Recent Advances in High-Energy Physics

By H. P. Noyes

THE PAST YEAR has seen what may turn out to be the start of great progress in our understanding of meson problems. This was brought into focus at the Third Annual Rochester Conference on High-Energy Physics, held December 18–20, 1952, and the topics discussed there form a convenient framework for presenting recent work in this field. The series of Rochester conferences, organized by R. E. Marshak and made possible by the support of a group of Rochester industries together, in the present instance, with that of the National Science Foundation, has consisted of informal sessions in which the latest experimental and theoretical results have been mulled over by representatives of most of the American and some of the foreign groups directly concerned with high-energy physics.

The starting point for the discussions last December was a survey of the experimental evidence for the hypothesis of the "charge independence" of nuclear forces. This hypothesis was originally suggested by the experimentally observed approximate equality of neutron-proton and proton-proton (symbolized below by *n-p* and *p-p*) scattering in the singlet state and eventually formulated in terms of a fictitious "isotopic spin space" or charge space. That is, just as elementary particles have an internal angular momentum or "spin" and reactions obey certain selection rules because the total angular momentum, J, is conserved, it is assumed that they also have an intrinsic "isotopic spin" (whose z component plus $1/2$ is their electric charge) and that in reactions the total isotopic spin, I, is conserved (in addition to the usual conservation of charge), also giving selection rules. This hypothesis was brought to the fore at the Second Annual Rochester Conference when it was pointed out that the π-meson scattering in hydrogen observed by the Chicago group in the one hundred Mev region could be most simply interpreted by assuming a "resonance" in the $I = 3/2$, $J = 3/2$ state of the pion-nucleon system and the conservation of isotopic spin.

But the experimental basis for the charge-independence postulate is still very shaky. In fact, as E. P. Wigner remarked, "never has there been as much theoretical thinking done on a subject the experimental foundation of which is as inadequate as this one". Thus, while there is a considerable body of evidence for the equality of *n-n* and *p-p* nuclear forces (which is sometimes referred to as "charge symmetry"), and while the correspondences between energy levels in light nuclei are suggestive of charge independence, the direct proof of the equality of *n-p* and *p-p* forces is still in doubt. It is known that the scattering lengths (essentially the strength of the nuclear potential) differ slightly for the two systems, but the comparison is subject to corrections involving the variation of the forces with distance and the interaction of the magnetic moments of the particles, which corrections cannot be made with sufficient precision without a more detailed knowledge than we possess about nuclear forces. Hence the single direct datum on which the charge independence hypothesis rests is the approximate equality of *n-p* and *p-p* effective ranges of interaction, and this is subject to about a twenty percent experimental error. In addition, charge independence requires that the *n-p* differential scattering cross section at 90° be greater than one-quarter of the corresponding *p-p* cross section; but again the experiments at high energy are not sufficiently precise to decide whether or not this condition is violated.

Charge independence has many detailed consequences for the production and scattering of π-mesons and nucleons, but unfortunately the verification of most of these relations would require the use of polarized beams and targets, which is beyond the reach of present technique. However, one special case that can be checked is the prediction that of two processes leading to the production of a π-meson and a deuteron, the process $p + p \rightarrow \pi^+ + d$ should have precisely twice the cross section for the process $n + p \rightarrow \pi^0 + d$ for the same energy and angle of emission of the pion. It is encouraging that experiments at Chicago have shown that the angular distributions coincide within experimental error; the ratio of two has yet to be demonstrated. During the past year there has been considerable improvement in the precision of the data on pion-nucleon scattering and the photoproduction of pions, but this will bear only indirectly on charge independence, and then only if it can be shown that "charge independent" meson theories are capable of explaining it. In particular, the extension of the energy range of the measurements of the photoproduction of π^0 mesons from hydrogen to 450 Mev at Caltech has shown a drop by a factor of four from the maximum cross section at 315 Mev, indicating that this is a rather special energy for the pion-nucleon system.

THEORETICAL PROGRESS made in the last year was summarized at the Third Annual Conference by J. R. Oppenheimer in the phrase "all the classic arguments that the pseudoscalar meson theory with pseudoscalar coupling—*PS* (*PS*) theory—is in disagreement with experiment have been shown to be incorrect." This is very important since it had already been shown that π-mesons have spin zero and odd parity with respect to nucleons, and the *PS* (*PS*) theory is, so far as we know at present, the only theory with these properties that is capable in principle of giving finite and unambiguous answers. The "pseudoscalar" character of the meson means essentially that if the nucleon

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velocity is nonrelativistic, the meson can only be emitted directly in states of odd parity and hence of odd angular momentum, that is, p-states at low energy, while the elementary interaction in states of even angular momentum (in particular in s-states) must involve nucleon pairs (which have odd parity by the Pauli principle) and hence high energies or an intrinsically strong interaction. "Pseudoscalar coupling" describes the specific meson-nucleon interaction Hamiltonian which has the property of including both types of interaction.

The difficulties with this theory came from trying to treat the interaction as intrinsically weak in the sense that only a couple of terms in a perturbation theory expansion need be included. The first great advance was made by Lévy, who showed that even though the interaction between two nucleons carried by this meson field is very strong at short distances, it is repulsive and hence can be simulated phenomenologically by an infinitely strong repulsion at a radius chosen to give agreement with experiment, while for low nucleon velocities the region outside this "core" could be represented by the potential derived from a few terms in a perturbation theory expansion. He was then able to fit all the low energy properties of the n-p system approximately by taking the dimensionless strength of the interaction $G^2/4\pi$ to be about 10 and the core radius to be about 0.4×10^{-13} cm. What was not realized immediately was that certain "radiative corrections" which enter as a multiplicative constant in certain terms of the potential are not affected by the nucleon velocities and involve arbitrarily high powers of the interaction parameter even outside the "core". Thus this theory actually contains a third arbitrary parameter which is in principle calculable, but is at present completely unknown. There is some reason to believe that it is much smaller than the value used in Lévy's calculations, but fortunately it has been shown that the results are very insensitive to the value of this parameter provided compensating adjustments are made in the interaction strength and core radius. The structure of the core, which has been ignored by this treatment, must rapidly become of decisive importance at higher energies, even perhaps at 20 or 30 Mev, and the quantitative predictions of the theory for p-p scattering in this region are still in doubt, but a not unreasonable theoretical program has led to a better over-all charge independent model for the nucleon-nucleon system than the previous phenomenological approaches. Further, when the three-body forces analogous to this potential are included, approximately the correct density and nucleon energy are obtained for infinite nuclear matter, whereas previous models led to collapse to very high densities.

It also became evident at the conference that calculations of the pion-nucleon scattering have been greatly improved by abandoning the straightforward perturbation theory expansion. The essential method used here (as well as in Lévy's work) was first suggested by Tamm and Dancoff. The basic idea is that even when the interaction is weak, a single meson can be absorbed and re-emitted many times in the course of a single scattering, and, since the energies of these successive intermediate states can be very close to the initial energy of the system, "resonance" effects can lead to results quite different from the perturbation theory approximation of including only one absorption and re-emission.

The simplest application of this point of view to the meson-nucleon system requires the inclusion of all states with zero, one, or two mesons present in the field at a time. G. F. Chew obtained an approximation to this situation by ignoring the relativistic properties of the nucleon and simulating nucleon recoil by simply cutting off integrals over momenta for values greater than the rest mass of the nucleon. His results reproduce the observed "resonance" in the $I = 3/2$, $J = 3/2$ state and fit the scattering in the other p-states approximately. It is clear from our previous discussion of angular momentum and parity that s-state scattering is ignored by treating the nucleon as nonrelativistic. When this approach is improved by taking the relativistic properties of the nucleon seriously, as has been done by F. J. Dyson and the group at Cornell, it is found that the quantitative behavior of the system does, in fact, depend very critically on the high momentum parts of the wave function, but it is still possible to obtain agreement with experiment for the p-state scattering using an interaction strength $G^2/4\pi$ of about 14 (the only parameter in the theory). Another interesting feature of these equations is that they predict that the resonance will be very closely followed by an anti-resonance much as has been observed in the photoproduction of π°'s (cf. above), although the exact relation between scattering and photoproduction is not clear.

Unfortunately, since the problem of formulating this approximation in a covariant way has not yet been solved, it is impossible to separate out divergences which occur in the $I = 1/2$ states in any satisfactory way. The s-state interaction in this approximation corresponds to a strong repulsion at the Compton wavelength of the proton; this "hard sphere" scattering varies with energy essentially as the first power of the meson momentum and has about the correct magnitude at 135 Mev. However, the experimental energy dependence is completely different, falling rapidly toward zero at 60 Mev and rising again at 40 Mev. If, as is now being investigated experimentally, the s-phase shift actually has opposite signs in the regions above and below 60 Mev, this would indicate an attractive region surrounding the "hard core" predicted by theory; in any case the experiments are extremely interesting because they provide evidence that pion and nucleon interact strongly at distances much greater than the proton Compton wavelength. Presumably this is a result of the interaction of the meson with the virtual meson cloud which envelops the nucleon out to distances of the order of the meson Compton wavelength. In fact, the theory does predict a very strong meson-meson interaction, but so far attempts to include it in the theory in a quantitative way have not been successful. Thus, although we are obviously still a long way from a quantitative theory of either the nucleon-nucleon or pion-nucleon system, the theoretical predictions have finally begun to bear some resemblance to what is found experimentally, which was hardly even remotely true a year ago.

But in order to keep this advance in its proper perspective, it must be remembered that only the vaguest guesses have been offered to explain the host of unstable particles heavier than π- or μ-mesons whose numbers keep on increasing. Since they are apparently produced with relative ease in very-high-energy nucleon-nucleon encounters, they must possess strong interactions with this system, and our present theoretical ideas would lead us to expect that they would decay to lighter particles via this interaction in times shorter by a factor of 10^{10} than are actually observed. The bright side of the picture has been the rapid experimental isolation of many of the new particles and the addition of a considerable amount of quantitative data. It is only possible, at present, to study these particles in the cosmic radiation, but it became apparent at the conference that a great deal has been learned from these studies. In fact considerably more is known about some of the particles than was known about π- and μ-mesons prior to the artificial production of pions by accelerators, and it is to be hoped that once the new particles have been produced by billion-volt accelerators, progress will be correspondingly rapid.

EXTENSIVE EXPERIMENTATION has been done at a number of laboratories on the charged and neutral V-particles first found by Rochester and Butler in 1948. It is well established that the type called V°_1 decays into a proton and a π-meson, but in order to prove that no neutral particle is also emitted, it is necessary to show that the plane defined by the charged daughters also contains the line of flight of the neutral parent. Cloud chamber studies at MIT, using several lead plates inside the chamber, reveal the high energy event in which the V°_1 originates in several cases and show conclusively that only the two charged particles are emitted in the decay; the decay energy, Q, is 37 Mev and the lifetime is about 3×10^{-10} seconds. A second neutral V-particle with the decay scheme $V^\circ_2 \rightarrow \pi^+ + \pi^-$ has also been observed, but the Q is only very roughly estimated as 200 Mev, while the lifetime is probably not very different from that for V°_1. Experiments at Caltech were also cited as giving evidence for $V^\circ_1{}' \rightarrow p + \pi^-$ with a Q of about 75 Mev, $V^+_1 \rightarrow p + (?)^\circ$, and $V^\circ_2 \rightarrow K^- + \pi^+$ where the negative particle is definitely heavier than a π^- meson and could be as heavy as a negative proton.

The alternative method used for the study of the decay of heavy particles is the study of their tracks in photographic emulsions, developed primarily at Bristol. Unstable charged particles whose masses probably fall in the range between 1000 and 1500 electron masses, and which are collectively denoted as K-particles, have been split into two types. The first to be discovered, the κ meson, has a μ-meson daughter whose energy is not unique and ranges up to a momentum of at least 280 Mev/c. Since at least two neutral particles must be emitted in addition to the μ-meson, and the decay appears quite analogous to the β-decay of the μ-meson, the tentative decay scheme is written as $\kappa \rightarrow \mu + 2\nu$, where ν may or may not prove to be the same neutrino as is "found" in β-decay. The second type of K-particle was at first classed with the κ-meson, but has since been shown to have a π-meson daughter with the unique momentum 212 Mev/c; in the decay scheme $\chi \rightarrow \pi + (?)^\circ$, the neutral particle could be as massive as V°_1 (i.e. $\sim 850 m_e$). A third type of charged particle, also observed first in emulsions, decays into three charged particles of mesonic mass, the preferred decay scheme being $\tau \rightarrow 3\pi$, although $\tau \rightarrow \pi + 2\mu$ cannot yet be completely excluded; the decay energy $Q = 74 \pm 2.5$ Mev in the former case. More work is needed to establish definitely the existence of another particle which appears to decay according to $\zeta^\pm \rightarrow \pi^\pm + (?\pi^\circ)$ with a Q-value less than 6 Mev.

Work with a multiplate cloud chamber has shown that many particles which stop in the plates and give rise to a meson (S-particles) or decay in the gas of the chamber ($V^\pm$-particles) are identical with the χ-mesons observed in emulsions in that they give rise to a π-meson with the same unique decay energy; that some of the other examples observed are κ-mesons is also quite likely. τ-mesons have also been observed in cloud chambers. It has recently been shown that the neutral pion exhibits an alternative mode of decay $\pi^\circ \rightarrow e^+ + e^- + \gamma$ which occurs with a frequency of 1/80 of the usual mode $\pi^\circ \rightarrow 2\gamma$; this is in good agreement with a previous theoretical prediction. Since the electron pair can be directly observed, its energy and distance from the point of origin of the π° give a much better indication of the π° lifetime than was previously obtainable; the result is that the π° meson decays in about 5×10^{-15} seconds. Thus, although there is no reason to believe that we have as yet seen anything like all the unstable particles, it is encouraging to see how much progress has been made toward establishing the decay schemes and energies of those already encountered.

Clearly, in so brief an account it has been impossible to touch on more than a few highlights of the Third Annual Rochester Conference on High-Energy Physics or even to give proper credit for the various contributions. The chairmen of the various sessions were C. D. Anderson, H. A. Bethe, E. Fermi, J. R. Oppenheimer, B. Rossi, and E. P. Wigner. Foreign representatives included E. Amaldi (Italy), C. J. Bakker (Holland), L. Le Prince-Ringuet (France), and D. H. Perkins (England). A comprehensive report of the proceedings has been prepared by three members of the Rochester staff: H. P. Noyes, M. Camac, and W. D. Walker, to which the interested reader is referred for details; the *Proceedings* are available through Interscience Publishers (New York) at a nominal cost.