5

The Resonances

A pattern evolves, 1952–1964.

Most of the particles whose discoveries are described in the preceding chapters have lifetimes of 10^{-10} s or more. They travel a perceptible distance in a bubble chamber or emulsion before decaying. The development of particle accelerators and the measurement of scattering cross sections revealed new particles in the form of resonances. The resonances corresponded to particles with extremely small lifetimes as measured through the uncertainty relation $\Delta t \Delta E = \hbar$. The energy uncertainty, ΔE, was reflected in the width of the resonance, usually 10 to 200 MeV, so the implied lifetimes were roughly $\hbar/100\,\text{MeV} \approx 10^{-25}$ s. As more and more particles and resonances were found, patterns appeared. Ultimately these patterns revealed a deeper level of particles, the quarks.

The first resonance in particle physics was discovered by H. Anderson, E. Fermi, E. A. Long, and D. E. Nagle, working at the Chicago Cyclotron in 1952 **(Ref. 5.1).** They observed a striking difference between the $\pi^+ p$ and $\pi^- p$ total cross sections. The $\pi^- p$ cross section rose sharply from a few millibarns and came up to a peak of about 60 mb for an incident pion kinetic energy of 180 MeV. The $\pi^+ p$ cross section behaved similarly except that for any given energy, its cross section was about three times as large as that for $\pi^- p$.

In two companion papers they investigated the three scattering processes:

(1)	$\pi^+ p \to \pi^+ p$	elastic π^+ scattering
(2)	$\pi^- p \to \pi^0 n$	charge-exchange scattering
(3)	$\pi^- p \to \pi^- p$	elastic π^- scattering

They found that of the three cross sections, (1) was largest and (3) was the smallest. The data were very suggestive of the first half of a resonance shape. The π^+ cross section rose sharply but the data stopped at too low an energy to show conclusively a resonance shape. K. A. Brueckner, who had heard of these results, suggested that a resonance in the πp system was being observed and noted that a spin-3/2, isospin-3/2 πp resonance would give the three processes in the ratio 9:2:1, compatible with the experimental result. Furthermore, the spin-3/2 state would produce an angular distribution of the form $1 + 3\cos^2\theta$ for each

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of the processes, while a spin-1/2 state would give an isotropic distribution. The $\pi^+ p$ state must have total isospin $I = 3/2$ since it has $I_z = 3/2$. If the resonance were not in the $I = 3/2$ channel, the $\pi^+ p$ state would not participate. Fermi proceeded to show that a phase shift analysis gave the $J = 3/2,\ I = 3/2$ resonance. C. N. Yang, then a student of Fermi's, showed, however, that the phase shift analysis had ambiguities and that the resonant hypothesis was not unique. It took another two years to settle fully the matter with many measurements and phase shift analyses. Especially important was the careful work of J. Ashkin *et al.* at the Rochester cyclotron, which showed that there is indeed a resonance, what is now called the $\Delta(1232)$ (Ref. 5.2). A mature analysis of the $J = 3/2, I = 3/2$ pion–nucleon channel is shown in Figure 5.1.

The canonical form for a resonance is associated with the names of G. Breit and E. Wigner. A heuristic derivation of a resonance amplitude is obtained by recalling that for s-wave potential scattering, the scattering amplitude is given by

$$f = \frac{\exp(2i\delta) - 1}{2ik} \tag{5.1}$$

where δ is the phase shift and k is the center-of-mass momentum. For elastic scattering the phase shift is real. If there is inelastic scattering δ has a positive imaginary part. For the purely elastic case it follows that

$$Im(1/f) = -k \tag{5.2}$$

which is satisfied by

$$1/f = (r - i)k \tag{5.3}$$

where r is any real function of the energy. Clearly, the amplitude is biggest when r vanishes. Suppose this occurs at an energy E_0 and that r has only a linear dependence on E, the total center-of-mass energy. Then we can introduce a constant Γ that determines how rapidly r passes through zero:

$$f = \frac{1}{2k(E_0 - E)/\Gamma - ik} = \frac{1}{k} \cdot \frac{\Gamma/2}{(E_0 - E) - i\Gamma/2}. \tag{5.4}$$

The differential cross section is

$$d\sigma/d\Omega = |f|^2 \tag{5.5}$$

and the total cross section is

$$\sigma = 4\pi |f|^2 = \frac{4\pi}{k^2} \frac{\Gamma^2/4}{(E - E_0)^2 + \Gamma^2/4}. \tag{5.6}$$

The quantity Γ is called the full width at half maximum or, more simply, the width. This formula can be generalized to include spin for the resonance (J), the spin of two incident particles (S_1, S_2), and multichannel effects. The total width receives contributions from various channels,

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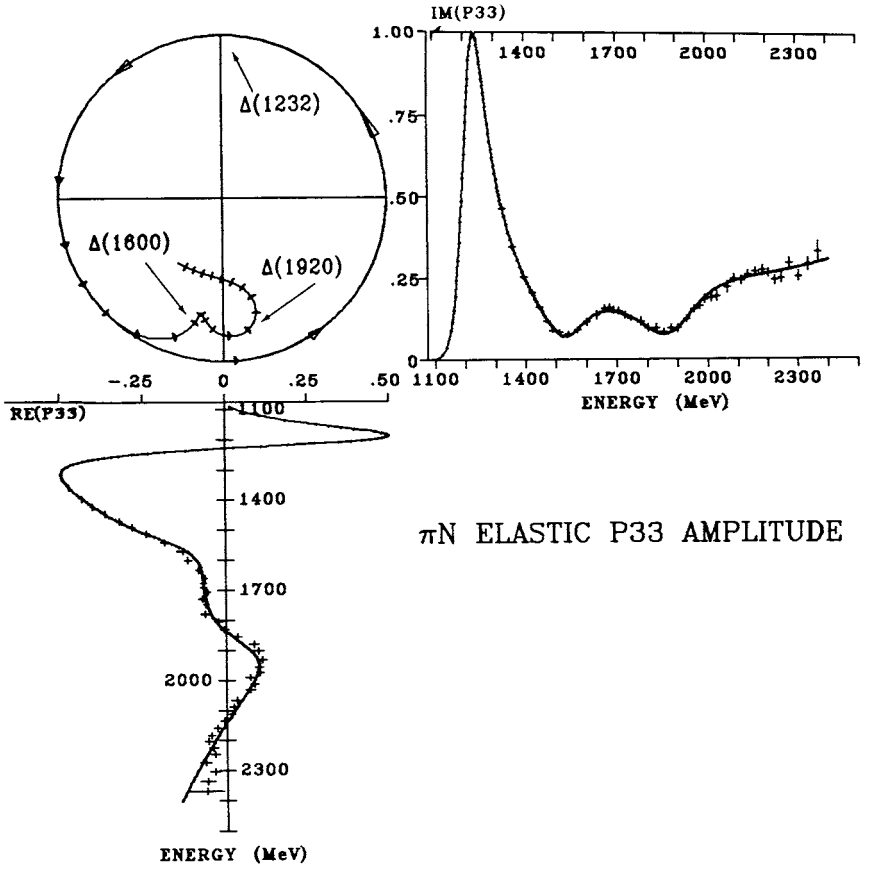


Figure 5.1. An analysis of the $J = 3/2, I = 3/2$ channel of pion–nucleon scattering. Scattering data have been analyzed and fits made to the various angular momentum and isospin channels. For each channel there is an amplitude, $a_{IJ} = (e^{i\delta_{IJ}} - 1)/2i$, where δ_{IJ} is real for elastic scattering and $\mathrm{Im}\delta_{IJ} > 0$ if there is inelasticity. Elastic scattering gives an amplitude on the boundary of the Argand circle, with a resonance occurring when the amplitude reaches the top of the circle. In the figure, the elastic resonance at 1232 MeV is visible, as well as two inelastic resonances. Tick marks indicate 50 MeV intervals. The projections of the imaginary and real parts of the $J = 3/2, I = 3/2$ partial wave amplitude are shown to the right and below the Argand circle [Results of R. E. Cutkosky as presented in *Review of Particle Properties, Phys. Lett.* **170B**, 1 (1986)].

$\Gamma = \sum_n \Gamma_n$, where Γ_n is the partial decay rate into the final state n. If the partial width for the incident channel is Γ_{in} and the partial width for the final channel is Γ_{out}, the Breit–Wigner formula is

$$\sigma = \frac{4\pi}{k^2} \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{\Gamma_{in}\Gamma_{out}/4}{(E-E_0)^2 + \Gamma^2/4}. \tag{5.7}$$

In this formula, k is the center-of-mass momentum for the collision.

As higher pion energies became available at the Brookhaven Cosmotron, more πp resonances (this time in the $I = 1/2$ channel and hence seen only in $\pi^- p$) were observed,

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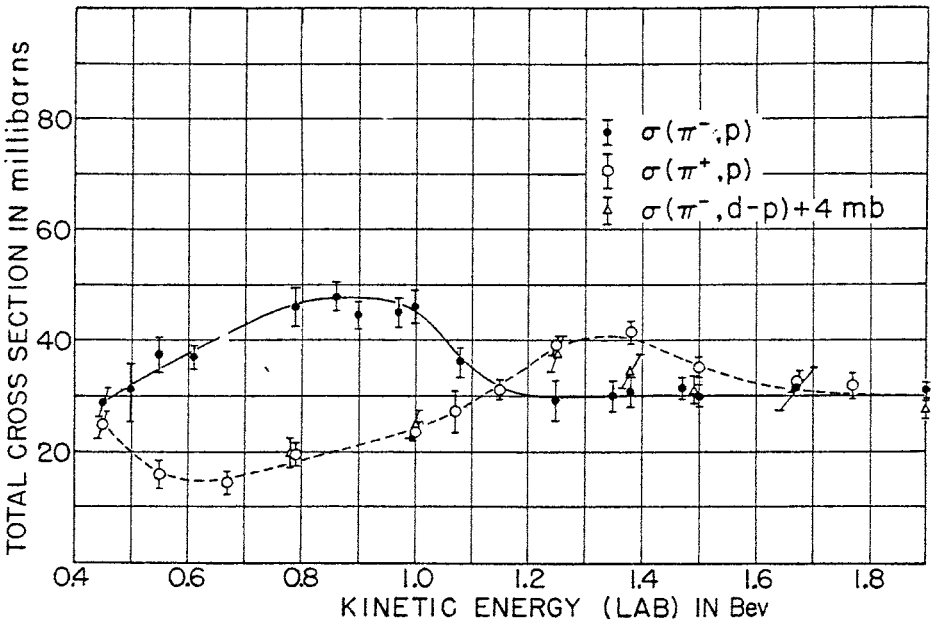


Figure 5.2. Data from the Brookhaven Cosmotron for $\pi^+ p$ and $\pi^- p$ scattering. The cross section peak present for $\pi^- p$ and absent for $\pi^+ p$ demonstrates the existence of an $I = 1/2$ resonance (N^*) near 900 MeV kinetic energy (center-of-mass-energy 1685 MeV). A peak near 1350 MeV kinetic energy (center-of-mass-energy 1925 MeV) is apparent in the $\pi^+ p$ channel, indicating an $I = 3/2$ resonance, as shown in Figure 5.1. Ultimately, several resonances were found in this region. (Ref. 5.3)

as shown in Figure 5.2. Improved measurements of these resonances came from photoproduction experiments, $\gamma N \rightarrow \pi N$, carried out at Caltech and at Cornell (Ref. 5.4).

The full importance and wide-spread nature of resonances became clear only in 1960 when Luis Alvarez and a team that was to include A. Rosenfeld, F. Solmitz, and L. Stevenson began their work with separated K^- beams in hydrogen bubble chambers exposed at the Bevatron. The first resonance observed **(Ref. 5.5)** was the $I = 1$ $\Lambda\pi$ resonance originally called the Y_1^*, but now known as the $\Sigma(1385)$. The reaction studied in the Lawrence Radiation Laboratory's 15-inch hydrogen bubble chamber was $K^- p \rightarrow \Lambda\pi^+\pi^-$ at 1.15 GeV/c. The tracks in the bubble chamber pictures were measured on semiautomatic measuring machines and the momenta were determined from the curvature and the known magnetic field. The measurements were refined by requiring that the fitted values conserve momentum and energy. The invariant masses of the pairs of particles,

$$M_{12}^2 = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\mathbf{p_1} + \mathbf{p_2})^2 \tag{5.8}$$

were calculated. For three-particle final states a Dalitz plot was used, with either the center-of-mass frame kinetic energies, or equivalently, two invariant masses squared, as variables. As for the τ-meson decay originally studied by Dalitz, in the absence of dynamical correlations, purely s-wave decays would lead to a uniform distribution over the Dalitz plot.

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The most surprising result found by the Alvarez group was a band of high event density at fixed invariant mass, indicating the presence of a resonance.

The data showed resonance bands for both the $Y^{*+} \rightarrow \Lambda\pi^+$ and the $Y^{*-} \rightarrow \Lambda\pi^-$ processes. Since the isospins for Λ and π are 0 and 1 respectively, the Y^* had to be an isospin-1 resonance. The Alvarez group also tried to determine the spin and parity of the Y^*, but with only 141 events this was not possible.

This first result was followed rapidly by the observation of the first meson resonance, the $K^*(890)$, observed in the reaction $K^- p \rightarrow \overline{K}^0 \pi^- p$, measured in the same bubble chamber exposure **(Ref. 5.6)**. This result was based on 48 identified events, of which 21 lay in the K^* resonance peak. The data were adequate to demonstrate the existence of the resonance, but provided only the limit $J < 2$ for the spin. The isospin was determined to be 1/2 on the basis of the decays $K^{*-} \rightarrow K^-\pi^0$ and $K^{*0} \rightarrow K^-\pi^+$.

A very important $J = 1$ resonance had been predicted first by Y. Nambu and later by W. Frazer and J. Fulco. This $\pi\pi$ resonance, the ρ, was observed by A. R. Erwin *et al.* using the 14-inch hydrogen bubble chamber of Adair and Leipuner at the Cosmotron **(Ref. 5.7)**. The reactions studied were $\pi^- p \rightarrow \pi^-\pi^0 p$, $\pi^- p \rightarrow \pi^-\pi^+ n$, and $\pi^- p \rightarrow \pi^0\pi^0 n$. Events were selected so that the momentum transfer between the initial and final nucleons was small. For these events, there was a clear peak in the $\pi\pi$ mass distribution. From the ratio of the rates for the three processes, the $I = 1$ assignment was indicated, as required for a $J = 1$ $\pi\pi$ resonance ($J = 1$ makes the spatial wave function odd, so bose statistics require that the isospin wave function be odd, as well).

By requiring that the momentum transfer be small, events were selected that corresponded to the "peripheral" interactions, that is, those where the closest approach (classically) of the incident particles was largest. In these circumstances, the uncertainty principle dictates the reaction be described by the virtual exchange of the lightest particle available, in this instance, a pion. Thus the interaction could be viewed as a collision of an incident pion with a virtual pion emitted by the nucleon. The subsequent interaction was simply $\pi\pi$ scattering. This fruitful method of analysis was developed by G. Chew and F. Low. For the Erwin *et al.* experiment, the analysis showed that the $\pi\pi$ scattering near 770 MeV center-of-mass energy was dominated by a spin-1 resonance.

Shortly after the discovery of the ρ, a second vector (spin-1) resonance was found, this time in the $I = 0$ channel. B. Maglich, together with other members of the Alvarez group, studied the reaction $\overline{p}p \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$ using a 1.61 GeV/c separated antiproton beam **(Ref. 5.8)**. After scanning, measurement, and kinematic fitting, distributions of the $\pi\pi\pi$ masses were examined. A clean, very narrow resonance was observed with a width $\Gamma < 30$ MeV. The peak occurred in the $\pi^+\pi^-\pi^0$ combination, but not in the combinations with total charges other than 0. This established that the resonance had $I = 0$. A Dalitz plot analysis showed that $J^P = 1^-$ was preferred, but was not a unique solution. The remaining uncertainty was eliminated in a subsequent paper (Ref. 5.9). The Dalitz plot proved an especially powerful tool in the analysis of resonance decays, especially of those into three pions. This was studied systematically by Zemach, who determined where zeros should occur for various spins and isospins, as shown in Figure 5.3.

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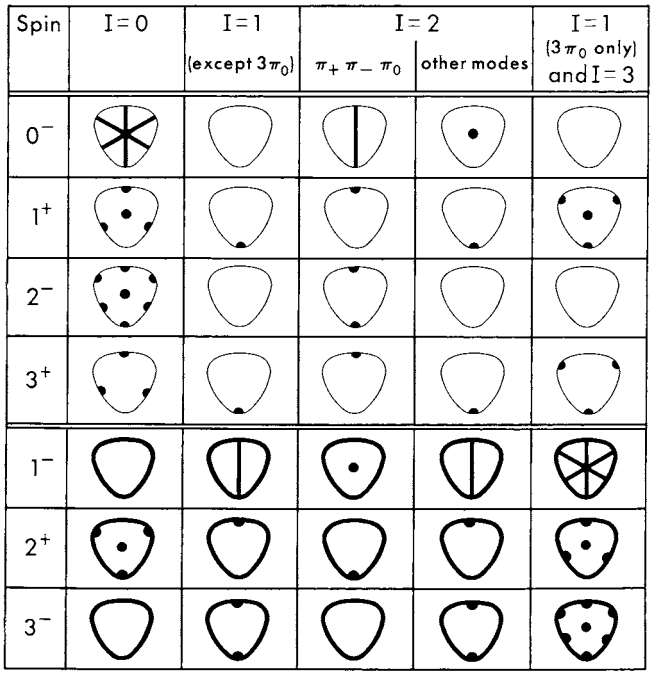


Figure 5.3. Zemach's result for the location of zeros in decays into three pions. The dark spots and lines mark the location of zeros. C. Zemach, *Phys. Rev.* **133**, B1201 (1964).

The discovery of the meson resonances took place in "production" reactions. The resonance was produced along with other final-state particles. The term "formation" is used to describe processes in which the resonance is formed from the two incident particles with nothing left over, as in the Δ resonance formed in πN collisions ($N = p$ or n).

The term "resonance" is applied when the produced state decays strongly, as in the ρ or K^*. States such as the Λ, which decay weakly, are termed particles. The distinction is, however, somewhat artificial. Which states decay weakly and which decay strongly is determined by the masses of the particles involved. The ordering of particles by mass may not be fundamental. Geoffrey Chew proposed the concept of "nuclear democracy," that all particles and resonances were on an equal footing. This view has survived and a resonance like K^* is regarded as no less fundamental than the K itself, even though its lifetime is shorter by a factor of 10^{14}.

The proliferation of particles and resonances called for an organizing principle more powerful than the Gell-Mann–Nishijima relation and one was found as a generalization of isospin. One way to picture isospin is to regard the proton and neutron as fundamental objects. The pion can then be thought of as a combination of a nucleon and an antinucleon, for example, $\overline{n}p \rightarrow \pi^+$. This is called the Fermi–Yang model. S. Sakata proposed to extend this by taking the n, p, and Λ as fundamental. In this way the strange mesons could be accommodated: $\overline{\Lambda}p \rightarrow K^+$. The hyperons like Σ could also be represented: $\overline{n}\Lambda p \rightarrow \Sigma^+$. Isospin, which can be represented by the n and p, has the mathematical structure of

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$SU(2)$. Sakata's symmetry, based on n, p, and Λ, is $SU(3)$. Ultimately, Murray Gell-Mann and independently, Yuval Ne'eman proposed a similar but much more successful model.

Each isospin or $SU(3)$ multiplet must be made of particles sharing a common value of spin and parity. Without knowing the spins and parities of the particles it is impossible to group them into multiplets. Because the decays $\Lambda \to \pi^- p$ and $\Lambda \to \pi^0 n$ are weak and, as we shall learn in the next chapter, do not conserve parity, it is necessary to fix the parity of the Λ by convention. This is done by taking it to have $P = +1$ just like the nucleon. With this chosen, the parity of the K is an experimental issue.

The work of M. Block *et al.* (Ref. 5.10) studying hyperfragments produced by K^- interactions in a helium bubble chamber showed the parity of the K^- to be negative. The process observed was $K^- \mathrm{He}^4 \to \pi^- \mathrm{He}^4_\Lambda$. The He^4_Λ hyperfragment consists of $ppn\Lambda$ bound together. It was assumed that the hyperfragment had spin-zero and positive parity, as was subsequently confirmed. The reaction then had only spin-zero particles and the parity of the K^- had to be the same as that of the π^- since any parity due to orbital motion would have to be identical in the initial and final states.

The parity of the Σ was determined by Tripp, Watson, and Ferro-Luzzi (Ref. 5.11) by studying $K^- p \to \Sigma\pi$ at a center-of-mass energy of 1520 MeV. At this energy there is an isosinglet resonance with $J^P = 3/2^+$. The angular distribution of the produced particles showed that the parity of the Σ was positive. Thus it could fit together with the nucleon and Λ in a single multiplet. The Ξ was presumed to have the same J^P.

In the Sakata model the baryons p, n, and Λ formed a 3 of $SU(3)$, while the pseudoscalars formed an octet. In the version of Gell-Mann and Ne'eman the baryons were in an octet, not a triplet. The baryon octet included the isotriplet Σ and the isodoublet Ξ in addition to the nucleons and the Λ. The basic entity of the model of Gell-Mann and Ne'eman was the octet. All particles and resonances were to belong either to octets, or to multiplets that could be made by combining octets. The rule for combining isospin multiplets is the familiar law of addition of angular momentum. For $SU(3)$, the rule for combining two octets gives $1 + 8 + 8 + 10 + 10^* + 27$. (Here the 10 and 10^* are two distinct ten-dimensional representations.) The "eightfold way" postulated that only these multiplets would occur. The baryon octet is displayed in Figure 5.4.

The pseudoscalar mesons known in 1962 were the π^+, π^0, π^-, the K^+, K^0, $\overline{K}^0$, and the K^-. Thus, there was one more to be found according to $SU(3)$. A. Pevsner of Johns Hopkins University and M. Block of Northwestern University, together with their coworkers found this particle, now called the η, by studying bubble chamber film from Alvarez's 72-inch bubble chamber filled with deuterium. The exposure was made with a π^+ beam of 1.23 GeV/c at the Bevatron **(Ref. 5.12)**. The particle was found in the $\pi^+\pi^-\pi^0$ channel at a mass of 546 MeV. No charged partner was found, in accordance with the $SU(3)$ prediction that the new particle would be an isosinglet. The full pseudoscalar octet is displayed in Figure 5.5 in the conventional fashion.

The η was established irrefutably as a pseudoscalar by M. Chrétien *et al.* (Ref. 5.13) who studied $\pi^- p \to \eta n$ at 1.72 GeV using a heavy liquid bubble chamber. The heavy liquid improved the detection of photons by increasing the probability of conversion. This enabled the group to identify the two-photon decay of the η. See Figure 5.6. By Yang's

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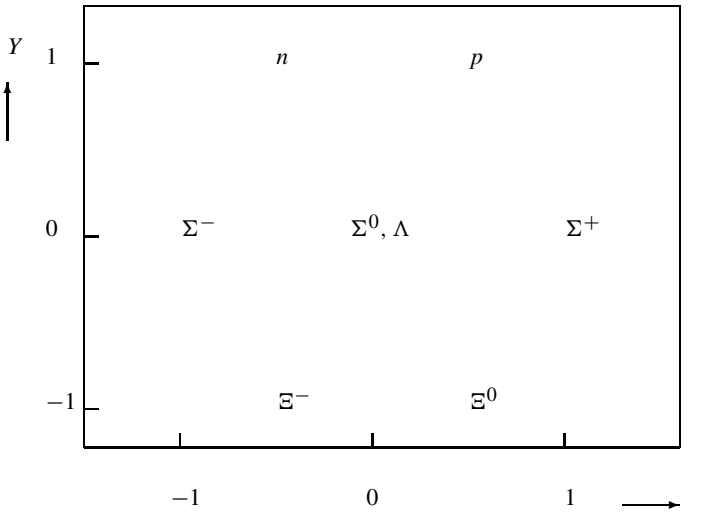


Figure 5.4. The baryon $J^P = 1/2^+$ octet containing the proton and the neutron. The horizontal direction measures I_z, the third component of isospin. The vertical axis measures the hypercharge, $Y = B + S$, the sum of baryon number and strangeness.

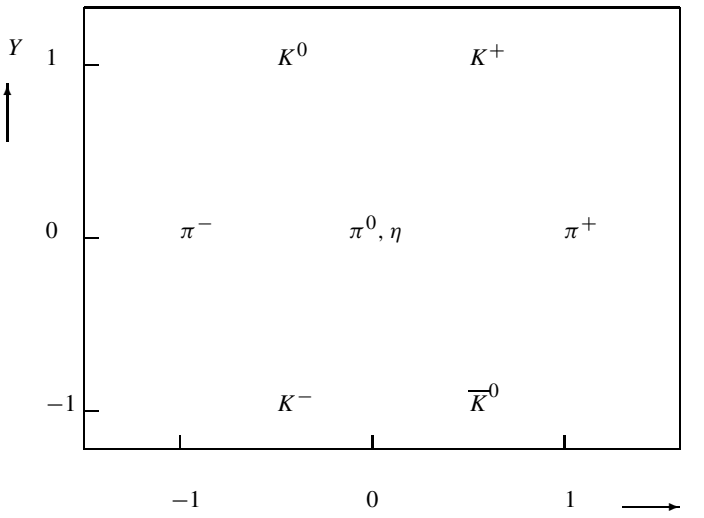


Figure 5.5. The pseudoscalar octet. The horizontal direction measures I_z while the vertical measures the hypercharge, $Y = B + S$.

theorem, this excluded spin-one as a possibility. The absence of the two-pion decay mode excluded the natural spin–parity sequence $0^+, 1^-, 2^+, \ldots$ If the possibility of spin two or higher is discounted, only 0^- remains.

Surprisingly the decay of the η into three pions is an electromagnetic decay. The η has three prominent decay modes : $\pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$, and $\gamma\gamma$. The last is surely electro-

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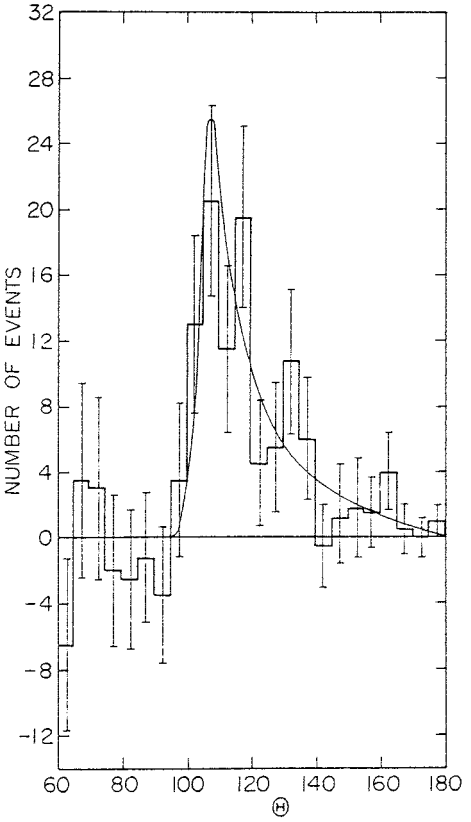


Figure 5.6. A histogram of the opening angle between the two photons in the decay $\eta \to \gamma\gamma$. The solid curve is the theoretical expectation corresponding to the mass of the η (Ref. 5.13).

magnetic, and since it is comparable in rate to the others, they cannot be strong decays. The absence of a strong decay is most easily understood in terms of G-parity, a concept introduced by R. Jost and A. Pais, and independently, by L. Michel.

G-parity is defined to be the product of charge conjugation, C, with the rotation in isospin space $e^{-i\pi I_y}$. Since the strong interactions respect both charge conjugation and isospin invariance, G-parity is conserved in strong interactions. The non-strange mesons are eigenstates of G-parity and for the neutral members like ρ^0 ($I = 1$, $C = +1$), ω^0 ($I = 0$, $C = -1$), η^0 ($I = 0$, $C = +1$), and π^0 ($I = 1$, $C = +1$), the G-parity is simply $C(-1)^I$. All members of the multiplet have the same G-parity even though the charged particles are not eigenstates of C. Thus the pions all have $G = -1$. The ρ has even G-parity and decays into an even number of pions. The ω has odd G-parity and decays into an odd number of pions.

The η has $G = +1$ and cannot decay strongly into an odd number of pions. On the other hand, it cannot decay strongly into two pions since the $J = 0$ state of two pions must have even parity, while the η is pseudoscalar. Thus the strong decay of the η must be into four pions. Now this is at the edge of kinematic possibility (if two of the pions are neutral), but

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to obtain $J^P = 0^-$, the pions must have some orbital angular momentum. This is scarcely possible given the very small momenta the pions would have in such a decay. As a result, the 3π decay, which violates G-parity and thus must be electromagnetic, is a dominant mode.

The $SU(3)$ symmetry is not exact. Just as the small violations of isospin symmetry lead to the proton–neutron mass difference, the larger deviations from $SU(3)$ symmetry break the mass degeneracy among the particles in the meson and baryon octets. By postulating a simple form for the symmetry breaking, Gell-Mann and subsequently, S. Okubo were able to predict the mass relations

$$\frac{1}{2}(m_p + m_\Xi) = \frac{1}{4}(m_\Sigma + 3m_\Lambda), \tag{5.9}$$

$$m_K^2 = \frac{1}{4}(m_\pi^2 + 3m_\eta^2). \tag{5.10}$$

The use of m for the baryons and m^2 for the mesons relies on dynamical considerations and does not follow from $SU(3)$ alone. The relations are quite well satisfied.

The baryon and pseudoscalar octets are composed of particles that are stable, that is, decay weakly or electromagnetically, if at all. In addition, the resonances were also found to fall into $SU(3)$ multiplets in which each particle had the same spin and parity. The vector meson multiplet consists of the ρ^+, ρ^0, ρ^-, K^{*+}, K^{*0}, $\overline{K}^{*0}$, K^{*-}, and ω. The spin of the $K^*(890)$ was determined in an experiment by W. Chinowsky *et al.* (Ref. 5.14) who observed the production of a pair of resonances, $K^+ p \to K^* \Delta$. They found that $J > 0$ for the K^*, while Alston *et al.* found $J < 2$. The result was $J^P = 1^-$. An independent method, due to M. Schwartz, was applied by R. Armenteros *et al.* (Ref. 5.15) who reached the same conclusion.

An additional vector meson, ϕ, decaying predominantly into $K\overline{K}$ was discovered by two groups, a UCLA team under H. Ticho (Ref. 5.16) and a Brookhaven–Syracuse group, P. L. Connolly *et al.* **(Ref. 5.17)**, the former using an exposure of the 72-inch hydrogen bubble chamber to K^- mesons at the Bevatron, the latter using the 20-inch hydrogen bubble chamber at the Cosmotron.
The reactions studied were

$$(1) \qquad K^- p \to \Lambda K^0 \overline{K}^0$$

$$(2) \qquad K^- p \to \Lambda K^+ K^-$$

A sharp peak very near the $K\overline{K}$ threshold was observed and it was demonstrated that the spin of the resonance was odd, and most likely $J = 1$.

The analysis relies on the combination of charge conjugation and parity, CP. From the decay $\phi \to K^+K^-$ we know that if the spin of the ϕ is J, then $C = (-1)^J$, $P = (-1)^J$, and so it has $CP = +1$. As discussed in Chapter 7, the neutral kaon system has very special properties. The K^0 and $\overline{K}^0$ mix to produce a short-lived state, K_S^0 and a longer-lived K_L^0. These are very nearly eigenstates of CP with $CP(K_S^0) = +1$, $CP(K_L^0) = -1$. M. Goldhaber, T. D. Lee, and C. N. Yang noted that

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a state of angular momentum J composed of a K_S^0 and a K_L^0 thus has $CP = -(-1)^J$. Thus the observation of the $K_S^0 K_L^0$ in the decay of the CP even ϕ would show the spin to be odd. Conversely, the observation of $K_L^0 K_L^0$ or $K_S^0 K_S^0$ would, because of Bose statistics, show the state to have even angular momentum. The long-lived K is hard to observe because it exits from the bubble chamber before decaying. Thus when the experiment of Connolly *et al.* observed 23 ΛK_S^0, but no events $\Lambda K_S^0 K_S^0$, it was concluded that the spin was odd, and probably $J = 1$.

With the addition of the ϕ there were nine vector mesons. This filled an octet multiplet and a singlet (a one-member multiplet). The isosinglet members of these two multiplets have the same quantum numbers, except for their $SU(3)$ designation. Since $SU(3)$ is an approximate rather than an exact symmetry, these states can mix, that is, neither the ω nor the ϕ is completely singlet or completely octet. The same situation arises for the pseudoscalars, where there is in addition an η' meson, which mixes with the η.

The octet of spin-1/2 baryons including the nucleons consisted of the p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-. This multiplet was complete. The Δ had spin 3/2 and could not be part of this multiplet. An additional spin-3/2 baryon resonance was known, the $Y^*(1385)$ or $\Sigma(1385)$. Furthermore, another baryon resonance was found by the UCLA group **(Ref. 5.18)** and the Brookhaven–Syracuse collaboration (Ref. 5.19) that discovered the ϕ. They observed the reactions

$$K^- p \to \Xi^- \pi^0 K^+$$
$$K^- p \to \Xi^- \pi^+ K^0$$

and found a resonance in the $\Xi\pi$ system with a mass of about 1530 MeV. Its isospin must be 3/2 or 1/2. If it is the former, the first reaction should be twice as common as the second, while experiment found the second dominated. The spin and parity were subsequently determined to be $J^P = (3/2)^+$.

The $J^P = (3/2)^+$ baryon multiplet thus contained 4Δs, $3\Sigma^*$s, and $2\Xi^*$s. The situation came to a head at the 1962 Rochester Conference. According to the rules of the eightfold way, this multiplet could only be a 10 or a 27. The 27 would involve baryons of positive strangeness. None had been found. Gell-Mann, in a comment from the floor, declared the multiplet was a 10 and that the tenth member had to be an $S = -3$, $I = 0$, $J^P = (3/2)^+$ state with a mass of about 1680 MeV. It was possible to predict the mass from the pattern of the masses of the known members of the multiplet. For the 10, it turns out that there should be equal spacing between the multiplets. From the known differences $1385 - 1232 = 153$, $1530 - 1385 = 145$, the mass was predicted to be near 1680. The startling aspect of the prediction was that the particle would decay weakly, not strongly since the lightest $S = -3$ state otherwise available is $\Lambda \overline{K}^0 K^-$ with a mass of more than 2100 MeV. Thus the new state would be a particle, not a resonance. The same conclusion had been reached independently by Y. Ne'eman, who was also in the audience.

Bubble chamber physicists came home from the conference and started looking for the Ω^-, as it was called. Two years later, a group including Nick Samios and Ralph Shutt

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working with the 80-inch hydrogen bubble chamber at Brookhaven found one particle with precisely the predicted properties **(Ref. 5.20)**. The decay sequence they observed was

$$\begin{aligned} K^- p &\to \Omega^- K^+ K^0 \\ \Omega^- &\to \Xi^0 \pi^- \\ \Xi^0 &\to \Lambda \pi^0 \\ \Lambda &\to p \pi^- \end{aligned}$$

The π^0 was observed through the conversion of its photons. The complete $J^P = 3/2^+$ decuplet is shown in Figure 5.7.

This was a tremendous triumph for both theory and experiment. With the establishment of $SU(3)$ pseudoscalar and vector octets, a spin-1/2 baryon octet, and finally a spin-3/2 baryon decuplet, the evidence for the eightfold way was overwhelming. Other multiplets were discovered, the tensor meson $J^{PC} = 2^{++}$, octet [$f_2(1270)$, $K_2(1420)$, $a_2(1320)$, $f_2'(1525)$], $J^{PC} = 1^{++}$ and $J^{PC} = 1^{+-}$ meson octets, and numerous baryon octets and decuplets. The discoveries filled the ever-growing editions of the *Review of Particle Physics*.

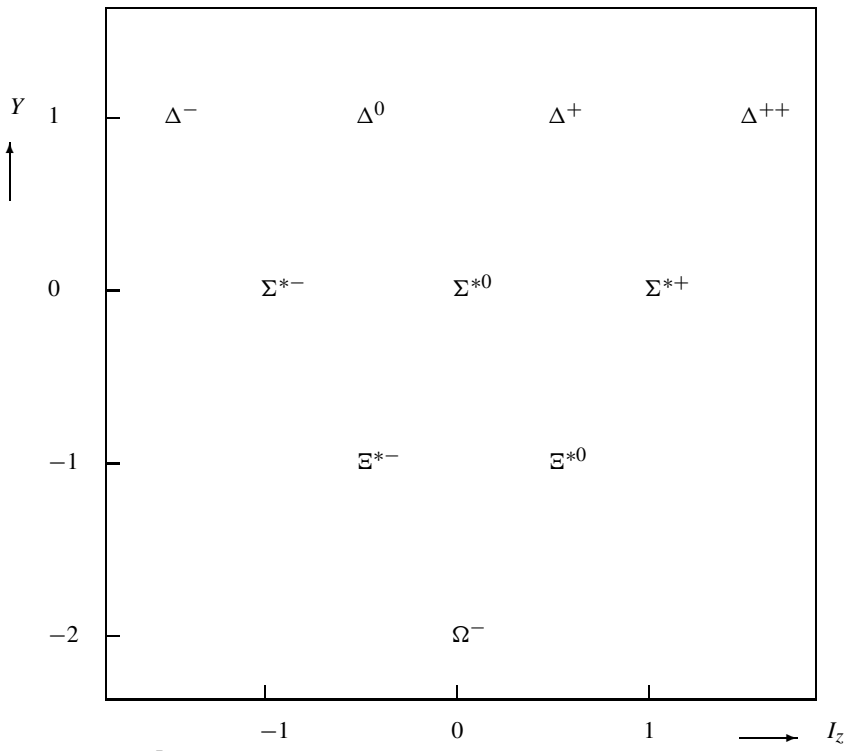
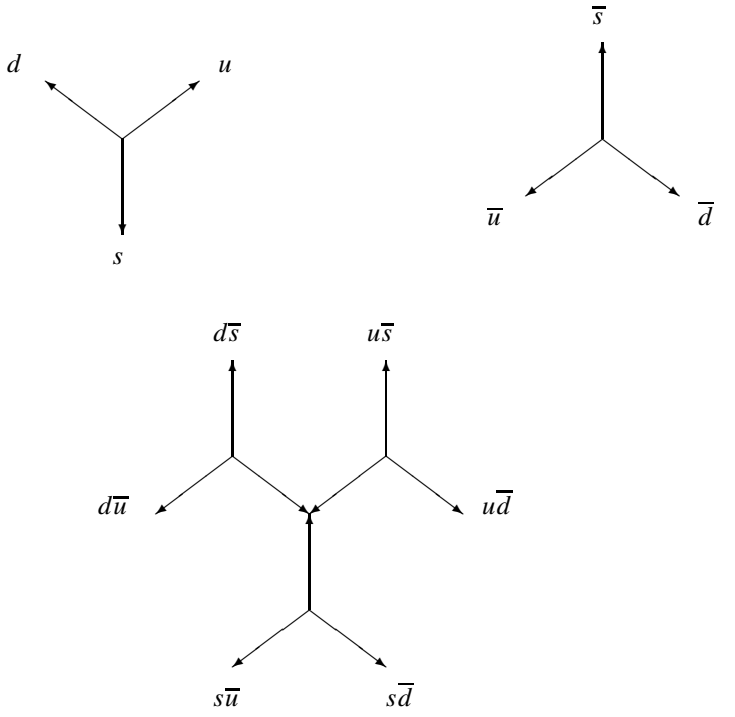


Figure 5.7. The $J^P = 3/2^+$ decuplet completed by the discovery of the Ω^-.

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A clearer understanding of $SU(3)$ emerged when Gell-Mann and independently, G. Zweig proposed that hadrons were built from three basic constituents, "quarks" in Gell-Mann's nomenclature. Now called u ("up"), d ("down"), and s ("strange"), these could explain the eightfold way. The mesons were composed of a quark (generically, q) and an antiquark ($\overline{q}$). The Sakata model was resurrected in a new and elegant form. The $SU(3)$ rules dictate that the nine combinations formed from $q\overline{q}$ produce an octet and a singlet. This can be displayed graphically in "weight diagrams," where the horizontal distance is I_z, while the vertical distance is $\sqrt{3}Y/2 = \sqrt{3}(B+S)/2$. The combinations $q\overline{q}$, which make an octet and a singlet of mesons, are represented as sums of vectors, one from q and one from $\overline{q}$.



In the $q\overline{q}$ diagram there are three states at the origin ($u\overline{u},\ d\overline{d},\ s\overline{s}$) and one state at each of the other points. The state $(u\overline{u} + d\overline{d} + s\overline{s})/\sqrt{3}$ is completely symmetric and forms the singlet representation. The eight other states form an octet. For the pseudoscalar mesons the octet is $\pi^+,\ \pi^0,\ \pi^-,\ K^+,\ K^0,\ \overline{K}^0,\ K^-,\ \eta$ and the singlet is η'. Actually, since $SU(3)$ is not an exact symmetry, it turns out that there is some mixing of the η and η', as mentioned earlier.

Baryons are produced from three quarks. The $SU(3)$ multiplication rules give $3\times3\times3 = 10 + 8 + 8 + 1$, so only decuplets, octets, and singlets are expected. The $J^P = (3/2)^+$ decuplet shown in Figure 5.7 contains states like $\Delta^{++} = uuu$ and $\Omega^- = sss$. The $J^P = (1/2)^+$ octet contains the proton (uud), the neutron (udd), etc. There are baryons that are

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primarily $SU(3)$ singlets, like the $\Lambda(1405)$, which has $J^P = (1/2)^-$, and the $\Lambda(1520)$, with $J^P = (3/2)^-$.

The simplicity and elegance of the quark description of the fundamental particles was most impressive. Still, the quarks seemed even to their enthusiasts more shorthand notation than dynamical objects. After all, no one had observed a quark. Indeed, no convincing evidence was found for the existence of free quarks during the years following their introduction by Gell-Mann and Zweig. Their later acceptance as the physical building blocks of hadrons came as the result of a great variety of experiments described in Chapters 8–11.

Exercises

5.1 Predict the value of the $\pi^+ p$ cross section at the peak of the $\Delta(1232)$ resonance and compare with the data.

5.2 Show that for an $I = 3/2$ resonance the differential cross sections for $\pi^+ p \to \pi^+ p$, $\pi^- p \to \pi^0 n$, and $\pi^- p \to \pi^- p$ are in the ratio 9:2:1. Show that the $\Delta(1232)$ produced in πp scattering yields a $1 + 3\cos^2\theta$ angular distribution in the center-of-mass frame.

5.3 For the $\Delta^{++}(1232)$ and the $Y^{*+}(1385)$, make Argand plots of the elastic amplitudes for $\pi^+ p \to \pi^+ p$ and $\pi^+ \Lambda \to \pi^+ \Lambda$ using the resonance energies and widths given in Table II of Alston *et al.* (Ref. 5.5).

5.4 Verify the ratios expected for $I(\pi\pi) = 0, 1, 2$ in Table I of Erwin *et al.* (**Ref. 5.7**).

5.5 Verify that isospin invariance precludes the decay $\omega \to 3\pi^0$.

5.6 What is the width of the η? How is it measured? Check the *Review of Particle Physics*.

5.7 Verify the estimate of Connolly *et al.* (**Ref. 5.17**) that if $J(\phi) = 1$, then

$$\frac{BR(\phi \to K_S^0 K_L^0)}{BR(\phi \to K_S^0 K_L^0) + BR(\phi \to K^+ K^-)} = 0.39.$$

5.8 How was the parity of the Σ determined? See (Ref. 5.11).

Further Reading

The authoritative compilation of resonances is compiled by the Particle Data Group. A new *Review of Particle Physics* is published in even numbered years and updated annually on the web.

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Total Cross Sections of Positive Pions in Hydrogen*

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(Received January 21, 1952)

In a previous letter,[1] measurements of the total cross sections of negative pions in hydrogen were reported. In the present letter, we report on similar experiments with positive pions.

The experimental method and the equipment used in this measurement was essentially the same as that used in the case of negative pions. The main difference was in the intensity, which for the positives was much less than for the negatives, the more so the higher the energy. This is due to the fact that the positive pions which escape out of the fringing field of the cyclotron magnet are those which are emitted in the backward direction with respect to the proton beam, whereas the negative pions are those emitted in the forward direction. The difficulty of the low intensity was in part compensated by the fact that the cross section for positive pions turned out to be appreciably larger than for negative pions. The results obtained thus far are summarized in Table I.

In Fig. 1 the total cross sections of positive and negative pions are collected. It is quite apparent that the cross section of the positive particles is much larger than that of the negative particles, at least in the energy range from 80 to 150 Mev.

In this letter and in the two preceding ones,[1,2] the three processes: (1) scattering of positive pions, (2) scattering of negative pions with exchange of charge, and (3) scattering of negative pions without exchange of charge have been investigated. It appears that over a rather wide range of energies, from about 80 to 150 Mev, the cross section for process (1) is the largest, for process (2) is intermediate, and for process (3) is the smallest. Furthermore, the cross sections of both positive and negative pions increase rather rapidly with the energy. Whether the cross sections level off at a high value or go through a maximum, as might be expected if there should be a resonance, is impossible to determine from our present experimental evidence.

Brueckner[3] has recently pointed out that the existence of a broad resonance level with spin 3/2 and isotopic spin 3/2 would give an approximate understanding of the ratios of the cross sections for the three processes (1), (2), and (3). We might point out in this connection that the experimental results obtained to date are also compatible with the more general assumption that in the energy interval in question the dominant interaction responsible for the scattering is through one or more intermediate states of isotopic spin 3/2, regardless of the spin. On this assumption, one finds that the ratio of the cross sections for the three processes should be (9:2:1), a set of values which is compatible with the experimental observations. It is more difficult, at present, to say anything specific as to the nature of the intermediate state or states. If there were one state of spin 3/2, the angular distribution for all three processes should be of the type $1+3\cos^2\theta$. If the dominant effect were due to a state of spin 1/2, the angular distribution should be isotropic. If states of higher spin or a mixture of several states were involved, more complicated angular distributions would be expected. We intend to explore further the angular distribution in an attempt to decide among the various possibilities.

Table I. Total cross sections of positive pions in hydrogen.

Energy (Mev)	Cross section (10^{-27} cm^2)
56±8	20±10
82±7	50±13
118±6	91± 6
136±6	152±14

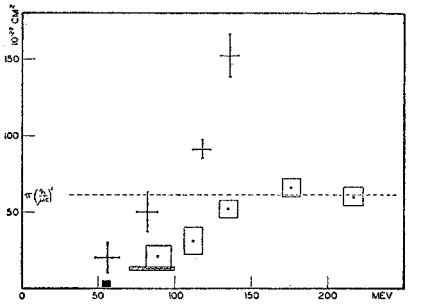


Fig. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

Besides the angular distribution, another important factor is the energy dependence. Here the theoretical expectation is that, if there is only one dominant intermediate state of spin 3/2 and isotopic spin 3/2, the total cross section of negative pions should at all points be less than $(8/3)\pi\lambda^2$. Apparently, the experimental cross section above 150 Mev is larger than this limit, which indicates that other states contribute appreciably at these energies. Naturally, if a single state were dominant, one could expect that the cross sections would go through a maximum at an energy not far from the energy of the state involved. Unfortunately, we have not been able to push our measurements to sufficiently high energies to check on this point.

Also very interesting is the behavior of the cross sections at low energies. Here the energy dependence should be approximately proportional to the 4th power of the velocity if only states of spin 1/2 and 3/2 and even parity are involved and if the pion is pseudoscalar. The experimental observations in this and other laboratories seem to be compatible with this assumption, but the cross section at low energy is so small that a precise measurement becomes difficult.

* Research sponsored by the ONR and AEC.
† Institute for the Study of Metals, University of Chicago.
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RESONANCE IN THE $\Lambda\pi$ SYSTEM*

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(Received October 31, 1960)

We report a study of the reaction

$$K^- + p \rightarrow \Lambda^0 + \pi^+ + \pi^- \qquad (1)$$

produced by 1.15-Bev/c K^- mesons and observed in the Lawrence Radiation Laboratory's 15-in. hydrogen bubble chamber. A preliminary report of these results was presented at the 1960 Rochester Conference.[1] The beam was purified by two velocity spectrometers.[2] A Ξ^0 hyperon observed during the run[3] and the preliminary cross sections[4] for various K^- reactions at 1.15 Bev/c have been reported previously. Reaction (1) was the first one selected for detailed study, because it appeared to take place with relatively large probability and because the event, a 2-prong interaction accompanied by a V, was easily identified. In a volume of the chamber sufficiently restricted so that the scanning efficiency was near 100%, 255 such events were found. These events were measured, and the track data supplied to a computer which tested each event for goodness of fit to various kinematic hypotheses. The possible reactions, the distribution of events, and the corresponding cross sections are given in Table I. An event was placed in a given category of Table I if the χ^2 probability for the other hypotheses was $<1\%$. It appears likely that the majority of the events in group (e) are also reactions of type (1). This belief is based on the following arguments:

1. Since the kinematics of a $\Lambda\pi\pi$ fit (four constraints) are more overdetermined than those of a $\Sigma^0\pi\pi$ fit (two constraints), it is relatively easy for a $\Lambda\pi\pi$ reaction to fit a $\Sigma^0\pi\pi$ reaction, but only

Table I. Distribution of events among different reactions.

Reaction	No. of events	Cross section (mb)
(a) $K^- + p \rightarrow \bar{K}^0 + p + \pi^-$	48	2.0 ± 0.3
(b) $K^- + p \rightarrow (\Lambda \text{ or } \Sigma^0) + \pi^+ + \pi^- + \pi^0$	39	1.1 ± 0.2
(c) $K^- + p \rightarrow \Sigma^0 + \pi^+ + \pi^-$	27	4.1 ± 0.4
(d) $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$	49	
(e) $K^- + p \rightarrow (\Lambda \text{ or } \Sigma^0) + \pi^+ + \pi^-$	92	
Total	255	7.2 ± 0.5

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very few Σ^0 configurations can fit the $\Lambda\pi\pi$ reactions.

2. The events of group (e) when treated as $\Sigma^0\pi\pi$ reactions give a χ^2 distribution which is much worse than that obtained when they are treated as $\Lambda\pi\pi$ reactions.

In what follows, the 141 events of groups (d) and (e) are treated as examples of reaction (1). We estimate that 10 to 15% are actually Σ^0 events.

The energy distribution of the two pions in the K^--p barycentric system is shown in Fig. 1. If the cross section were dominated by phase space alone, the distribution of the points on the two-dimensional plot of Fig. 1 should be uniform. This is clearly not the case. On the contrary, both the π^+ and the π^- distributions have peaks near 285 Mev, such as would be expected from a quasi-two-body reaction of the type

$$K^- + p \rightarrow Y^{*\pm} + \pi^{\mp}, \tag{2}$$

the Y^* having a mass spectrum peaking at ~1380 Mev. If the Y^* of mass 1380 Mev breaks up according to

$$Y^{*\pm} \rightarrow \Lambda^0 + \pi^{\pm}, \tag{3}$$

the pions from this breakup are expected to have energies ranging from 58 to 175 Mev in the K^-p rest system. Those pions from (3) are well separated from the pions arising from reaction (2) in the energy histograms.

The isotopic spin of this excited hyperon must be one, since it breaks up into a Λ and a π. Since the Y^* is produced with a pion, also of isotopic spin one, the reaction could proceed either in the $I=0$ or the $I=1$ state. Therefore the ratio of Y^{*+} to Y^{*-} will depend on the relative magnitude and phase of the two isotopic-spin amplitudes and thus could differ from unity. We observed 59 Y^{*+} events and 82 Y^{*-} events, using the criterion for separation that the high-momentum π meson is the pion from reaction (2).

Figure 2 shows the distribution in mass of the Y^* state (both Y^{*+} and Y^{*-}) including all 141 events, again using the higher energy pion in each event to calculate the Y^* mass. The experimental uncertainty in the mass for each event is small compared to the observed width of the curve. The curves of Fig. 2 are discussed later.

Figure 3 shows production angular distributions for Y^{*+} and Y^{*-} in the K^-p rest system. Partial waves with $l > 0$ appear to be present, as would be expected since $\hbar k/m_\pi c$ approximately equals 3. The difference between the Y^{*+} and Y^{*-} angular distributions may reflect the different superposi-

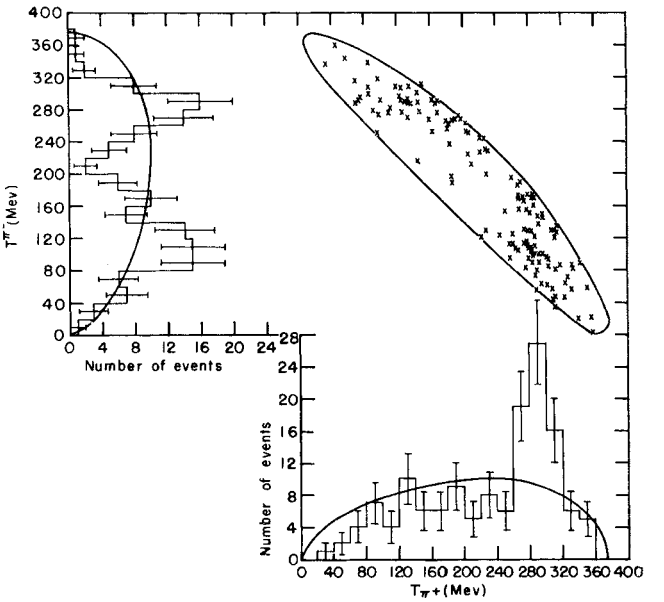


FIG. 1. Energy distribution of the two pions from the reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$. Each event is plotted only once on the Dalitz plot, which should be uniformly populated if phase space dominated the reaction. The two energy histograms are merely one-dimensional projections of the two-dimensional plot, and each event is represented once on each histogram. The solid lines superimposed over the histograms are the phase-space curves.

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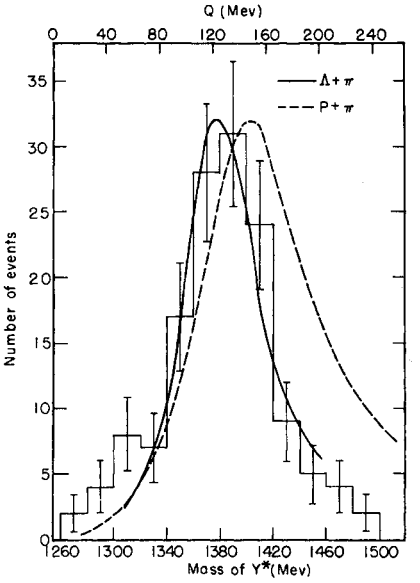


FIG. 2. Mass distribution for Y^* and fitted curves for $\pi\Lambda$ and πp resonances. The lower scale refers only to the $\pi\Lambda$ resonance. Q is the kinetic energy released when either isobar dissociates. The curve for the $\pi\Lambda$ resonances is fitted to the center eight histogram intervals of our data. The πp curve is the fit obtained by Gell-Mann and Watson,[7] to πp scattering data. Both fits are to the formula $\sigma \propto \lambda^2\Gamma^2/[(E-E_0)^2+\frac{1}{4}\Gamma^2]$, where $\Gamma = 2b(a/\lambda)^3/[1+(a/\lambda)^2]$.

tions of the isotopic-spin zero and one amplitudes for the two cases.

The following two methods were used in an effort to determine the spin of Y^*.

(a) The angular momentum of Y^* was investigated by means of an Adair analysis.[5] We first restricted ourselves to production angles with $|\cos\theta| \geq 0.8$. For this angular range the Adair analysis should be valid if only S and P waves are present in the production process. We then computed η for each event, where

$$\eta = \vec{P}_{K^-} \cdot \vec{P}_\Lambda / (|\vec{P}_{K^-}||\vec{P}_\Lambda|).$$

Of the 29 events with $|\cos\theta| \geq 0.8$, the fraction 0.62 ± 0.09 has $|\eta| \geq 0.5$. If the above-mentioned restriction on the angular interval is sufficient to insure the validity of the Adair analysis, this ratio is expected to be 0.50 for $j = 1/2$ and 0.73 for $j = 3/2$. The experimental result is thus ~ 1.3 standard deviations from both possibilities, and no conclusion may be drawn from the data. Similar results were obtained for several larger values of the cutoff angle. Presence of D waves, however, cannot be excluded by the production angular distributions (Fig. 3). If they are present, indeed, then none of these choices of angle would be sufficiently restrictive to guarantee the success of the Adair analysis.

(b) Since Y^* may be polarized perpendicular to its plane of production, correlations can exist between the decay angle of the Y^* and the polarization of the resulting Λ. Also, a net Λ polarization

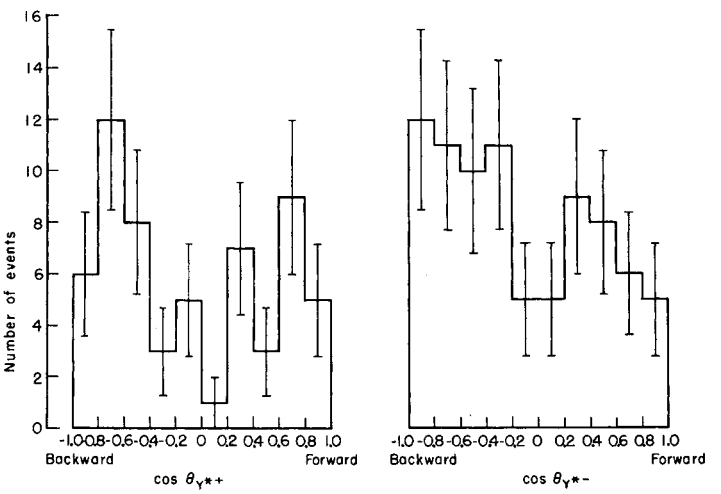


FIG. 3. Angular distribution of $Y^{*\pm}$ in the K^-p barycentric system for the reactions $K^- + p \rightarrow Y^{*\pm} + \pi^\mp$.

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can result. With our limited data, we see no statistically significant Λ polarization or angular correlations.

However, one can also look for anisotropy, i.e., a polar-to-equatorial ratio, in the decay angle of Y^* with respect to the normal to the plane of production. For spin 3/2, the distribution must be of the form $A + B\xi^2$ by the Sachs-Eisler theorem,[6] independent of the Y^* parity, where we have

$$\xi = (\vec{P}_{K^-} \times \vec{P}_{Y^*}) \cdot \vec{P}_\Lambda / (|\vec{P}_{K^-} \times \vec{P}_{Y^*}||\vec{P}_\Lambda|),$$

and $\vec{P}_a$ is the momentum of the particle a in the $K^- p$ barycentric system.

Since the coefficient B is a function of the production angle, we want to restrict ourselves to that range of the solid angle where the polar-to-equatorial anisotropy is probably greatest along the normal to the production plane. For production angles near 0 deg and 180 deg (Adair-analysis region), one expects the polar-to-equatorial ratio to be most different from unity in another direction (namely along the direction of the beam). Thus the equatorial region of production angles is more likely to show a large anisotropy along the direction in question. Therefore the production-angle range $\sin\theta \geq 0.866$ was selected for study. We find the ratio of events with $|\xi| > 0.5$ to all events is 0.355. If the distribution is isotropic, as is required for spin 1/2, we expect 0.500 ± 0.063 for our 62 events. The result is thus 2.3 standard deviations from isotropy. The 45-to-1 odds against isotropy overstate the case for higher spin because this is the fourth anisotropy looked for.

Since Y^* may be regarded as a hyperon isobar, which decays into a π and a Λ, it evidently corresponds to a resonance in pion-hyperon scattering. The mass distribution of Fig. 2 then invites a comparison to the cross section for pion-nucleon scattering in the 3/2 - 3/2 state. For this purpose a p-wave resonance formula employed by Gell-Mann and Watson[7] for pion-nucleon scattering was fitted to our $\pi\Lambda$ data by using the eight central histogram intervals of Fig. 2. In fitting the curve, it was found that the interaction radius (a) could be varied over a wide range without changing the goodness of fit appreciably, provided that the reduced width (b) was also changed appropriately. The radius parameter was therefore fixed arbitrarily at $\hbar/m_\pi c$. Table II summarizes our results for Y^*, along with those of Gell-Mann and Watson for the 3-3 resonance.

Even if Y^* does turn out to be a p-wave resonance, there are still many reasons why the π - Λ resonance parameters must not be taken too literally: (a) There is a small contamination of $\Sigma^0\pi\pi$ events in our data. (b) A nonresonant background may be present. (c) The production matrix element for reaction (2) might well depend on the outgoing momentum, and hence distort the mass distribution of Y^*. (d) Two thresholds for other possible decay modes of Y^* appear within the mass interval covered by the resonance curve; i.e., the $\Sigma\pi$ mode threshold around 1330 Mev and the $\bar{K}N$ threshold around 1435 Mev. This must have some effect on the shape of the mass spectrum as observed via the $\Lambda\pi$ decay mode. (e) Final-state pion-pion interaction could disturb the spectrum. (f) Even when the two resonances, Y^{*+} and Y^{*-}, are well resolved in terms of intensity—as in our experiment—there can still be an appreciable interference between the amplitude in which the π^+ arises from reaction (2) and the π^- from reaction (3) and the amplitude in which the roles of the two pions are reversed.

Table II. Parameters for $\pi - \Lambda$ and $\pi - p$ resonance fitted to $\sigma \propto \lambda^2 \Gamma^2/[(E - E_0)^2 + \frac{1}{4}\Gamma^2]$, where $\Gamma = 2b(a/\lambda)^3/[1 + (a/\lambda)^2]$.

Parameter	$\pi - p$	$\pi - \Lambda$
Interaction radius a in units of $\hbar/m_\pi c$	0.88	1
Reduced width b (Mev)	58	33.4
Resonance energy E_0 (Mev)	159	129.3
Full width at half maximum (Mev)	100	64
Lifetime (sec)		$\sim 10^{-23}$

If we bear all these uncertainties in mind, the resemblance to the 3-3 resonance is certainly remarkable (Fig. 2). The resonance energies when expressed in terms of barycentric kinetic energies differ by only 30 Mev, which is much less than the width of either resonance. Furthermore, the widths are at least comparable.

These results are strongly reminiscent of the concept of global symmetry which predicts two spin 3/2 pion-hyperon resonances, one with $T = 1$, the other with $T = 2$.[8] These are the hyperon counterparts of the $J = T = 3/2$ resonance of the pion-nucleon system. On the other hand, the possibility that Y^* is a $J = 1/2$ resonance cannot be excluded on the basis of our data. The concept of pion-hyperon resonance in either $J = 1/2$ or 3/2 state has been discussed recently by several authors.[9]

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A study of $\Sigma^{\mp}\pi^{\pm}\pi^{0}$ events in our experiment is under way at present. The results, however, are too incomplete for us to be able to draw any definite conclusions.

The authors are greatly indebted to the bubble chamber crew under the direction of James D. Gow for their fine job in operating the chamber, especially Robert D. Watt and Glen J. Eckman for their invaluable help with the velocity spectrometers. We also gratefully acknowledge the cooperation of Dr. Edward J. Lofgren and the Bevatron crew, as well as the skilled work and cooperation of our scanning and measuring staff. Special thanks are due the many colleagues in our group who developed the PANG and KICK computer programs—especially Dr. Arthur H. Rosenfeld, and to Dr. Frank Solmitz for many helpful discussions.

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VOLUME 6, NUMBER 6 PHYSICAL REVIEW LETTERS MARCH 15, 1961

RESONANCE IN THE K-π SYSTEM*

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(Received February 16, 1961)

In a continuation of the study of the interaction of 1.15-Bev/c K^- mesons in hydrogen by means of the Lawrence Radiation Laboratory 15-inch hydrogen bubble chamber, we now report a study of the reaction[1]

$$K^- + p \rightarrow \bar{K}^0 + \pi^- + p. \qquad \text{(A)}$$

Examples of this reaction were easily identified in those cases in which the $\bar{K}^0$ decayed into charged pions and appeared in the chamber as a two-prong interaction associated with a V. A kinematic analysis isolated 48 events of reaction (A) from other events with similar topology.[2] In only one case was the identification not unique. Correcting for neutral decays of the $\bar{K}^0$ and for escape from the chamber, we find a total cross section of 2.0 ± 0.3 mb for Reaction (A).

The events are shown on a Dalitz plot in Fig. 1. If the reaction were entirely dominated by phase space, the Dalitz plot would be uniformly populated. Instead, a strong clumping around proton kinetic energy of 20 Mev is observed. This effect cannot be explained by an interaction matrix element that increases monotonically with decreasing proton energy. Whereas an extrapolation from the region 15 Mev $\leq T_p \leq$ 25 Mev would lead one to expect a minimum of 16 events in the region $T_p \leq 15$ Mev, only three are found there. No experimental bias against very low energy protons in the K-p center-of-mass system can exist, since such protons have laboratory-system momenta of approximately 600 Mev/c, and are easily identified. The observed distribution can best be explained by a quasi-two-body reaction of the type

$$K^- + p \rightarrow K^{*-} + p, \qquad \text{(B)}$$

followed by a decay,

$$K^{*-} \rightarrow \bar{K}^0 + \pi^-. \qquad \text{(C)}$$

The 3-3 resonance of the pion-nucleon system would show itself on the Dalitz plot as a concentration of points along the diagonal line drawn through Fig. 1. The absence of any evidence for this resonance in our data can be explained if Reaction (A) proceeds primarily through the $I = 0$ channel, which cannot produce a p-π^- system in the $I = 3/2$ state. Further, even in the $I = 1$ channel, the 3-3 resonance favors $(n + \pi^0) + \bar{K}^0$ over $(p + \pi^-) + \bar{K}^0$, and hence provides additional suppression of this resonance.

The mass distribution of the K^{*-} is shown in

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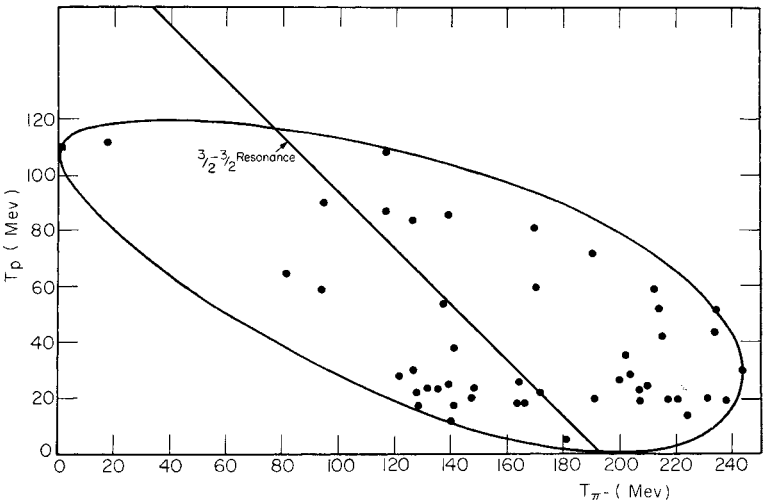


FIG. 1. Phase-space plot of the 48 examples of $K^- + p \to \bar{K}^0 + \pi + p$ reactions.

Fig. 2. The mean value is 885 ± 3 Mev. After removing the number of background events estimated from the phase-space distribution and unfolding the experimental error on each of the remaining 22 events (typically 3 to 4 Mev), we obtained a full width at half maximum of 16 Mev, corresponding to a lifetime of 4×10^{-23} second.

The angular distribution for Reaction (B) is consistent with isotropy. Assuming that the K^{*-} system is produced predominantly in the s state (which appears likely both because of the closeness to the threshold and because of the isotropic distribution), we can obtain an upper limit of the $\bar{K}^*$ spin S. If $S = 0$, then the reaction can be produced only through the $p_{1/2}$ ingoing channel; if $S = 1$, through $s_{1/2}$ and $d_{3/2}$, etc. In any case the decay angular distribution[3] is given by

$$I(\theta) = |aY_{S,0}(\theta, \phi)|^2 + |bY_{S,1}(\theta, \phi)|^2, \qquad (1)$$

with $|a|^2 + |b|^2 = 1$, where $a = 1$ for $S = 0$. Here θ is the angle of the $\bar{K}^0$ in the K^{*-} rest system with respect to the incoming K^- direction. The mean value of $\cos^2\theta$, based on the distribution function (1), is

$$\langle \cos^2\theta \rangle = \frac{(2S^2 + 2S - 3) + 2|a|^2}{4S^2 + 4S - 3}. \qquad (2)$$

Experimentally, $\langle \cos^2\theta \rangle$ for the 21 events lying in the K^{*-} mass range between 870 and 900 Mev is 0.275. Using $S = 2$ in Eq. (2), we find the expected value of $\langle \cos^2\theta \rangle \geq 0.429$, with a standard deviation of 0.051. The experimental result thus deviates from the range of values expected for $S = 2$ by three standard deviations. For $S > 2$ the discrepancy is even greater. On the other hand, the experimental result is consistent (within errors) with $S = 0$ or $S = 1$. It is worth noting that an isotropic decay distribution is obtained both for $S = 0$ and for $S = 1$ if the $d_{3/2}$ input channel does not contribute. For this reason, if $S = 0$, experiments at several momenta will be required to settle this problem.

Assuming that the K^- and $\bar{K}^0$ are an isotopic-

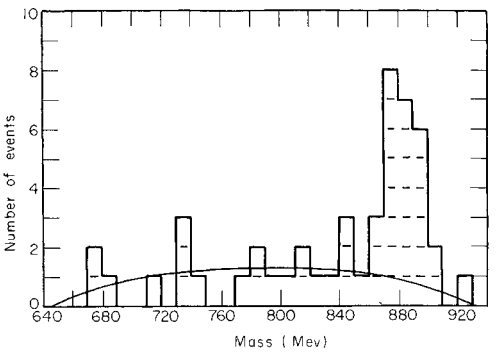


FIG. 2. Mass spectrum of the $\bar{K}^0 - \pi^-$ system. The solid line represents the phase-space curve normalized to background events.

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spin doublet, and $I = 1/2$ for the K^{*-} isotopic spin, the branching ratio $R = (K^{*-} \to K^- + \pi^0)/(K^{*-} \to \bar{K}^0 + \pi^-)$ equals 1/2; for $I = 3/2$, $R = 2$. In either case another charge state of $\bar{K}^*$, namely $\bar{K}^{*0}$, should exist and decay into $K^- + \pi^+$ or $\bar{K}^0 + \pi^0$. The value of this branching ratio, also, depends on the isotopic spin of the $\bar{K}^*$.

To investigate the isotopic spin properties of the $\bar{K}^*$, we searched for examples of the following two reactions:

$$K^- + p \to K^- + \pi^0 + p, \qquad \text{(D)}$$

$$K^- + p \to K^- + \pi^+ + n. \qquad \text{(E)}$$

These events appear as two-prong interactions and are much more difficult to identify than the events already discussed, since there are usually several possible interpretations for each inelastic two-prong event. In particular, there was a pion contamination of about 10% in our incident K^- beam, and the inelastic pion interactions are kinematically very similar to Reactions (D) and (E). Both the kinematic fits and the ionization of the tracks were used to identify the events, but these criteria were not always sufficient to distinguish between various hypotheses. At present we have processed only about 2/3 of our two-prong interactions, but we feel that the data obtained are reasonably unbiased.

In both Reactions (D) and (E) there are peaks in the nucleon kinetic energy distribution in the $\bar{K}^*$ resonance region. On the basis of the number of events in the proton peak of Reaction (D), our present data allow us to make a crude estimate of the branching ratio: $R = 0.75 \pm 0.35$. The data thus strongly favor the $I = 1/2$ state.

The experimental production ratio of $\bar{K}^*$ via Reactions (A) and (E) is about 1, and is thus consistent with the production of the $\bar{K}^*$ through a pure isotopic spin state.

An $I = 1/2$ particle, called the K', with negative parity with respect to the K meson, has been invoked by Tiomno to explain the backward Λ peaking in associated production.[4] Gell-Mann postulated the existence of such a particle to permit the construction of a strangeness-violating weak-interaction axial current.[5] The K^* that we have observed has properties consistent with those postulated for the K', but, as discussed above, the K^* spin and parity remain to be established.

As in our previous communication, we acknowledge gratefully the assistance of the many people who helped us to obtain and analyze these data. One of us (P.E.) is grateful to the Philippe's Foundation, Incorporated, and to the Commissariat a l' Énergie Atomique for a fellowship.

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[1]Preliminary versions of this report were given by M. L. Good at the meeting of the American Physical Society, Chicago, November, 1960 [Bull. Am. Phys. Soc. 5, 414 (1960)]; and by Margaret H. Alston at the Topical Conference on Strong Interactions, Berkeley, December, 1960 (unpublished).

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EVIDENCE FOR A π-π RESONANCE IN THE $I=1$, $J=1$ STATE*

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(Received May 11, 1961)

Since the earliest data became available on pion production by pions, certain features have been quite clear. The main feature which is strongly exhibited above energies of 1 Bev is that collisions are preferred in which there is a small momentum transfer to the nucleon.[1] This is shown by the nucleon angular distributions which are sharply peaked in the backward direction. These results suggest that large-impact-parameter collisions are important in such processes. The simplest process that could give rise to such collisions is a pion-pion collision with the target pion furnished in a virtual state by the nucleon. The quantitative aspects of such collisions have been discussed by a number of authors. Goebel, Chew and Low, and Salzman and Salzman[2] discussed means of extracting from the data the π-π cross section.

Holladay and Frazer and Fulco[3] deduced from electromagnetic data that indeed there must be a strong pion-pion interaction. In particular, Frazer and Fulco deduced that there probably was a resonance in the $I=1$, $J=1$ state. A qualitative set of π-p phase shifts in the 400-600 Mev[4] region were used by Bowcock et al.[5] to deduce an energy of about 660 Mev in the π-π system for the resonance. The work of Pickup et al.[6] showed an indication of a peak in the π-π spectrum at an energy of about 600 Mev.

The present experiment was designed to explore the π-π system up to an energy of about 1 Bev. The π^- beam was produced by the external proton beam No. 1 at the Cosmotron. A suitable set of quadrupole and bending magnets focussed the pion beam on a Hevimet slit about 10 ft from the Adair-

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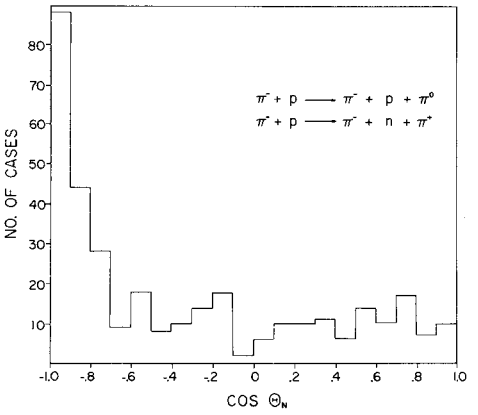


FIG. 1. The angular distribution of the nucleons from the processes $\pi^- + p \to \pi^- + \pi^0 + p$ and $\pi^- + p \to \pi^- + \pi^+ + n$.

Leipuner 14-in. H_2 bubble chamber. The pions were guided into the chamber by another bending magnet. The measured momentum was 1.89 ± 0.07 Bev/c.

Events selected for measurement were taken in a fiducial volume of the chamber. The forward-going track was required to be at least 10 cm long. Measurements were made on a digitized system and the output was analyzed by use of an IBM-704. The events were analyzed by means of a program based on the "Guts" routine written by members of the Alvarez bubble chamber group.

Figure 1 shows the combined angular distribution for the nucleons from the two processes, $\pi^- + p \to \pi^- + \pi^0 + p$ and $\pi^- + p \to \pi^- + \pi^+ + n$, which appear to be identical within statistics. The results indicate a large number of events with small momentum transfer to the nucleons.

We concentrate our interest on those events with small momentum transfer since these events satisfy the qualitative criterion of being examples of π-π collisions. Somewhat arbitrarily, we center our attention on cases in which the momentum transfer to the nucleon is less than 400 Mev/c. Table I gives the ratios of the three possible final states $\pi^-\pi^+ n$, $\pi^-\pi^0 p$, and $\pi^0\pi^0 n$, assuming the π-π scattering to be dominated, respectively, by the $I = 0$, 1, 2 scattering states of the π-π system.

The experimental results in the last column indicate a strong domination by $I = 1$ state. For the $I = 1$ state the basic π-π scattering cross sections $\sigma(\pi^-\pi^0 \to \pi^-\pi^0)$ and $\sigma(\pi^-\pi^+ \to \pi^-\pi^+)$ are equal.

Table I. Ratios of final states.

	$I=0$	$I=1$	$I=2$	Experiment ($\Delta \leq 400$ Mev/c)
$\pi^-\pi^+ n$	2	2	2/9	1.7 ± 0.3
$\pi^-\pi^0 p$	0	1	1	1
$\pi^0\pi^0 n$	1	0	4/9	$< 0.25 \pm 0.25$

The nucleon four-momentum transfer spectrum seems to be in qualitative agreement with the theory for the process in which a π is knocked out of the cloud. Figure 2 shows ideograms for the mass spectrum of the di-pions for cases with $\Delta \leq 400$ Mev/c and $\Delta > 400$ Mev/c, where Δ is the four-momentum transfer to the nucleon. The curve for $\Delta \leq 400$ Mev/c clearly shows a peak at 765 Mev/c. In the ideogram for $\Delta > 400$ Mev/c the peak is still present but seems to be smeared to higher values of the di-pion mass, m^*. One worries that diagrams other than the one involving

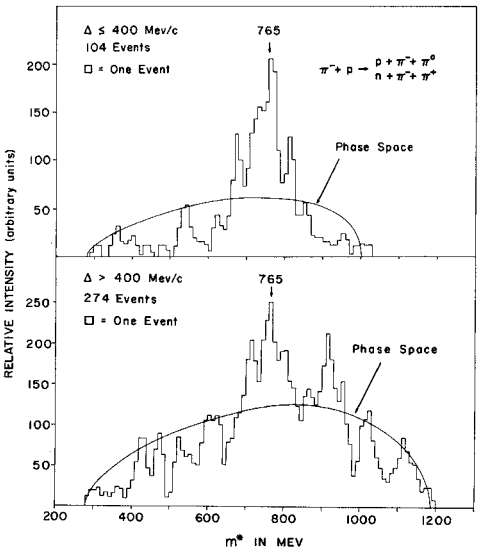


FIG. 2. The combined mass spectrum for the $\pi^-\pi^0$ and $\pi^-\pi^+$ system. The smooth curve is phase space as modified for the included momentum transfer and normalized to the number of events plotted. Events used in the upper distribution are not contained in the lower distribution.

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one-pion exchange might be contributing to the observed peak in this m^* spectrum. In particular, an important contribution at lower energies comes from a diagram in which one of the π's rescatters off the nucleon and ends up in the 3-3 state with respect to the nucleon. If one restricts the data to cases with $\Delta \leq 400$ Mev/c this diagram does not seem to be very important, but if one takes cases with $\Delta > 400$ Mev/c many cases consistent with rescattering are found.

In order to deduce values of the π-π cross section, we use the formula[2]

$$\frac{d^2\sigma}{dm^* d\Delta^2} = \frac{3f^2}{\pi} \frac{\Delta^2}{(\Delta^2+1)^2} \left(\frac{m^*}{q_{iL}}\right)^2 K \bar{\sigma}_{\pi-\pi},$$

where $\bar{\sigma}_{\pi-\pi}$ is the mean of $\sigma(\pi^-\pi^0 \to \pi^-\pi^0)$ and $\sigma(\pi^-\pi^+ \to \pi^-\pi^+)$. In the above formula all momenta and energies are measured in units of pion masses. q_{iL} = momentum of the incoming pion measured in units of the pion mass. K = momentum of the pions in the di-pion center-of-mass system. Then

$$\delta\sigma = \frac{3f^2}{\pi} \left(\frac{m^*}{q_{iL}}\right)^2 K \bar{\sigma}_{\pi-\pi} \delta m^* \int_{\Delta_{\min}(m^*)}^{\Delta_{\max}} \frac{\Delta^2 d\Delta^2}{(\Delta^2+1)^2}.$$

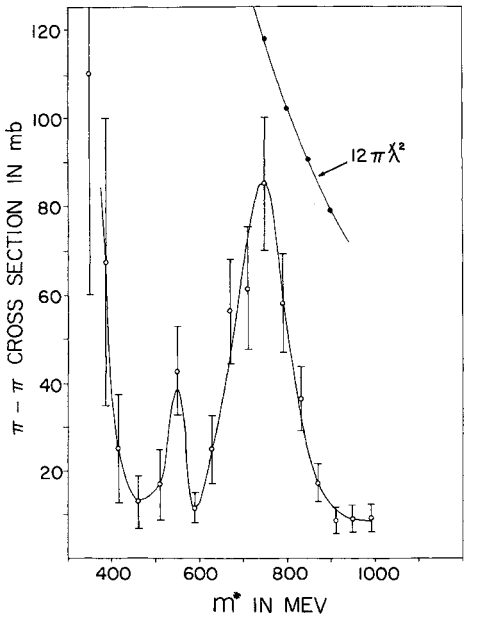


FIG. 3. The π-π cross section as deduced from cases with the four-momentum transfer less than 400 Mev/c.

The results of this calculation using the experimentally determined $\delta\sigma$'s are shown in Fig. 3. The results indicate a peak in the neighborhood of 750 Mev with a width of 150-200 Mev, which is about 3/4 of what it would be ($12\pi\lambda^2$) for a resonance in the $I=1$, $J=1$ state. Since this cross section was determined off the energy shell, it is difficult to estimate the effect of the interference of other diagrams and also the effect of line broadening.[7] Whether or not the other peak and the S-wave scattering indicated in Fig. 3 are real will have to await better statistics for verification.

We wish to acknowledge with gratitude the help and cooperation of R. K. Adair and L. Leipuner in the use of their bubble chamber, and to the latter also for his assistance in adapting the "Guts" routine to our use. We also acknowledge the help of J. Boyd, J. Bishop, P. Satterblom, R. P. Chen, C. Seaver, and K. Eggman in measuring, scanning, and tabulating. We were greatly aided by Dr. J. Ballam and Dr. H. Fechter in setting up the beam. We have had helpful conversations with Dr. R. K. Adair, Dr. C. J. Goebel, Dr. M. L. Good, and in particular Dr. G. Takeda.

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VOLUME 7, NUMBER 5 PHYSICAL REVIEW LETTERS SEPTEMBER 1, 1961

EVIDENCE FOR A $T=0$ THREE-PION RESONANCE*

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(Received August 14, 1961)

The existence of a heavy neutral meson with $T=0$ and $J=1^-$ was predicted by Nambu[1] in an attempt to explain the electromagnetic form factors of the proton and neutron. Chew[2] has pointed out that such a vector meson should exist on dynamical grounds as a three-pion resonance or a bound state. Such a particle is also expected in the vector meson theory of Sakurai[3] and, as a member of an octet of mesons, according to the unitary symmetry theory[4]; and for other reasons.[5] We will refer to it as ω.

Previous searches[6] for ω have primarily been confined to the mass region $m_\omega < 3\mu$, with μ = the pion mass, where only the following radiative decay modes are allowed: $\omega \to \pi^0+\gamma$, $\omega \to 2\pi^0+\gamma$, and $\omega \to \pi^+ + \pi^- + \gamma$. The ω cannot decay into two pions.

The present search was made assuming $m_\omega > 3m_\pi$, where the decay

$$\omega \to \pi^+ + \pi^- + \pi^0 \qquad (1)$$

is possible.[7] We have searched for such a 3-pion decay mode by studying the effective mass distribution of triplets of pions in the reaction

$$\bar{p} + p \to \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^0. \qquad (2)$$

We have measured 2500 four-prong events produced by antiprotons of 1.61 Bev/c in the 72-inch hydrogen bubble chamber.[8] The c.m. energy is 2.29 Bev. Upon fitting these 2500 four-prong events by using our kinematics program KICK, 800 four-prong events had a $\chi^2 \leq 6.5$ for hypothesis (2) and would not fit the hypothesis that no π^0 was produced (610 of these 800 had a $\chi^2 < 2.5$).

The 800 four-prong events must have some small contamination of events in which two π^0's were produced, but inspection of the "missing mass" distribution convinces us that it is <7%. Other tests confirm this low contamination. For example, the angular distribution of the π^0 is symmetric within statistics, and the momentum of the π^0 resembles the momentum distribution of the charged pions.

We have evaluated the 3-body effective mass,

$$M_3 = [(E_1+E_2+E_3)^2 - (\vec{P}_1+\vec{P}_2+\vec{P}_3)^2]^{1/2}, \qquad (3)$$

for each pion triplet in Reaction (2). Each of the 800 four-prong events yields ten such quantities corresponding to the following charge states:

$|Q| = 0$: $\pi^+\pi^-\pi^0$ (800×4 combinations), (4)

$|Q| = 1$: $\pi^\pm\pi^\pm\pi^\pm$ (800×4 combinations), (4′)

and

$|Q| = 2$: $\pi^\pm\pi^\pm\pi^0$ (800×2 combinations). (4″)

For each value of M_3 as given by Eq. (4) we can calculate an uncertainty δM_3, by using the variance-covariance matrix of the fitted track variables, which is evaluated by KICK. By using these δM_3 we have formed the resolution function of M_3, and find that it has a half-width at half-maximum, $\Gamma_{\text{resol}}/2$, equal to 8.7 Mev. However, our input errors to KICK allow only for Coulomb scattering and estimated measurement accuracy, and do not account for optical distortion and unknown systematic errors. For example, our distributions have the correct shape but are too wide by a scale factor of about 2. This suggests that our average input error is too small by about $\sqrt{2}$. Hence, our estimate of δM_3 must be increased by about $\sqrt{2}$, and of $\Gamma_{\text{resol}}/2$ to 12 Mev. We chose 20-Mev histogram intervals for plotting our M_3 distribution.

In Fig. 1 we have plotted the M_3 distributions for the 800 Reactions (2). Distributions 1(A) and 1(B) are for charge combinations $|Q| = 1$ and 2, respectively. The solid curves are an approximation to phase space.

The neutral M_3 distribution, 1(C), shows a peak centered at 787 Mev that contains 93 pion triplets above the phase-space estimate of 98. To contrast the difference between the neutral M_3 distribution and that for $|Q| > 1$, we have replotted at the bottom of Fig. 1 both the neutral distribution and $\frac{2}{3}$ the sum of the $|Q| = 1$ and $|Q| = 2$ distributions.

Figure 2 shows the M_3 spectra with phase space subtracted. The absence of the peak in the $|Q| > 0$ distributions determines the isotopic spin of the resonance,

$$T_\omega = 0.$$

The χ^2 distribution of the events in the "peak region" was compared with the χ^2 distribution of the events in the adjacent "control region," ranging from $M_3 \geq 820$ to $M_3 < 900$ Mev. These distributions agree with each other, which indicates that the events in the peak are genuine, rather than being caused by some unknown background reaction which was misinterpreted as Reaction

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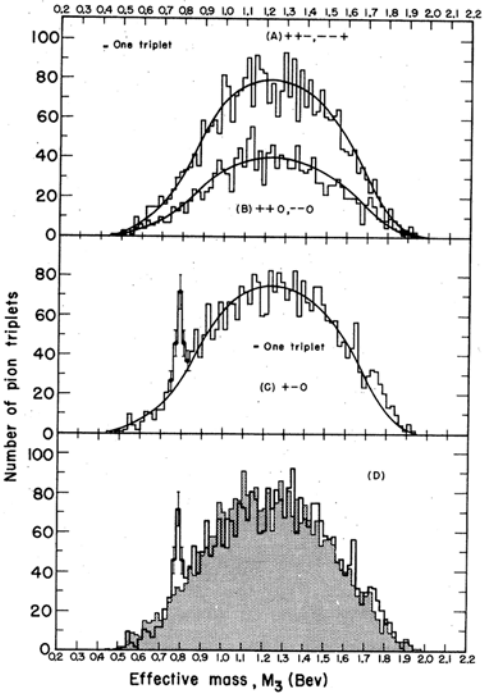


FIG. 1. Number of pion triplets versus effective mass (M_3) of the triplets for reaction $\bar{p}+p \rightarrow 2\pi^+ + 2\pi^- + \pi^0$. (A) is the distribution for the combination (4′), $|Q|=1$; (B) is for the combination (4″), $|Q|=2$; and (C) for (4), $Q=0$, with 3200, 1600, and 3200 triplets, respectively. Full width of one interval is 20 Mev. In (D), the combined distributions (A) and (B) (shaded area) are contrasted with distribution (C) (heavy line).

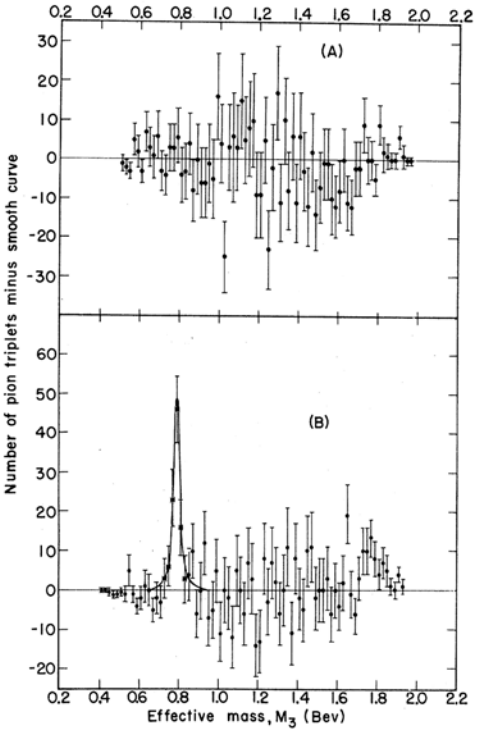


FIG. 2. (A) M_3 spectrum of the pion triplets in the combined distributions 1(A) and 1(B), with the smooth curve subtracted. (B) M_3 spectrum of the neutral pion triplets in distribution 1(C), again with the smooth background subtracted; a resonance curve is drawn through the peak at 787 Mev with $\Gamma/2=15$ Mev. The error flags are $\sqrt{N}$, where N is the total number of triplets per 20-Mev interval before subtraction of the smooth background curve.

(2). The missing-mass distributions in the two regions also agree with each other, thus supporting the above conclusion.

The peak in Fig. 2(B) appears to have a half-width $\Gamma/2<15$ Mev. This is so close to our resolution, $\Gamma_{\text{resol}}/2$, of 12 Mev that we cannot unfold it without further study and at present can only conclude that

$$M_\omega = 787 \text{ Mev},$$

and

$$\Gamma/2<15 \text{ Mev}. \quad (5)$$

By using the uncertainty principle, we see that this half-width implies a mean life $\tau>4\times10^{-23}$ sec. Our ω's are produced with a typical c.m. momentum of 800 Mev/c, so that in a mean life they travel farther than 13 f.

We now assume that the ω peak is real, and want to estimate how many ω mesons it contains. As shown in Fig. 1(C), 191 triplets have M_3 values between 740 and 820 Mev. (We call this the "peak region.") However, these 191 triplets come from only 170 different four-prong events [i.e., 21 Reactions (2) have two values of M_3 in the peak region]. We use the charged M_3 distribution to estimate the background in the interval as 98 triplets, and then calculate a production of 83 ± 16 ω mesons out of 800 Reactions (2); i.e.,

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$(10 \pm 2)\%$ of Reactions (2) proceed via

$$\bar{p} + p \rightarrow \pi^+ + \pi^- + \omega. \quad (6)$$

Among the same 800 five-pion events, we have searched for—and found—the $T = J = 1$ pion-pion resonance (ρ meson).[9] We found that approximately 30% of them proceed via

$$\bar{p} + p \rightarrow 2\pi + \rho. \quad (7)$$

We have checked whether there is any correlation between the observed ρ mesons and the ω mesons. For each triplet inside the peak region, $740 \leq M_3 < 820$ Mev, we have evaluated the effective mass of the remaining $\pi^+\pi^-$ doublet, M_2. The M_2 distribution is consistent with a continuum, starting from about 300 Mev, that has $(10 \pm 2)\%$ of the doublets with values of M_2 in the region of ρ, which we took to be 750 ± 50 Mev. There is no evidence that the ω and the ρ are produced in association.

Although the masses of ω and ρ differ by only 35 Mev, we believe that they cannot be the same particle, because of their different widths (the $\Gamma/2$ for ρ being 40 Mev), isotopic spin, and G-conjugation parity—which forbids $2\pi \rightarrow 3\pi$.

In referring to the $T = 0$ 3π resonance as ω, we have tacitly supposed that it is in fact a vector state with $J = 1^-$. However, the spin and parity must be decided by experiment. Even if we assume the spin is < 2, there are left three possibilities which are listed in Table I. A $T = 0$ state of three pions must be antisymmetric in all pairs; hence all three pions must have different charges, i.e., $\pi^0\pi^0\pi^0$ is forbidden. The matrix element of the $\pi^+\pi^-\pi^0$ state is conveniently analyzed in terms of a single pion plus a di-pion. The pions of the di-pion are assigned momentum $\vec{P}$ and angular momentum $\vec{L}$ (in the di-pion rest frame). Then another pair of variables, $\vec{p}$ and $\vec{l}$, describe the remaining pion in the 3π rest frame. Because the state is antisymmetric in any pair, $\vec{L}$ must be odd; henceforth, we assume $L = 1$. Then if $l = 0$ we have a $J = 1^-$ (i.e., vector) matrix element, as listed on the bottom line of Table I. Since three pions are involved, there is an intrinsic parity of $(-1)^3$, so that the corresponding "meson" is not V, but A.

If $l = 1$, the matrix element can be 1+ (axial) or 0+ (scalar) corresponding, respectively, to a vector meson (ω) or a pseudoscalar (PS) meson.

Do we have enough data to distinguish between totally antisymmetric A vs S vs V matrix elements? It is convenient to make a Dalitz plot[10] [Fig. 3(D) for the peak region events, 3(A) for the control region events] that displays the threefold symmetry of three pions in an antisymmetric state. Unit area on a Dalitz plot is proportional to the corresponding Lorentz-invariant phase space, so that the density of plotted points is proportional to the square of the matrix element. It is easily shown that the size of the figure is proportional to $T_1 + T_2 + T_3 = Q = m_\omega - (2m_{\pi^\pm} + m_{\pi^0})$.[11] Because of the finite width of the peak and the control regions, Q varies from event to event, so we use normalized variables, T_i/Q. The antisymmetry allows the plot to be folded about any median, so that in Figs. 3(C) and 3(B) all the data have been concentrated into $\frac{1}{6}$ of the plot area; the statistical distribution of the events is then more evident.

All three competing matrix elements, being antisymmetric, must vanish where any two pions "touch" in momentum space. If two pions touch, the third must have its maximum kinetic energy [regions (d), (f), and (b) on the plot]. The resonance region points [Figs. 3(C) and 3(D)] seem to show the required depopulation at points (d), (f), and (b).

More evident, however, on the plot is the fact that near $p = 0$ [points (a), (c), and (e)] the density of peak-region points is only one half of that on the control plot. This is all the more suggestive when it is remembered that even the peak-region data contain only $(43 \pm 7)\%$ resonance events. This depopulation at $p = 0$ suggests an angular momen-

Table I. Possible three-pion resonances with $T = 0$, $J \leq 1$.

"Meson" Type, $\vec{J}$	$\vec{l}$, $\vec{L}$	Matrix element Type, $\vec{J}$	Simple example	Vanishes at:
V, 1−	1, 1	A, 1+	$E_-(\vec{p}_0 \times \vec{p}_+) + E_0(\vec{p}_+ \times p_-) + E_+(\vec{p}_- \times \vec{p}_0)$	whole boundary
PS, 0−	1, 1	S, 0+	$(E_- - E_0)(E_0 - E_+)(E_+ - E_-)$	$a, c, e + b, d, f$
A, 1+	0, 1	V, 1−	$E_-(\vec{p}_0 - \vec{p}_+) + E_0(\vec{p}_+ - \vec{p}_-) + E_+(\vec{p}_- - \vec{p}_0)$	b, d, f only

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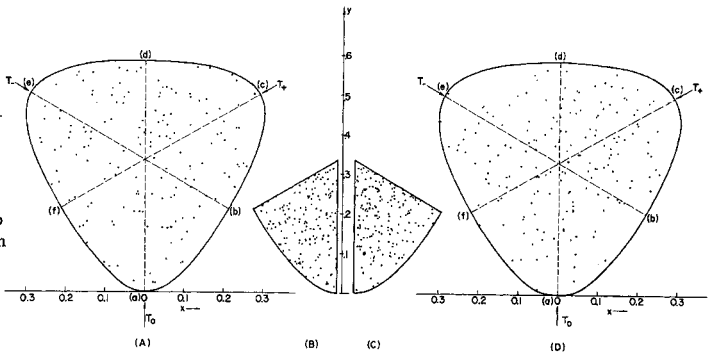


FIG. 3. (A): Dalitz plot of 171 triplets from the control region ($820 \leq M_3 < 900$); (B): folded control region plot; (D): Dalitz plot for 191 triplets in the peak region, $43 \pm 7\%$ of which are due to ω mesons; (C) folded peak region plot. T_+, T_-, and T_0 are kinetic energies of the π^+, π^-, and π^0, respectively.

tum barrier ($l > 0$) and constitutes mild evidence against a V matrix element (A meson).

The two stronger remaining candidates have A vs S matrix elements. The dashed lines in Fig. 3(D), as well as the two straight lines of the folded distribution in Fig. 3(C), correspond to equal energies of two pions. The scalar matrix element (S) of Table I vanishes when any two pions have the same energy, and therefore would require depopulation along these lines. This is not observed. An A matrix element has terms in $\vec{p}_i \times \vec{p}_j$, which vanish for collinear pions. The boundary of the plot represents collinearity, and seems indeed to be depopulated; although clearly more statistics and more detailed analysis such as investigation of polarization and alignment are needed.

We conclude that the data fit the qualitative criteria for an axial vector matrix element (ω meson); there is reasonable evidence against both an A meson and a PS meson.

The film used in this measurement was obtained in collaboration with J. Button, P. Eberhard, G. Kalbfleisch, J. Lannutti, G. Lynch, and N. H. Xuong; and this experiment would not have been possible without their help. It is a pleasure to thank Professor Murray Gell-Mann for his theoretical discussions. We wish to acknowledge the active participation of C. Tate, L. Champomier, A. Hussain, C. Rinfleisch, and F. Richards in the final stages of this experiment.

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VOLUME 7, NUMBER 11 PHYSICAL REVIEW LETTERS DECEMBER 1, 1961

EVIDENCE FOR A THREE-PION RESONANCE NEAR 550 Mev*

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(Received November 10, 1961)

A study has been under way of multipion resonances in $\pi^+ + d$ reactions observed in the Lawrence Radiation Laboratory 72-in. bubble chamber exposed to a 1.23-Bev/c pion beam from the Bevatron. A preliminary report on this research was given at the Aix-en-Provence Conference on Elementary Particles[1] where the existence of the ω^0 meson reported by the Berkeley group[2] was confirmed. Since then these data have been substantially increased, although the experiment is still in progress. The existence of a second neutral 3-pion resonance with a mass of approximately 550 Mev is indicated by this larger sample of events.

Many authors[3] have speculated on the existence of neutral, strongly interacting bosons of mass of the order of $3\text{-}4 m_\pi$, in order to fit the data for nucleon form factors obtained from electron scattering experiments. These bosons could be readily identified experimentally in the reaction

$$\pi^+ + d \rightarrow p + p + X^0. \tag{1}$$

In order to observe the possible decay mode,

$$X^0 \rightarrow \pi^+ + \pi^- + \pi^0, \tag{2}$$

we consider the reaction

$$\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0. \tag{3}$$

Only events where both protons are visible and at least one proton stops in the chamber with a range less than 15 cm were accepted for analysis.[4]

The events were measured with a digitized microscope and reconstructed by the Berkeley PANG program. A kinematic fit[5] was obtained for the assumed π^0 using the KICK program, and the effective mass of the fitted 3-pion system was then calculated. In order to check the identification of the π^0, we have calculated the missing neutral mass for events which fit our criteria. An ideogram[6] for this missing neutral mass is given in Fig. 1 for the first 199 of our events.

Figure 2 is a histogram of the effective mass of the 3-pion system for our 233 events. An average mass uncertainty on a given event is ~±20 Mev. The large peak near 770 Mev is clearly identifiable as the ω^0. Another large peak in the 3-pion mass plot of Fig. 2 is seen near 550 Mev, which strongly suggests the existence of a second 3-pion resonance (or particle). We shall hereafter refer to this particle as η.

In order to estimate the number of events in this peak which are reasonably due to the η particle, we make the following interpretation of our data. We believe the impulse approximation is reasonably valid because of the loose structure of the deuteron. Thus the basic reaction we are looking at is

$$\pi^+ + n \rightarrow p + X^0, \tag{4a}$$

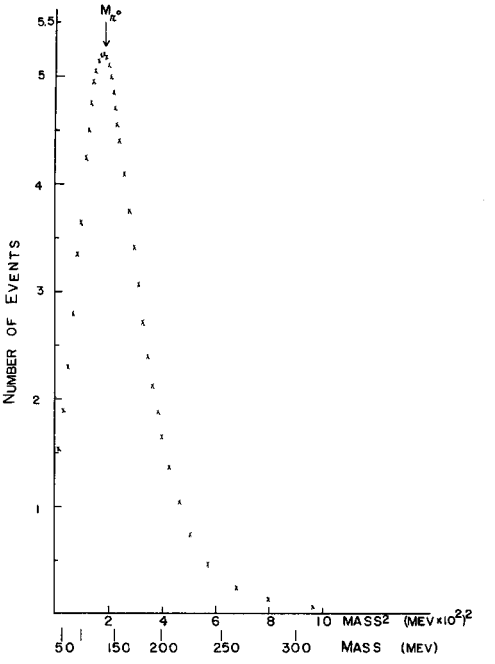


FIG. 1. Ideogram of the missing mass in the reaction ($\pi^+ + d \rightarrow p + p + \pi^+ + \pi^-$ + missing mass) for 199 events which meet the selection criteria.

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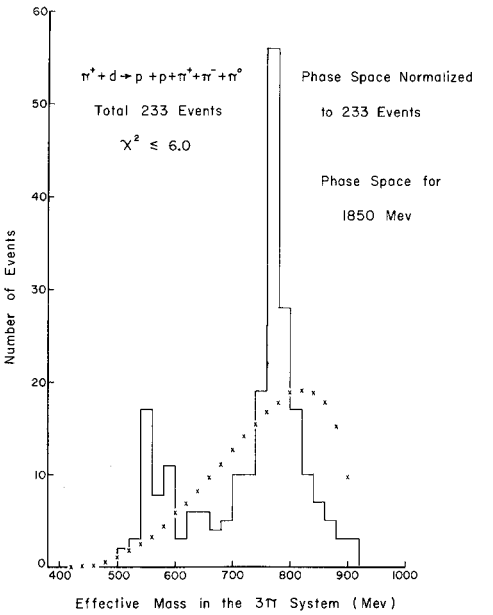


FIG. 2. Histogram of the effective mass of the three-pion system for 233 events.

where

$$X^0 \rightarrow \pi^+ + \pi^- + \pi^0. \qquad (4b)$$

We have calculated the Lorentz-invariant phase space[7] for the 3-pion mass from the background reaction to (4a), i.e.,

$$\pi^+ + n \rightarrow p + \pi^+ + \pi^- + \pi^0, \qquad (5)$$

using the experimental average of the total energy in the p-3π center-of-mass system (1850 Mev). This curve, normalized to the total number of events, is plotted in Fig. 2.

Clearly, because of the presence of the ω^0 particle at 770 Mev, such a normalization of phase space yields a gross overestimate of events expected near 550 Mev. Between 540 and 600 Mev there are 36 events in the experimental distribution, whereas the overestimated phase space would account for 12.

An analysis of the data, which takes into account the spread in errors on the individual events on the histogram, gives a mass of approximately 764 Mev with a half-width at half maximum of $\leq$20 Mev for the ω^0 and a mass of ~546 Mev with a half-width at half maximum of $\leq$25 Mev for the η.

An attempt is being made to determine the isotopic spin for both peaks by studing the reaction

$$\pi^+ + d \rightarrow p + \pi^+ + \pi^+ + \pi^- + n. \qquad (6)$$

Only 61 events were found in an analysis of one-half the film represented by Fig. 2. The low yield is probably indicative of the lack of any resonance in the isotopic spin states 1 and 2. This is in accord with the Berkeley assignment of $T = 0$ to the ω^0.

A search for the $\pi^0 + \gamma$ decay mode of the ω^0 and η is being carried out by a study of events of the type

$$\pi^+ + d \rightarrow p + p + (\text{neutrals}). \qquad (7)$$

The results will be available shortly.

The proton form factor F_{1p} obtained from electron scattering experiments[8] cannot be fitted using only the ω^0 and ρ particles.[9] However, a three-pion resonance of mass $\leq 4m\pi$ having $T = 0$ and spin 1^- would make a fit to the data possible.[10] With the film on hand we expect to more than double our statistics, so that a determination of the isotopic spin and spin of the η may be possible to see whether it fits these theories.

The authors wish to thank Dr. Luis Alvarez, Dr. Edwin McMillan, Dr. Frank Crawford, and the staff of the Lawrence Radiation Laboratory for their cooperation and for the facilities which made this experiment possible. We also wish to thank Dr. Walter Selove of the University of Pennsylvania and Dr. Leon Madansky and Dr. Gordon Feldman of The Johns Hopkins University for helpful discussions, and Dr. A. Rosenfeld, Dr. P. Berge, and Mr. R. Harvey of the Lawrence Radiation Laboratory, Mrs. Doris Ellis of The Johns Hopkins University, and Dr. David Onley and Mr. Arthur Kovacs of Duke University, for their invaluable help with the computer programs.

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*Work supported by the U. S. Air Force Office of Scientific Research, the National Science Foundation, and Office of Naval Research.

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[3]Y. Nambu, Phys. Rev. 106, 1366 (1957); G. F. Chew, Phys. Rev. Letters 4, 142 (1960); J. J. Sakurai, Ann. Phys. 11, 1 (1960); S. Bergia, A. Stanghellini, S. Fubini, and C. Villi, Phys. Rev. Letters 6, 367 (1961).

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[4]In a sample representing one-fourth of the film reported here, the requirement that one of the protons had to stop with a range ≤ 15 cm was removed. The results agree within statistics with those reported here.

[5]Events were accepted for analysis which fit the following criteria: (a) $\chi^2 \leq 6$ for the hypothesis $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0$. (b) $\chi^2 \geq 25$ for the hypothesis $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^-$. (c) If the nonstopping proton had a momentum ≥ 700 Mev/c, where it becomes difficult to differentiate a proton from a π^+ by ionization in this chamber, then the χ^2 had to be greater than 15 for the hypothesis $\pi^+ + d \rightarrow p + n + \pi^+ + \pi^+ + \pi^-$, which is another background reaction under these circumstances.

[6]The ideogram was calculated in units of mass squared since our experimental errors are Gaussian in this representation. Each event was given a constant-area Gaussian distribution.

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EXISTENCE AND PROPERTIES OF THE φ MESON*

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In a previous publication[1] we reported evidence for the existence of a resonance in the $K\bar{K}$ system (which we shall call the φ meson[2]) with a mass of ~1020 MeV and a width ≤20 MeV. The purpose of this Letter is to report additional data, the analysis of which confirms the existence of the resonance[3] and provides a conclusive determination of the mass, width, parity, spin, isospin, and branching ratios of this resonance. In particular we find $M = 1019 \pm 1$ MeV, $\Gamma = 1^{+2}_{-1}$ (with $\Gamma > 0$), parity $(P) = -1$, spin $(J) = 1$, isotopic spin $(I) = 0$, and charge conjugation $(C) = -1$. The vector nature of the φ clearly establishes that it is not related to the mass enhancement in the K_1K_1 system observed by other groups.[4]

This experiment is part of a continuing study of the $K^- - p$ interaction[5] at 2.23 BeV/c. The data were collected in two exposures of the 20-

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inch BNL hydrogen chamber at Brookhaven's AGS. Our study of the $K\bar{K}$ system is based upon the reactions

$$K^- + p \rightarrow \Lambda + K^0 + \bar{K}^0, \quad (1)$$

$$K^- + p \rightarrow \Lambda + K^+ + K^-. \quad (2)$$

We shall refer to (1) as the "neutral channel" and to (2) as the "charged channel." At present, the total analyzed data consist of channels (1) and (2) from the first exposure[6] and channel (1) from the second exposure; the numbers of events involved are summarized in Table I. A total of 36 events in the neutral channel and 22 events in the charged channel have been analyzed.

The general analysis procedure used to identify events on the basis of χ^2 fitting and ionization information is described in detail in a previous publication.[5] Background contamination and detection bias are negligible. Owing to the difference in neutral missing mass, channel (1) events are easily distinguished from the competing reactions, $K^- + p \rightarrow \Xi^0 + K^0$ and $\pi^- + p \rightarrow (\Lambda \text{ or } \Sigma^0) + K^0\ (+\pi^0)$. Competition from $\pi^- + p \rightarrow \Lambda + K^0 + 2\pi^0$ is negligible due to the small pion contamination in the beam and the small phase space available for this reaction. This is further substantiated by the paucity of events of the type $\pi^- + p \rightarrow \Lambda + K^0 + \pi^+ + \pi^-$, only two such events occurring in the first run. The only significant background is due to the reaction $K^- + p \rightarrow \Sigma^0 + K^0 + \bar{K}^0$, which we estimate on the basis of missing mass studies and other information to be ~10%. Because of severe competition from other modes, candidates for channel (2) are used only if the Λ decays visibly. Due to the more frequent occurrence of the topologically similar reactions $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$ and $K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0$, it was necessary to measure all events consisting of a V and two charged prongs. For those cases which were kinematically ambiguous it was always possible to determine the $\Lambda K^+ K^-$ events due to the difference in predicted ionization for the K's and π's. We therefore believe the charged channel to be free from bias.

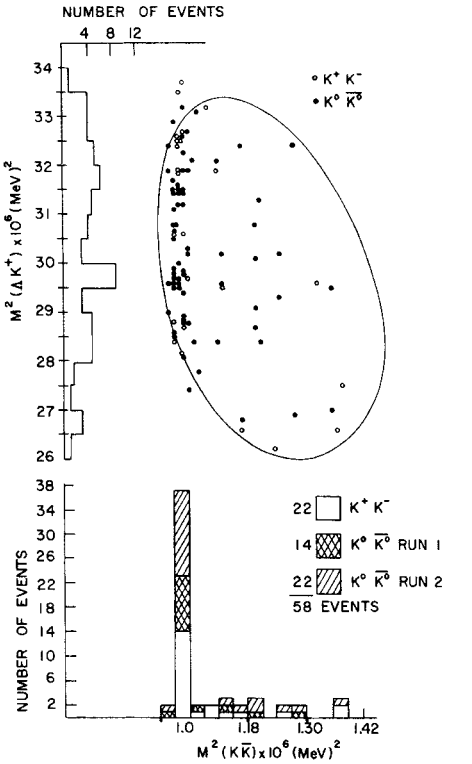


FIG. 1. Dalitz plot for the reaction $K^- + p \rightarrow \Lambda + K + \bar{K}$. The effective-mass distribution for $K\bar{K}$ and for ΛK^+ are projected on the abscissa and ordinate (see reference 7).

The Dalitz plot of the (squared) $K\bar{K}$ and ΛK[7] effective masses of 58 events from both the neutral and charged $K\bar{K}$ channels is shown in Fig. 1. The enhancement over the phase-space distribution in the region $M^2(K\bar{K}) = 1.04$ BeV^2 is ap-

Table I. Summary of events from both exposures.

	No. of events Channel (1)	No. of events Channel (2)	No. of events in peak Channel (1)		No. of events in peak Channel (2)	
			Obs.	Corrected	Obs.	Corrected
First exposure	14	22	9	19	14	23
Second exposure	22	Not analyzed	13	Not Useful	Not analyzed	

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parent,[8] as is the lack of any significant irregularity in the $M^2(\Lambda K)$ distribution, indicating the absence of any appreciable ΛK-$K\bar{K}$ interference. A comparison of the observed φ peak with the K_1K_1 enhancement found by Alexander et al.[4] clearly indicates on the basis of widths alone that the two effects are different.

We have examined the enhancement region of Fig. 1 by plotting an ideogram of $M(K\bar{K})$ for events between 1000 and 1040 MeV. This distribution peaks at 1019 ± 1 MeV and has an observed width of ~10 MeV. We defer a discussion of the true width Γ since its determination is to some extent influenced by the spin quantum number assigned to the φ.

First, we consider the parity of the φ, or that which is equivalent for a $K\bar{K}$ system, the charge conjugation number, C. Determination of C rests upon the observation by Goldhaber et al.[9] that if the $K\bar{K}$ system has $C = +1$, it may decay into K_1K_1 or K_2K_2, while if it has $C = -1$, it may decay only into K_1K_2. Taking account of these correlations we may compute, for both $C = +1$ and $C = -1$ hypotheses, the expected rates of φ decay into the experimentally observable topological variations of final states of channel (1), which we label by their visible V's as follows: ΛK_1K_1, ΛK_1, and K_1K_1. The predicted[10] relative rates of ΛK_1K_1, ΛK_1, and K_1K_1 are given in Table II. If these are compared with the observed rates, also given in Table II, one sees that the $C = -1$ hypothesis is in excellent agreement with the data, while the $C = +1$ hypothesis is in disagreement with the data by 12 standard deviations; this is just a reflection of the fact that there are 23 events in the peak which are ΛK_1, and not one ΛK_1K_1 or K_1K_1. We conclude, therefore, that the φ has $C = P = -1$, or equivalently that its spin is odd, the most likely values being $J = 1$ or 3.

Information concerning the spin can be obtained from a consideration of the (relative) decay rate α_J, where

$$\alpha_J = \frac{\varphi \to K_1K_2}{\varphi \to K_1K_2 + K^+K^-}.$$

In the absence of a K^+K^0 mass difference and charge effects, the ratio α is clearly independent of J (in fact $\alpha = 0.5$). The spin dependence of α_J arises from the different angular momentum and Coulomb barriers appropriate to the (K_1K_2) and (K^+K^-) systems. Using an interaction radius[11] of $(2M_\pi)^{-1}$, a Coulomb correction of 4% for $J = 1$ and 3% for $J = 3$, and center-of-mass momenta of $P_\pm = 125$ MeV/c and $P_0 = 107$ MeV/c, we estimate $\alpha_{J=1} = 0.39$ and $\alpha_{J=3} = 0.26$. From the (first exposure) data of Table I, after correcting for neutral modes and fiducial region differences, we find $\alpha_{\text{expt}} = 0.45 \pm 0.10$. Comparing this with our theoretical estimates we see that the observed ratio of relative kaon decay modes is in good agreement with the $J = 1$ hypothesis and disagrees with that of $J = 3$ by ~2 standard deviations. In principle further information on the spin can be obtained from the shape of the φ peak. If the φ meson has a finite width, and if our experimental resolution is symmetric, then the observed shape of $M(K\bar{K})$ should exhibit an asymmetry depending on the spin J. The $M(K^+K^-)$ and $M(K_1^0K_2^0)$ distributions in the form of Gaussian ideograms as well as their respective resolution functions[12] are shown in Fig. 2. In both instances there appear similar asymmetries. Since the phase-space background is extremely small ($1\frac{1}{2}$ events) it is probable that the $M(K\bar{K})$ asymmetry[13] reflects the spin dependence of the φ decay. The experimental data was then fitted with both p- and d-wave modified Breit-Wigner formula including the experimental mass resolution. Both

Table II. Predicted and observed relative rates for different topological types of channel (1).

Topological Type of Channel (1)	Predicted Relative Rates $C = -1$ (K_1K_2)	$C = +1$ (K_1K_1) (K_2K_2)	Observed Relative Rates For Events in Peak
ΛK_1K_1	0	0.4	0 ± 0.04
ΛK_1	1	0.4	1 ± 0.2
K_1K_1	0	0.2	0 ± 0.04

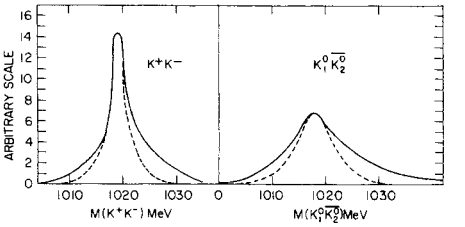


FIG. 2. The solid curve is the Gaussian ideogram of the $(K\bar{K})$ mass spectrum after subtraction of phase space. The dashed curve is the Gaussian ideogram of the $(K\bar{K})$ mass resolution function.

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spin-1 and spin-3 cases fit the data for slightly different values of the true width Γ_T. Since the charged (K^+K^-) masses are considerably better determined ($\Gamma_{+-}^{\text{res}} = 3 \pm 1$ MeV) than their neutral ($K_1^0 K_2^0$) counterpart ($\Gamma_{00}^{\text{res}} = 8 \pm 2$ MeV), they constitute a more suitable sample from which to obtain Γ_T. Taking into account background and statistical uncertainties we find $\Gamma_T = 1^{+2}_{-1}$ MeV, and as argued above we believe $\Gamma_T > 0$.

Next, we consider the isotopic spin of the φ. The strongest evidence concerning isospin comes from a determination of the G-parity (G). Since we have established that the φ spin is odd, then $G = -(-1)^I$. If the G-parity of the φ were +1, the G-allowed 2π decay mode would predominate over the $K\bar{K}$ mode. From the ratio of phase space and barrier penetration factors (for $J = 1$) we find that $(Q \to 2\pi)/(Q \to K\bar{K}) \cong 10$ for an interaction radius $R = (1/2m_\pi)$ and increases to $\cong 20$ for $R = (1/2m_k)$. We have searched for a 2-pion decay mode by investigating the $M(\pi^+\pi^-)$ distribution from the reaction

$$K^- + p \to \Lambda + \pi^+ + \pi^-. \qquad (3)$$

The $\Lambda\pi^+\pi^-$ final state frequently results from the decay of a Y_1^* intermediate state,[14] a circumstance which would complicate the search for $\varphi \to 2\pi$, therefore the Y_1^* production events were removed on the basis of their $M(\Lambda\pi)$ values (taken as 1385 ± 40 MeV for present purposes).[15] The $M(\pi^+\pi^-)$ distribution of the remaining events is shown as the solid curve of Fig. 3. There is no evidence of enhancement at 1020 MeV which would indicate $\Lambda + \varphi$ production. We estimate that the 300-event sample of Fig. 3 (from the first exposure only) does not contain more than five $\varphi \to 2\pi$ events. From this, and the $K\bar{K}$ data of the first exposure (see Table I), taking into account corrections for unobservable modes, we find an upper limit to the relative 2π rate of

$$\left(\frac{\varphi \to 2\pi}{\varphi \to K\bar{K}}\right) = \frac{5}{19 + 23} < 0.2.$$

Since the discrepancy between this upper limit and the predicted lower limit of this $G = +1$ decay is about 2 orders of magnitude, we conclude[16] that the φ has negative G-parity, which implies isotopic spin 0.

For a φ with negative G-parity and spin 1, the main competition to the $K\bar{K}$ decay mode is expected to come from[17] 3π decay, and in particular from the mode $\varphi \to \rho + \pi$. We have searched for the latter decay mode in the final state

$$\Lambda + \pi^- + \pi^+ + \pi^0. \qquad (4)$$

As discussed in an earlier publication,[5] only ~60% of the final states (4) arise from the nonresonant reaction $K^- + p \to \Lambda + \pi^- + \pi^+ + \pi^0$. The remainder of the $\Lambda + \pi^+ + \pi^- + \pi^0$ final states result from the decay of the following resonant intermediate states: (5) $Y_1^* + \pi + \pi$ or (6) $\Lambda + \omega$, (7) $\Lambda + \varphi$, (8) $\Lambda + \rho + \pi$. In order to avoid correlations in the 3π system due to Y_1^* decay, the intermediate states (5), which may be recognized by means of a $\Lambda\pi$ effective mass[15] of 1385 ± 30, are removed from the sample of $\Lambda + \pi^+ + \pi^- + \pi^0$ final states. The 2π mass spectrum is searched for events with a ρ mass, taken[15] to be 750 ± 75 MeV. For events satisfying these criteria, their 3π effective mass spectrum, shown as the solid curve of Fig. 4, is examined for evidence of a

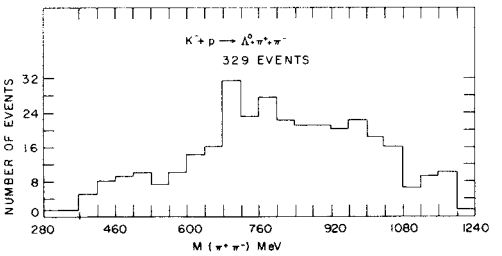


FIG. 3. The $M(\pi^+\pi^-)$ distribution from the reaction $K^- + p \to \Lambda + \pi^+ + \pi^-$ after removing Y_1^* production events (see text).

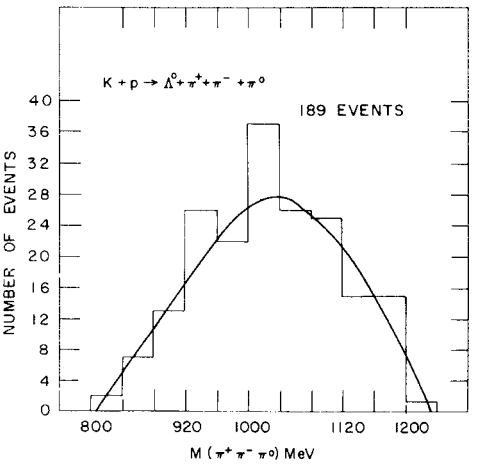


FIG. 4. The $M(\pi^+\pi^-\pi^0)$ distribution from the reaction $K^- + p \to \Lambda + \pi^+ + \pi^- + \pi^0$ after removing Y_1^* production events (see text).

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peak at the φ mass. There is a deviation at $M(3\pi) = 1020$ MeV of about 1.5 standard deviations above background and of width consistent with the experimental resolution at this mass. The sample of Fig. 4 representing all available data from the first exposure contains ~10 $\varphi \to \rho + \pi$ events. From this and the relevant $K\bar{K}$ data (see Table I) we find, correcting for neutral modes,

$$\beta = \frac{\varphi \to \rho + \pi}{\varphi \to K + \bar{K}} \approx 0.35 \pm 0.2.$$

One can estimate β_J either from the ratio of phase space, barrier penetration, spin, and isospin factors which give $\beta_{J=1} \approx 4$ for an interaction radius of $(2m_\pi)^{-1}$ or from a dynamical approach as done by Sakurai[2] giving $\beta_{J=1} \approx 3$. The observed rate is lower than these predicted values by one order of magnitude; however the above estimates are uncertain[18] by at least this amount so that this discrepancy need not be disconcerting.

It should be noted that the φ, being a 1^{--} meson, may be accommodated within a number of theories of elementary particles. In the unitary symmetry model of Gell-Mann,[19] the φ could be the heretofore absent (singlet) partner of the vector meson octet. It has been noted that the pseudoscalar meson octet and baryon supermultiplets satisfy the generalized mass formula[19,20] to a high accuracy. However, the same mass formula applied to the vector meson octet predicts an isosinglet mass of 930 MeV, which is different from the observed ω mass of 780 MeV. This discrepancy might be explained by the mixing of the ω and φ,[2] a possibility which arises since they have the same quantum numbers. Within the framework of Sakurai's "vector theory of strong interactions"[21] the φ may play the role of the vector meson B_Y coupled to the hypercharge current. Finally, with respect to the Chew-Frautschi conjecture,[22] the φ presumably starts a new trajectory, as do the other vector mesons.

We would like to acknowledge the invaluable assistance of the AGS staff, the BNL 20-inch crew, and many technical assistants. Two of us (J. L. and N. P. S.) are indebted to Professor J. Sakurai for stimulating conversations and correspondence.

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[1] L. Bertanza et al., Phys. Rev. Letters 9, 180 (1962).

[2] This was suggested by J. J. Sakurai, Phys. Rev. Letters 9, 472 (1962).

[3] The existence of this resonance has also been confirmed by P. Schlein, W. E. Slater, L. T. Smith, D. H. Stork, and H. K. Ticho, Phys. Rev. Letters 10, 368 (1963).

[4] A. R. Erwin et al., Phys. Rev. Letters 9, 34 (1962); G. Alexander et al., Phys. Rev. Letters 9, 460 (1962).

[5] L. Bertanza et al., Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), pp. 279-284.

[6] The data published in reference 1 consisted of a partial sample at 2.23 BeV/c from the first exposure along with 8 events at 2.50 BeV/c.

[7] Since the K^0 cannot be distinguished from the $\bar{K}^0$, both the ΛK^0 and $\Lambda \bar{K}^0$ masses are plotted in the Dalitz plot. However, each one of these points is counted only as 1/2 event in the $M^2(\Lambda K)$ projection, so that it is properly normalized.

[8] As determined by a χ^2 test, the probability that the observed $M^2(K\bar{K})$ distribution is due to phase space production is less than 10^{-6}.

[9] M. Goldhaber, T. D. Lee, and C. N. Yang, Phys. Rev. 112, 1796 (1958).

[10] In determining these rates and all other K_1^0 decay rates we have taken $\Gamma(K_1^0 \to \pi^0 + \pi^0)/\Gamma(K_1^0 \to \text{total}) = 1/3$. See Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 836.

[11] The choice $M = 2M_\pi$ is clearly open to question. It should be emphasized however that the predicted rates are not sensitive to the choice of M so long as $M \geq 2M_\pi$. The values of α_J for $M = 2M_K$ are $\alpha_{J=1} = 0.38$, $\alpha_{J=3} = 0.26$.

[12] A study of the shape of our mass resolution was carried out by measuring the $M(\pi^- p)$ distribution from Λ^0 decay, which is known to have 0 width and a Q value similar to φ decay. The observed $M(\pi^- p)$ distribution was indeed symmetric, being characterized by $M_\Lambda = 1116 \pm 0.5$ MeV.

[13] The $\Lambda^0 K^+ K^-$ sample is completely free from contamination, in particular from $\Sigma^0 K^+ K^-$. Although $\Sigma^0 K^0 \bar{K}^0$ contamination is present in the neutral sample, the similarity in the asymmetry of both distributions allows us to conclude that the contamination does not appreciably contribute to the observed asymmetry.

[14] L. Bertanza et al., Phys. Rev. Letters 10, 176 (1963).

[15] The data were studied using several values of the resonance width and no significant difference resulted.

[16] Additional direct evidence for $I = 0$ which is of an entirely preliminary nature comes from the absence of a φ-type enhancement in the $M^2(K\bar{K})$ distribution of

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16 $I=1$ combinations, K^0K^- and $\bar{K}^0K^+$ produced in the reactions $K^-+p\to\Sigma^-+K^++\bar{K}^0$ and $K^-+p\to\Sigma^++K^-+K^0$. Further, if one assumes $I=1$, the triangular inequality relating these reactions to their neutral counterparts $K^-+p\to\Sigma^0+K^0+\bar{K}^0$ and $\Sigma^0+K^++K^-$, $[\sigma(\Sigma^+)]^{1/2}+[\sigma(\Sigma^-)]^{1/2}\geq 2[\sigma(\Sigma^0)]^{1/2}$, is violated to the extent $(3\pm 3)^{1/2}+(0\pm 1)^{1/2}\geq 2(22\pm 5)^{1/2}$.

[17]We estimate, for example, that $\varphi\to 2\pi$ via an electromagnetic transition is $\sim 2\times 10^{-3}$ less frequent than $\varphi\to K\bar{K}$. The 3π rate is dominated by $\varphi\to\rho+\pi$ because only two-body phase space is involved.

[18]Due to these uncertainties the ratio β provides essentially no new information on the φ spin.

[19]M. Gell-Mann, Phys. Rev. 125, 1067 (1962); California Institute of Technology Report CTSL-20, 1961 (unpublished). For appropriate remarks, also see reference 2.

[20]S. Okubo, Progr. Theoret. Phys. 27, 949 (1962).

[21]J. J. Sakurai, Ann. Phys. 11, 1 (1960); Phys. Rev. Letters 7, 335 (1961).

[22]G. F. Chew and S. C. Frautschi, Phys. Rev. Letters 8, 41 (1962).

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RESONANCE IN THE ($\Xi\pi$) SYSTEM AT 1.53 GeV*

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We wish to report the existence of a narrow resonance in the ($\Xi\pi$) system which we observed in the study of the interactions of negative K mesons in the LRL 72-in. hydrogen bubble chamber. The separated incident K^- beam, originating in the Bevatron, had a momentum of 1.80 ± 0.08 GeV/c; the uncertainty includes both the 6% momentum spread of the beam and the momentum loss in the chamber. The film was scanned for events with the following topology: "one positive secondary, one negative secondary with a decay, and one or two associated V's." This topology includes the reactions

$$K^- + p \rightarrow \Xi^- + K^+, \quad (1)$$

$$\rightarrow \Xi^- + K^+ + \pi^0, \quad (2)$$

$$\rightarrow \Xi^- + K^0 + \pi^+. \quad (3)$$

The events located by the scanners were analyzed using the kinematic fitting programs PANG and KICK. Based on a second scan of 80% of the film, the scanning efficiency was 99%. Only one possible example of multiple pion production was found. Table I gives the observed numbers of events of types (1), (2), and (3). Four events with charged K_1^0 decay were also consistent with the reaction $\pi^- + p \rightarrow \Sigma^- + K^0 + \pi^+$ due to a (presumed but as yet not studied) pion background. However, the χ^2 for this hypothesis is quite abnormal. Furthermore, the expected ratios of events of type (3) with charged Λ decay only, charged K_1^0 only, and with both charged Λ and charged K_1^0 decays, 4:1:2, agree well with the experimental numbers. These observations, coupled with the fact that the effective-mass distribution for ($\Xi\pi$) systems for events with charged K_1^0 agrees with those for the other cases, suggest strongly that all of these events are, in fact, examples of Reaction (3). Preliminary cross sections, based on a τ count and including corrections for neutral decays and for scanning bias of events with Ξ's shorter than 0.5 cm, are given in the third column of Table I. The detailed results of a study of our examples of Reaction (1) will be communicated in the near future.

Table I. Summary of Ξ^- production events at 1.80 GeV/c.

Reaction		Events	σ (μb)
$\Xi^- K^+$		94	135 ± 22
$\Xi^- K^+ \pi^0$		20	30 ± 8
$\Xi^- K^0 \pi^+$:	Λ decay 38		
	K_1^0 decay 10		
	Λ and K_1^0 decay 18		
	Total $\Xi^- K^0 \pi^+$	66	75 ± 13

Figure 1 shows Dalitz plots of the invariant mass squared of the ($\Xi\pi$) systems, $M_{\Xi\pi}^2$, vs $M_{K\pi}^2$ for the observed examples of Reactions (2) and (3). In both neutral ($\Xi^-\pi^+$) and charged

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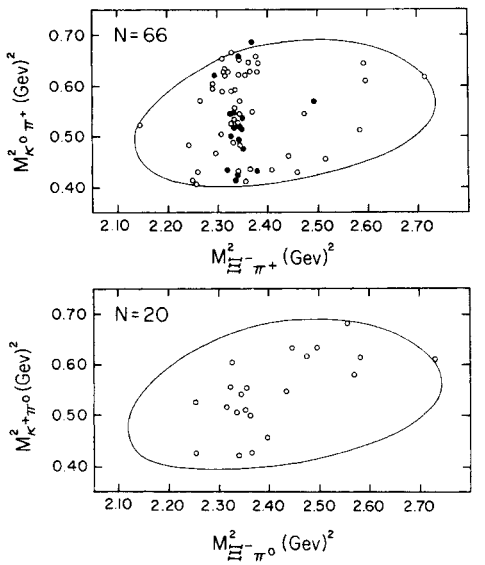


FIG. 1. Invariant-mass-squared Dalitz plots for the examples of Reactions (2) and (3). Solid dots represent events with both charged Λ and K_1^0 decays.

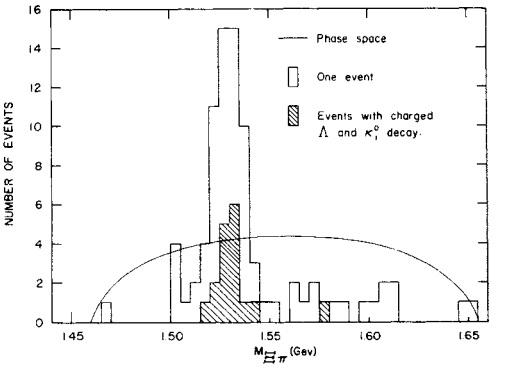


FIG. 2. Effective-mass plot for all $\Xi\pi$ systems observed in this experiment. The line is the relativistic three-body phase space.

($\Xi^-\pi^0$) systems, but especially the former, there is evidence for a pronounced resonance. There is no evidence for a resonance in other particle pairs. Figure 2 shows an effective-mass plot for all ($\Xi\pi$) pairs, regardless of charge. Defining all events between 1.515 and 1.545 GeV as within the resonance and neglecting the small nonresonant background, the resonance peaks at $M_{\Xi\pi} = 1.529 \pm 0.005$ GeV. The uncertainty is due primarily to as yet incompletely studied systematic errors. The resonance is quite sharp. The observed $\Gamma/2$ is comparable with our experimental errors which are typically ~5 MeV. In the case of events of type (3) where both Λ and K_1^0 decay via charged modes (shown shaded in Fig. 2), the momenta of all final reaction products may be individually measured. The experimental errors are accordingly somewhat smaller, ~2.5 MeV. The calculated Γ for these events is ~7 MeV. Within our precision, the width of the resonance can therefore not be determined, but it is not likely to be larger than $\Gamma = 7$ MeV.

The production amplitudes for the ($\Xi\pi K$) reaction, starting with K^- on protons, may be written as follows:

$$\Xi^-\pi^0K^+ \to [-\sqrt{2}a_{3/2,1} + a_{1/2,1} - a_{1/2,0}], \quad \text{(a)}$$

$$\Xi^-\pi^+K^0 \to [a_{3/2,1} + \sqrt{2}a_{1/2,1} + \sqrt{2}a_{1/2,0}], \quad \text{(b)}$$

$$\Xi^0\pi^0K^0 \to [\sqrt{2}a_{3/2,1} - a_{1/2,1} - a_{1/2,0}], \quad \text{(c)}$$

$$\Xi^0\pi^-K^+ \to [-a_{3/2,1} - \sqrt{2}a_{1/2,1} + \sqrt{2}a_{1/2,0}], \quad \text{(d)}$$

where $a_{t,T}$ is the amplitude for the production of the ($\Xi\pi$) system in isospin state t from an overall isospin state T. Assuming that the resonance occurs in a unique isospin state and neglecting interference effects with nonresonant backgrounds, (a) and (b) predict a production ratio $(\Xi^-\pi^0K^+)/(\Xi^-\pi^+K^0) = 2$ for $t = \frac{3}{2}$. The observed ratio in the $M_{\Xi\pi}$ region between 1.515 and 1.545 GeV is, in fact, 0.21 ± 0.07 which suggests strongly that the ($\Xi\pi$) resonance occurs in the $t = \frac{1}{2}$ state where the $a_{1/2,1}$ and $a_{1/2,0}$ amplitudes may interfere such as to give any $(\Xi^-\pi^0K^+)/(\Xi^-\pi^+K^0)$ production ratio. If the $a_{3/2,1}$ amplitude is indeed negligible, then the reaction

$$K^- + p \to \Xi^0 + \pi^- + K^+ \quad (4)$$

should occur twice as often as Reaction (2). Accordingly, we expect to find ~40 events in our film. We have searched 25% of our total exposure for events with the topology "two prong plus V" and found six events which fit only Hypothesis (4) while three additional ones fit (4) and other hypotheses, although with very high χ^2's. The observed number of examples of (4) is thus not in disagreement with the expected

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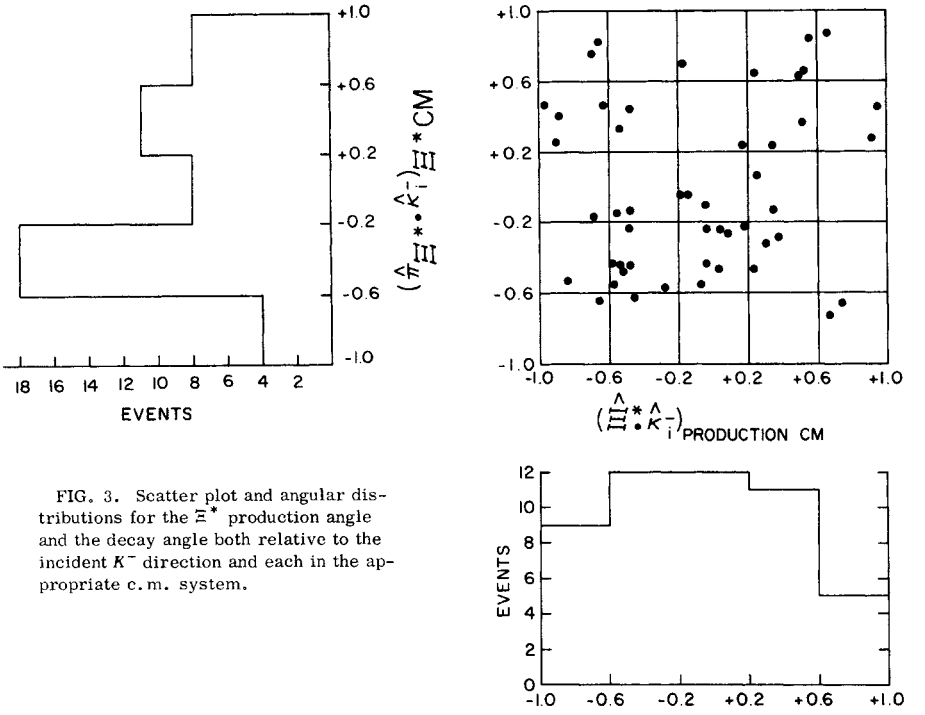


FIG. 3. Scatter plot and angular distributions for the Ξ^* production angle and the decay angle both relative to the incident K^- direction and each in the appropriate c.m. system.

number, ~10. Pending clarification of the systematics of boson-baryon resonances, the $(\Xi\pi)$ resonance should therefore be called $\Xi_{1/2}{}^*$.

Figure 3 shows a scatter diagram of the cosine of the Ξ^* production angle in the production c.m. system versus the cosine of the emission angle of the pion from Ξ^* decay with respect to the direction of the incident K^-. Only $\Xi^-\pi^+K^0$ events in the $M_{\Xi\pi}$ range from 1.515 to 1.545 GeV have been used. As only 14% of the events are expected to show charged $K_1{}^0$ decay alone, the detection of the events depends primarily on the existence of a Ξ track of observable length. At our cutoff of 0.50 cm, the probability of missing an event varies from 9% for extreme forward Ξ's to 24% for extreme backward Ξ's. Hence, large systematic biases in Fig. 3 are not likely. The angular distribution at production appears isotropic. At a $\Gamma \leq 7$ MeV, the mean separation of the Ξ^* and K^0 at the time of Ξ^* decay is $\gtrsim 20$F; hence final-state interactions between the K^0 and the other particles do not appear likely. This seems to be borne out by the fact that there appears to be no significant asymmetry about 90° in the Ξ^* decay relative to the Ξ^* direction of motion. The outgoing momentum in the two-body process

$$K^- + p \rightarrow \Xi^{*0} + K^0 \qquad (5)$$

is 0.32 GeV/c and large P-wave contributions are not expected but cannot be ruled out experimentally. At corresponding outgoing momenta the Ξ^-K^+ reaction shows large contributions from higher partial waves.[1] The distribution of the Ξ^* decay angle relative to the incident K^- also appears isotropic within statistics. According to the well-known argument of Adair,[2] S-wave production coupled with a flat decay distribution along the production direction would establish the Ξ^* spin to be $\frac{1}{2}$.

However, in view of the poor statistics, it is impossible to rule out some suitably chosen combination of S and P waves, coupled with a $\Xi_{1/2}{}^*$ with spin $\frac{3}{2}$. Hence, the Ξ^* spin is as yet not determined. Further work on this question is in progress.

We acknowledge with gratitude the assistance of many members of the hydrogen bubble cham-

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ber group at Lawrence Radiation Laboratory and, in particular, the support of Professor Luis Alvarez. Without the cooperation of the Bevatron personnel under the direction of Dr. E. J. Lofgren this work could not have been carried out. We are indebted to Professor N. Byers for many stimulating discussions and for clarification of questions regarding the Ξ^* spin. Last, but not least, we wish to acknowledge the painstaking and patient work of our scanners.

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OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

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It has been pointed out[1] that among the multitude of resonances which have been discovered recently, the $N_{3/2}^*(1238)$, $Y_1^*(1385)$, and $\Xi_{1/2}^*(1532)$ can be arranged as a decuplet with one member still missing. Figure 1 illustrates the position of the nine known resonant states and the postulated tenth particle plotted as a function of mass and the third component of isotopic spin. As can be seen from Fig. 1, this particle (which we call Ω^-, following Gell-Mann[1]) is predicted to be a negatively charged isotopic singlet with strangeness minus three.[2] The spin and parity should be the same as those of the $N_{3/2}^*$, namely, $3/2^+$. The 10-dimensional representation of the group SU_3 can be identified with just such a decuplet. Consequently, the existence of the Ω^- has been cited as a crucial test of the theory of unitary symmetry of strong interactions.[3,4] The mass is predicted[5] by the Gell-Mann–Okubo mass formula to be about 1680 MeV/c^2. We wish to report the observation of an event which we believe to be an example of the production and decay of such a particle.

The BNL 80-in. hydrogen bubble chamber was exposed to a mass-separated beam of 5.0-BeV/c K^- mesons at the Brookhaven AGS. About 100 000 pictures were taken containing a total K^- track length of ~10^6 feet. These pictures have been partially analyzed to search for the more characteristic decay modes of the Ω^-.

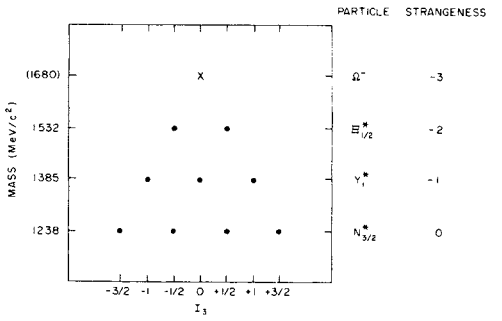


FIG. 1. Decuplet of $\frac{3}{2}^+$ particles plotted as a function of mass versus third component of isotopic spin.

The event in question is shown in Fig. 2, and the pertinent measured quantities are given in Table I. Our interpretation of this event is

$$\begin{aligned} K^- + p &\to \Omega^- + K^+ + K^0 \\ &\quad\; \Xi^0 + \pi^- \\ &\quad\; \Lambda^0 + \pi^0 \\ &\quad\; \gamma_1 + \gamma_2 \\ &\quad\; e^+ + e^- \\ &\quad\; e^+ + e^- \\ &\quad\; \pi^- + p. \end{aligned} \tag{1}$$

From the momentum and gap length measurements, track 2 is identified as a K^+. (A bubble density of 1.9 times minimum was expected for this track while the measured value was 1.7 ± 0.2.) Tracks 5 and 6 are in good agreement with the decay of a Λ^0, but the Λ^0 cannot come from the primary interaction. The Λ^0 mass as calculated from the measured proton and π^- kinematic quantities is 1116 ± 2 MeV/c^2. Since the bubble density from gap length measurement of track 6 is 1.52 ± 0.17, compared to 1.0 expected for a π^+ and 1.4 for a proton, the interpretation of the V as a K^0 is unlikely. In any case, from kinematical considerations such a K^0 could not come from the production vertex. The Λ^0 appears six decay lengths from the wall of the bubble chamber, and there is no other visible origin in the chamber.

The event is unusual in that two gamma rays, apparently associated with it, convert to electron-positron pairs in the liquid hydrogen. From measurements of the electron momenta and angles, we determine that the effective mass of the two gamma rays is 135.1 ± 1.5 MeV/c^2, consistent with a π^0 decay. In a similar manner, we have used the calculated π^0 momentum and angles, and the values from the fitted Λ^0 to deter-

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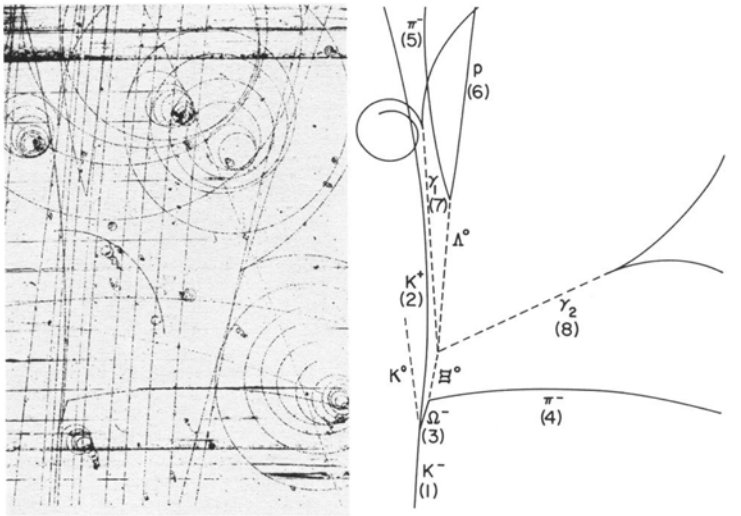


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

mine the mass of the neutral decaying hyperon to be 1316 ± 4 MeV/c^2 in excellent agreement with that of the Ξ^0. The projections of the lines of flight of the two gammas and the Λ^0 onto the XY plane (parallel to the film) intersect within 1 mm and in the XZ plane within 3 mm. The calculated momentum vector of the Ξ^0 points back to the decay point of track 3 within 1 mm and misses the production vertex by 5 mm in the XY plane. The length of the Ξ^0 flight path is 3 cm with a calculated momentum of 1906 ± 20 MeV/c. The transverse momenta of the Ξ^0 and of track 4 balance within the errors, indicating that no other particle is emitted in the decay of particle 3.

We will now discuss the decay of particle 3. From the momentum and gap length measurements on track 4, we conclude that its mass is less than that of a K. Using the Ξ^0 momentum and assuming particle 4 to be a π^-, the mass of particle 3 is computed to be 1686 ± 12 MeV/c^2 and its momentum to be 2015 ± 20 MeV/c. Note that the measured transverse momentum of track 4, 248 ± 5 MeV/c, is greater than the maximum momentum for the possible decay modes of the known particles (given in Table II), except for $\Xi^- \to e^- + n + \nu$. We reject this hypothesis not only because it involves $\Delta S = 2$, but also because it disregards the previously established associations of the Λ and two gammas with the event.

Table I. Measured quantities.

Track	Azimuth (deg)	Dip (deg)	Momentum (MeV/c)
1	4.2 ± 0.1	1.1 ± 0.1	4890 ± 100
2	6.9 ± 0.1	3.3 ± 0.1	501 ± 5.5
3	14.5 ± 0.5	-1.5 ± 0.6	...
4	79.5 ± 0.1	-2.7 ± 0.1	281 ± 6
5	344.5 ± 0.1	-12.0 ± 0.2	256 ± 3
6	9.6 ± 0.1	-2.5 ± 0.1	1500 ± 15
7	357.0 ± 0.3	3.9 ± 0.4	82 ± 2
8	63.3 ± 0.3	-2.4 ± 0.2	177 ± 2

Table II. Maximum transverse momentum of the negative decay product for various particle decays.

Decay modes	Maximum transverse momentum (MeV/c)
$\pi^- \to \mu^- + \nu$	30
$K^- \to \mu^- + \nu$	236
$K^- \to \pi^- + \pi$	205
$K^- \to e^- + \pi^0 + \nu$	229
$\Sigma^- \to \pi^- + n$	192
$\Sigma^- \to e^- + \Lambda^0 + \nu$	78
$\Sigma^- \to e^- + n + \nu$	229
$\Xi^- \to \pi^- + \Lambda^0$	139
$\Xi^- \to e^- + \Lambda^0 + \nu$	190
$\Xi^- \to e^- + n + \nu$	327

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The proper lifetime of particle 3 was calculated to be 0.7×10^{-10} sec; consequently we may assume that it decayed by a weak interaction with $\Delta S=1$ into a system with strangeness minus two. Since a particle with $S=-1$ would decay very rapidly into $Y+\pi$, we may conclude that particle 3 has strangeness minus three. The missing mass at the production vertex is calculated to be 500 $\pm$ 25 MeV/c^2, in good agreement with the K^0 assumed in Reaction (1). Production of the event by an incoming π^- is excluded by the missing mass calculated at the production vertex, and would not alter the interpretation of the decay chain starting with track 3.

In view of the properties of charge ($Q=-1$), strangeness ($S=-3$), and mass ($M=1686\pm12$ MeV/c^2) established for particle 3, we feel justified in identifying it with the sought-for Ω^-. Of course, it is expected that the Ω^- will have other observable decay modes, and we are continuing to search for them. We defer a detailed discussion of the mass of the Ω^- until we have analyzed further examples and have a better understanding of the systematic errors.

The observation of a particle with this mass and strangeness eliminates the possibility which has been put forward[6] that interactions with $\Delta S=4$ proceed with the rates typical of the strong interactions, since in that case the Ω^- would decay very rapidly into $n+K^0+\pi^-$.

We wish to acknowledge the excellent cooperation of the staff of the AGS and the untiring efforts of the 80-in. bubble chamber and scanning and programming staffs.

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