elementary particle is not yet at hand.

(There is another variation of Churchill's remark: *'Never have so many done so little in so long a time'*. The value of achievement, however, must be measured in terms of the greatness of the task. Let me quote a favourite story of Niels Bohr about a British Lord telling of his exploits in lion hunting. When a young lady in the audience asked him how many lions he caught, he replied *'None'*. Whereupon the lady retorted *'Isn't that rather few'*. The Lord's reply was: *'Not for lions'*.)

So far, we have sketched the development of our knowledge of the structure of matter in the 20th century, from atomic physics to modern particle physics. Science develops not only in this 'intensive' direction towards smaller sizes, higher energies and towards phenomena and laws which are hidden deeper within the units of matter. There is also an 'extensive' direction of development in which the knowledge of the basic laws and properties of matter are applied to the understanding of broader fields of enquiry.

Modern physics of the solid state can

give a detailed account of the behaviour of metals, semi-conductors and crystals of all kinds. In particular, the behaviour of solid matter at very low temperature revealed phenomena such as superconductivity, which, for a long time, defied all explanation. But also these phenomena together with the superfluidity of certain liquids at low temperature, turned out to be understandable and derivable from the same basic assumptions about the quantum nature of atomic dynamics. It took a long time until adequate concepts were found which made it possible to formulate the main features of the quantum behaviour of systems with many constituents. Once such concepts were formed, they helped not only to understand the strange behaviour of bulk matter at low temperatures, but also some features in the behaviour of heavy nuclei, and these concepts served even to elucidate some problems of quantum electrodynamics and other field theories. The applicability of new concepts in many fields of physics is one of the gratifying developments which emphasize the unity of physics.

New vacuum techniques, microwave devices and strong magnetic fields make it possible to study plasmas, a form of matter at high temperatures and low pressure where most electrons are no longer in their atomic quantum orbits. This state of matter is very common in the universe, in the interior of stars as well as in the expanses of space. The behaviour of the plasma state is dictated by very simple laws; the electromagnetic interaction between nuclei and electrons. Quantum effects are negligible because of the high excitation. Hence we are dealing with the classical physics of electrons and nuclei which, surprisingly, is more complicated than quantum physics because of non-linear effects and various instabilities.

An account of physics in the 20th century would be very incomplete without mentioning astrophysics. It is a science born in this century and is the frontier of physics at extremely large distances, in contrast to particle physics, which is the frontier of extremely small distances. There is good reason to believe that the two are intimately related. There were two major insights which have shaped this branch of

science. First, the recognition of nuclear reactions as the source of stellar energy, and second, the discovery of the expanding universe. The first discovery has shown that nuclear reactions are infinitely more important for the production of energy than ordinary chemical reactions. However, nuclear processes do not occur on earth with the exception of those few radioactive elements which are the last embers left over from the great supernova explosion in which our terrestrial matter was produced. We had to reproduce nuclear processes in our laboratories in order to study them. The places in the universe where they occur at a large scale are the interiors of the stars and the big star explosions. It was no mean feat of man to recreate on earth processes which naturally are found only in the centre of stars and to make technical use of them, although some of these uses have been destructive ones.

The second discovery, the expansion of the universe, is mysterious and of fundamental significance. A new time and space scale appears. It is the time in which the universe has expanded to its present state, an interval of approximately 10^{10} years. We are very far from knowing what the universe was like at the beginning of this time, but one fact is sure: the matter of our present universe was in a very different state at that time. The time interval also defines a length (the distance that light travels during that interval); it is the radius of the present universe, from beyond which no message can ever reach us. It defines a maximum size — about 10^{10} light years — in which our world is embedded.

The 20th century is to the universe what the 16th was to the earth: Magellan sailed around the planet and showed that there is a finite surface to it. We have learnt in this century that there is a finite universe which we can be in contact with and we have almost fathomed its depth when stellar objects were seen with a red shift of the order unity.

Modern astrophysics has brought a new aspect into physics: the historical perspective. Previously, physics was the science of things as they are; astrophysics deals with the development of stars, of galaxies, with the formation of the elements, with the expanding universe. There are many un-

solved questions in this history, many phenomena such as quasars, which are unexplained, but part of this history is fairly well understood. It is the part in which stars are formed from a hydrogen cloud, elements are formed by synthesis from hydrogen, stars are developing through different states — some ending as cold chunks of solid matter, others ending in tremendous explosions which we observe as supernovas, sometimes leaving behind fast spinning neutron stars. One of these explosions occurred in the year 1054 AD and left the famous Crab Nebula behind in which we see the expanding remnants of the explosion with a pulsar in the centre.

The kinetic energies produced when larger stars contract after their nuclear fuel is exhausted, are such that individual protons reach energies of the order of a GeV, that is the energy of their rest mass. Therefore high energy physics will come into play at these stages of development and all the newly discovered phenomena of nucleon excitation and meson production will take place at a large scale, just as nuclear reactions take place at a large scale in the centre of ordinary stars. Perhaps it is significant that such energies are reached when the gravitational energy of a particle becomes of the order of its mass. This is the so-called Schwarzschild limit, at which the gravitational field becomes critically large and bends the local space such that light may not be able to leave, if our present ideas of gravity are still applicable to such unusual conditions. This may point to a connection between high energy physics and gravitational phenomena.

The cosmological aspects of matter reveal a certain insignificance of electronic quantum physics in the universe. Only rarely is matter in a state where the quantum properties of electrons around nuclei are of relevance. Mostly, matter is too hot or too dilute. But it is at those special spots where quantum orbits can be formed that nature developed its atoms, its aggregates, its macromolecules and its living objects. It is there where the greatest adventure of the universe takes place where Nature in the form of man begins to understand itself.