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[12] We must point out two minor qualifications to these results: (a) The cut on $|M^2(\text{all neutrals})| \leq 0.01$ results in the loss of a small fraction of $\eta(959)$ events due to resolution. Thus, we would expect this effect with approximately the same magnitude to occur in the case of the φ; (b) our data at this time do not rule out the possibility of a weak alternate decay mode, $\varphi\to\rho+\pi$ (branching ratio = 18 ± 8%). Again due to resolution we may be including a small amount of $\rho^0\pi^0$ in our $\rho^0\gamma$ and $\pi^+\pi^-\gamma$ determinations. The effect of (a) is to underestimate and (b) to overestimate the limits on $\rho\gamma$ and $\pi^+\pi^-\gamma$. However, the net effect can alter our conclusions on the branching ratios by no more than ±1 to 2%.

[13] We have assumed an all-neutrals branching ratio of 69% for the $\eta(548)$ and 10% for the ω in arriving at these branching ratios. We have introduced a slight bias in the $\omega\gamma$ and $\eta(548)\gamma$ determinations because of the removal of events with $M^2(\text{all neutrals}) < 4m_{\pi^0}{}^2$, inasmuch as the lower bound for these cases would be $m_{\pi^0}{}^2$ [ω or $\eta(548)\to\pi^++\pi^-+\pi^0$] or zero [$\eta(548)\to\pi^++\pi^-+\gamma$]. Therefore, the branching ratios for these modes should be somewhat larger, but probably by no more than 1 to 2%.

SPIN OF THE $Y_0{}^*(1405)$*

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(Received 9 June 1965)

A study has been completed of three-body final states, hyperon $+K+\pi$, in pion-nucleon collisions at an incident pion momentum of 1.68 BeV/c. The purpose of this investigation was to obtain information on the spin of the $Y_0{}^*(1405)$ resonance by observing angular correlations in its decay. Our results, by use of a moments analysis,[1] are consistent with spin $\frac{1}{2}$, but our statistics at present are too poor for a parity determination. We have also examined the decay of the $Y_1{}^*(1385)$ resonance and find, in agreement with other authors,[2] that spin $\frac{1}{2}$ is ruled out, spin $\frac{3}{2}$ is acceptable, and spin $\frac{5}{2}$ is not required by these data.

The data were obtained from approximately 2×10^5 π^-p and 1.2×10^5 π^+d pictures in the Brookhaven National Laboratory 20-in. bubble chamber exposed at the AGS. The incident beam momentum corresponds to a c.m. energy 50 MeV below the threshold for the reaction $K^*(890)+\Sigma$.

Table I gives the number of events in the various final states. For the reaction $\pi^++d\to$ hyperon $+K+\pi+$ nucleon, only events with a nucleon momentum of ≤ 200 MeV/c are included.[3] In these events the nucleon is considered to be a "spectator" not affected by the primary π-nucleon interaction, except for energy-momentum conservation. The Dalitz plot and its mass-squared projections for 220 events in

Table I. Number of observed events in each final state of the reaction $\pi+N\rightarrow$ hyperon $+K+\pi$.

Final state	Number of observed events	Final state	Number of observed events
$\pi^-+p\rightarrow\Sigma^-+K^0+\pi^+$	108	$\pi^++n\rightarrow\Sigma^++K^++\pi^-$	19
$\Sigma^++K^0+\pi^-$	75	$\Sigma^-+K^++\pi^+$	17
$\Lambda^0+K^++\pi^-$	189	$\Lambda^0+K^0+\pi^+$	29
$\Lambda^0+K^0+\pi^0$	95	$\Lambda^0+K^++\pi^0$	36
$\Sigma^0+K^++\pi^-$	42	$\pi^++p\rightarrow\Lambda^0+K^++\pi^+$	102
$\Sigma^-+K^++\pi^0$	47		

the $\Sigma^\pm K\pi^\mp$ final state is shown in Fig. 1. The $K\pi$-invariant mass-squared spectrum is consistent with phase space. The $\Sigma^\pm\pi^\mp$-invariant mass-squared spectrum shows a prominent peak in the vicinity of 1.9 $(\mathrm{BeV})^2$ and a small spike at 2.3 $(\mathrm{BeV})^2$.

The $\Sigma^\pm\pi^\mp$ mass spectrum has been fitted by a maximum-likelihood method[4] to the following expression:

$$N(M)=(a+b\,|T|^2_{1405}+c\,|T|^2_{1520})\rho, \tag{1}$$

where $|T|^2=\Gamma_4^2/[(E-M_0)^2+\Gamma_4^2]$ and ρ is phase space. The free parameters in the fit are Γ and M_0 for the $Y_0^*(1405)$ resonance and the intensities a, b, and c.[5] The result of this fit is consistent with negligible background, $(16\pm5)\%$ $Y_0^*(1520)$ resonance and $(84\pm5)\%$ Y_0^* resonance with $M_0=1382\pm8$ MeV and $\Gamma=89\pm20$ MeV. These values for the mass and width of the $Y_0^*(1405)$ resonance are about two standard deviations from values obtained in other experiments.[6] Examination of the data, to be discussed below, does not reveal either interference with nonresonant background or a serious contamination of the Y_0^* by events from the $\Sigma^\pm\pi^\mp$ decay modes of the $Y_1^*(1385)$ resonance. Thus these values for the mass and width of the $Y_0^*(1405)$ resonance may be the result of (a) statistical fluctuation, (b) dynamical effects in the production process,[7] or (c) the parameters of this resonance being indeed somewhat different from those hitherto believed.

About two-thirds of the data are events in which the K^0 is not visible. These are record-

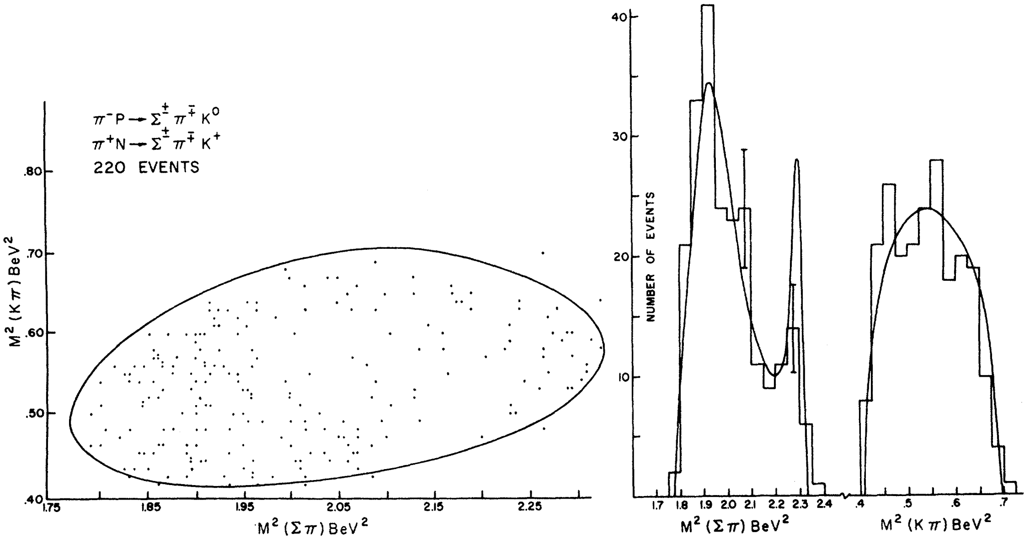

FIG. 1. Dalitz plot for the reaction $\pi+\text{nucleon}\rightarrow\Sigma+K+\pi$, with $\Sigma\pi$ and $K\pi$ mass-squared projections. Events which fall outside the kinematic limit are due to π^+d interactions. The solid curve superimposed on the $\Sigma\pi$ mass-squared plot represents the result of the fit using Eq. (1). The curve fitted to the $K\pi$ mass-squared spectrum is the invariant phase space normalized to the total number of events (220).

ed only if the Σ decay is detectable as a "kink." Events are missed if either the Σ is too short or its lab decay angle is too small. After applying a correction[8] for these missed events, we find that

$$\frac{\text{no. of events with } K^0}{\text{no. of events without } K^0} = 0.57 \pm 0.08,$$

which is consistent with the expected value 0.5. For the total sample the corrected ratio

$$\frac{\Sigma^+ \to p + \pi^0}{\Sigma^+ \to \pi^+ + n} = 1.4 \pm 0.3.$$

For a pure Y_0^* resonance the expected ratio $\Sigma^+\pi^-/\Sigma^-\pi^+$ is unity. Our experimental value is 1.03 ± 0.16 for 170 events in the mass interval 1340-1460 MeV. The absence of interference with background or another resonance requires the distribution in $\hat{\Sigma}\cdot\hat{Y}^*$ (in the Y_0^* rest frame) to be symmetric. Within statistics this distriubtion is symmetric and the ratio forward/backward is 1.05 ± 0.18.

From the observed number of $\Lambda^0\pi^0K^0$ events which have a $\Lambda\pi$ mass in the region 1340-1430 MeV, we estimate (assuming a branching ratio of 10% for the $\Sigma\pi/\Lambda\pi$ decay mode of the[9] Y_1^*) that no more than 30 $\Sigma^\pm\pi^\mp$ events due to the Y_1^* lie in the Y_0^* mass region. Production and decay angular distributions of events attributed to the Y_1^* ($T_Z = 0$) and Y_0^* resonance are shown in Fig. 2. The Y_0^* data differ markedly from the Y_1^* data both in production and decay. Since our sample of Y_0^* events is reasonably clean, a spin analysis may be attempted.

The production angular distribution of the Y_0^* [Fig. 2(a)] clearly indicates that at least two partial waves of opposite parity are involved. Such a production angular distribution suggests that the Y_0^* could be polarized. The distribution[10] in $\hat{\Sigma}\cdot\hat{n}$ is consistent with isotropy [Fig. 2(b)] as is required for a spin-$\frac{1}{2}$ Y_0^*.

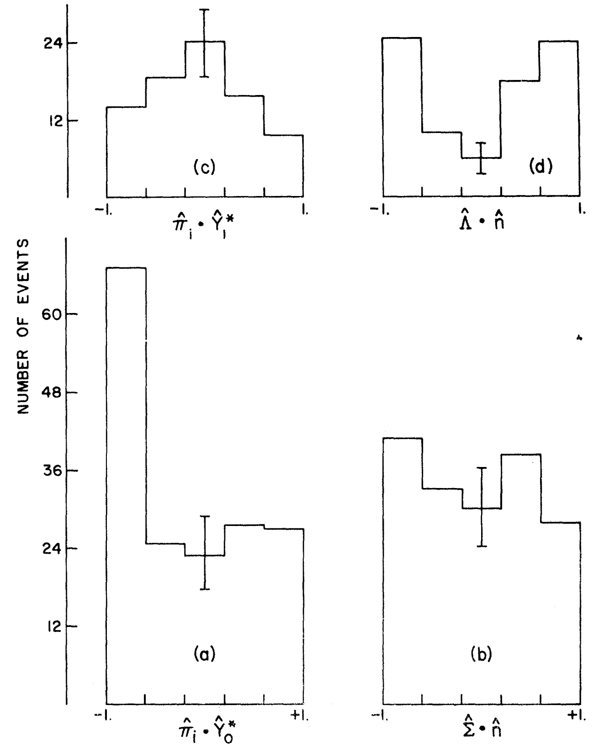

FIG. 2. (a) Y_0^* production angular distribution, and (b) the distribution of $\hat{\Sigma}\cdot\hat{n}$ for 170 events in the mass interval 1340-1460 MeV. (c) Y_1^* production angular distribution, and (d) the distribution of $\hat{\Lambda}^0\cdot\hat{n}$ for 83 events in the mass interval 1340-1430 MeV.

The method of moments permits the determination of a set of parameters $t_L{}^M$ from the experimental data.[1] These parameters are the expectation values of a complete set of spherical tensor operators. If J is the spin of the resonance, the following conditions must hold: $L \leq 2J$ and $-L \leq M \leq L$. With the Z axis taken to be the production-plane normal, parity conservation in the production of the Y_0^* restricts M to even values.[11] In the strong

Table II. Moment analysis results for 170 Y_0^* events, at all production angles.

$J=\frac{3}{2}$	$\mathrm{Re}t_2{}^{-2}=-0.06\pm0.06$	$J=\frac{5}{2}$	$\mathrm{Re}t_4{}^{-4}=0.06\pm0.06$
	$\mathrm{Im}t_2{}^{-2}=0.03\pm0.06$		$\mathrm{Im}t_4{}^{-4}=0.03\pm0.07$
	$t_2{}^0=0.06\pm0.08$		$\mathrm{Re}t_4{}^{-2}=0.06\pm0.06$
$J=\frac{5}{2}$	$\mathrm{Re}t_2{}^{-2}=-0.05\pm0.06$		$\mathrm{Im}t_4{}^{-2}=0.08\pm0.06$
	$\mathrm{Im}t_2{}^{2}=0.03\pm0.05$		$t_4{}^0=0.03\pm0.08$
	$t_2{}^0=0.06\pm0.08$		

$\chi^2(t_2\text{'s}=0)=1.75$ (three degrees of freedom); probability = 62%.
$\chi^2(t_4\text{'s}=0)=3.99$ (three degrees of freedom); probability = 54%.
$\chi^2(t_2\text{'s and }t_4\text{'s}=0)=6.08$ (eight degrees of freedom); probability = 65%.

Table III. Number of observed events in the final states of the reaction $\pi+N\rightarrow Y_1^*(1340\text{-}1430\text{ MeV})+K$, and the chi-squared probabilities for the assumptions (a) t_2^M and $t_3^M=0$, and (b) t_4^M and $t_5^M=0$.

Reaction	Number of events in mass interval 1340-1430 MeV	$\chi^2(t_2$ and $t_3=0)$ Nine degrees of freedom	Probability	$\chi^2(t_4$ and $t_5=0)$ 15 degrees of freedom	Probability
$\pi^-+p\rightarrow\Lambda^0+K^++\pi^-$ $\pi^++n\rightarrow\Lambda^0+K^0+\pi^+$	163	27	0.001	31	0.01
$\pi^-+p\rightarrow\Lambda^0+K^0+\pi^0$ $\pi^++n\rightarrow\Lambda^0+K^++\pi^0$	83	30.6	0.001	11.4	0.72
$\pi^++p\rightarrow\Lambda^0+K^++\pi^+$	70	18	0.03	16.0	0.40

decay $Y_0^*\rightarrow\Sigma+\pi$ the experimental angular distribution of the Σ is related to the parameters t_L^M by the equation

$$n_{L0}t_L^M=(1/N)\sum_{K=1}^{N}Y_L^M(\theta_K,\varphi_K),\text{ with } L \text{ even.}\quad(2)$$

The n_{L0} are constants depending on J; N is the number of observed events; Y_L^M are the spherical harmonics; and θ,φ are the polar and azimuthal angles of the Σ taken in the Y_0^* rest frame.[10] For an assumed value of the spin, J, any t_L^M with $L>2J$ must vanish. The Y_0^* parity can be determined by observation of the Σ^+ polarization through the weak decay $\Sigma^+\rightarrow p+\pi^0$. Since the number of events in which the latter decay mode occurs is small (35 events), the t_L^M's with odd L, which are related to the polarization, are statistically poorly determined.

Table II lists the experimentally determined even-L parameters t_L^M for spin up to $\frac{5}{2}$. We have examined the behavior of the t_L^M's in the low- and high-mass portions of the Y_0^* and find no statistically significant variation of these parameters as a function of the mass of the resonance. Using these t_L^M's, we have calculated the chi-squared probabilities, including correlation, for the hypotheses that the t_2^M, or the t_4^M, are zero, and the joint hypothesis that the t_2^M and the t_4^M are zero. The results, also shown in Table II, indicate that the probabilities for the above hypotheses are high, i.e., a Y_0^* spin greater than $\frac{1}{2}$ is not required by our data.[12]

We shall now discuss breifly the data concerning the Y_1^* resonance. There is no direct evidence for interference in any of the three-body final states giving rise to the Y_1^*.[13] The chi-squared probabilities for the various spin assumptions are shown in Table III. In agreement with previous results,[2] we find that spin $\frac{1}{2}$ is ruled out, spin $\frac{3}{2}$ is acceptable, and spin $\frac{5}{2}$ is not required by these data.

We wish to thank the Brookhaven National Laboratory Bubble Chamber Group, members of the AGS staff, and our scanners for their invaluable services. We are indebted to Professor Julius Ashkin for many fruitful discussions concerning the moments method, and to Dr. Janice B. Shafer for valuable comments and for providing us with the analysis program SPINPAR.

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*Work supported by the U. S. Atomic Energy Commission.

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[3] A comparison between the experimental nucleon recoil spectrum and the momentum distribution of the nucleon in the deuteron as predicted by the Hulthén wave function shows reasonable agreement for momenta up to 200 MeV/c. For events with momenta $\leq$200 MeV/c, the momentum of the target nucleon has been taken to be equal and opposite to the recoil momentum.

[4] The minimizing routine MINFUN written by W. E. Humphrey has been used in the fit. We wish to thank Dr. Humphrey and Dr. Ross for valuable comments in applying this method.

[5] The $Y_0^*(1520)$ parameters used in this fit were mass $=1519$ MeV, width $=16$ MeV.

[6] M. Alston et al., in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962, edited by J. Prentki (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 311; G. Alexander et al., Phys. Rev. Letters 8, 447 (1962);

A. Barbaro-Galtieri et al., Bull. Am. Phys. Soc. 10, 518 (1965).

[7] It has been pointed out to us by Professor G. B. Yodh that at c.m. energies close to threshold, the mass of the Y_0^* might be rather sensitive to the relative Y_0^*-K angular momentum, which might cause a shift in the observed mass of the resonance.

[8] A total of 10 events have been recorded in which the K^0 decays in the chamber, but no Σ decay is observed (two prongs plus one "vee"). The kinematic fits of these events yield two decays $\Sigma^- \rightarrow \pi^- + n$, one decay $\Sigma^+ \rightarrow \pi^+ + n$, and seven decays $\Sigma^+ \rightarrow p + \pi^0$. These events are included in Table I. For all the ratio tests mentioned, twice the above numbers have been added to the appropriate channels to take into account the events which were missed. The distribution of the protons from the above $\Sigma^+ \rightarrow p + \pi^0$ events evaluated in the Σ^+ rest frame indicates no significant forward-to-backward bias.

[9] The most recent value for this ratio of $(9 \pm 4)\,\%$ has been given by D. Huwe, University of California Radiation Laboratory Report No. UCRL 11291 (unpublished).

[10] The basic X, Y, Z lab coordinate system is $\hat{\pi}$, $(\hat{\pi} \times \hat{\pi})/|\hat{n} \times \hat{\pi}|$, and $\hat{n} = (\hat{\pi} \times \hat{k})/|\hat{\pi} \times \hat{k}|$, respectively, where $\hat{\pi}$ denotes the unit vector along the beam direction, $\hat{k}$ the unit vector along the outgoing K, and $\hat{n}$ is normal to the production plane. All four-vectors were transformed successively to the production c.m., Y^*, and hyperon rest frames using a direct Lorentz transformation without rotation [H. P. Stapp, University of California Radiation Laboratory Report No. UCRL 8096 (unpublished)].

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[12] In the analysis of low-energy K-N interactions by Dalitz and Tuan [Phys. Rev. Letters 3, 425 (1960); Ann. Phys. (N. Y.) 3, 307 (1960)], a resonance with mass and width close to those of the Y_0^* appears as a $T = 0$, $S_{1/2}$, $\bar{K}N$ bound state. The most recent application of the Dalitz-Tuan model is due to J. K. Kim, Phys. Rev. Letters 14, 29 (1965).

[13] For the final state $\Lambda^0 K^+ \pi^-$, the forward-backward ratio in $\hat{\Lambda} \times \hat{Y}_1^*$ is 0.70 ± 0.14.