Resonances in Strange-Particle Production*

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In an exposure of propane to 2.0-BeV/c π^- mesons at the Cosmotron in the Columbia 30-in. chamber, reactions have been analyzed for resonances between the particles present in the final state. The reactions studied were sufficiently overdetermined to permit a separation of hydrogen events from carbon. We find definite evidence for resonances in the $\Lambda\pi$ system (Y_1^*) with $M_0=1392\pm7$ MeV and $\Gamma/2=40\pm10$ MeV; in the $K\pi$ system (K^*) with $M_0=897\pm10$ MeV and $\Gamma/2=30\pm10$ MeV. We also seem to see the 1404- and 1525-MeV $\Sigma\pi$ resonances. The data indicate that the Y_1^* has spin 3/2 and its parity is even.

I. INTRODUCTION

THE existence of an excited hyperon of mass 1385 MeV, $\Gamma/2\approx25$ MeV, and isotopic spin one, as well as an excited K meson of mass 885 MeV, $\Gamma/2\approx16$ MeV, and isotopic spin one-half, are well demonstrated.[1] The spin and parities of these states are of substantial interest and, although some relevant data exist,[1,2] are still unclear. In addition, the existence of excited hyperons of mass 1404 and 1525 MeV and isotopic spin zero is indicated by experiments.[3]

The bulk of the available data on these resonances comes from experiments in which they are produced with K^- mesons. A typical reaction is (a) $K^-+p\rightarrow\pi^-+\pi^++\Lambda^0$. We report here an experiment in which the resonances are produced in pion-proton collisions. The reactions which have been studied are

$$\pi^-+p\rightarrow\Lambda^0+\pi^-+K^+, \tag{1}$$

$$\pi^-+p\rightarrow\Sigma^\pm+K^0+\pi^\pm, \tag{2}$$

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

Some results on these reactions for pions of 1.6[4] and 1.9[5] BeV/c, and 2.1 BeV/c (Alexander *et al.*[3]) laboratory momentum have already been reported. The present work supplements them and yields additional information on the spin and parity of the Y_1^*.

The reactions (1)–(3) have the advantage that the interference effects due to the Bose character of the pions, which hamper the spin determination of the Y_1^* in reaction (a),[6] are absent. There remain, of course, other interference effects which may also frustrate the attempts to make spin determinations using reactions (1)–(3).

II. PROCEDURE

The experiment is based on the analysis of some 140 000 photographs obtained at the BNL Cosmotron in a 30-in. propane filled chamber.[7] One-fifth of these pictures were obtained with incident negative pion momentum of 1.92 BeV/c, one-fourth at 2.01 BeV/c, and the rest at 2.05 BeV/c. The resolution of the beam is $\pm1/2\%$. All events of the type (a′) two-prong stars with one V and (b′) stoppings and two V's were measured. Those events kinematically compatible with the reactions (1) to (3) were selected and fitted with the best values of the observables, using the fitting program developed by Berge, Solmitz, and Taft.[8] An additional program was written to obtain the distributions in the various center-of-mass systems necessary for the understanding of the data.

A. Incident Beam Energy

The mean energy of the incident beam was determined in two ways: (1) The momentum of noninteracting beam tracks was measured; the error in each measurement was typically 105 MeV/c. (2) In addition, we have measured a group of about 100 elastic π^--p scattering events with protons stopping in the chamber. Each of these permitted a determination of the incident beam momentum typically with an error of 50 MeV/c. The beam spread of $\pm1/2\%$ is determined from the geometry of the beam (see Fig. 1) and wire measurements. The beam momentum used in fitting the events were corrected for ionization loss in the chamber and

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[1] See, for instance, M. H. Alston and M. Ferro-Luzzi, Revs. Modern Phys. **3**, 416 (1961); and M. H. Alston, L. W. Alvarez, P. Eberhard, M. L. Good, W. Graziano, H. K. Ticho, and S. Wojcicki, Phys. Rev. Letters **6**, 300 (1961).

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[4] Saclay, Orsay, Bari, Bologne (to be published).

[5] A. R. Erwin, R. H. March, and W. D. Walker, Nuovo cimento (to be published).

[6] R. H. Dalitz and D. H. Miller, Phys. Rev. Letters **6**, 562 (1961).

[7] Al Prodell and Jack Steinberger, Rev. Sci. Instr. (to be published).

[8] P. Berge, F. Solmitz, and H. Taft, University of California Radiation Laboratory Report UCRL-9097 (unpublished).

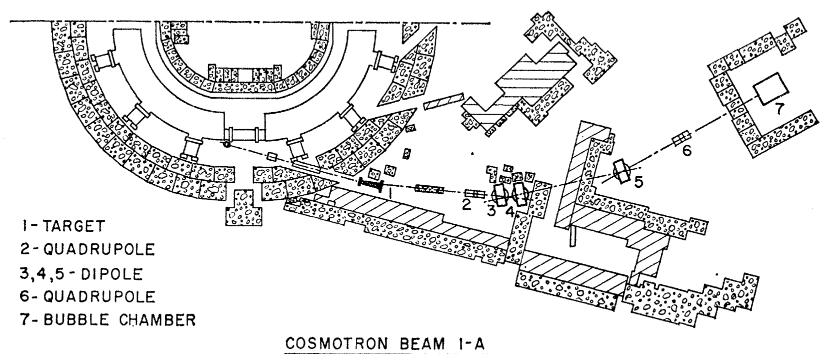

FIG. 1. Beam setup.

given an uncertainty of ± 15 MeV/c to cover the width and errors in the mean momentum measurements.

B. Carbon Background

Propane is by no means ideal for this experiment. The selected events presumably contain all free proton events as well as those carbon events which fit the hydrogen kinematics within the measurement error. The rejection of the carbon contamination is expected to be more efficient in reactions (1) and (2), which are overdetermined in a fourfold way, than in reaction (3) which is only singly overdetermined. To estimate the carbon contamination, we have analyzed events of the form Λ^0+K^0+negative track. These events have been fitted to reaction (3) by using only the Λ^0 and K^0. Out of a total of 46 events found, only 12 were seen to fit hydrogen kinematics within the acceptance criteria. Except for the difference in the isotopic spin state, this is also the number of events of type (3) due to bound protons in carbon which we can expect to contaminate our sample of 48 events; a carbon background of 25%. In addition, the events were fitted to the reaction $\pi^-+n\rightarrow\Lambda^0+K^0+\pi^-$ using also the π^- measurements. Four events fitted the kinematics. Since we see three times as many K^+'s as K^0's, we may expect then about 12 events of type (1) due to bound protons. This corresponds to a carbon background of 9% for reaction (1). Reaction (2) is expected to have a similar carbon contamination since both the kinematics and measurement accuracy are similar.

There is an additional source of background for reactions (1) and (3), due to the fact that the Λ^0 may actually be the result of Σ^0 decay. We have found 3 cases of the materialization of a γ ray among the events which otherwise fit reaction (1). The conversion efficiency of γ rays is approximately 20% in our chamber. From this, the estimated Σ^0 background is $3/0.2=\sim 15$ events minus the 3 events where the γ ray is present. Because of the complication of the π^0 γ rays, we have no corresponding value for reaction (3).

TABLE I. Summary of cross sections.

Reaction	No. of events found	Estimated carbon background	Cross section (μb)
$\pi^-+p\rightarrow\Lambda^0+K^++\pi^-$	142	9%	72±12
$\pi^-+p\rightarrow\Sigma^++K^0+\pi^-$	26	9%	34±9
$\pi^-+p\rightarrow\Sigma^-+K^0+\pi^+$	47	9%	51±12

C. Total Cross-Section Measurements

For the purpose of cross-section determinations, both the pion flux and the number of events were measured in a fiducial region, which, for simplicity, was taken to be a rectangle in one of the photographic projections. Corrections were made for the probability of charged Λ^0 decay (2/3), charged K^0 decay (1/3), probability of Λ^0 or K^0 decay in the chamber (0.95), μ and e contamination (0.1), and estimated detection efficiency (0.9). We do not present a value for the $\Lambda^0K^0\pi^0$ production cross section for the following reasons: (1) We do not know the $\Sigma^0K^0\pi^0$ background. (2) We only considered for analysis those events which had very small measurement errors and which fitted very well the hydrogen kinematics; this was done to minimize the carbon and Σ^0 background. The assigned errors contain the statistical as well as the systematic errors. Table I summarizes the cross sections.

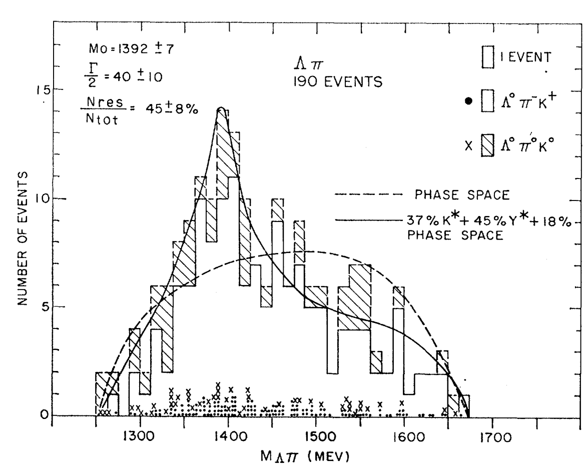

FIG. 2. Mass distribution of the $\Lambda\pi$ system.

III. INVARIANT MASS DISTRIBUTION

For each event we calculate the invariant mass $m_{ij}=[(E_i+E_j)^2-(\mathbf{p}_i+\mathbf{p}_j)^2]^{1/2}$ for all pairs of outgoing particles. The rms errors in these masses average 7 MeV for reaction (1) and (2) and 15 MeV for reaction (3). The experimental mass distribution are shown in Figs. 2–7. The theoretical phase-space distributions are also shown in these figures. The phase space for a given value of the pion incident energy E_{in} is calculated according to the simple relation $P_{E_{in}}(m_{ij})dm_{ij}\propto(E_{\max}-E_{\min})\times m_{ij}dm_{ij}$ where $E_{\max}$ and $E_{\min}$ are the maximum and minimum energies that either particle i or j can have for a given m_{ij}. This distribution is averaged over the energy distribution of the pions producing the observed events,

$$P=\text{const}\sum_{k=1}^{n}(E_{\max}{}^k-E_{\min}{}^k)m_{ij}.$$

The constant is chosen to normalize the phase space to the observed number of events.

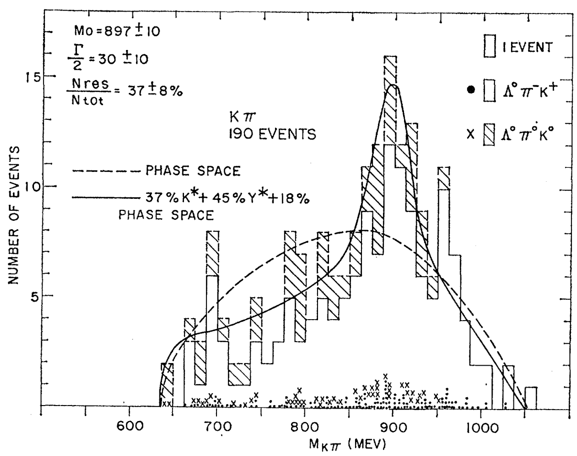

FIG. 3. Mass distribution of the $K\pi$ system.

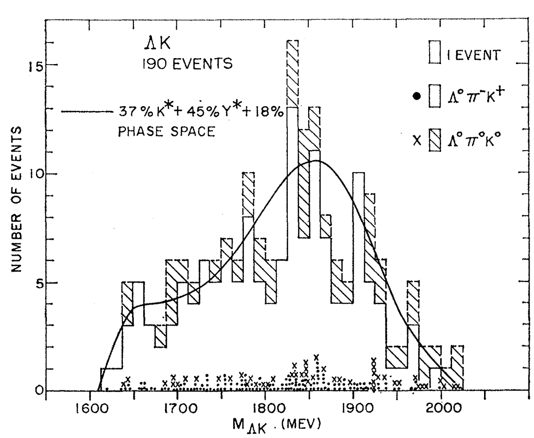

FIG. 4. Mass distribution of the ΛK system.

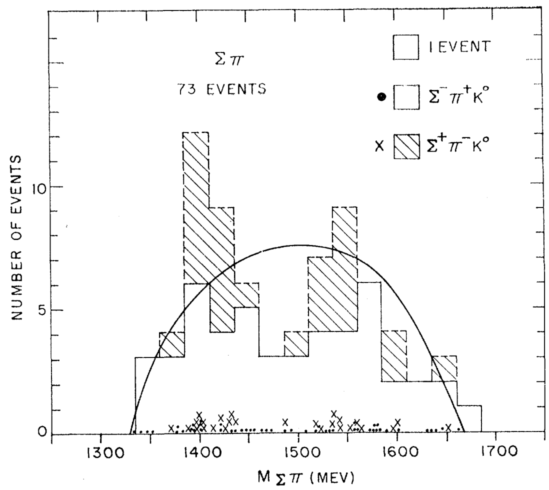

FIG. 5. Mass distribution of the $\Sigma\pi$ system.

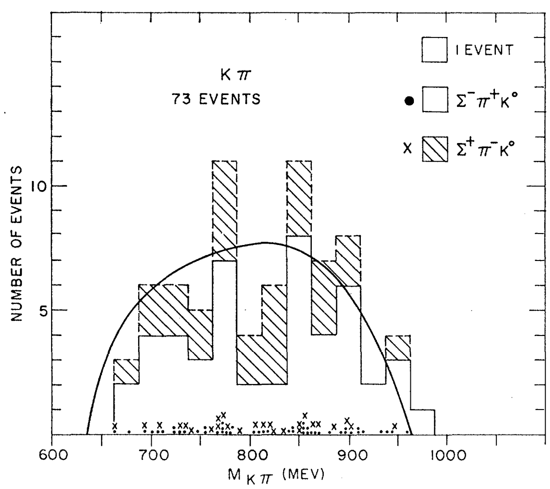

FIG. 6. Mass distribution of the $K\pi$ system.

A. Resonances in the Reactions $\pi^-+p\to\Lambda^0+K^0+\pi^0$ and $\Lambda^0+K^++\pi^-$

The mass distributions for these two reactions were combined into single plots which appear in Figs. 2, 3, and 4. It is apparent that they show a resonant structure in which both the Y_1^* and K' play a large role. We fit the experimental distributions with a distribution of the form $F(m_{ij})=\alpha$ (phase space)$+\beta$ (Y_1^* distribution) $+\gamma$ (K' distribution) where the Y_1^* and K' distributions are of the Breit-Wigner form

$$f(m)=(N/\pi)\frac{\Gamma/2}{(m-m_0)^2+(\Gamma/2)^2},$$

N being the total number of events. The following parameters with approximate errors give a good fit:

	M_0 (MeV)	Γ (MeV)
Y_1^*	1392±7	40±10
K'	897±10	30±10

and

α	β	γ
0.18	0.45±0.08	0.37±0.08

We conclude that reactions (1) and (3) are dominated by Y_1^* and K' production. However, we see no evidence for a $K-\pi$ resonance at a mass of 730 MeV reported for the same reactions at the same energy (Alexander *et al.*[3]).

It is interesting to note that the prominent peak in the $\Lambda^0 K$ mass can be described as being just a kinematic reflection of the Y_1^* resonance and not due to a $\Lambda^0 K$ resonance. We point out also that our mass values as well as the widths of the Y_1^* and K' are slightly larger than those of previous measurements.

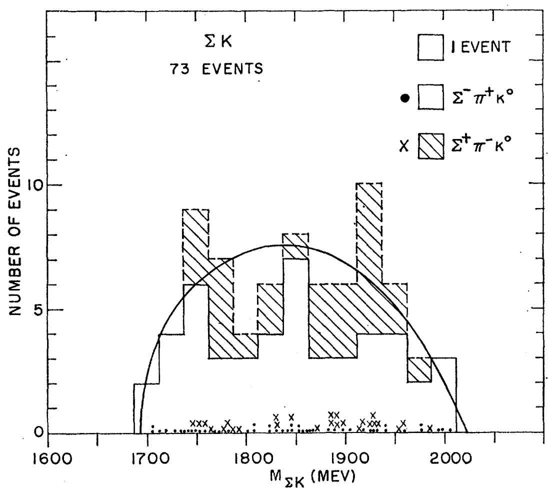

FIG. 7. Mass distribution of the ΣK system.

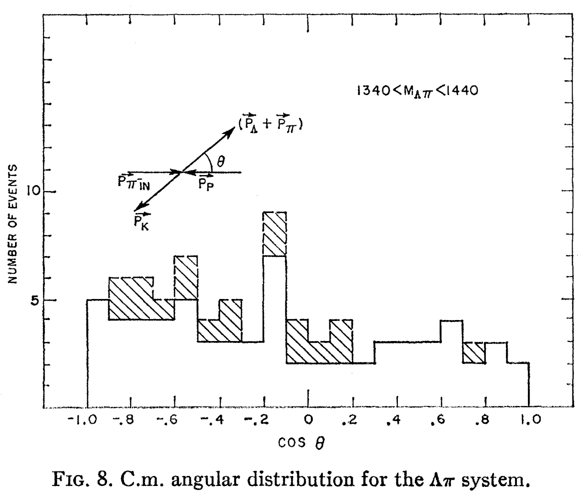

FIG. 8. C.m. angular distribution for the $\Lambda\pi$ system.

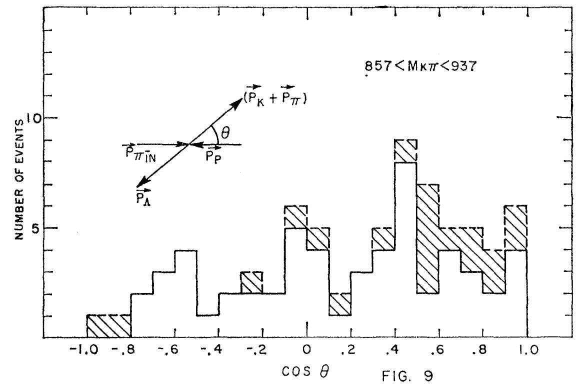

FIG. 9. C.m. angular distribution for the $K\pi$ system.

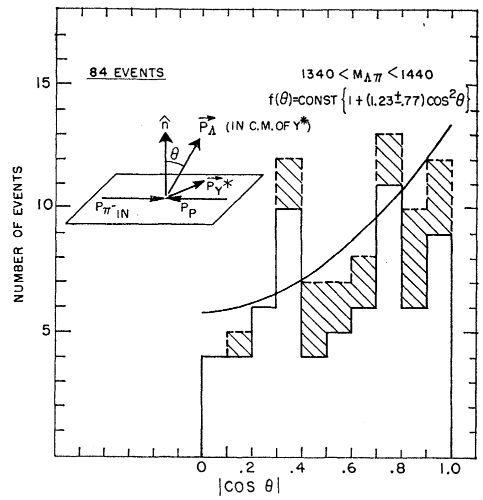

FIG. 10. Correlation of the Y_1^* decay and the plane of production.

B. Resonance in the Reaction $\pi^- + p \rightarrow \Sigma^{\mp} + K^0 + \pi^{\pm}$

In previous experiments[3] indications have been seen of resonances in the $\Sigma\pi$ system at 1404 and 1525 MeV. Our distributions appear in Figs. 5, 6, and 7. Both of these seem to be present in the $\Sigma\pi$ mass spectrum.

IV. PRODUCTION ANGULAR DISTRIBUTIONS OF THE Y_1^* AND K'

These are shown in Figs. 8 and 9. The Y_1^* are produced preferentially backwards and the K' forwards, consistent with the general observation that nature abhors large momentum transfers.

V. SPIN AND PARITY OF THE Y_1^*

There are several ways in which the data could be analyzed to yield information of the spin of the Y_1^*. We feel that we are too much above threshold to justify the use of the Adair analysis. Instead the data are analyzed for correlations between the Λ^0 momentum and three orthogonal directions: the production plane normal, the Y_1^* direction, and the normal to the two.

TABLE II. Analysis of the data for events in the mass interval $1340 \leq m_{Y_1^*} \leq 1440$ MeV.

(1) Y_1^* decay $f(\cos\theta) = \text{const}[1+a\cos\theta+b\cos^2\theta]$	a	b
$f[\hat{P}_\Lambda \cdot \hat{n}]$[a]	-0.29 ± 0.29	1.29 ± 0.78
$f[\hat{P}_\Lambda \cdot \hat{P}_{Y_1^*}]$	-0.29 ± 0.17	-0.14 ± 0.34
$f[\hat{P}_\Lambda \cdot (\hat{P}_{Y_1^*} \times \hat{n})]$	0.12 ± 0.14	-0.50 ± 0.24
(2) Λ^0 Y_1^* decay $f(\cos\eta) = \text{const}[1+\alpha\bar{P}\cos\eta]$		$\lvert\alpha\bar{P}\rvert$
$f[\hat{P}_{\pi^-\Lambda} \cdot \hat{n}]$		0.55 ± 0.17
$f[\hat{P}_{\pi^-\Lambda} \cdot \hat{P}_{Y_1^*}]$		0.40 ± 0.18
$f[\hat{P}_{\pi^-\Lambda} \cdot (\hat{P}_{Y_1^*} \times \hat{n})]$		0.25 ± 0.18

[a] $\hat{n}$ = unit vector normal to the plane of production.

The frame of reference is obtained by first transforming to the production c.m. and then to the Y_1^* c.m. The analysis for events in the mass interval $1340 \leq m_{Y_1^*} \leq 1440$ is tabulated in Table II. The distribution relative to the production plane normal has a large anisotropy; the coefficient of the $\cos^2\theta$ term is 1.29 ± 0.78 (see also Fig. 10). The smallness of the $\cos\theta$ term gives some assurance that the interference with K' and nonresonant production is small. Within the mass interval of the Y_1^*, the Y_1^* is dominant: 70% of the observed events are resonant, according to the model we have used to fit the mass spectra. The large $\cos^2\theta$ term is most likely then an anisotropy in the decay of the Y_1^* itself, or a statistical fluctuation. Given that the effect is real, it must be inferred that the Y_1^* is produced polarized or aligned and has spin greater than 1/2. Spin 3/2 is the simplest possibility; it also is the spin predicted by a model of the Y_1^* in which it is the counterpart in "global symmetry" of the spin 3/2, isospin 3/2 pion-nucleon p-wave resonance.[9] This prediction is in agreement with some of the results of the K^--meson experiments for producing the Y_1^*.[2]

Although the assignment of the spin of the Y_1^* is not very strong statistically, it is possible to show that, given the spin of the $Y_1^*=3/2$, the resonance is a p-state resonance as the globally symmetric model predicts, and that consequently the $Y_1^*-\Lambda^0$ relative parity is even. This is done by analyzing the correlation in η, the angle between the pion in Λ^0 decay and the Y_1^* production normal. The pion has been successively transformed to the production c.m., the Y_1^* c.m. and the Λ^0 c.m. The expected distribution is $g(\eta)=1+\alpha\bar{P}\cos\eta$, where $\bar{P}$ is the average polarization of our sample of Λ^0's and $\alpha=-0.67\pm0.07$.[10] For the events in the Y_1^* peak, in the mass interval 1340–1440 MeV, we find $\alpha\bar{P}=0.55\pm0.17$. This is in agreement with the Wisconsin group which finds $\alpha\bar{P}=0.61\pm0.28$.[5] The maximum Λ polarization compatible with the observed Y_1^* decay correlation is $\lvert\bar{P}_\Lambda\rvert_{\max}=0.47\pm0.09$ if the resonance is in the p state, and $\lvert\bar{P}_\Lambda\rvert_{\max}=0.28\pm0.05$ if the resonance is in the d state. The experimental value is $\lvert\bar{P}\rvert=0.82\pm0.27$, in better agreement with the p-wave or even-parity case. If it should turn out instead that the Y_1^* has spin 1/2, then the Λ^0 polarization shows in a similar way that the Y_1^* decays via s wave.

[9] M. Gell-Mann, Phys. Rev. **106**, 1297 (1957).

[10] J. Cronin (private communication), $\alpha=-0.62\pm0.07$. J. Leitner, L. Gray, E. Harth, *et al.*, Phys. Rev. Letters **7**, 264 (1961), $\alpha=-0.75_{-0.15}^{+0.50}$.

TABLE III. Analysis of K' decay events $857 \leq M_{K'} \leq 937$.

K' decay $f(\cos\theta) = \text{const}(1+a\cos\theta+b\cos^2\theta)$	a	b
$f[\hat{P}_K \cdot \hat{n}]$	-0.11 ± 0 2	0.33 ± 0.48
$f[\hat{P}_K \cdot \hat{P}_{K'}]$	0.43 ± 0.23	-0.14 ± 0.39
$f[\hat{P}_K \cdot (\hat{P}_{K'} \times \hat{n})]$	0.05 ± 0.2	0 ± 0.4

VI. THE K' SPIN

We have performed the same analysis for the K' that was made for the Y_1^*. The results appear in Table III. As can be seen, there is no appreciable $\cos^2\theta$ dependence in the angular distribution. We cannot make any conclusions as to the spin of the K' from such a result.

VII. CONCLUSIONS

(1) We have clear evidence that not only the Y_1^* but also the K' are produced in $\Lambda^0K\pi$ production at 2-BeV/c incident π^- momentum. There is no evidence for a $K\pi$ resonance at 730 MeV.

(2) We seem to observe the 1404- and 1525-MeV $\Sigma\pi$ resonances.

(3) The most probable interpretation of the observed angular correlation in the Y_1^* decay requires that the spin be greater than 1/2. If the Y_1^* spin is then assumed to be 3/2, the relative parity of the Y_1^* and the Λ^0 must be even to account for the Λ^0 polarization. However, if the Y_1^* has spin 1/2, the parity must be odd.

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