

by an isotropic statistical model<sup>11</sup> normalized to a total cross section<sup>2,8</sup> of 50  $\mu\text{b}$  is also shown in Fig. 1.

Qualitatively, our results agree rather well with Drell's model, although the experimental cross sections are in general considerably larger than those calculated from Eq. (3), and do not show any decrease at the smallest angle measured. One should perhaps not expect a better quantitative agreement since Drell's diagram of Fig. 3 is not the only one leading to pion pair production, and other relatively small amplitudes may produce appreciable effects by interference with the Drell term.

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<sup>1</sup>S. D. Drell, Phys. Rev. Letters 5, 278 (1960).

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<sup>7</sup> $\sigma(\theta, \omega)d\Omega d\omega$  is the cross section for producing a  $\pi^-$  at an angle  $\theta$  and an energy  $\omega$  within the intervals  $d\Omega$  and  $d\omega$ .

<sup>8</sup>M. Bloch and M. Sands, Phys. Rev. 113, 305 (1959).

<sup>9</sup>This is Eq. (2) of reference 1 with  $\sigma_{\pi^+ + p}(k - \omega)$  replaced by  $\sigma_{\pi^+ + p}(Q)$ .

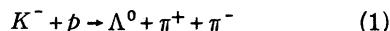
<sup>10</sup> $\sigma_{\pi^+ + p}(Q)$  is from S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. 100, 306 (1955), and Phys. Rev. 111, 1380 (1958); R. Cool, O. Piccioni, and D. Clark, Phys. Rev. 103, 1082 (1956); S. W. Barnes, B. Rose, G. Giacomelli, J. Ring, K. Miyake, and K. Kinsey, Phys. Rev. 117, 226 (1960).

<sup>11</sup>Extrapolated from curves given in reference 8.

### RESONANCE IN THE $\Lambda\pi$ SYSTEM\*

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We report a study of the reaction



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.<sup>1</sup> The beam was purified by two velocity spectrometers.<sup>2</sup> A  $\Xi^0$  hyperon observed during the run<sup>3</sup> and the preliminary cross sections<sup>4</sup> 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  $\chi^2$  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.

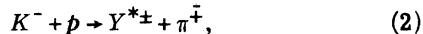
Reaction	No. of events	Cross section (mb)
(a) $K^- + p \rightarrow \bar{K}^0 + p + \pi^-$	48	$2.0 \pm 0.3$
(b) $K^- + p \rightarrow (\Lambda \text{ or } \Sigma^0) + \pi^+ + \pi^- + \pi^0$	39	$1.1 \pm 0.2$
(c) $K^- + p \rightarrow \Sigma^0 + \pi^+ + \pi^-$	27	
(d) $K^- + p \rightarrow \Lambda + \pi^+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

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

2. The events of group (e) when treated as  $\Sigma^0\pi\pi$  reactions give a  $\chi^2$  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  $\Sigma^0$  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  $\pi^+$  and the  $\pi^-$  distributions have peaks near 285 Mev, such as would be expected from a quasi-two-body reaction of the type



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



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  $\Lambda$  and a  $\pi$ . 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  $\pi$  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-

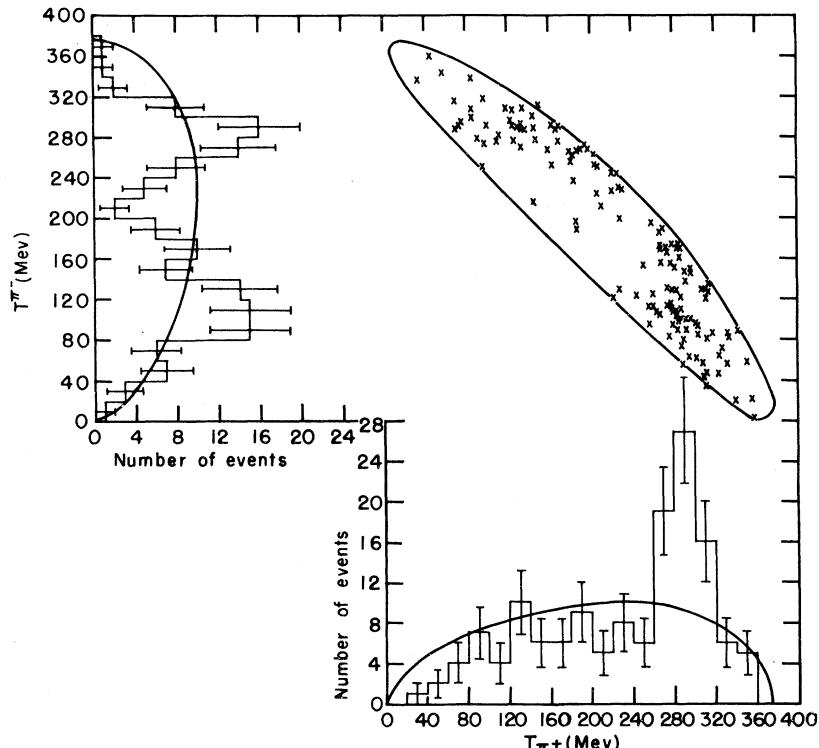


FIG. 1. Energy distribution of the two pions from the reaction  $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$ . Each event is plotted only once on the Dalitz plot, which should be uniformly populated if phase space dominated the reaction. The two energy histograms are merely one-dimensional projections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

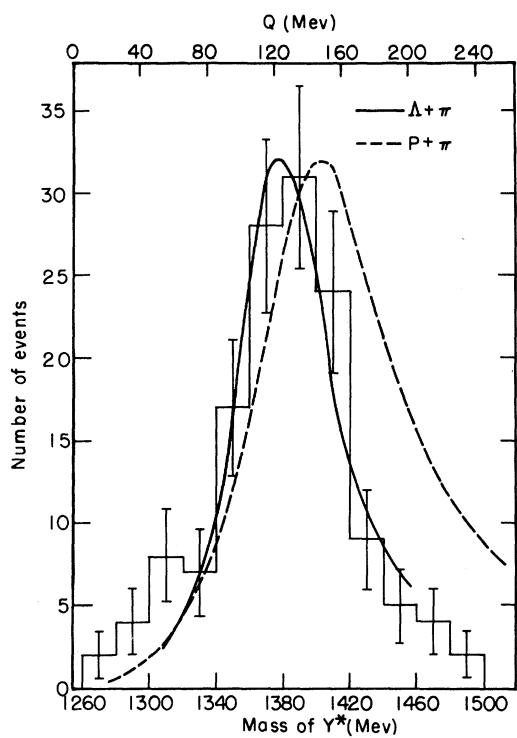


FIG. 2. Mass distribution for  $Y^*$  and fitted curves for  $\pi\Lambda$  and  $\pi p$  resonances. The lower scale refers only to the  $\pi\Lambda$  resonance.  $Q$  is the kinetic energy released when either isobar dissociates. The curve for the  $\pi\Lambda$  resonances is fitted to the center eight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

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.<sup>5</sup> 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  $\eta$  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  $0.62 \pm 0.09$  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  $\sim 1.3$  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  $\Lambda$ . Also, a net  $\Lambda$  polarization

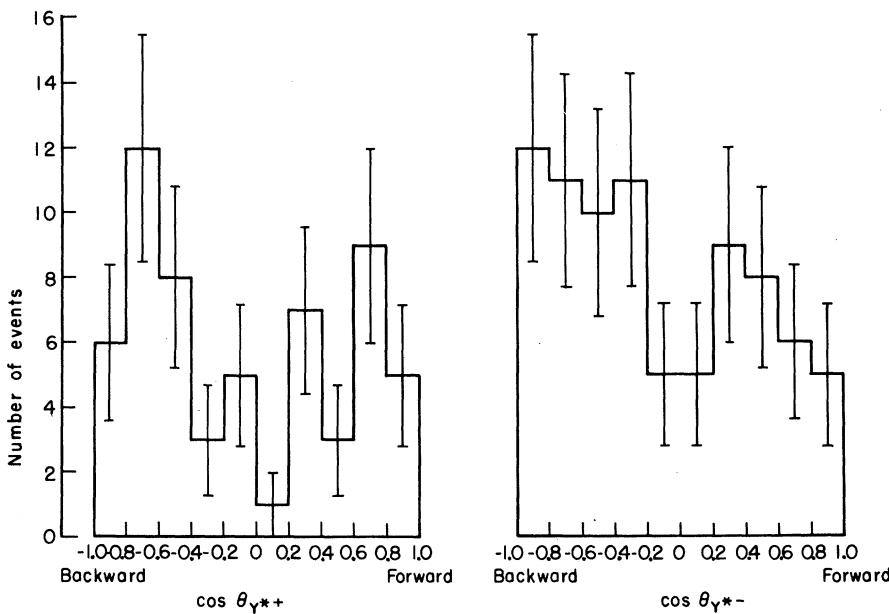


FIG. 3. Angular distribution of  $Y^{*\pm}$  in the  $K^-p$  barycentric system for the reactions  $K^- + p \rightarrow Y^{*\pm} + \pi^\mp$ .

can result. With our limited data, we see no statistically significant  $\Lambda$  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,<sup>6</sup> 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  $0.500 \pm 0.063$  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  $\pi$  and a  $\Lambda$ , 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<sup>7</sup> 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 reso-

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

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)		$\sim 10^{-23}$

nance, there are still many reasons why the  $\pi - \Lambda$  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  $\pi^+$  arises from reaction (2) and the  $\pi^-$  from reaction (3) and the amplitude in which the roles of the two pions are reversed.

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  $T=2$ .<sup>8</sup> 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.<sup>9</sup>

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.

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## SOME CONSIDERATIONS ON THE RECENTLY FOUND EVIDENCE FOR A $\pi\Lambda$ RESONANCE

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Some interest in the possible existence of resonant states in the pion-hyperon system has been raised of late by the analysis of the pion spectra in the reaction  $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$ .<sup>1</sup> The experimental data fit indeed a phenomenological picture where about 75% of the  $\pi^+$  in the previous reaction are produced together with a resonant  $\pi\Lambda$  state, whose  $Q$  value is peaked at about 115 Mev and whose half-width is  $\sim 30$  Mev. A detailed analysis of such a resonant state is still missing and many of its characteristics (like its total and orbital angular momentum and the branching ra-

tios in decay) are as yet unknown. It is, however, clear that the very presence of a resonant pion-hyperon state is of importance, as it will help in a deeper understanding of the processes among strongly interacting particles.<sup>2</sup>

On the other hand, the existence of this resonance can give us more confidence in the validity of some theoretical models for the investigation of the pion-hyperon interaction. This was indeed the case with the one-pion approximation static model of Chew and Low for pion-nucleon scattering. As a matter of fact the subsequent dispersive