A summary of the 4th Annual Conference on High Energy Nuclear Physics held at the University of Rochester last January.

Developments in High

By H. P. Noyes

THE CONFERENCE on January 25–27 at Rochester demonstrated that considerable progress has been made in our experimental understanding of the fundamental properties of nucleons and mesons and their mutual interactions during the past year, but that theoretical insight into the meaning of these results still leaves much to be desired. This was the fourth in the series of annual conferences organized by Professor R. E. Marshak and jointly sponsored by a group of Rochester industries and the National Science Foundation. These informal sessions serve as a meeting ground for representatives from most American and several European laboratories actively engaged in high-energy nuclear physics and cosmic-ray research, and have proved extremely valuable both for clarifying the amount of progress already made and the outstanding problems yet to be solved. In view of the wealth of material discussed, I have singled out only a few topics for detailed discussion in what follows.

The direct attack on the study of the forces between neutron and proton and between two protons has been broadened during the past year by the development of techniques which allow observation of the noncentral character of these forces. The basis of the method is the same as that first used to demonstrate the polarization of x-rays, namely a double scattering experiment. This is schematically indicated in Figure 1. The incident beam is scattered through an angle θ_1 defined by collimating slits or counters and then scattered by a second target at an angle θ_2 relative to this direction. If the force between the particles in the beam and the scattering centers is purely central, the intensity at all points along the indicated cone will be the same, so that a measured variation in intensity as the azimuthal angle ϕ is varied provides direct evidence that the forces acting are noncentral. In the language of the optical analogy, the first scattering is then said to produce a polarized beam, and the second scattering serves to analyze the amount of polarization produced. Prior to the double scattering experiments, attempts to explain the angular distribution observed in the scattering of unpolarized high-energy protons by protons had been made in terms of very strong noncentral forces. This hypothesis has now been strikingly confirmed experimentally by the discovery of large azimuthal asymmetries in double proton scattering at high energy. By now there is good agreement between several laboratories as to the variation of this asymmetry with the angle θ_2, but the interpretation of the even larger polarizations observed in the double scattering of protons by complex nuclei is still a matter of controversy. The fact that the charge distribution in the deuteron is not spherically symmetric has long been evidence for the existence of noncentral forces in the interaction between neutron and proton, but when a high-energy neutron beam is produced by protons incident on beryllium (quasi *p-n* scattering) and then scattered in hydrogen, the azimuthal asymmetry is considerably smaller than that observed in double proton scattering. However, since a *free p-n* double scattering experiment has yet to be done, it is by no means clear that polarization in *p-n* scattering is actually smaller than in *p-p* scattering. On the theoretical side, there is not at present even a phenomenological model capable of describing both the scattering process and the polarization effects in a quantitative way.

If one takes the point of view that nuclear forces are due primarily to the exchange of charged and neutral π mesons between nucleons,[1] the understanding of the interaction of π mesons with nucleons is the basic problem of nuclear physics. Extension of the empirical result that at low energy the neutron-proton and proton-proton forces in the same state are approximately equal (charge independence hypothesis) to the π meson-nucleon system leads to the idea that π^+, π^0, and π^- mesons are three charge states of a fundamental entity called the pion, just as neutron and proton are considered to be two charge states of a fundamental entity called the nucleon. Since the algebra used to combine charge states is strictly analogous to that used to combine orbital angular momentum with spin angular momentum, this is formalized by assigning an angular

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[1] See, for instance, the excellent review article by H. A. Bethe, *Physics Today*, February 1954, p. 5.

Energy Physics

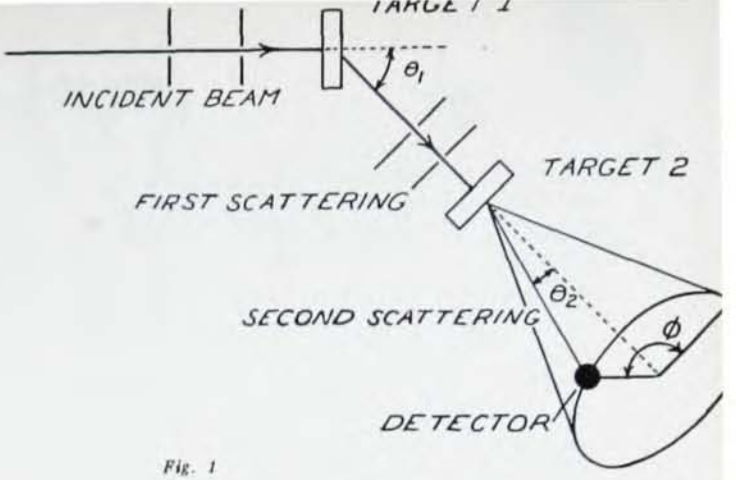

Fig. 1

momentum in a fictitious charge space, called the "isotopic spin", to each particle. In this notation the nucleon is a state of isotopic spin $I = 1/2$, the two possible projections of this spin along a given direction z being $I_z = +1/2$ for the proton and $I_z = -1/2$ for the neutron, while the pion is assigned an isotopic spin $I = 1$, with $I_z = +1$, 0, or -1 corresponding to π^+, π^0, or π^- respectively. By the usual rules for the composition of angular momenta, the pion-nucleon system can then be split into two states, one of isotopic spin 3/2 and the other of isotopic spin 1/2; the charge independence hypothesis asserts that each of these states should scatter independently, but that any state of the same isotopic spin should scatter the same way, regardless of what its precise composition is in terms of nucleons and pions. Under this hypothesis, one can then obtain *complete* information on the interaction of a free pion with a free nucleon from a study of any two of the three observed scattering processes $\pi^+ + p \rightarrow \pi^+ + p$, $\pi^- + p \rightarrow \pi^- + p$, and $\pi^- + p \rightarrow \pi^0 + n$, the third serving as a check on the assumption. This is fortunate, since scattering from free neutrons (which are unavailable as a target) or with π^0 mesons as the incident beam (with the lifetime of the π^0 being about 10^{-15} seconds) is hardly amenable to direct experimental study.

Recent experiments show that the total scattering cross section of π^+ mesons by protons goes through a fairly sharp maximum as a function of energy when the energy of the incident π^+ mesons is near 200 Mev, and that this cross section is nearly three times that for π^- mesons of the same energy in this region. Since $\pi^+ + p$ is a pure isotopic spin $I = 3/2$ state, while $\pi^- + p$ is a mixed state containing one-third $I = 3/2$ and two-thirds $I = 1/2$, this is good evidence for some sort of strong interaction or "resonance" in the $I = 3/2$ state at this energy. Moreover, the angular distribution of the scattered particles is consistent with that to be expected for a state of orbital angular momentum 1 and total angular momentum $J = 3/2$ (i.e. a $P_{3/2}$ state in spectroscopic notation). It is of great theoretical interest to see if this tentative conclusion can be put on a firm experimental basis, since the currently fashionable pseudoscalar meson theory can be made to yield a prediction that the $I = 3/2$, $J = 3/2$ state of the pion-nucleon system should exhibit some such behavior. Although alternative explanations of the observed angular distributions are allowed, it is possible to show that experiments at somewhat higher energies could confirm or confute this theoretical interpretation. Preliminary total cross section measurements have been extended all the way up to 1.5 Bev by experiments at the Brookhaven Cosmotron, and show that around 1 Bev, the π^- cross section goes through a broad maximum where it is about twice that for π^+. It is tempting to speculate that this is due to a second "resonance", this time in the $I = 1/2$ state, but other explanations are possible, and so far no theoretical reasons have been advanced which would lead one to expect this behavior.

Progress has also been made in pushing pion-nucleon scattering experiments to lower energies. In this region the interference between the usual inverse square law scattering due to the electric charges of the particles and that due to the short-range nuclear forces allows in principle a determination of whether the pion-nucleon force is attractive or repulsive in certain states. Recent experiments at 40 and 65 Mev give the theoretically expected answer to this question, but also allow an alternative explanation with attraction and repulsion interchanged, which more accurate experiments could probably either confirm or disallow. In addition, when these results are combined with experiments on the production of π^+ mesons by high-energy gamma rays incident on protons, they yield extremely interesting qualitative information about pion-proton forces. This concerns particularly the states of pion and proton which have zero relative angular momentum (S states); there are two such states, one of which has $I = 3/2$, and the other $I = 1/2$. Since, when a gamma ray has barely sufficient energy to produce a π^+ meson, this meson will tend to come off with zero relative angular momentum, it might be expected that this process will bear some relation to the low-energy pion-nucleon scattering. Studies of the production of π^+ mesons by gamma rays on hydrogen have now been pushed to low enough energy to disentangle these S wave effects. We now have to see how the connection to the scattering experiments can be made in a quantitative way.

The first thing to note in this connection is that the capture of negative mesons in hydrogen goes about half the time by the reaction $\pi^- + p \rightarrow \pi^0 + n$, which is clearly a "charge exchange scattering" at zero energy. The absolute rate for this capture is not known, but is approximately equal to the rate for the competing process $\pi^- + p \rightarrow n + \gamma$. The principle of detailed balancing would therefore enable us to compute this rate if

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the cross section for the inverse process $\gamma + n \rightarrow \pi^- + p$ were known. Unfortunately, since free neutron targets are unavailable, it is only possible to get at this cross section by assuming that the loosely bound neutron in the deuteron acts essentially as if it were "free" in the photoproduction process. What is measured is the ratio of negative to positive mesons produced in the two competing processes $\gamma + d \rightarrow \pi^- + p + p$ and $\gamma + d \rightarrow \pi^+ + n + n$. Finally, then, we have made a quantitative connection to the directly measured cross section for $\gamma + p \rightarrow \pi^+ + n$. The deductive chain can be written schematically as:

$$(\gamma+p \rightarrow \pi^+ + n) \times \text{Ratio} \frac{(\gamma+d \rightarrow \pi^- + p + p)}{(\gamma+d \rightarrow \pi^+ + n + n)} = (\gamma+n \rightarrow \pi^- + p)$$

$$(\gamma+n \rightarrow \pi^- + p) \times \text{Detailed Balancing} = (\pi^- + p \rightarrow \gamma + n)$$

$$(\pi^- + p \rightarrow \gamma + n) \times \text{Ratio} \frac{(\pi^- + p \rightarrow \pi^0 + n)}{(\pi^- + p \rightarrow \gamma + n)} = (\pi^- + p \rightarrow \pi^0 + n)$$

The S wave effect in the production of π^+ mesons by gamma rays on hydrogen therefore gives us a quantitative value for the cross section for charge exchange scattering at zero energy.

Unfortunately, the direct measurements of pion-nucleon scattering have almost entirely been for energies above 40 Mev, so that a direct comparison with the scattering experiments is still not possible, and some sort of theoretical argument must be used to make the extrapolation from the 40 Mev data to zero energy. The straightforward way to describe any scattering process is in terms of a parameter called the "phase shift" which measures the distortion of the motion of the particles relative to what would happen if there were no force between them. It is easy to show that if the two particles are in a state of zero relative orbital angular momentum (S state), the phase shift at low energy is simply proportional to the relative linear momentum of the particles, independent of the nature of the force acting. But if one assumes that 40 Mev is a "low" energy in this sense, and makes the extrapolation, the cross section predicted for charge exchange scattering at zero energy is four times larger than the value calculated in the manner indicated above from the threshold photoproduction cross section for π^+ mesons; this is well outside the error of the experiments. Since the sign of the phase shifts indicates whether the effect of the force between the particles is attractive or repulsive, and since the charge exchange cross section depends on the *difference* between the phase shifts for $I = 3/2$ and $I = 1/2$, the large charge exchange cross section above 40 Mev shows that one state is attractive and the other repulsive; conversely, the small value of this cross section at zero energy shows that the net force in this region is attractive (or repulsive) in both states. The charge independence hypothesis asserts that the same phase shifts describe the elastic scattering process $\pi^- + p \rightarrow \pi^- + p$, but that the cross section depends on their *sum* rather than their difference. This is consistent with the results above 40 Mev, since the elastic scattering is indeed considerably smaller than the charge exchange scattering. But our interpretation of the small charge exchange scattering at zero energy then forces us to assume that the elastic scattering will be large; preliminary experiments at 5 Mev tend to confirm this, and thus strengthen our conclusion that both states act the same way at very low energy.

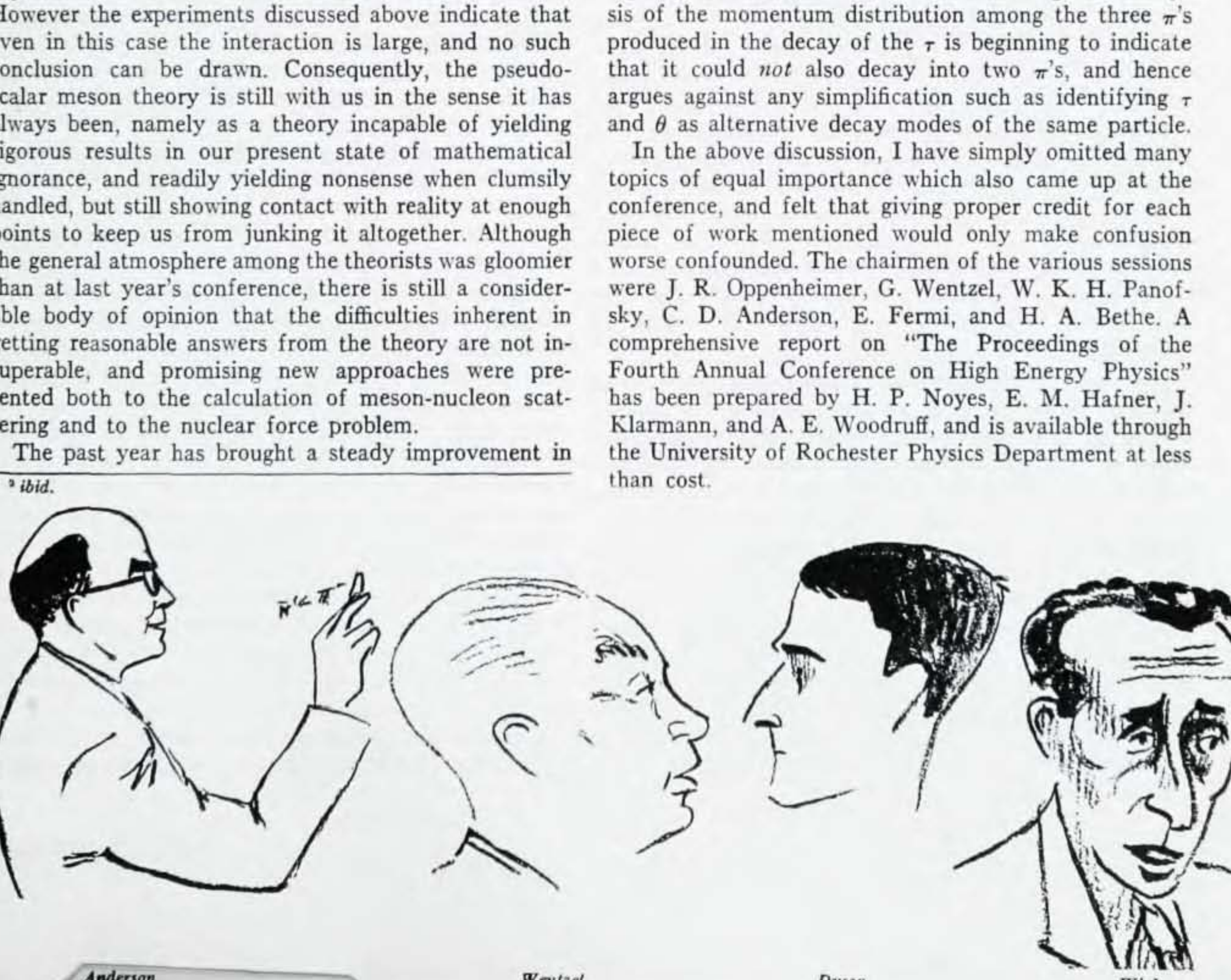
Comparison with the "resonance" at 200 Mev in the $I = 3/2$, $J = 3/2$ state, which could only be due to a strong attractive force, shows that it is the S state with $I = 1/2$ which is attractive above 40 Mev, and if this behavior persists to lower energies, we must explain the reversal in behavior of the $I = 3/2$ state. The simplest way to do this is to assume that both states exhibit an attraction between pion and nucleon when the distances of separation are large, but that in the $I = 3/2$ state there is in addition an extremely strong repulsion at short distances. (This is just the sort of behavior we would expect if the meson is attracted by the cloud of virtual mesons which must surround the nucleon, but repelled in interaction with the nucleon "core" itself.) At low energy the over-all effect in the $I = 3/2$ state will be one of attraction; at higher energies the attractive region becomes less and less effective in changing the direction of motion of the particle, whereas the particle still cannot enter the region of strong repulsion, and the net effect is one of repulsion. Until scattering experiments around 5 Mev show us once and for all whether both states are attractive or both repulsive at low energy, we could take the alternative view that the $I = 3/2$ state retains its repulsive character down to low energies while the $I = 1/2$ interaction somehow changes from attraction to repulsion. But it is extremely difficult to picture any dependence of force on distance which could lead to this type of behavior.

Attempts to describe the properties of free π mesons in terms of the conventional meson theories have been extremely successful, and have shown conclusively that this particle has spin zero and pseudoscalar parity relative to the nucleon.[2] But, although there is only one known way of describing the interaction of these mesons with nucleons that is consistent with charge independence and can even in principle lead to finite and unambiguous predictions, order of magnitude estimates of the strength of the interaction parameter make it so large as to make all approximate methods of calculation extremely questionable. Since this parameter is unknown, in order to check the theory it is necessary to find two processes, both of which are capable of rigorous theoretical treatment and experimental evaluation, and, by using the value of the interaction parameter calculated from one of them, predict the experimental result for the other. This past year brilliant attempts have been made to calculate both pion-nucleon scattering at zero energy and photoproduction of pions at threshold *rigorously* in order to make this check. Unfortunately, the removal of infinite quantities from the theory is done in different ways in the two calculations, leading to a different definition of the interaction parameter, and comparison can be made between the two only in terms of expansions in powers of this parameter. It looked for a while as if one of the parameters was so small that the expansion would converge, and if this had turned out to be true, the theory would have been in such clear-cut disagreement with experiment that it would have had to be abandoned. However the experiments discussed above indicate that even in this case the interaction is large, and no such conclusion can be drawn. Consequently, the pseudoscalar meson theory is still with us in the sense it has always been, namely as a theory incapable of yielding rigorous results in our present state of mathematical ignorance, and readily yielding nonsense when clumsily handled, but still showing contact with reality at enough points to keep us from junking it altogether. Although the general atmosphere among the theorists was gloomier than at last year's conference, there is still a considerable body of opinion that the difficulties inherent in getting reasonable answers from the theory are not insuperable, and promising new approaches were presented both to the calculation of meson-nucleon scattering and to the nuclear force problem.

The past year has brought a steady improvement in our knowledge of the various shortlived unstable particles originally discovered in the cosmic radiation, some of which are now artificially produced at Brookhaven. They are now divided into two classes, those heavier than neutrons being called hyperons, and those intermediate in mass between proton and π mesons being collectively denoted as K-particles. The most commonly observed hyperon is $\Lambda_0 \rightarrow p + \pi^- + 35$ Mev; a few cases of other decay energies are reported, one with a negative particle of close to protonic mass and a π^+ meson as decay products. Some examples of $\Lambda^+ \rightarrow n + \pi^+ + 135?$ Mev and $\Omega^- \rightarrow \Lambda^0 + \pi^- + 65$ Mev are also seen. Among the K-particles, $\tau^\pm \rightarrow \pi^\pm + \pi^+ + \pi^- + 74$ Mev is well established, and an alternative mode of decay $\tau^\pm \rightarrow \pi^\pm + 2\pi^0$ is also reported. $\theta^0 \rightarrow \pi^+ + \pi^- + 214$ Mev is often seen, although the possibility that one of the decay products may be a μ instead of a π is not completely excluded. $\chi^\pm \rightarrow \pi^\pm + (?)^0$ with the momentum of the π approximately 200 Mev/c is in dispute; $\kappa^\pm \rightarrow \mu^\pm + 2(?)^0$ with the momentum of the μ ranging from a few Mev/c up to 280 Mev/c is still with us. Evidence was presented at this conference for still another particle, namely $K_\mu \rightarrow \mu + (?)^0$, the momentum of the μ being 220 ± 3 Mev/c, so it is probably premature to hope that the list is near completion. Theoretical attempts to reconcile the ease of production of these particles with their subsequent long lifetimes are still in the speculative stage. Evidence that the Λ^0 can replace a neutron in a complex nucleus is available experimentally, and explicable phenomenologically if one takes its free behavior as given. Analysis of the momentum distribution among the three π's produced in the decay of the τ is beginning to indicate that it could *not* also decay into two π's, and hence argues against any simplification such as identifying τ and θ as alternative decay modes of the same particle.

In the above discussion, I have simply omitted many topics of equal importance which also came up at the conference, and felt that giving proper credit for each piece of work mentioned would only make confusion worse confounded. The chairmen of the various sessions were J. R. Oppenheimer, G. Wentzel, W. K. H. Panofsky, C. D. Anderson, E. Fermi, and H. A. Bethe. A comprehensive report on "The Proceedings of the Fourth Annual Conference on High Energy Physics" has been prepared by H. P. Noyes, E. M. Hafner, J. Klarmann, and A. E. Woodruff, and is available through the University of Rochester Physics Department at less than cost.

[2] *ibid.*



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