RESONANT INTERACTIONS OF π MESONS WITH STRANGE PARTICLES (Experimental data)

I. V. CHUVILO

Usp. Fiz. Nauk **76**, 329-350 (February, 1962)

THERE is a large amount of experimental material concerning the interactions of various elementary particles with one another. The values of total interaction cross sections, cross sections for elastic and exchange scattering and of inelastic interactions of nucleons with nucleons and of π mesons with nucleons have been and are being studied over a very wide range of energies of the interacting particles (cf. the survey in [1]). After the discovery of the series of the new "strange" particles, the hyperons and K mesons, in addition to investigating the properties of the free particles (their masses, lifetimes, spins, parities, types of decay, etc), attempts were made to study the interactions of these particles with the previously known particles, the π meson and nucleon. By now data have been accumulated on the scattering of K mesons by nucleons, as well as on other reactions produced by them. Investigations of hyperon-nucleon interactions have begun. But it is also important to know the characteristics of the interactions of the unstable particles with one another, for example the interaction of π mesons with hyperons, or of π mesons with K mesons, or, finally, of K mesons with hyperons. The difficulty with such experiments is that these particles are extremely shortlived and it is impossible at present to produce the "classical" conditions for experiments to observe the interactions of beams and targets of particles like hyperons or K mesons. Nevertheless, recently many new experimental results have been obtained which shed light on some of the characteristic features of pion-hyperon and pion-K meson interactions. These are experimental studies of resonances in π-Σ hyperon and π-Λ^0 hyperon interactions, and also in the interaction of π and K mesons.

In this survey the attempt is made to systematize the very interesting experimental data on these two questions and on some of the properties of these interactions. Since, however, the experimental investigations of these phenomena are not completed, we shall not deal with possible theoretical aspects of the question.

1. MASS OF THE RESONANT $\pi\Lambda^0$ INTERACTION

In treating the experimental material obtained with the 15-inch liquid hydrogen bubble chamber irradiated with a beam of K mesons of momentum 1.15 BeV/c, in addition to other reactions there were also 141 cases of the reaction [2]

$$K^- + p \to \Lambda^0 + \pi^+ + \pi^-. \quad (1)$$

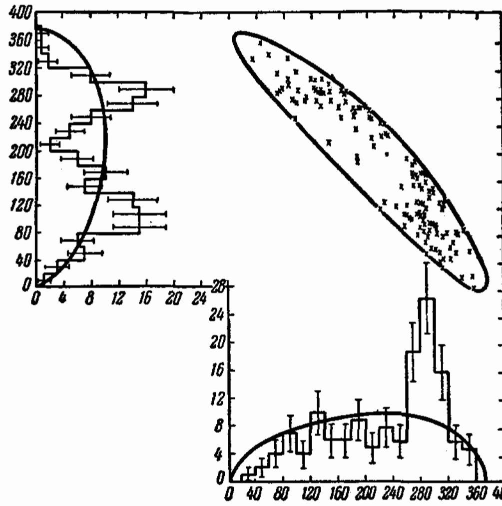

FIG. 1.

The lower part of Fig. 1 shows the spectrum of kinetic energies, T_+, of positive π mesons in the center-of-mass system of reaction (1). A striking feature is the strong peaking of the spectrum around the value $T_+ = 300$ MeV. At this point the spectrum differs markedly from that expected on statistical grounds, which is given by the phase curves shown in the same figure.

This result can be explained if we assume that reaction (1) proceeds in two stages, the first of which is a two-particle reaction in which a $\pi^-\Lambda^0$ system and a π^+ meson are produced according to the reaction

$$K^- + p \to (\pi^-\Lambda^0) + \pi^+,$$

and then the $\pi^-\Lambda^0$ system dissociates, giving reaction (1). Since a system consisting of a negative π meson and a Λ^0 hyperon is produced, it is of interest to know whether there is formation of a similar system containing a positive π meson. For this purpose we examine the spectrum of negative π mesons. It is shown in the left part of Fig. 1 and exhibits two peaks: in the region of values of T_- around 100 MeV and, as in the case of the π^+ mesons, at $T_- = 300$ MeV. This means that a $\pi^+\Lambda^0$ system is formed with the same mass as the $\pi^-\Lambda^0$ system. In this case it is easily shown from energy and momentum conservation that if the reaction proceeds via a primary formation of the $\pi^-\Lambda^0$ system with a mass around 1380 MeV, this will lead to the appearance of a maximum in the spectrum of kinetic energies of π^- mesons in the range of values between 35 and 170 MeV. If we subtract from the π^+ spectrum the part due to the statistical mechanism of the three-particle channel of reaction (1), the remaining π^+ mesons

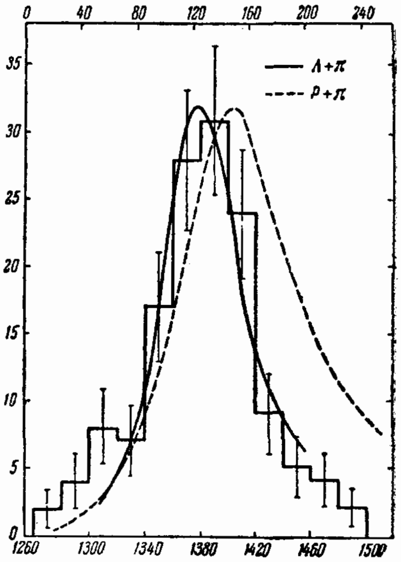

FIG. 2.

with T_+ around 300 MeV account for $^3/_4$ of the yield of π^- mesons in the spectrum interval 35–170 MeV. One can draw similar conclusions about the contribution of the $\pi^+\Lambda^0$ system from a comparison of the yield of π^- mesons at T_- = 300 MeV and of π^+ mesons in the energy interval 35–170 MeV. Thus an analysis of the spectra of π mesons produced in reaction (1) leads most naturally to the assumption that the quasi-two-particle channel gives a sizable contribution to this reaction. This quasi-two-particle character is a consequence of the existence of a resonant $\pi\Lambda^0$ interaction during the process of development of reaction (1), so that we may consider this reaction to occur in two stages: first, as a result of K^--p interaction, we "create" a π meson and a tightly bound $\pi\Lambda^0$ system, which we shall call a Y* particle, and then the Y* (excited hyperon) decays into a Λ^0 and a π meson. It appears that in approximately 75% of the cases reaction (1) proceeds via formation and subsequent decay of the Y*, i.e., in two successive stages, in accordance with the scheme

$$K^- + p \rightarrow Y^{*\pm} + \pi^{\mp}, \qquad (2)$$
$$\hookrightarrow \Lambda^0 + \pi^{\pm}.$$

Figure 2 shows the distribution of Y* masses obtained from these experimental data. The data shown in the histogram were approximated using a resonance expression of the form

$$\sigma \sim \frac{\lambda\!\!\!{}^-{}^2\Gamma^2}{(E-E_0)+\frac{1}{4}\Gamma^2}, \qquad (3)$$

where

$$\Gamma = 2b\,\frac{\left(\frac{a}{\lambda\!\!\!{}^-}\right)^3}{1+(a/\lambda\!\!\!{}^-)^2}$$

and a is the interaction radius in units of $\hbar/m_\pi c^2$, b is the reduced width in MeV, and E_0 is the resonance energy. Comparison with experiment gives the

Table I. Parameters of the $\pi\Lambda^0$ and pion-nucleon resonances when the experimental data are approximated by the formula

$$\sigma \sim \frac{\lambda\!\!\!{}^-{}^2\Gamma^2}{(E-E_0)^2 + {}^1\!/_4\Gamma^2} \quad \text{[cf. (3)]}$$

Parameters	pion-nucleon	$\pi\Lambda^0$-hyperon
Radius of interaction, 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

following values of these quantities: the mass of the Y* is 1384.3 MeV with a half-width of 64 MeV. The energy release in the Y* decay is Q = 129.3 MeV. The relative momentum of the emerging Λ^0 hyperon and π meson is of order 200 MeV/c, which is extremely close to the analogous quantity for the nucleon and π meson in the familiar ($^3/_2$, $^3/_2$) resonance in pion-nucleon scattering. For comparison, the curve for the resonant state in pion-nucleon scattering is shown by the dashed line in Fig. 2. If we interpret the $\pi\Lambda^0$ system in the same way, this means that there is a resonance in the $\pi\Lambda^0$ system, and Q is the kinetic energy for resonance in $\pi\Lambda^0$ scattering in the rest frame of the $\pi\Lambda^0$ system. A comparison of data for the $\pi\Lambda^0$ resonance and the pion-nucleon ($^3/_2$, $^3/_2$) resonance is given in Table I.

Later on,[3] an analysis from this point of view was made of 500 cases of reaction (1), obtained with beams of K^- mesons with momenta ranging from the threshold for this reaction, p_K^{lab} = 405 MeV/c up to 850 MeV/c. If the reaction occurs in two stages, through the two-particle reaction,

$$K^- + p \rightarrow Y^* + \pi,$$

followed by the decay,

$$Y^* \rightarrow \Lambda^0 + \pi,$$

then in the primary reaction the π mesons will be produced with a fixed energy and an energy spread due to the half-width $\Gamma/2$ in the distribution of masses of the Y*. Figure 3 shows the distribution of events of reaction (1) for p_K^{lab} = 850 MeV/c over the kinetic energies T_+ and T_- of the π^+ and π^- mesons, respectively. If, for example, all cases of this reaction occurred through the channel

$$K^- + p \rightarrow Y^{*-} + \pi^+,$$

the points would be distributed around the vertical line labelled Y^{*-}. If the reaction proceeded via the channel with formation of the Y^{*+}, the points would be located around the horizontal line Y^{*+}. The ellipse shows the region of allowed values of kinetic energies of the π mesons in the three-particle reaction $\pi^+\pi^-\Lambda^0$. As we see from this picture, it is by no means evident that reaction (1) occurs in two stages, through formation and rapid decay of the Y*. There are a large number

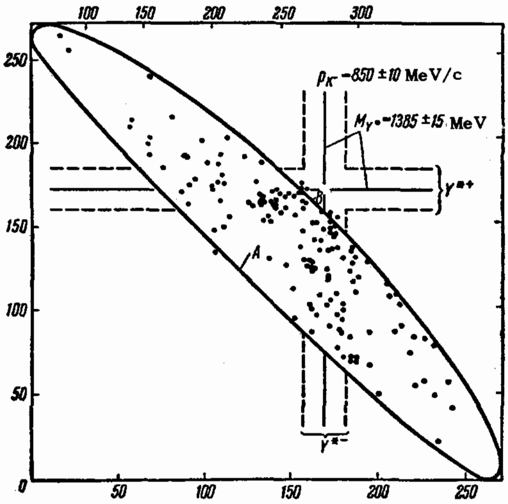

FIG. 3.

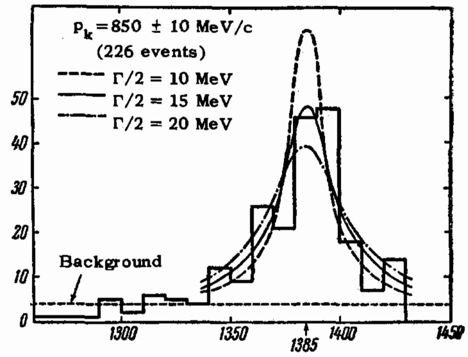

FIG. 4.

of cases of this reaction which are not fitted by such a model. The reason for this discrepancy will be considered later. In Fig. 4 we show the mass distribution for 226 Y* particles found in these experiments. The accuracy of the mass measurement in each individual case was from 3 to 5 MeV. Using the resonance formula (3) for describing the experimental histogram shows that the half-width of this distribution is between 15 and 20 MeV. Thus these facts also show that there is a baryon state Y* with mass of order $M_{Y*} = 1380$ MeV, which decays via strong interactions into a Λ^0 hyperon and a π^+ meson.

We arrive at similar conclusions from the analysis of experimental data on the interaction of K_2^0 mesons with protons in the 14-inch liquid hydrogen chamber.[4] In this experiment, 60 cases of the reaction

$$\widetilde{K}^0 + p \rightarrow \Lambda^0 + \pi^+ + \pi^0, \qquad (4)$$

were studied, produced in a beam of K_2^0 mesons with momentum (975 ± 100) MeV/c. The distribution found for the Q values of the decay $Y^* \rightarrow \Lambda^0 + \pi$ is shown in Fig. 5. As a supplement to the experiments with negative K mesons, observation of reaction (4) made it possible to show that in addition to the charged systems $Y^{*\pm}$, there also exists a neutral Y^{*0} particle, which decays according to the scheme

$$Y^{*0} \rightarrow \Lambda^0 + \pi^0. \qquad (4')$$

Forty of the 60 cases of reaction (4) were found at the maximum, of which 22 correspond to the reaction with formation of the Y^{*+} and 18 with Y^{*0}. The overall result for Q was the value 129 MeV with a half-width of 29 MeV, which corresponds to a Y* mass of 1384 MeV.

The half-width of the Q-distribution is determined by the square root of the sum of the squares of the natural width of this distribution and of the experimental resolution used in determining it. An analysis of the accuracy of the experiment shows that the instrumental half-width cannot be less than 20 MeV and is more likely close to 30 MeV. This means that the natural width of the Q-distribution in the Y* decay lies in the range $0 \leq \Gamma \leq 20$ MeV.

Since reaction (2) is a threshold reaction for capture of stopped K^- mesons in hydrogen, it cannot be observed. But in the capture of slow K^- mesons by a multinucleon system like a nucleus, reactions for producing the Y* are still possible via the scheme

$$K^- + 2N \rightarrow Y^* + N.$$

Investigations of the capture reaction[5a] for stopping K^- mesons in deuterium, which occurs according to the scheme

$$K^- + D^2 \rightarrow \Lambda^0 + p + \pi^-,$$

have shown that the observed experimental facts for this reaction can be explained only by assuming that approximately one third of the cases occur through the channel

$$K^- + D^2 \rightarrow Y^{*-} + p.$$

Spectra calculated on this basis for the protons produced in the reaction are in good agreement with the experimental measurements. This is evidence in favor of the hypothesis, and shows the important role of the effects of resonant $\pi\Lambda^0$ interactions (Y^* particles) in reactions of capture of K^- mesons by nuclei with formation of Λ^0 hyperons together with π mesons.

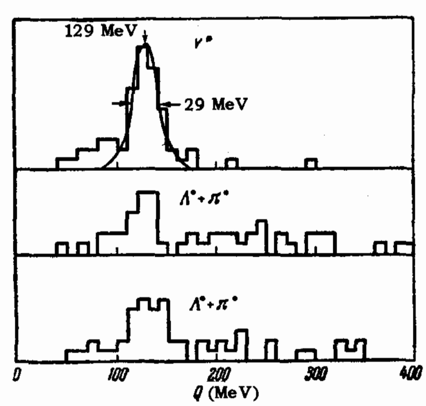

FIG. 5.

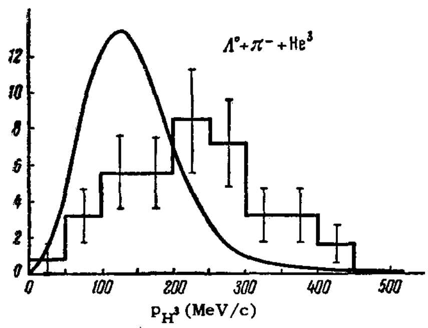

FIG. 6.

Finally, information concerning the Y^{*-} particles can also be obtained by studying the reaction

$$K^- + He^4 \to \Lambda^0 + \pi^- + He^3, \tag{5}$$

which was identified by studying stoppings of K^- mesons in a helium bubble chamber.[5] Figure 6 shows the momentum spectrum of He^3 recoil nuclei in reaction (5), while Fig. 7 gives the spectrum of H^3 recoils from the reaction

$$K^- + He^4 \to \Sigma^\pm + \pi^\mp + H^3. \tag{5a}$$

Comparison of these spectra with calculations in the impulse approximation[6] shows a considerable difference between the computed and experimental spectra for He^3. This difference is interpreted as a consequence of the fact that reaction (5) proceeds in 65% of the cases via formation of the Y^{*-}, i.e., according to the scheme

$$K^- + He^4 \to Y^{*-} + He^3, \quad Y^{*-} \to \Lambda^0 + \pi^-. \tag{6}$$

The observed peak in the He^3 momentum distribution at $p_{He^3} = 250$ MeV/c corresponds to a Y^{*-} mass of 1385 MeV, with a half-width of order 35 MeV. Since the energy resolution in these experiments was around 3 MeV, this means that the observed half-width corresponds to the natural half-width of the mass distribution of the Y^{*-} particles.

Thus a perusal of all this experimental material gives a strong indication that a resonant $\pi\Lambda^0$ interaction exists, which can be interpreted as the existence of an unstable Y^* particle with mass 1385 MeV and half-width of order 20 MeV. There exist three charge states of the Y^*, which decay via strong interaction according to the schemes

$$Y^{*\substack{+\\0\\-}} \to \Lambda^0 + \pi^{\substack{+\\0\\-}}$$

with Q = (130 ± 20) MeV. Since strangeness and isotopic spin are conserved in such a decay, the Y^* is characterized by isotopic spin 1 and strangeness −1. In the future we shall refer to the isotopic triplet of Y^* particles with the above decay scheme as the Y_1^*, where the subscript 1 gives the total isotopic spin. We shall consider other internal properties of the Y_1^* in Sec. 4.

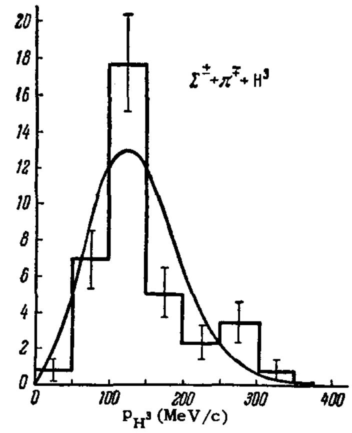

FIG. 7.

If we take the mass of the Y_1^* to be 1385 MeV, then other channels for strong decay are possible, for example,

$$Y_1^* \to \Sigma + \pi$$

with appropriate Q values depending on the type of the final Σ and π. But the probability of Y_1^* decays via channels involving Σ hyperons is much smaller than for channels with Λ^0 hyperons. From data on absorption of K^- mesons in the helium bubble chamber,[5] the contribution to the effect from the decay channel $Y_1^{*0} \to \Sigma + \pi$ is no more than 20%. In experiments with K^- mesons having a momentum of 760 MeV/c, an upper limit of 3% was found for the ratio of yields of Σ and Λ^0 hyperons in Y_1^* decay, and 5% for a K^- meson momentum of 850 MeV/c. The "maximum possible" limiting values of these ratios were estimated to be 20 and 10%, respectively.[3]

In reaction (1), for K^- mesons with momentum 1.15 BeV/c, it was found[7] that the ratio of the yields of Σ and Λ^0 hyperons in Y_1^* decays does not exceed 8% and is consistent with a value of zero.

2. RESONANCES IN $\pi\Sigma$ INTERACTIONS

In studying correlation effects in reactions of production of Σ hyperons along with three or four π mesons in K^--p interactions, and comparing them with Λ^0-hyperon reactions at momentum 1.15 BeV/c, i.e., reactions of the type

$$K^- + p \to \begin{cases} \Sigma^{\substack{+\\0\\-}} + \pi^{\substack{-\\0\\+}} + \pi^+ + \pi^-, \\ \Lambda^0 + \pi^0 + \pi^+ + \pi^-, \end{cases}$$

and

$$K^- + p \to \Sigma^0(\Lambda^0) + \pi^+ + \pi^- + \pi^0 + \pi^0,$$

an indication was found of the existence of resonant interactions of π mesons with Σ hyperons.[7] Resonant states are found only in the neutral $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, and $\pi^0\Sigma^0$ systems. No resonant states are found in the singly and doubly charged $\pi\Sigma$ systems. The mass of the $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$ resonant states is 1405 MeV with a half-width of 20 MeV. The mass of the resonant $\pi^0\Sigma^0$ state is found to be 19 ± 6 MeV lower, i.e., 1386 MeV. To explain this triplet of $\pi\Sigma$ systems from the point of view of a single resonant state in the $\pi\Sigma$ interaction is somewhat difficult because of this mass difference, which cannot be explained by electromagnetic interactions. Possibly the inclusion of the effects of the identity of the π mesons on the emergence of the particles in the final states of the various reactions may give an explanation of the observed difference.

A study has been made [7a] of the production of the neutral $\pi^{\pm}\Sigma^{\mp}$ systems in the capture of K^- mesons (with kinetic energy around 50 MeV) by nuclei in an emulsion. They looked for reactions leading to simultaneous production of charged Σ hyperons and π mesons. The mass

$$M = [(E_\Sigma + E_\pi)^2 - (\overline{\mathbf{P}}_\Sigma + \overline{\mathbf{P}}_\pi)^2]^{1/2}$$

was determined for each case of appearance of one of the neutral pairs. The error in the individual mass measurements was ±6 MeV. Analysis of the experimental data shows that the M-distribution is a combination of two effects. First there is a broad M-distribution caused by production of $\Sigma + \pi$ pairs in the three-particle reactions

$$K^- + 2N \rightarrow \Sigma + \pi + N$$

on bound nucleons in nuclei. Secondly, about ⅓ of the reactions in which $\Sigma + \pi$ pairs are produced proceed via production of resonant $\pi^{\pm}\Sigma^{\mp}$ states. However the mass of the $\pi^{\pm}\Sigma^{\mp}$ systems found by this procedure was 10–15 MeV greater than the mass of the charged Y_1^* particles which decay into a $\Lambda^0 + \pi$ pair. With a resonance energy around 1400 MeV for the $\pi^{\pm}\Sigma^{\mp}$ states, the energy width was found to be of order 40 MeV, including instrumental error. The result found here thus confirms the information on the existence of neutral resonant $\pi^{\pm}\Sigma^{\mp}$ states which was found in hydrogen bubble chambers in irradiations with beams of K^- mesons.

If we assume that all three neutral resonant $\pi\Sigma$ states are the manifestation of a single resonant $\pi\Sigma$ interaction, we find, from the ratio

$$\beta = \frac{\pi^0\Sigma^0}{\pi^+\Sigma^- + \pi^-\Sigma^+}$$

of the yields of $\pi^0\Sigma^0$ and $(\pi^{\pm}\Sigma^{\mp})$ decays, the value of the total isotopic spin I of this state; the value of β should be 2, 0, or 0.5, depending on whether I is 2, 1, or 0. It was found experimentally [7] that $\beta = 0.6 \pm 0.2$; this favors the value I = 0. Thus the resonant $\pi\Sigma$ interaction occurs in an isotopic singlet state. By analogy with the $\pi\Lambda^0$ resonance, we can also identify this $\pi\Sigma$ interaction with some particle, which we denote by the symbol Y_0^*. The $\pi\Sigma$ resonance does not occur in K^--p reactions for production of Σ hyperons accompanied by only two π mesons. This can be understood by assuming that the reaction

$$K^- + p \rightarrow \Sigma + \pi + \pi$$

occurs only in the channel with total isospin zero. One can check this argument by studying the reaction

$$\widetilde{K}^0 + p \rightarrow \Sigma + \pi + \pi,$$

which should not be observed, since we have here only a state with isotopic spin unity. At the very least, its yield should be noticeably less than that of the reaction induced by K^- mesons.

The possible existence of resonant $\pi\Sigma$ interactions with a mass of 1500–1540 MeV, with total isotopic spin 2, i.e., a Y_2^*, is indicated [8] from the study of the reaction

$$K^- + p \rightarrow \Sigma^{\pm} + \pi^{\mp} + \pi^0$$

using K^- mesons with momenta of 760 and 850 MeV/c. The experimental material is, however, not sufficient for drawing any definite conclusions.

3. SOME PROPERTIES OF REACTIONS CREATING THE Y_1^*

For those channels of the reaction type

$$\widetilde{K} + N \rightarrow \Lambda^0 + \pi + \pi,$$

in which the resonant $\pi\Lambda^0$ interaction appears and results in a two-particle type of reaction, we can write the following schemes:

$$K^- + p \rightarrow \begin{cases} Y_1^{*\pm} + \pi^{\mp} \rightarrow \Lambda^0 + \pi^+ + \pi^-, & \text{(7a)} \\ Y^{*0} + \pi^0 \rightarrow \Lambda^0 + \pi^0 + \pi^0, & \text{(7b)} \end{cases}$$

$$\widetilde{K}^0 + p \rightarrow Y^{*\overset{+}{0}} + \pi^{\overset{0}{+}} \rightarrow \Lambda^0 + \pi^0 + \pi^+. \qquad \text{(7c)}$$

a) Excitation functions and angular distributions. Figure 8 shows the data [3] on excitation functions for the $\pi^+\pi^-\Lambda^0$ reaction, where we also give results separately for Y_1^{*+} and Y_1^{*-} as a function of the momentum of the initial K^- meson in the laboratory system. The graph also shows two possible dependences of the cross section on the momentum of the Y_1^* in the c.m.s. of the reaction, with shapes proportional to the first power of the momentum and the cube of the momentum

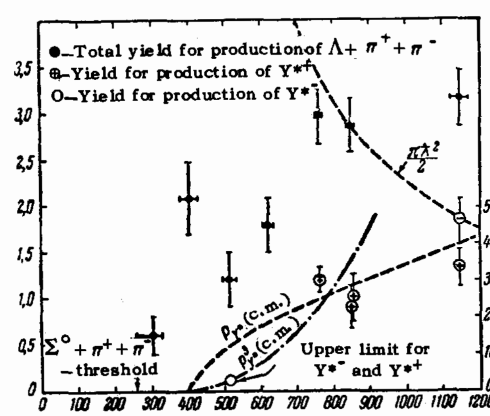

FIG. 8.

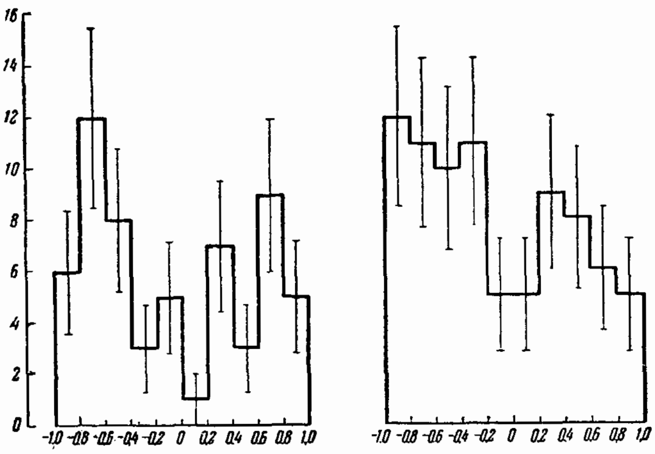

FIG. 9.

p_{Y^*}. The curve $\pi\lambda^2/2$ shows the maximum value of the cross section for creating Y_1^* particles for a single isotopic spin partial wave with total angular momentum of the reaction equal to $j = 1/2$. This is done on the basis of arguments that the angular distributions of these reactions are isotropic within statistical accuracy for K^- meson momenta of 850 MeV/c, which favors the value $j = 1/2$. But the fact that the $\pi^+\pi^-\Lambda^0$ cross section is very close to $\pi\lambda^2/2$ seems to indicate that there is also a contribution from other partial waves. That this is possible can be seen from the angular distributions for reactions producing Y_1^* particles by using K^- mesons of momentum 1.15 BeV/c, which are shown in Fig. 9. The possible anisotropy of these angular distributions is caused by the contribution from partial waves with $l > 0$, since at these energies of the K^- mesons, $\hbar k/m_\pi c \sim 3$. The difference in the shapes of the angular distributions for production of Y_1^{*+} and Y_1^{*-} particles may be related to the different superpositions of isotopic amplitudes for isospins 1 and 0 for these two reaction channels.

b) Final state interaction of reaction products. Although the two-particle nature of reaction (7) appears quite clearly, for example in the energy spectrum of the π mesons, the extent to which such a two-particle picture of reactions of the type of (1) can be used in treating other properties is still an important question. We shall therefore discuss it briefly. From the estimates of the half-width of the Q-distribution for Y_1^* particles, with a value of 20—30 MeV, it follows that the lifetime of the Y_1^* is approximately an order of magnitude greater than the lifetime of the $(3/2, 3/2)$ isobar in pion-nucleon scattering. There is therefore some hope of getting information about some of its properties by assuming that it decays in the free state, i.e., the products of the Y_1^* decay do not interact with the π mesons that are formed along with the Y_1^* particle. Some results of such an analysis will be given below. Although the lifetime of the $\pi\Lambda^0$ resonance is greater than that of the pion-nucleon isobar, it is still of the order of the duration of processes caused by strong interactions. Thus for a rigorous treatment we should take into account interactions in the final state of the $\pi\pi\Lambda^0$ system. That this is the case can be seen from an analysis of the angular distributions of Y_1^* decays. In fact, if we represent the angular distribution of the products of the decay of the Y_1^* as a polynomial in $\cos\vartheta$:

$$\frac{dn}{d\Omega} \sim 1 + a_1 \cos\vartheta + a_2 \cos^2\vartheta + \ldots, \tag{8}$$

then, because of conservation of spatial parity, the Y_1^* decay via strong interaction should have no fore-aft asymmetry in the emerging decay products, i.e., the coefficients of odd powers of $\cos\vartheta$ in the expansion should be equal to zero. But the experimental data [3] indicate that the coefficient a_1 of $\cos\vartheta$ is different from zero, since the Λ^0 hyperons from Y_1^* decays emerge preferentially forward (cf. the histogram in Fig. 11).[1] This shows that one must include the effects of interaction of the three particles in the final state of this interaction. The presence of such an interaction requires us to consider interference effects which arise from the requirements of Bose-Einstein statistics for the two π mesons in the final state.[9] Only then do we get rigorous conditions for determining the internal properties of the Y*.

c) Isotopic spin. Reaction (7c) induced by $\tilde{K}^0$ mesons is characterized by total isotopic spin 1, whereas in reaction (7a) with K^- mesons both total isotopic spin 1 and 0 are present. Since reaction (7c) has a large cross section, this means that the state with isotopic spin 1 must necessarily participate in these reactions. Whether there is a contribution from the isospin 0 state must be determined from further analysis of the experimental data.

The isotopic spin of the Y_1^* is 1, which follows from the fact that it decays into the isotopic singlet Λ^0-hyperon and π meson; it is a component of an isotopic triplet, characterized by total isospin 1.

Both Y_1^{*+} and Y_1^{*-} are formed in K^--p reactions, but the ratio of the yields is different from 1 and is equal to [3] $Y_1^{*+}/Y_1^{*-} = 59/82$. The deviation of this ratio from unity is of course not well founded statistically, but if this is actually the case it means that the ratio of the isotopic amplitudes and their phases in these reactions are different from unity.

In reactions like (7c), where the total isotopic spin is 1, the unit of isospin is transferred to the two π mesons since the Λ^0 is an isotopic singlet. Thus the spatial wave function merely changes sign when the π mesons are interchanged. If the interaction is charge-independent, any description of the distribution of the reaction products must be independent of the charge of the π meson. Conversely, the observation of a symmetry of this sort is evidence for the charge independence of interactions involving strange particles. The mass spectrum data for Y_1^* particles from $\tilde{K}^0$-p reactions [4] shown in Fig. 5 have similar shapes for both the $\pi^0\Lambda^0$ and $\pi^+\Lambda^0$ combinations. The smaller of the two Q values found in this way gave a curve with a single maximum around Q = 129 MeV. The fact that the Q value is independent of any detailed assumptions about the origin of the peaks near Q = 130 MeV, and the similarity of the Q-distributions for the $\pi^+\Lambda^0$ and $\pi^0\Lambda^0$ combinations is evidence for charge independence of the interaction which gives rise to these reactions for creating Y_1^* particles.

Further information concerning the isotopic properties of reaction (7) can be obtained by studying the consequences of including the interaction of the Λ^0 and the two π mesons in the final state of the reaction.

Since the Y_1^* during its lifetime travels a distance greater than 4 Fermis, one might think that the processes of successive emission of the first and second π mesons do not interfere dynamically to any great extent. We can write the amplitude M(1, 2) for such a reaction in the form [9]

$$M(1,2)=\Phi(\sigma, \mathbf{q}, \mathbf{p}_1, \mathbf{p}_2)\, A(p_2), \tag{9}$$

where $\mathbf{q}$ and $\mathbf{p}_1$ are the momenta of the K^- meson and the first π meson in the center-of-mass system of the reaction, while $\mathbf{p}_2$ is the momentum of the π meson from the Y_1^* decay, in the rest system of the Y_1^*. The argument σ contains the dependence of Φ on angular momenta and spins which are important for the reaction. The effect of the resonant state is given by the second factor

$$A(p)=\frac{\exp[i\delta(p)]\sin\delta(p)}{p^{2L+1}}, \tag{10}$$

where L is the orbital angular momentum of the $\pi\Lambda^0$ system, and determines the spin and parity of the Y_1^*. In the final $\pi_1\pi_2\Lambda^0$ configuration, it is still important to know the value l of the orbital angular momentum of the first π meson. Thus, for a given total angular momentum j of the reaction, the function Φ is determined by the angular momentum L of the $\pi_2\Lambda^0$ system, by the relative parity of K and Λ^0, and by the centrifugal barrier which depends on l.

The amplitudes for reactions involving the Y_1^{*+} and Y_1^{*-} should add coherently, and their sum should correspond to a final state with the correct symmetry with respect to interchange of the positions of the two π mesons. We can write the following equations for the amplitudes M_0 and M_1 with total isospin 0 and 1, respectively:

$$M_0=M'(1,2)+M'(2,1),$$
$$M_1=M''(1,2)-M''(2,1).$$

For comparison with experiment, it is convenient to treat the probability distribution $P(T_+, T_-)$ in the phase space of the kinetic energies of the π mesons (T_+, T_-). Since this distribution is summed over all orientations of the $\pi\Lambda^0$ system, the contributions to it from initial states with different angular momenta and parity add incoherently. Since

$$P(T_+, T_-)=\frac{1}{2}|M_0+M_1|^2,$$
$$P(T_-, T_+)=\frac{1}{2}|M_0-M_1|^2,$$

the symmetrized probability distribution $\{P(T_+, T_-) + P(T_-, T_+)\}$ is simply the superposition of the individual distributions I = 0 and I = 1, without any interference between them.

Now let us look at the corresponding representation of the data given in Fig. 3. We see that the distributions $P(T_+, T_-)$ and $P(T_-, T_+)$ are not essentially different. This indicates that the reaction probably proceeds mainly through a single isospin channel.

It is especially interesting to treat the two limiting cases, with $T_+ = T_-$, where the Λ^0 either receives the maximum recoil momentum or is left at rest. In the first situation, M(1, 2) = M(2, 1), since the momenta of the π mesons are equal and are in the same direction. In this case, at point A of the diagram in Fig. 3, we can expect considerable interference between these two states. The interference will be constructive in the state with I = 0 and destructive in the state with I = 1. Since there is no concentration of the distribution at point A, this is evidence that the reaction proceeds via the I = 1 channel. In the second case, where the Λ^0 is at rest, the nature of the interference between M(1, 2) and M(2, 1) in the various isospin states depends on whether the sum of the angular momenta $L + l$ is even or odd. In a state with I = 1 (I = 0), the interference will be constructive if the sum $L + l$ is odd (even) and destructive if it is even (odd). The experimental data presented in Fig. 3 show a concentration of points around the point B, corresponding to this case, i.e., they are evidence for a large constructive interence between M(1, 2) and M(2, 1). An examination of the reaction mechanism shows that in this case the state with total isospin I = 1 should be preferred. This means that the sum $L + l$ is odd. From a comparison with the experimental data, we can then draw conclusions about the possible values of the Y_1^* spin and parity. These will be discussed in the next section.

4. SPIN AND PARITY OF THE Y_1^*

Before going on to present the facts concerning the determination of the spin and parity of the Y_1^*, we make a few general remarks. Since we are considering the process of Y_1^* decay caused by strong interactions, spatial parity is conserved, so we are dealing with the determination of the relative parity of the Y_1^* and the Λ^0. If we start from the decay scheme

$$Y_1^* \to \Lambda^0 + \pi$$

and remember that the π meson is a pseudoscalar particle, for the case of the $\pi\Lambda^0$ system with even orbital angular momentum of the relative motion of the components of the system (L = 0, 2, . . .), the relative $Y_1^*\Lambda^0$ parity is negative, while odd values of L would mean positive relative $Y_1^*\Lambda^0$ parity. Since the relative momentum of the particles at the resonance is of order 200 MeV/c, this means that the D state (L = 2) of the $\pi\Lambda^0$ system can hardly give any contribution to the effect. So in our further analysis of the experimental material we shall proceed on the assumption that the states which dominate the $\pi\Lambda^0$ resonance scattering are either L = 0 (S states) or L = 1 (P states). Since the spin of the Λ^0 is $1/2$, for the case of an S state of the $\pi\Lambda^0$ system the spin of the Y_1^* is $J = 1/2$ ($S_{1/2}$ state). In the P state of the $\pi\Lambda^0$ system, the two possible combinations of the spin $J = 1/2$ of the Λ^0 and the relative angular momentum L = 1 give two possible values for the spin of the Y_1^*: $J = 1/2$ ($P_{1/2}$ state) and $J = 3/2$ ($P_{3/2}$ state).

It is now completely clear that the interaction of the three product particles of reactions like (1) in the final state has a significant effect on the final outcome of the reaction. A rigorous treatment of the observed effects should therefore include this interaction.

The possibility of getting information about the spin and parity of the Y_1^* on the assumption that it decays in the free state is very attractive. Let us see what one gets from proceeding on this assumption.

Information about the spin of a free noninteracting unstable particle can be obtained by analyzing the angular distributions of its decay products. If we represent the angular distribution of the decay products of such a particle around some arbitrary direction as a polynomial in the cosine of the decay angle ϑ, the expansion will contain only even powers of cos ϑ. The highest power will be 2a, where a is the spin of the particle, in the case of a boson, or the spin minus $1/2$, in the case of a fermion. Thus one immediately gets a lower limit on the spin of the decaying particle.

Let us assume that the Y_1^* is formed in the reaction

$$K^- + p \to Y_1^* + \pi$$

and leaves the region of interaction, so that its decay products, the Λ^0 and π meson, do not interact with the π meson initially formed in this reaction. It is easy to show [10] that if we select those cases where the Y_1^* emerges at an angle close to 0° to 180° to the direction of the initial particle, expression (8) for the angular distribution of the decay products in the rest frame of the Y_1^* will have the following forms, as a function of the spin J of the Y_1^*:

$$J = \frac{1}{2}, \quad \frac{dn}{d\Omega} \sim 1,$$

$$J = \frac{3}{2}, \quad \frac{dn}{d\Omega} \sim \frac{1}{2} + \frac{3}{2}\cos^2\vartheta. \tag{11}$$

One can also write the forms of the angular distributions for higher spin values, but the two cases given above are sufficient.

In [4], 17 cases of Y_1^* particles were selected for analysis, for which the angle φ between the initial K_2^0 meson and the Y_1^* satisfied the condition $|\cos\varphi| \geq 0.7$. Of these, (50 ± 15)% decayed so that the decay angle ϑ satisfied the condition $|\cos\vartheta| \geq 0.5$. It follows from the angular distributions that the expected fraction of decays satisfying this condition on the decay angle ϑ is 0.5 for the case of spin $1/2$ for the Y_1^*, and 0.69 for spin $3/2$. The result agrees with that expected for spin $1/2$ of the Y_1^*, but it is only 1.3 standard deviations away from that expected for $J = 3/2$. Thus one cannot draw a statistically definite conclusion about the spin of the Y_1^* from the experimental material. Other methods of analysis of this same experimental data also give no basis for a definite conclusion. A similar analysis of 29 events, obtained in another experiment, [3] gave the same indefinite conclusion about the spin of the Y_1^*.

An attempt was also made to determine J by measuring the anisotropy of the Y_1^* decays relative to the normal to the production plane of the Y_1^*.[2] For spin $J = 3/2$, the angular distribution of the Y_1^* decays should have the form $A + B\xi^2$, and not depend on the parity of the Y_1^*.[11] The quantity ξ is

$$\xi = \frac{(\mathbf{P}_K \times \mathbf{P}_{Y_1^*})\,\mathbf{P}_{\Lambda^0}}{|\mathbf{P}_K \times \mathbf{P}_{Y_1^*}|\,(\mathbf{P}_{\Lambda^0})},$$

where $\mathbf{P}_a$ is the momentum of a particle of type a in the center of mass of the $K^- + p$ reaction. Since the coefficient B is a function of the production angle for the Y_1^*, one must limit oneself to the region where the anisotropy will be a maximum relative to the normal to the production plane. Events were selected with creation angles φ for the Y_1^* satisfying the condition $|\sin\varphi| \geq 0.866$. Of the 62 cases of production in this angular interval, 35.5% had $|\xi| > 0.5$. If the distribution were isotropic, as it should be for $J = 1/2$, we would expect a yield of (50 ± 6.3) % of cases with such values of ξ. Thus the result obtained is 2.3 standard deviations away from that expected for an isotropic distribution, which is evidence in favor of a larger value of $S_{Y_1^*}$ than $1/2$.

One can also try to determine the spin of the Y_1^* from experimental data obtained using a helium bubble chamber.[5] If we assume that the K^- meson is absorbed by the He^4 nucleus in an S state, the total angular momentum of the particles produced in the reaction

$$K^- + He^4 \to Y_1^* + He^3 \tag{6}$$

will be 0. If we now choose our axis along the direction of motion of the Y^{*-}, the angular distribution of the decay products in the center-of-mass system will be determined by (11) as a function of J. The corresponding experimental data on angular distributions of Y_1^* decays are given in Fig. 10. The distribution shown describes 30 cases of Y_1^* decay in which the He^3 momentum exceeded 200 MeV/c. Clearly the experimental material is very sparse but the distribution does favor isotropy. The χ^2 test gives 4.0 for an isotropic distribution and 17.2 for a distribution of the form

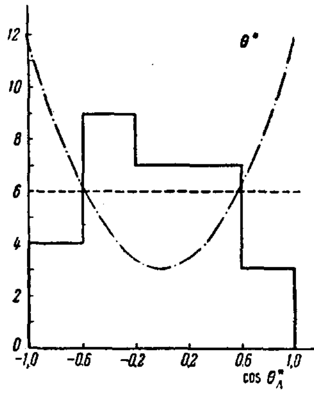

FIG. 10.

$\frac{1}{2} + \frac{3}{2}\cos^2\vartheta$, while the expected value from these data is 4 ± 2. Thus the experimental data on absorption of K^- mesons in He^4 with formation of the Y_1^* favor $J = \frac{1}{2}$.

If we take this value for the spin of the Y_1^*, we can draw some conclusions about its parity. We again use L for the relative orbital angular momentum of the Λ^0 and the π meson in the Y_1^* decay, and l for the orbital angular momentum of the relative motion of the Y_1^* and the He^3 nucleus in reaction (6). If we assume that $J = \frac{1}{2}$ and that the K^- is pseudoscalar, only two combinations are possible:

$$\text{either } L=0,\ l=0,$$
$$\text{or } L=1,\ l=1.$$

The second combination corresponds to a flipping of the spin of the absorbing nucleon, and should be diminished because of considerations about the centrifugal barrier. Since 65% of the reactions we are considering go via the Y_1^*, the second combination of values of L and l is improbable. Thus from the fact that the reaction via the channel with formation of the Y_1^* dominates, and that the K^- absorption by He^4 occurs in an S state, we arrive at the choice of the combination $L = 0$, $l = 0$. Thus, according to these data, the Y_1^* system is in an $S_{1/2}$ state.

Information about the parity of the Y_1^* can be gotten by assuming that it is produced polarized in reaction (2). Assuming $J = \frac{1}{2}$, we can in that case obtain the following expression for the unit vector $\mathbf{P}$ along the direction of polarization of the Λ^0 in the decay of the Y_1^*: [12]

$$\mathbf{P} = (\mathbf{pn})\,\mathbf{p} + \gamma(\mathbf{p}\times\mathbf{n})\times\mathbf{p}, \tag{12}$$

where $\mathbf{n}$ is the unit vector normal to the plane of production of the Y_1^*, and $\mathbf{p}$ is a unit vector along the momentum of the Λ^0 in the rest system of the Y_1^*, and $\gamma = \pm 1$, where the sign is determined by whether the Y_1^* decays into an $S_{1/2}$ or a $P_{1/2}$ state of the $\pi\Lambda^0$ system. For decay into an $S_{1/2}$ state, we have $\gamma = +1$ and

$$\mathbf{P} = \mathbf{n}, \tag{13}$$

i.e., the hyperons are polarized along the normal to the plane of production of the Y_1^*.

For the decay of the Y_1^* into the $P_{1/2}$ state of the $\pi\Lambda^0$ system, we find, setting $\gamma = -1$ in (12), the expression

$$\mathbf{P} = -\mathbf{n} + 2(\mathbf{np})\,\mathbf{p} \equiv \mathbf{m} \tag{14}$$

for the polarization vector of the Λ^0. The angular distribution of the Λ^0 decays will have the form

$$1 + P_{Y_1^*}\alpha\cos\theta, \tag{15}$$

where $P_{Y_1^*}$ is the degree of polarization of the Y_1^*, α is the asymmetry parameter for Λ^0 decays ($\alpha \approx 1$), and θ is the angle between the direction of the Λ^0 decay and the direction of the polarization vector $\mathbf{P}$ of the Λ^0, which is given by either formula (13) or (14). The vector $\mathbf{m}$ lies in the plane defined by the normal to the production plane of the Y_1^* and the direction of its decay. The angle this vector makes with the normal $\mathbf{n}$ is twice the angle between the direction of the Y_1^* decay and the normal $\mathbf{n}$.

Information about the polarization of Y_1^* particles produced in K^--p interactions was obtained in [3]. The polarizations had the following values:

$$P_{Y_1^{*-}} = (+11 \pm 21)\% \quad\text{and}\quad P_{Y_1^{*+}} = (-16 \pm 21)\%$$

for a momentum of 760 MeV/c for the K^- meson, and

$$P_{Y_1^{*-}} = (-56 \pm 20)\% \quad\text{and}\quad P_{Y_1^{*+}} = (+12 \pm 28)\%$$

for a K^- meson momentum of 850 MeV/c. Assuming that the value of the polarization found for the Y_1^* particles is not a statistical fluctuation, on the assumption that $J = \frac{1}{2}$ one can attempt to determine whether the Y_1^* decays into the $S_{1/2}$ or $P_{1/2}$ state of the $\pi\Lambda^0$ system. We denote by P_n the measured polarization of the Λ^0 from Y_1^* decays in the direction of the vector $\mathbf{n}$, and by P_m the same quantity in the direction of the vector $\mathbf{m}$. Then for the case of Y_1^* decay into an $S_{1/2}$ state of the $\pi\Lambda^0$ system,

$$P_n = P_{Y_1^*},\ P_m = -\frac{1}{3}P_{Y_1^*} \quad\text{and}\quad \frac{P_m}{P_n} = -\frac{1}{3}\,.$$

For the case of Y_1^* decay into the $P_{1/2}$ state, the roles of the vectors $\mathbf{n}$ and $\mathbf{m}$ are interchanged and we get

$$P_n = -\frac{1}{3}P_{Y_1^*},\ P_m = P_{Y_1^*} \quad\text{and}\quad \frac{P_m}{P_n} = -3.$$

Experimentally it was found [3] that $P_n = (-56 \pm 20)\%$ and $P_m = (+33 \pm 25)\%$, i.e., $|P_m/P_n| = 0.6$. The large statistical uncertainties in the determination of the necessary quantities makes it impossible to draw any definite conclusions about our problem. Use of the χ^2 test gave the following result. The average value of χ^2 should be 1.0. For the hypothesis of decay into the $S_{1/2}$ state, they found $\chi_S^2 = 0.3$, which indicates a high probability, while for the hypothesis of decay into the $P_{1/2}$ state the value was $\chi_P^2 = 4.5$, which indicates a probability around 3%. An analysis of the

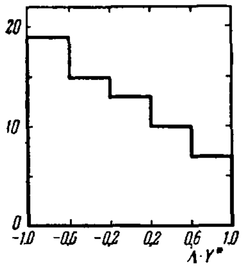

FIG. 11.

data[4] gave the result that $P_n = (-0.38 \pm 0.25)$ and $P_m = 0.19 \pm 0.25$, which gives $\chi_S^2 = 0$ and $\chi_P^2 = 1$. Thus these data do not enable us to arrive at a definite conclusion concerning these properties of the Y_1^*.

The presence of a $\cos^2 \vartheta$ term in expression (8) for the angular distribution of Y_1^* decays would be evidence in favor of $J > 1/2$. Within the limits of statistical error, the experimental data[3] indicate that $a_2 = 0$. An analysis of the same experimental material by Adair's method[10] [cf. formula (11) and the accompanying text] was done for cases where the production angle φ of the Y_1^* satisfied the condition $|\cos\varphi| \geq 0.80$. The angular distribution of the 62 Y_1^* decays selected in this way is shown in Fig. 11. It does not correspond to the shape $1/2 + 3/2 \cos^2 \vartheta$ which holds for $J = 3/2$, and is rather closer to linear in $\cos\vartheta$. Thus from these data too we can draw no conclusion about the spin of the Y_1^*.

Summarizing the attempts to determine the spin and parity of the Y_1^* on the assumption that it decays when free, it must be admitted that they give no definite conclusion about these properties. Obviously, in addition to the paucity of experimental data, there is also a deeper reason for the difficulties in making a consistent analysis. The main reason for these difficulties is that the interaction of the three particles in the final state gives rise to serious changes in the results.

Now let us see what one gets when this interaction is included.[9] We also take into account the require-

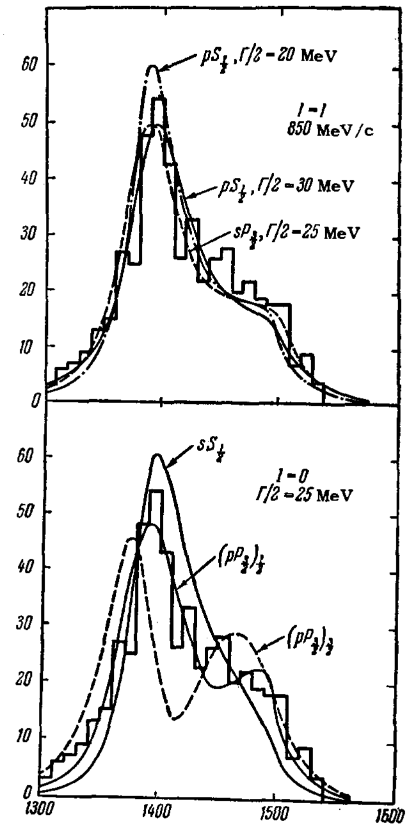

FIG. 12.

ments of Bose statistics, since we have two bosons, the π mesons, in the final state of reaction (1). In Sec. 3 it was shown that reactions of this type, in which there is a resonant $\pi\Lambda^0$ interaction, proceed mainly through the channel with total isotopic spin unity. It then followed that the sum of the orbital angular momentum L of the $\pi_2\Lambda^0$ system and the orbital angular momentum l of the $\pi_1 Y_1^*$ system must be odd. This means that for an S state of the $\pi_2\Lambda^0$ system $(L = 0)$ the $\pi_1 Y_1^*$ system emerges in a P state $(l = 1)$, while for a P state of the $\pi_2\Lambda^0$ system, the $\pi_1 Y_1^*$ system is formed in an S state.

Table II. Expected density of events of reaction (1) near point A of Fig. 3, assuming various combinations of isospins, spins and angular momenta, and comparing them with the experimentally determined density (T_m is the maximum kinetic energy of the π mesons)

	Expected number of events in the configuration $(lL_J)_j^I$					Observed number of events
	$(sS_{1/2})_{1/2}^0$	$(pP_{3/2})_{1/2}^0$	$(pP_{3/2})_{3/2}^0$	$(pS_{1/2})_{1/2}^1$	$(sP_{3/2})_{3/2}^1$	
$P_h = 850$ MeV/c						
$T_m = 150$ MeV	35.8	26.0	8.5	12.3	11.0	11/262
$P_h = 760$ MeV/c						
$T_m = 125$ MeV	29.8	32.8	8.6	9,7	10.5	18/252
$T_m = 120$ MeV	17.4	21.1	4,2	3.1	2.2	8/252

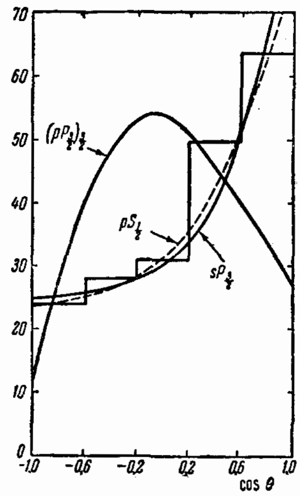

FIG. 13.

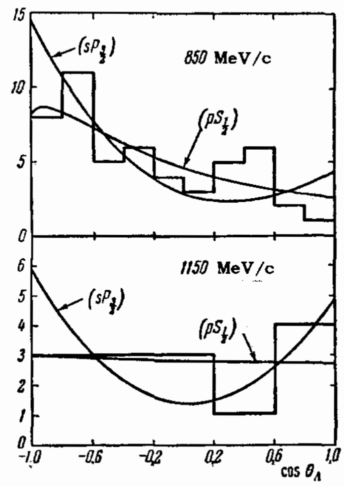

FIG. 14.

Figure 12 shows a comparison with the experimental histograms of mass distributions of the Y_1^* computed taking account of the identity of the π mesons and making various assumptions about the isotopic spin of reaction (1) and about the spin and parity of the Y_1^*. In Table II we give the computed density distributions in the phase plane of the kinetic energies of the π mesons (T_+, T_-) at point A of Fig. 3, and also the experimental data for this quantity. We see that the results obtained for the state with $I = 1$ give better agreement with the experimental data than do those for the various combinations of L and l in the state with $I = 0$. It is still impossible to distinguish between $pS_{1/2}$ and $sP_{3/2}$ states. Earlier we mentioned the anisotropy of the angular distribution of Y_1^* decays, which should not occur for free Y_1^* decay via strong interaction. In the state with $I = 1$ and odd $L + l$, there is constructive interference in the configuration when the second π meson emerges forward. Then the Λ^0 will be emitted preferentially in the backward direction. The computational results for $sP_{3/2}$ and $pS_{1/2}$ states at a K^- meson momentum of 850 MeV/c correspond to such an angular distribution. The corresponding results are shown in Fig. 13 together with the experimental data. For comparison, we also give the results of computations for $(pP_{3/2})_{3/2}$ states. From these data we see that it is not possible by this method to draw any conclusions about the spin and parity of the Y_1^*, since the angular distributions in the $pS_{1/2}$ and $sP_{3/2}$ states are practically indistinguishable.

Taking into account the identity of the π mesons [9] also modifies the results of the Adair analysis. A comparison of the results for the modified computations for two K^- energies are shown in Fig. 14. As we see from these graphs, for a K^- meson momentum of 850 MeV/c, it is impossible to obtain any information about the spin and parity. Moreover, even a significant improvement in the statistical accuracy of the experiments at this momentum gives no prospect of getting conclusions, since the computed distributions differ only insignificantly. But with increasing energy of the primary K^- mesons, the effect of identity of the π mesons decreases. The reason for this is that, during the course of the reaction, the presence of the resonant $\pi\Lambda^0$ interaction leads to a more pronounced two-particle character for the reaction. The first π meson gets more energy and leaves the range of interaction, so it has less probability of interacting with the decay products of the Y_1^*. Results of computations by Adair's method are less affected by this interaction, and their features are similar to those for the free decay of the Y_1^*. The results for a K^- momentum of 1.15 BeV/c are already significantly different, as shown in the lower part of Fig. 14. Although it is clear from these data that one still cannot draw any conclusion about the spin and parity of the Y_1^*, there is still hope that by increasing the statistical accuracy of the experiments one may reach some definite conclusion. The prospects of obtaining the necessary information are even better if one does experiments with K^- mesons of somewhat higher momentum. An analysis of data from the helium bubble chamber would already, it seems, satisfy our requirements.

Finally we point out that [9] from a comparison of the geometrical limit for the reaction, $(2j+1)\pi\lambda^2/4$, which is equal to 2.85 mb for K^- mesons with 850 MeV/c, with the experimental value of 3.2 ± 0.3 mb, we can conclude that the reaction occurs in a state with total angular momentum $j = 1/2$. In the case of $I = 1$ this is evidence that the reaction occurs in the $sP_{3/2}$ state, and excludes the $sP_{1/2}$ state. But the possibility of having a $(pS_{1/2})_{3/2}$ state with some admixture of $(pS_{1/2})_{3/2}$ also satisfies the experimental conditions. The isotropic distribution of the Y_1^* produced at 760 and 850 MeV/c is definitely in favor of the $sP_{3/2}$ state. If the reaction proceeded through the $(pS_{1/2})_{3/2}$ state, including the identical nature of the π mesons would lead to considerable anisotropy of the reaction. This difference might be reduced by an admixed $(pS_{1/2})_{1/2}$ state with the appropriate phase.

The large value of the cross section for $K^- + p \rightarrow \Lambda^0 + \pi + \pi$ makes it most likely that this reaction has mixed character. Apparently several partial waves and configurations contribute to it, and only the main terms have the symmetry properties which we have just discussed.

5. RESONANT πK INTERACTION

At the 9th Annual Conference on High Energy Physics at Kiev,[13] Wang Kang-ch'ang reported on the observation in a propane bubble chamber of an event which allowed two interpretations. First, it might have been a case of the reaction

$$K^+ + n \rightarrow K^0 + \pi^+ + n \tag{16}$$

produced by a K^+ meson with momentum 1.2 BeV/c, where the recoil neutron received a negligibly small recoil momentum, since the initial K^+ meson and the K^0 and π meson were almost coplanar and there was a complete compensation of transverse and longitudinal momenta of the particles identified in this reaction.

A second possibility arose from the fact that the tracks were coplanar and that there was compensation of the momenta. The conclusion was that one might have found a case of the decay of a new unstable particle according to the scheme

$$D^+ \rightarrow K^0 + \pi^+$$

with a mass of order 720 MeV.

Further investigations[14] showed that the first way of treating this event is preferable, since several cases of noncoplanar events were found, and cases were observed of the analogous reaction on hydrogen

$$K^+ + p \rightarrow K^0 + \pi^+ + p \tag{17}$$

with low recoil momentum of the proton. The interesting point was the strong correlation of the K^- and π mesons. Calculations of the mass of the πK system gave values in the range 800—900 MeV/c. The grouping of the masses in such a narrow range was evidence for a strong πK interaction. The investigation of the properties of such a πK interaction can be done only under specially prepared conditions.

Recently the hypothesis of strong πK interaction, which first made in the papers cited above has been confirmed in more careful experiments[15] in separated beams of K^- mesons with a momentum of 1.15 BeV/c. Forty-eight cases of the reaction

$$K^- + p \rightarrow K^0 + \pi^- + p \tag{18}$$

were found, and the cross section for this K^- energy was 2.0 ± 0.3 mb. An attempt to find an influence of the $(^3/_2, {}^3/_2)$ resonance in πp scattering gave no positive result. But it appeared that in this reaction there is preferential emission of protons with energies in the range 15—25 MeV, i.e., as if the reaction given above occurs in two stages, the first of which is a two-particle reaction in which a K^{*-} is produced, which then decays into a π^- meson and a K^0 meson:

$$K^- + p \rightarrow K^{*-} + p, \quad K^{*-} \rightarrow K^0 + \pi^-. \tag{19}$$

Since the $(^3/_2, {}^3/_2)$ resonance of the π^-p system has no influence on the final result of reaction (18), this means that the reaction occurs in the state with total isotopic spin I equal to 0. Moreover, even in the I = 1 state, the $(^3/_2, {}^3/_2)$ resonance preferentially produces the system $(n + \pi^0) + K^0$, and not $(p + \pi^-) + K^0$, which is still more reduced in this reaction.

Thus in complete analogy to the treatment of the $\pi\Lambda^0$ resonance in the reaction

$$K^- + p \rightarrow \Lambda^0 + \pi^+ + \pi^-$$

in the first part of this survey, in the course of reaction (18) there is a strong resonant πK interaction, which can be interpreted as some very shortlived K^{*-} particle. The distribution of masses of the K^{*-} particles is shown in Fig. 15. The average value of this quantity was found to be 885 ± 3 MeV. After subtracting the statistically distributed cases of reaction (18), from the remaining 22 cases a width at half maximum equal to 16 MeV was found. The error in the determination of individual mass values for the K^{*-} was of order 3—4 MeV.

The angular distribution of reaction (18) was isotropic. Starting from the assumption that the reaction occurs in an S state, one can attempt to set an upper limit for the spin S_{K^*} of the particle. It turns out that $S_{K^*} \leq 1$.

Now let us make a few remarks about the isospin of the K^{*-}. Depending on its value, one finds for the ratio of the probabilities for decay through the two possible channels

$$R = \frac{K^{*-} \rightarrow K^- + \pi^0}{K^{*-} \rightarrow K^0 + \pi^-}, \tag{20}$$

the values $R = 1/2$ for $I = 1/2$, or $R = 2$ for $I = 3/2$. This follows from the fact that the isotopic spin is conserved in a decay which is so fast and is caused by strong interaction, and from the fact that the K mesons form an isotopic doublet and the π mesons a triplet. Comparison of experimental data on the reactions

$$K^- + p \rightarrow K^- + \pi^0 + p, \quad K^- + p \rightarrow K^- + \pi^+ + n, \tag{21}$$

and (18) gives $R = 0.75 \pm 0.35$. This means that the isotopic spin of the K^{*-} is $1/2$.

6. CONCLUSION

Thus the experimental material supports the conclusion that $\pi\Sigma$ and $\pi\Lambda^0$ interactions, like the πK interaction for relative energies of the order of 100—300 MeV, have a resonance character. The mass of the resonant $\pi\Lambda^0$ system (the Y_1^*) is 1385 MeV with a

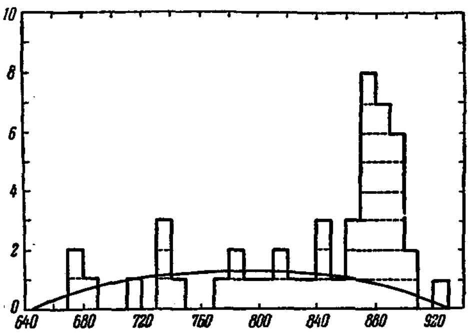

FIG. 15.

half-width of about 20 MeV. For the mass of the resonant neutral $\pi\Sigma$ system (the Y_0^*) the mass was 1405 MeV with a half-width also equal to 20 MeV. The mass of the resonant πK system (the K*) was 885 MeV with a half-width of order 16 MeV. Such widths for the mass distributions of these particles indicate that their lifetimes are of order 4×10^{-23} sec. Although these lifetimes are an order of magnitude greater than that of the ($^3/_2$, $^3/_2$) resonance in the pion-nucleon interaction, they are still comparable to the duration of processes caused by strong interactions. This means that in investigating the properties of the Y* as well as the K*, one cannot strictly speaking neglect the interaction of the decay products with other strongly interacting particles which take part in the production reactions for the Y* and K* particles.

As is obvious from the decay scheme $Y_1^* \rightarrow \Lambda^0 + \pi$, the isotopic spin of the Y_1^* is 1. The isotopic spin of the neutral resonant $\pi\Sigma$ interaction which has been observed is equal to 0. The isotopic spin of the K* is $^1/_2$.

Attempts to analyze the experimental data from the point of view of decay of free Y_1^* and K^* particles give the following results. Possibly the Y* is an $S_{1/2}$ state of the $\pi\Lambda^0$ system. But a more stringent analysis does not support this conclusion, and rather favors a $P_{3/2}$ state. But this result is also not conclusive. There is still no possibility of deciding in favor of any particular variant, since the available experimental material is insufficient. There are still no data on the spin and parity of the resonant $\pi\Sigma$ interactions. The spin of the K* is 0 or 1.

Since the experimental study of the new phenomena is still incomplete, we have deliberately not discussed the theoretical aspects of the problem in this summary. We mention only briefly that the existence of pion-hyperon resonances was expected both as a consequence of certain models of elementary particles and their interactions (the "global" symmetry model [16]), and from the analysis of data on K^--nucleon interactions at low energies. [17,18] "Global" symmetry, for example, predicts a resonance in the $P_{3/2}$ state for the $\pi\Lambda^0$ system. From the second argument, one expects such a resonance in the $S_{1/2}$ state. From this it is clear how important it is to determine the spin and parity of the Y_1^*. Although the properties of the newly discovered resonance states which involve the strange particles Σ and Λ^0 and the K meson have still not been fixed, the fact of their discovery is of fundamental importance for understanding the properties of elementary particles, their interactions, and the general laws of nature.

Note added in proof. The results of recent experiments[19] on the reactions

$$\text{(I)}\ K^- + n \rightarrow Y_1^{*\bar{0}} + \pi^{\bar{0}}, \qquad \text{(II)}\ K^- + p \rightarrow Y^{*\pm} + \pi^{\mp}$$

gave a ratio of cross sections σ_I/σ_{II} equal to 1 for a K⁻ meson momentum of 600 MeV/c, 1.4 ± 0.3 for 765 MeV/c, and about 2 for 865 MeV/c. The expected value of these ratios is two, if the reactions proceed via the channel with isotopic spin 1, and the ratio is one if the I = 0 channel dominates. The results show that with increasing energy of the K⁻ mesons, the contribution from the I = 0 channel decreases, and that at 865 MeV/c the I = 1 channel plays the the main role in the reactions for producing the Y_1^*.

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Translated by M. Hamermesh