HIGH-ENERGY PHYSICS

TENTH ROCHESTER CONFERENCE

THE annual international conference on high-energy physics, known more commonly as the 'Rochester Conference', has, over the past decade, produced a sequence of elaborate progress reports on the status of current experimental and theoretical research in one of the most rapidly growing fields of physics. Under the leadership of Prof. Robert E. Marshak, it began in 1950 as an informal seminar at which a handful of specialists considered the implications of the newly discovered π-mesons. When even newer classes of particles were observed in cosmic radiation, and when the great accelerators began to operate, the scope of the conference naturally widened, so as gradually to encompass all the problems that make up the modern science of particle physics. The size of the delegation increased as well, reflecting the growth in the number of physicists engaged in these problems. At the tenth Conference, which was recently held in Rochester, 350 delegates from more than twenty nations gathered in order to assess the results of their most recent research, and to plan the work that lies ahead. The meeting lasted from August 25 until September 1. During the first two days, detailed reports were presented in four simultaneous sessions. These were followed by four plenary sessions during which the earlier discussions were summarized by *rapporteurs*, and three sessions of invited papers on topics of general interest. It is impossible to give a useful account of all these proceedings in abbreviated form, particularly when it is addressed to an audience of non-specialists. I have therefore chosen to review the set of fundamental principles toward the study of which the work at high energies is being directed. I shall then describe some of the more prominent features of the tenth Conference, emphasizing those reports that appear to provide new links in the chain of argument.

Outside gravitation, which seems to play no significant part in nuclear physics, there are three kinds of forces in Nature. The most familiar of them is the electromagnetic interaction, for which the classical theory was developed by Maxwell and Lorentz. Its extension to microscopic phenomena has been achieved in a quantum theory of electrodynamics. The theory describes the interaction in terms of the typical virtual process $e \rightarrow e + \gamma$, where e is any charged particle and γ is a photon. The symbol e also represents the unit of charge, of which all natural charges appear to be exact multiples. The strength of the interaction is measured by the dimensionless universal constant $e^2/\hbar c = 1/137$, $\hbar$ being Planck's constant and c the speed of light in vacuum. The theory has scored many successes, and its essential validity, except possibly at very high energies, is not questioned.

The second kind of force encompasses the 'strong' interactions between particles of certain classes. A quantum field theory of the strong interactions has developed from the original work of Yukawa, and is typified by the virtual process $p \rightarrow n + \pi^+$, where p is a proton, n a neutron, and π^+ a positively charged pion. The dimensionless coupling constant for the pion-nucleon interaction is $g^2/4\pi\hbar c \simeq 14$, where g has the physical dimension of charge. The fundamental significance of the charge g is no more clearly understood than that of the electric charge e. Furthermore, the coupling constants associated with other strong interactions are presumably different, but all are believed to be of the same order of magnitude. Because of several technical difficulties the theory of strong interactions has proceeded cautiously, guided closely by new experimental discoveries. But certain simplified forms of the theory, developed principally by Chew and his collaborators, have provided semi-quantitative descriptions of many phenomena.

We encounter finally the 'weak' interactions, which are the most mysterious of all the forces. They are typified by the β-decay of a nucleon; for example, $n \rightarrow p + e^- + \bar{\nu}$, where $\bar{\nu}$ is an antineutrino. Weak interactions couple other classes of particles as well. There is no experimentally identified field quantum, analogous to the photon and the pion, associated with the weak interactions. The present description of the phenomena is a development of the original work of Fermi. In his theory, the coupling constant characteristic of a weak interaction is not immediately dimensionless, but it is conventionally written in units that involve the Compton wave-length of the charged pion. Weak couplings so defined have strengths of the order of 10^{-14}, a number to be contrasted with 10^{-2} for the electromagnetic coupling, and with 10 for strong coupling. It appears that weak interactions have at least roughly the same strengths in all their manifestations. This observation has led to the hypothesis of the universality of weak interactions, but a precise formulation of the principle has not yet been made, nor has it been applied quantitatively to experimental data in an unambiguous way. A great advance in our knowledge of weak forces was recently initiated by Lee and Yang. Their suggestion that the interactions need not be invariant to spatial reflexion has been experimentally verified in many different ways, and has led to important clarifications of symmetry principles underlying all physics.

The particles of physics, among which the three types of forces are supposed to act, are separated first into two general groups: the bosons and the fermions. By definition, bosons have spins (intrinsic angular momenta) that are integral multiples of $\hbar$. Fermions have half-integral spins. Bosons are regarded as the quanta of the several kinds of field. Thus photons, with spin unity, are quanta of the electromagnetic field; pions, with zero spin, are quanta of the strong nuclear field. If quanta of the weak field exist, they are also presumably bosons. There is no conservation principle governing the number of bosons that may be created or destroyed in a collision. It is only necessary that energy, momentum, angular momentum, and charge be conserved. The number of fermions, on the other hand, is believed to be subject to strict conservation laws which I shall discuss shortly.

The bosons specifically associated with strong interactions are called 'mesons', and two classes of these particles have so far been observed. In addition to the pions (π) with masses near 0·14 BeV., there are the heavier 'kaons' (K) with masses near 0·50 BeV. (By the 'mass' of a particle I mean, of course, its rest mass. It is most convenient to write rest masses as rest energies in units of MeV. (10^6 electron-volts) or BeV. (10^9 electron-volts).)

There are two sets of fermions. One consists of particles lighter than the mesons, and are called 'leptons'. It includes the neutrino (ν), the electron (e^-), and the muon (μ^-). (Although once called the 'μ-meson' because of its intermediate mass, the muon does not conform to the modern definition of a meson.) The neutrino has zero mass, the electron mass is about 0·5 MeV., and the muon mass is about 106 MeV. The other set of fermions consists of particles heavier than mesons, and is called the set of 'baryons'. It includes the nucleons (N) with masses of about 0·94 BeV.; the Λ-hyperon, with mass 1·12 BeV.; the Σ-hyperons, with masses near 1·19 BeV.; and the Ξ-hyperons, with masses of about 1·31 BeV. The spins of all fermions are almost certainly 1/2. The baryons interact strongly with each other and with the mesons, and weakly with the leptons.

One may well wonder about the meaning of the term 'elementary particles'. The early periods of modern physics were characterized by searches for ultimate constituents of matter, and there were times when it appeared that the search had ended. The current point of view on this matter is somewhat different. The concept of an elementary particle is now thought to be useful only within a specific context of the contemporary experimental and theoretical situation, taking into account the types of interaction that one is investigating, and the particle properties that one regards as fundamental. In this sense the present list of elementary particles need not be final, even if no new species are discovered.

So far I have mentioned ten classes of particles (γ, ν, e^-, μ^-, π, K, N, Λ, Σ, Ξ). A further subdivision occurs when we take account of the different states of electric charge which most of the mesons and baryons can assume. Thus the π has three charge states (π^+, π^0, π^-); the K has two (K^+, K^0); the N has two (p, n); the Σ has three (Σ^+, Σ^0, Σ^-); and the Ξ has two (Ξ^-, Ξ^0). We then have a total of 17 particles. Furthermore, there is believed to be an antiparticle associated with each particle, having properties that are very simply related to those of the particle. This would give a total of 34. However, four of the antiparticles ($\bar{\gamma}, \bar{\pi}^+, \bar{\pi}^0, \bar{\pi}^-$) are experimentally indistinguishable from four of the particles. In this way, we arrive at the 30 unique objects which are under study in high-energy physics.

The multiplicity of charge states bears much formal resemblance to the multiplicity associated with ordinary spin. This observation has led to the idea of an 'isotopic spin vector', I, connected with a given particle or system of particles, and an isotopic spin space in which the vector resides. The z-component of isotopic spin, I_z, selects one of the possible multiplets of the system. For example, the vector I has magnitude unity for the π, with three possible projections on the z-axis representing a triplet (π^+, π^0, π^-). The importance of isotopic spin to the subject rests in the observation that I appears to be strictly conserved in strong interactions. The idea has not yet been given significance in the description of leptons.

The mathematical transformation of a particle into its antiparticle is called 'charge conjugation', and is denoted by the operator C. It is equivalent to a reflexion in isotopic spin space. Under the assumption that particle physics conforms to the principles of special relativity, it has been shown that perfect symmetry exists between a particle and its antiparticle. The two have the same mass, spin, lifetime, and modes of decay; they have opposite charge and magnetic moment. This symmetry is beautifully apparent in the electron-positron pair, on which precise experiments have been done. One believes not only that each of the other antiparticles exists (some of the antihyperons have yet to be discovered) but also that it must exhibit the same symmetry. Another powerful theorem based on relativity has been proved by Pauli and Lüders. It asserts that all interactions are invariant under the combined operation CPT, where C is charge conjugation, P is spatial reflexion (the parity operation), and T is time inversion.

All the conservation and invariance principles that are currently accepted in particle physics can now be stated in summary form. Some are taken over from classical physics, but most have only recently come to light as generalizations from new experiments. The list is as follows:

(A) Principles valid in all interactions:
1. Conservation of energy and momentum.
2. Conservation of angular momentum.
3. Conservation of charge.
4. Conservation of baryons (number of baryons minus number of antibaryons).
5. Conservation of leptons (number of leptons minus number of antileptons).
6. Lorentz invariance (CPT theorem; symmetry of particle and antiparticle).
7. Invariance under T (time inversion).

(B) Principles valid in strong and electromagnetic interactions, and violated in weak interactions:
8. Invariance under charge conjugation.
9. Invariance under spatial reflexion.
10. Conservation of I_z.

(C) Principle valid in strong interactions, and violated in electromagnetic and weak interactions:
11. Conservation of I.

In addition to these strict principles, there are several recently formulated selection rules for which much evidence has accumulated. The most completely confirmed of them states that, when mesons or baryons decay into one another, the magnitude of I for the system changes by $\frac{1}{2}$. This rule and some of the conservation principles can be illustrated by considering the modes of decay of the Λ-hyperon. The particle is electrically neutral, has half-integral spin, and has zero isotopic spin. There are several decay modes which are consistent with principles 1–5. Those that involve no more than three decay particles are:

$$\begin{array}{lll} \Lambda \rightarrow n + \pi^0 & (1) & \Lambda \rightarrow p + \mu^- + \bar{\nu} \;\; (5) \\ \quad\;\; p + \pi^- & (2) & \qquad\; n + \nu + \bar{\nu} \;\; (6) \\ \quad\;\; n + \gamma & (3) & \qquad\; n + e^+ + e^- \;\; (7) \\ \quad\;\; p + e^- + \bar{\nu} & (4) & \end{array}$$

Since the first two modes involve only baryons and mesons, which are strongly coupled to each other, we might expect that the decay would proceed very rapidly through these channels. But notice that the isotopic spin of the system $N + \pi$ must be a combination of two vectors the magnitudes of which are $\frac{1}{2}$ and 1 respectively. The only isotopic spin states allowed for this system are $I = 1/2$ and $3/2$. Therefore neither I nor I_z can be conserved, and a decay through strong interactions is impossible. The non-conservation of I_z also inhibits the radiative decay (3). We see in addition that, although decay modes of the type $\Lambda \rightarrow N + \bar{K}$ would satisfy conservation of isotopic spin, the mass of the final state exceeds that of the Λ and the mode is impossible if energy is to be conserved. We have thus shown that the particle cannot decay through strong interactions. Furthermore, since the decay does in fact proceed slowly through channels (1) and (2), we know that a weak interaction couples the particles, and we can use the decay rate to obtain an estimate of its strength. (If the Λ could decay through a strong interaction, its life-time would be of the order of 10^{-23} sec. The observed life-time is about 10^{-10} sec.)

Of the remaining modes of decay, (4) and (5) are not forbidden by any known rules, and can be expected to occur as poor competitors of (1) and (2). The remaining modes are forbidden by selection rules that have not been mentioned. Finally, it is to be noted that the $\Delta I = \frac{1}{2}$ rule requires the $N + \pi$ system in the Λ decay to occur only in the $I = \frac{1}{2}$ state. One can deduce from this that the mode $p + \pi^-$ should occur twice as frequently as $n + \pi^0$, a prediction that is well confirmed by experiment.

The fact that Λ cannot decay promptly permits us to regard it as an elementary particle, even though its life-time is short by ordinary standards. The situation is similar for all the unstable elementary particles, which constitute a majority of the list already given. Outside the stable particles (γ, ν, e^-, p), the longest lived is the neutron with a mean life of 10^3 sec., and the shortest lived is probably the Σ^0-hyperon, the life-time of which, although not yet measured, is expected to be in the neighbourhood of 10^{-19} sec. This example also illustrates the kinds of experiments that must be done in particle physics, and it gives a hint about their difficulty. In order to produce a Λ under controlled conditions, and to observe such a decay mode as $n + \pi^0$, one needs a large accelerator and detectors of considerable refinement. Notice that all the particles are neutral, and so do not produce ionized tracks.

Although the foregoing review constitutes a mere sketch of the high-energy field, it may serve as an adequate background for a short summary of the tenth Rochester Conference. I shall begin with developments concerning the weak interactions. Feynman has looked carefully at the question of universality, with particular attention to the life-time of the muon. Using recent experimental data on the beta decay of oxygen-14, he calculates a muon life-time of 2·251 ± 0·012 μsec. This is slightly longer than the best measured life-time, the discrepancy of about 2 per cent being considerably larger than the combined error. He concludes that the principle as commonly formulated is not quantitative, and he finds further that high-order corrections to the theory only aggravate the discrepancy. Gell-Mann reported on many recent speculations about this general question. He outlined a more abstract formulation of the universality idea, which might be able to cope with the weak interactions of all particles.

Several new experimental results have lent support to other ideas about weak interactions. Ljubimov (Moscow) described an investigation of the 'helicities' of muons in cosmic radiation. According to current theory, the muons in the decay $\pi^+ \rightarrow \mu^+ + \nu$ should spin in the left-handed sense around their direction of motion. The muons from π^- decay should be right-handed. Experiment confirms both predictions. Chuvilo (Dubna) reported on new observations of the decay modes of K^0, and showed that they are in agreement with predictions based on the $\Delta I = \frac{1}{2}$ rule. Additional support for the rule, based on asymmetry measurements in pionic decay of Σ and Λ, was reported by Cronin. It might be said here that none of the many experiments recently carried out has cast any doubt on the invariance principles and selection rules outlined above. With regard to strong interactions, I might first mention the current status of one of the oldest problems in nuclear physics. It concerns the force between nucleons. Early research brought out little more than qualitative facts about the strength and range of the force, without clarifying its details. With the advent of the synchrocyclotron, nucleon scattering could be done at energies up to several hundred MeV. It was discovered that such collisions lead to a strong polarization of the scattered beam, and this phenomenon has become an important tool in the most recent measurements of the interaction. At the conference, representatives of the groups at Harwell, Rochester, Harvard, and Dubna reported that almost all their results now fit into a unique and concise empirical scheme, which it is the aim of theorists to explain. With regard to the theory, one can say that the force at relatively large distances (down to about 3×10^{-13} cm.) is now well understood in terms of a single pion exchange potential. The behaviour at shorter distances, where multiple meson exchange is important, has not yet been dealt with quantitatively.

The strong interactions of K, Λ and Σ particles have also been studied intensively in recent work at the higher energies. The reports from Cornell, Saclay, Brookhaven, Berkeley, Dubna and CERN constitute an enormous library of new data on processes of many different kinds. A particularly interesting result was reported by Good (Wisconsin), who has studied the reaction $K^- + p \rightarrow \Lambda + \pi^- + \pi^+$, and has measured the momentum spectra of the pions. He finds structure in the spectra, suggesting the existence of quasi-stationary states of the $\pi - \Lambda$ system.

Bernardini (CERN) reported progress on the design of experiments for the utilization of energetic neutrino beams derived from the great accelerator in Geneva. It is expected on certain theoretical grounds that the cross-sections for neutrino reactions will be much larger at high energies than they are at low energies. For example, Lee and Yang have speculated about the reaction $\nu + N \rightarrow W + \mu + N$, where W is the hypothetical boson associated with weak interactions. The calculated cross-section for this reaction is 10^{-35} cm.^{2} at high energies; the cross-section for the only neutrino reaction carried out to date ($\bar{\nu} + p \rightarrow e^+ + n$) is 10^{-44} cm.^{2} at low energy.

Another important experiment still in the preparatory stage was described by Panofsky. It will investigate colliding beams of electrons, produced in the Stanford linear accelerator and stored in two magnet rings. The equivalent laboratory energy of the collision will be several thousand BeV., and will in this sense represent by far the highest controlled energy available to physics. It is hoped that the beams can be used to examine the validity of quantum electrodynamics in an energy region which has so far only been accessible in rare cosmic ray events.

Finally, I shall discuss a report by Heisenberg on progress being made in his theoretical group (Munich) toward the development of a general theory of elementary particles. They assume that the most general symmetry principles of the type summarized above are sufficient to specify a differential equation, the eigenvalues of which are connected with properties of the particles. Thus the symmetry principles rather than the particles themselves are regarded as the elementary notions of physics. A prototype of such theories is the relativistic wave equation proposed thirty years ago by Dirac, who was able to give a deductive account of electron spin and to anticipate the discovery of the positron. Several years ago, Heisenberg and Pauli proposed a non-linear spinor equation to which they were led by symmetry considerations. It appears that, since then, some significant steps have been taken toward illuminating the mathematical properties of the equation and deducing some of its physical consequences. There is as yet, however, no strong experimental evidence for or against the theory. Aside entirely from computational difficulties, the theory is open to certain conceptual objections. One of them stems from the fact that, for the equation to have non-trivial solutions, it must deal with an indefinite metric in Hilbert space. This leads to probability amplitudes of negative norm, for which no interpretation can be given in the usual formulation of quantum mechanics. Heisenberg hopes, however, that all such cases will correspond to virtual states of physical systems, and that negative probabilities may for this reason not be incompatible with the present structure of physics.

It may be clear from this sampling of the conference that the physics of high energies is active on many fronts. It should also be clear that there are fundamental questions still unanswered. Are there still more classes of particles ? Are the strict principles of present theory applicable at very small distances and at very high energies ? Is there a 'universal' weak interaction, and is there a field quantum associated with it ? Are the particles themselves to be regarded as the ultimate entities of physics, or are their properties derivable from a set of simple principles ? At any stage in the development of our knowledge there is always a class of questions which seems inaccessible to the methods of physics, but which is nevertheless eventually answered within the context of later developments. It is with a faith strongly supported by this observation that physicists are attacking the provocative questions now before them.

E. M. HAFNER

NEWS and VIEWS

Cloud Physics at the Imperial College of Science and Technology, London : Prof. B. J. Mason

DR. B. J. MASON has been appointed to a newly created chair in cloud physics at the Imperial College of Science and Technology as from October 1960, thus gaining academic recognition for sustained original work in this field over the past decade or so. He joined the Department of Meteorology at the Imperial College of Science and Technology in 1948, following graduation in physics with first-class honours at University College, Nottingham, in 1947 and some research with Dr. G. D. Yarnold on surface tension in the following year. Mason was led to take up research in cloud physics on reaching the Imperial College of Science and Technology, and he soon formed around him an active group of research students concerned mainly with microphysical processes, while his colleague, Dr. F. H. Ludlam, led parallel work on the macrophysics of clouds, to the benefit of the subject as a whole. Cloud microphysics, in Mason's hands, has advanced mainly by his skill in exploiting laboratory techniques and he has designed a number of quite beautiful experiments. Notable among these is the use of the diffusion cloud chamber, in collaboration with Dr. J. Hallett, to determine the forms—needles, plates, prisms, dendrites—in which ice is deposited as a function of temperature and supersaturation. This work has contributed not only to meteorology but, quite notably also, to modern solid-state physics. Mason was awarded the D.Sc. of the University of London in 1956, and was appointed Warren Research Fellow of the Royal Society in 1957. His authoritative text, "The Physics of Clouds", was published in 1957, and he has served on the Councils of the Royal Meteorological Society and the British Association and on Government research committees. Prof. Mason may now, with extra facilities and his noted enthusiasm, be expected to make an increasing impact on the study of cloud physics in Great Britain.

Physics in Hong-Kong : Prof. W. D. Chesterman

DR. W. D. CHESTERMAN has been appointed to the vacant chair of physics in the University of Hong-Kong. Dr. Chesterman graduated at the University of Bristol in 1934. He then became a student apprentice at the British Thomson-Houston Co. and on completion of his apprenticeship was appointed to the staff of the Company, where he remained until 1939, when he joined the Admiralty. His work in the Admiralty has been mainly in the fields of photographic and optical techniques and in underwater acoustics. He became a Fellow of the Institute of Physics in 1943 and of the Physical Society in 1945. During the past ten years he has gained an international reputation for his work on photographic techniques. He has published a book and a number of papers on high-speed photography, which have been very well received. During 1956–58 he was chairman of the International Committee on High Speed Photography, and in 1958 he was elected a Fellow of the Royal Photographic Society. In 1959 he was awarded the degree of doctor of science by the University of Bristol. The papers put forward for his doctorate included published accounts of his work in the fields of underwater acoustics, illumination optics, high-speed photography and oceanographic research.