STRONG INTERACTIONS

A Conference Report by ***A. C. Helmholz***

A TOPICAL Conference on Strong Interactions took place on December 27, 28, and 29, 1960 at the Department of Physics of the University of California in Berkeley. The Conference overlapped by one day the regular Pacific Coast Meeting of the American Physical Society. This meeting was sponsored by the American Physical Society; financial support was generously provided by the Atomic Energy Commission and by the Air Force Office of Scientific Research.

The sessions were held in LeConte Hall on the Berkeley campus for the first two days and on the third day in Wheeler Auditorium. The meeting was open, and about three hundred high-energy physicists attended. The Wednesday afternoon program was abbreviated so that all could visit the Bevatron at the Lawrence Radiation Laboratory. A large number of those attending took this opportunity and had a chance to inspect several of the different experimental setups as well as the Bevatron itself. At five o'clock that afternoon at the Claremont Hotel in Berkeley a cocktail party was held for those at the Conference and their wives. On Thursday morning along with the American Physical Society visitors, some of the wives took a bus trip over the "Three Bridges" with luncheon in Sausalito.

On Tuesday and Wednesday the program was essentially experimental, but a number of problems in theory were brought up and discussed. The Thursday sessions were devoted entirely to theory. The most interesting development concerned the Y^* phenomena, treated in more detail below. There was considerable talk about and reference to the $\pi-\pi$ interaction although no positive experimental evidence concerning it was presented. Attention was called to the importance of high-energy inelastic processes of the peripheral or one-pion exchange type. The choice of strong interactions seemed a timely one; and the meeting was lively, interesting, and informative. It is hoped that most of the reports with discussion will be published in the 1961 July issue of the *Reviews of Modern Physics*.

THE first session on Tuesday morning was devoted to fundamental interactions, mainly π-nucleon. E. H. Rogers of the Lawrence Radiation Laboratory talked about the $\pi^+ - p$ interaction at 310 Mev, particularly of some relatively accurate measurements of the differential cross section and the polarization of the recoil protons. Polarization gives additional information concerning the phase shifts in the $\pi^+ - p$ system. If one assumes that only S, P, and D waves are significant, the polarization results definitely show that the so-called Fermi phase shifts rather than the Yang phase shifts are valid. The results are unique and the statistical errors are small. However, when small F phase shifts are allowed, ambiguities in the S, P, and D phase shifts are possible. Hence the situation is not so well settled as had been hoped and further polarization measurements over a larger range of scattering angles are needed.

Paul Falk-Vairant of Saclay, France, reported results on the reaction $\pi^- + p \rightarrow$ neutrals from 400 to 1600 Mev, along with simultaneous measurement of the total cross section. Analysis of the 900-Mev resonance seems to indicate that it is elastic with $J = 5/2$ or $7/2$. Analysis of the existing data on the reactions $\pi^- + p \rightarrow \pi^+ + \pi^- + n$ and $\pi^- + p \rightarrow 2\pi^0 + n$ indicates that the final state of the two pions is a $T = 1$ state. Falk-Vairant then described an experiment to differentiate between one and more than one

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Wilson Powell (right) shows Berkeley's 72-inch bubble chamber to R. K. Adair, E. O. Salant, and E. C. Fowler. (*Photos courtesy Lawrence Radiation Laboratory, University of California.*)

neutral pion in the reaction of π^- with protons, by studying the properties of the decay photons. The simple charge-exchange (one π^0) reaction shows the same structure as the total charge exchange. The inelastic reaction $\pi^- + p \rightarrow 2\pi^0 + n$ shows a broad peak of 4 mb at 800 Mev and drops to 2 mb at 1200 Mev.

B. J. Moyer of the Lawrence Radiation Laboratory reported the $\pi^- - p$ scattering experiment of Wood, et al., in which the angular distribution of the elastically scattered π^- mesons at 550, 600, 720, 900, and 1020 Mev was measured. For the 600-Mev resonance the angular distribution shows only very small contributions higher than $\cos^2$ of the center-of-mass scattering angle. Some interference effects must eliminate higher powers of the cosine since the polarization measurements of recoil protons in photo-π^0 production indicate a strong contribution of the $D_{3/2}$ state at this energy. The angular distribution at the 900-Mev resonance shows strong spin-flip effects ($\cos^4$ and $\cos^5$ effects) indicating that this resonance is a mixture of D and F states rather than a resonance in a single angular-momentum state.

E. C. Fowler of Yale University discussed an experiment carried out at the Brookhaven National Laboratory. The reaction $\pi^+ + p \rightarrow K^+ + \Sigma^+$ was studied in a hydrogen bubble chamber. For an incident pion energy of 1 Bev the total and differential cross sections were measured. Comparison of these with the previously measured cross sections for $\pi^- + p \rightarrow K^+ + \Sigma^-$ and $\pi^- + p \rightarrow K^0 + \Sigma^0$ at the same energy indicate that the inequality required by the charge-independence hypothesis is satisfied for these strange-particle reactions.

On Tuesday afternoon R. K. Adair of Yale University and Brookhaven reported on work with the

R. H. Dalitz and V. F. Weisskopf

interaction of K_2^0 particles in a hydrogen bubble chamber. He discussed particularly the reaction leading to $\Lambda + \pi^+ + \pi^0$. This system can be conveniently studied with the help of a Dalitz plot in which the energy of one π is plotted versus the energy of the other. If there are only S waves and no interaction in the final state, the energetically allowed region of the Dalitz plot should be uniformly populated. However, neither of these conditions is valid. In addition, the fact that the π's are bosons may alter the distribution. Adair's results point to a "resonance" in the Λ, π system with a Q value of 130 ± 10 Mev, a probable spin of 1/2, and a width which is consistent with 0. Max Ferro-Luzzi that afternoon and Margaret Alston the next morning (both of the Lawrence Radiation Laboratory) reported on their findings in the reaction $K^- + p \rightarrow Y^{*\pm} + \pi^{\mp}$, $Y^{*\pm} \rightarrow \Lambda + \pi^{\pm}$. When the Dalitz plot for the reaction is examined, there is a strong peaking of points at energies of 1385 Mev for the system Λ,π, which corresponds to $Q = 130$ Mev. Alston reported a half-width of the "resonance" of 32 Mev; Ferro-Luzzi, 15 Mev. Attempts to determine the spin and angular momentum of this Y^* lead to the tentative conclusion that it is an $S_{1/2}$ state. No evidence is found for the decay of the Y^* into $\Sigma + \pi$. There was considerable discussion of these results from the point of view of theory. All experimental values reported at the conference disagreed significantly with one another and with the prediction of global symmetry. In comments both at the Tuesday afternoon and the Thursday morning sessions, Dalitz (University of Chicago) distinguished several types of resonant state for elementary-particle systems. Simple resonances where the confinement mechanism is the centrifugal barrier, such as the (3,3) pion-nucleon resonance, are well known. For multichannel systems, "bound state" resonances can also occur, the bound state arising primarily from the forces between particles in the closed channels. Coupling to energetically available channels leads to rapid decay of the state, so that it will be seen as a scattering resonance in the open channels. This possibility was pointed out several years ago for the $\bar{K}$-nucleon system by Dalitz and Tuan, and one of their four sets of $\bar{K} - N$ scattering parameters which are consistent with the low-energy $\bar{K}$-proton data allows a straightforward interpretation of the $\Lambda - \pi$ resonance (Y^*) as an $I = 1$ "bound state" of the $\bar{K} - N$ system. This interpretation requires $J_{Y^*} = 1/2$, as appears to be the case, and it also allows the position and relatively narrow width of the Y^* resonance to be explained in a natural way. The evidence that the $\Lambda - \pi$ resonant state is $S_{1/2}$ suggests odd (K,Λ) parity as is consistent with what other indications exist. The smallness of the Σ/Λ ratio at resonance follows if the (Σ,Λ) parity is odd, but other interpretations are also possible. Rosenfeld and Gell-Mann also discussed the relative parities, and Gell-Mann conjectured that the Y^* and the Σ may be identical particles but of opposite parity.

Margaret Alston in her talk also pointed out evidence for a resonance in the K, π system, called the K^*, which was observed in the reaction $K^- + p \rightarrow K^{*-} + p$ at an incident K momentum of 1.15 Bev/c. Decays of the K^{*-} into $K^0 + \pi^-$ and $K^- + \pi^0$ were observed; and from the ratio of the two decay modes, it was suggested that the isotopic spin of the K^* is 1/2. The mass appears to be 885 Mev with a width of about 15 Mev.

A. M. Wetherell of CERN reported on the high-energy experiments of several groups at CERN. These were the total cross sections for $p - p$ and $\bar{p} - p$ at high energy, $\pi^- - p$ production of strange particles at 16 Bev/c, and work on inelastic collisions in the nucleon-nucleon system. The $p - p$ cross section appears nearly constant at 39–40 mb between 4 and 28 Bev/c. The $\bar{p} - p$ cross section is greater than the $p - p$ but appears to be decreasing with energy in a manner which would be consistent with Pomeranchuk's theorem which predicts that at infinite energies these two cross sections should be equal. At 13 Bev/c the total $\bar{p} - p$ cross section is 47 mb. If one assumes the nonannihilation part is equal to the $p - p$ cross section, 39 mb, then 8 mb is left for the annihilation cross section. A guess of 10 mb for the elastic part leaves 29 mb for the inelastic part of the $\bar{p} - p$ cross section. At 13 Bev/c measurements on the $K^- + p$ and $K^+ + p$ cross sections indicate that the K^- cross section is about 25% greater and the two cross sections are apparently not approaching a common high-energy value, in contradiction to Pomeranchuk's theorem; but the π^- and π^+ data are tending to the same value.

The angular distribution of the strange particles produced in the $\pi^- + p$ reactions at 16 Bev/c is unusual. For example, of the 34 lambda particles, all went backward in the center-of-mass system. It was suggested that an explanation might involve the exchange of a strangeness-bearing particle in peripheral collisions. The inelastic scattering of protons on Be gives yields in general agreement with Drell's ideas on peripheral inelastic collisions. Structure is ob-

served in the proton spectrum for incident energies less than 15 Bev/c. At 24.5 Bev/c the structure seems to have vanished.

The final speaker on the Tuesday afternoon program was Leroy Kerth of the Lawrence Radiation Laboratory, who surveyed the $K^{\pm} - p$ cross sections. One essentially new result was the observation of a resonance in the $K^- - p$ total cross section at momentum 1050 Bev/c. Kerth discussed the attempts to analyze the data in the light of dispersion relations, pointing out particularly the additional data necessary before such an approach will be meaningful.

WEDNESDAY morning's session was entitled "Interactions in the Final State." A. Abashian of the Lawrence Radiation Laboratory opened with an account of the experiments of Crowe, Booth, and himself on the momentum spectrum of H^3 and He^3 in the reaction $p + d$. That portion of the He^3 spectrum associated with double-meson production appears to show a deviation from phase-space predictions in the form of a bump which can be accounted for by a neutral particle of mass about 310 Mev or a resonant system with isotopic spin 0. Chew speculated that if $J=0$ this "particle" would show up in K decay and that therefore it might have $J = 1$.

Observations on the annihilation of 1.61 Bev/c antiprotons in passing through a liquid-hydrogen bubble chamber were reported by G. R. Lynch of the Lawrence Radiation Laboratory. The branching ratios for the annihilation modes in which 2π mesons and in which $2K$ mesons are formed were given as approximately 2×10^{-3} and 1×10^{-3}, respectively. In the $2K$ mode, a tendency for the K^- to go forward was noted. Cross sections were also reported for the $\Lambda\Sigma$ charge-exchange reactions producing $\Lambda\bar{\Lambda}$, $\Lambda\bar{\Sigma}^0$, and $\bar{\Lambda}\Sigma^0$. The inelastic reactions $\bar{p} + p \rightarrow \bar{p} + p + \pi^0$ and $\bar{p} + p \rightarrow \bar{p} + n + \pi^+$ were observed and cross sections reported. A possible method, utilizing these data, for establishing invariance of the strong interactions under charge conjugation was discussed.

The results of G. Goldhaber et al., on pion-pion correlations in antiproton annihilations were discussed by W. Chinowsky of the Lawrence Radiation Laboratory and Brookhaven. The observed distribution in angle between pairs of pions of like charge is greater for small pair angles and smaller for large pair angles than the predictions of the statistical model. It was pointed out that the inclusion of the effect of Bose statistics in the statistical model produces such a correlation but the required interaction volume (radius $\approx 0.7\hbar/m_\pi c$) is inconsistent with the multiplicity distribution. No marked deviations are observed for the unlike-pair angular correlations. Phenomenological calculations of Goldhaber and Lee to include the effect of the $T = 1$, $J = 1$ resonance at energy about $3m_\pi c^2$ indicate an effect opposite to that observed; that is, the calculations favor smaller angles for unlike pion pairs.

P. G. Burke of the Lawrence Radiation Laboratory reported an experiment on the reaction $\pi^{\pm} + N \rightarrow N + 2\pi$ for the purpose of obtaining the cross section for $\pi - \pi$ scattering by the polology technique. The incident pion momentum was 1.03 Bev/c, which is close to the Σ-K threshold as well as to the third $\pi - N$ resonance, but the effects of these two reactions are expected to be small. Subject to the usual uncertainties in this type of extrapolation, they find the cross section for $\pi - \pi$ scattering is small up to values of w^2 (w = total energy of the two-pion system in its own rest frame) between 15 and 18 pion rest masses squared; the cross section then begins to rise to a value of 150 mb at $w^2 = 21$. This does not agree with the prediction of Frazer and Fulco of a peak in the cross section in the neighborhood of $w^2 = 10$–12 pion rest masses squared.

The final speaker on the morning program was E. O. Salant of the Brookhaven National Laboratory, who reported on recently completed measurements on the inelastic reactions $\pi^- + p \rightarrow \pi^- + \pi^+ + n$ and $\pi^- + p \rightarrow \pi^- + \pi^0 + p$ at the pion-nucleon resonance of 900 Mev. These are of particular interest because of the speculation of Carruthers and Bethe on the existence of an isotopic spin 1 resonance. Previous measurements had indicated that the quantity $(r - 1/2)^{-1}$ (where r is the ratio of the first to the second cross section above) rises to 4 at 900 Mev, while it is less than 1 at 800 and 1000 Mev. Salant's measurements give a value of 0.6 at 900 Mev for

Shown listening to speaker E. C. Fowler of Yale are some of the 300 high-energy physicists who attended the APS-sponsored Conference on Strong Interactions, held last December on the Berkeley campus of the University of California.

$(r - 1/2)^{-1}$, thus eliminating the need for any resonance of the type suggested.

The Wednesday afternoon program was mainly devoted to "The Cusp in Λ Production at Σ Threshold". The first speaker, M. Schwartz of Columbia University and Brookhaven, reviewed the cusp theory of Baz and Okun. One hopes to find the (Λ,Σ) relative parity by observing which powers of cos θ (in the angular distribution and polarization of $\pi^- + p \rightarrow \Lambda + K$) vary strongly with beam energy at the threshold for $\pi^- + p \rightarrow \Sigma + K$. The "cusp" arises from interference between normal $\pi^- + p \rightarrow \Lambda + K$, and $\pi^- + p \rightarrow$ (virtual $\Sigma + K$ in $S_{1/2}$ state) $\rightarrow \Lambda + K$ in $S_{1/2}$ state if the (Λ,Σ) parity is even and $P_{1/2}$ state if the parity is odd. Schwartz presented the Λ, K angular distributions from the Columbia-Brookhaven bubble chamber experiment. The results indicate that higher waves than S and P are present in Λ production, and further, that there is a cusp in the $\cos^3\theta$ distribution.

The second speaker, Frank S. Crawford, Jr., of the Lawrence Radiation Laboratory, presented current data from the Berkeley 72-inch hydrogen chamber. The chamber is "thick" enough so that a single setting gives a sufficient range of energy to observe the entire cusp. The reactions $\pi^- + p \rightarrow \Sigma^0 + K^0$ and $\Sigma^- + K^+$ were shown to be consistent with S wave up to 20 Mev/c above threshold. (Results show that $\Sigma^- + K^+$ is heavier than $\Sigma^0 + K^0$ by 2.2 ± 0.6 Mev.) Crawford then presented current (incomplete) Berkeley results on the Λ, K angular distributions and polarizations versus energy. Higher waves than S and P are present, and there is a cusp in $\cos^3\theta$. Thus the Berkeley and Columbia results agree. However, the situation is complicated; the resolution of the "Minami ambiguity" requires further information than described here and a good deal of additional work will be necessary to determine the relative parity of (Λ,Σ).

As the final speaker on Wednesday afternoon, A. Salam of Imperial College, London, gave a brief survey of some theoretical ideas concerning unstable elementary particles and resonances. Salam recalled that in addition to theoretical arguments mentioned by Gell-Mann, which call for K' and π' elementary particles of spin 0 in connection with weak interactions, there have been numerous conjectures about spin 1 elementary particles associated through gauge principles to conservation laws. If the "ω^0 particle" (of the type mentioned by Abashian) really exists and has spin 1, it would be interesting in this connection.

At the Thursday meetings, the opening speaker was S. Mandelstam of the University of Birmingham. He reviewed his reformulation of the 4-particle scattering amplitudes $A + B \rightarrow C + D$. In this reformulation, unitarity, causality, and "crossing symmetries" between different channels provide double dispersion relations for the scattering amplitudes. R. E. Cutkosky (Carnegie Institute of Technology) discussed progress made toward generalizing Mandelstam's theory to more complicated processes in which several particles are produced. The goal is to re-express the conventional field theory for scattering processes completely in terms of dispersion relations.

S. Fubini of the University of Padua and CERN, and S. Drell of Stanford University presented papers dealing with the practical use of dispersion relations to calculate the long-range interactions for a variety of processes. The longest-range interactions are provided by exchanges of one or two light particles, while short-range interactions involve exchange of many particles and pose a much more complicated and as yet little understood problem. Fubini discussed progress in understanding the long-range interactions in pion-nucleon scattering, with special emphasis on the role played by exchange of two pions if a pion-pion resonance exists in the state with $I = 1$, $J = 1$. This two-pion resonance has not been observed directly but is strongly suggested by electromagnetic properties of the nucleon. Drell considered one-pion exchange, the longest range contribution to inelastic processes. At high energies, one-pion exchange produces sharp peaking at forward angles as mentioned by Wetherell. This seems to be the basis of the well-collimated high-energy beams observed at the high-energy CERN and Brookhaven machines. It is also likely that the one-pion exchange is partly responsible for the strong forward and backward peaking observed in the scattering of cosmic rays and multi-Bev particles.

In the concluding talk, G. F. Chew of the Lawrence Radiation Laboratory described an attempt to understand the dynamical role of Mandelstam's double spectral function in strong interactions. The most startling and controversial aspect of this work is the prediction of a limit on the strength of strong interactions in the low-energy elastic scattering region permitting, for example, only S and P waves to be large in low-energy pion-pion scattering. The proposed limitation arises from the particle-exchange nature of the interaction. Such exchanges are believed to be bounded because particles exchanged with large momentum transfers in one channel also contribute to high-energy scattering in a crossed channel, and high-energy cross sections are bounded by the finite range of strong interactions. These proposals did not evoke Mandelstam's full assent and more work is needed before they can be reliably assessed.

The presiding officers at the sessions were W. K. H. Panofsky, R. L. Thornton, R. L. Cool, V. F. Weisskopf, S. Mandelstam, and A. C. Helmholz. Scientific secretaries for the meeting are R. W. Kenney, T. Ypsilantis, and S. Frautschi. The conference was arranged by a committee consisting of D. Glaser, G. F. Chew, W. K. H. Panofsky, V. F. Weisskopf, R. L. Cool, and A. C. Helmholz, Chairman.