Final States with Two or More Strange Particles from 4.25-BeV/c K^-p Interactions*

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Final states with two or more strange particles produced by 4.25-BeV/c K^-p interactions were studied in a 5.3-event/μb exposure. A search for Ξ^* resonances found only the $\Xi^*(1530)$ produced in measurable amounts. The data suggest a $\Xi^*(2225)$ with isotopic spin $\frac{3}{2}$. The mass of the ϕ meson is measured to be 1021.5±0.8 MeV from $\Lambda\phi$ events with $\phi \to K_1^0K_2^0$. This result is 3 MeV higher than that found in other experiments using stopping K^+ and K^- mesons from $\phi \to K^+K^-$. The results of a search for other meson and baryon resonances are presented.

I. INTRODUCTION

THE authors have studied a 4.2-BeV/c K^- exposure for the production of baryon resonances with strangeness $S=-2$, generically labeled Ξ^* resonances. Preliminary reports[1–3] discussing portions of the data have already appeared in the literature. This paper contains our final results.[4,5]

Final states of Ξ, $\Lambda\bar{K}$, and $\Sigma\bar{K}$ production processes were analyzed for possible structure. By-products of this analysis were the observation of the production[1] of an Ω^- and final states containing $NK\bar{K}\bar{K}$. Cross sections for the observed processes were found to be of the order of 10 μb or less in any single final state, so that with the path length of this experiment (5.3 events/μb) the observed number of events in each channel is typically less than 50. Detailed analysis of the individual channels is therefore not warranted, but we have tabulated the observed cross sections and compared them, where data were available, with values from experiments at different energies.

II. DATA COLLECTION AND EVALUATION

The Brookhaven National Laboratory 80-in. hydrogen bubble chamber[6] was exposed to a high-energy (electrostatically) separated K^- beam.[7,8] Approximately 110 000 pictures were taken in two exposures. The beam momentum was 4.25 BeV/c (as determined from a kinematic fitting of τ decays of beam tracks) with a momentum spread of ±0.031 BeV/c. The beam had a light-particle (pion, muon, and electron) impurity of ~20% (determined from a count of δ rays >120 MeV on beam tracks); π^- contamination was determined to be (3.4±0.9)% from pion-induced associated production events observed in the film. From 2500 τ decays of beam tracks, we estimate that 1.2 million K^- mesons entered the chamber. The path length in the fiducial volume corresponded to an interaction rate of 5.3±0.2 events/μb of cross section.

The entire film was scanned twice for events with two or more visible signs of strangeness (a sign of strangeness being the decay of a charged or neutral particle) and for τ decays of beam tracks. Charged meson decays and γ-ray conversions were eliminated wherever possible on the scanning table through a visual ionization estimate. The $K^\pm$ decays were ignored because of the overwhelming contamination by pion decays. The random scanning efficiency was (99±1)% for two strangeness events, and (98±1)% for τ decays (for the combined scans).

Events were measured on standard film plane digitizers, and processed by the Maryland three-view version of PACKAG. Kinematic fits or missing mass (MM) calculations were performed for all K^-p and π^-p production hypotheses consistent with the observed decays. About 40% of all events were ambiguous after kinematic fitting.

All events found in the scan were checked on the scanning table by two physicists for consistency of the acceptable (at the 1% level of χ^2) hypotheses with observed ionization. Where visual estimates were inadequate to distinguish alternative hypotheses, a measurement of the gap-length distribution was made on a digitized microscope. The microscope measurement easily distinguished a track of 1.3×minimum from one

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1 G. S. Abrams, R. A. Burnstein, G. R. Charlton, T. B. Day, B. Kehoe, B. Sechi-Zorn, G. A. Snow, M. C. Whatley, G. Wolsky, G. B. Yodh, and R. G. Glasser, Phys. Rev. Letters **13**, 670 (1964).

2 G. S. Abrams, T. B. Day, R. G. Glasser, B. Kehoe, B. Sechi-Zorn, G. A. Snow, G. Wolsky, and G. B. Yodh, in *Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, 1966* (University of California Press, Berkeley, 1967).

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4 G. Wolsky, University of Maryland Technical Report No. 704 (Ph.D. thesis, 1967) (unpublished). This reference and the following one provide more details of the experiment.

5 G. S. Abrams, University of Maryland Technical Report No. 720 (Ph.D. thesis, 1967) (unpublished).

6 E. L. Hart, Brookhaven National Laboratory Internal Report BC-04-3-B, 1965 (unpublished). This reference contains the bubble-chamber optical constants used in this experiment.

7 I. Skillicorn and M. S. Webster, Brookhaven National Laboratory Bubble Chamber Group Report No. H-10, 1962 (unpublished).

8 D. C. Rahm, Brookhaven National Laboratory Bubble Chamber Group Report No. H-17, 1965 (unpublished).

of minimum ionization if sufficient length of track was available. The ionization measurements reduced the ambiguity rate to $\sim 10\%$, small enough so the error introduced by event misidentification is usually negligible. All events with no physically acceptable hypothesis were studied and remeasured if necessary. The final two-strangeness sample contained about 1000 events.

To ensure a uniform efficiency and to eliminate many events included because of meson kinks and electron pairs arising from γ-ray conversions, several requirements were imposed on the decaying strange particles. A minimum projected length of 0.25 cm and a maximum total length of 60 cm were required. The decay was also required to occur within a volume which ensured its measurability.

Small angle decays of charged strange particles ($\Sigma^{\pm}, \Xi^-$) were missed, but the observed angular distributions were consistent with the hypothesis that there was no significant loss of events for decays in which the projected angle (between the charged decaying track and its charged secondary) was greater than 5°. The sample was therefore limited to decays with projected angle greater than 5°. Corrections have been made for the loss of events at smaller angles as well as for the events lost by the length requirements. The length cuts required a correction of only a few percent of the events, while the angle cut required a 30–40% correction. The corrected data agree with the expected decay distributions of the particles, providing a check on the validity of the corrections used.

The distribution of mass measurements of the K_1^0 and the Λ, from measured (unfitted) momenta of their charged decay secondaries, indicated that the magnetic field as determined by Brookhaven[9] was 0.5% too low. The field used in our geometry and analysis program was altered accordingly. In addition, an asymmetric shift, from measured to fitted value, of some of the track parameters was observed. The effect of this on all the results presented later was reduced to a negligible level by the imposition of lower limits on the calculated angle errors. These adjustments are discussed more fully in Refs. 4 and 5. After these adjustments we determined a Λ mass of 1115.75 ± 0.09 MeV and a K_1^0 mass of 497.5 ± 0.2 MeV, and our measurements of the masses of most of the well-known resonances are consistent with accepted values.

III. ANALYSIS OF THE DATA

We have examined the square of the effective mass, M^2, for various combinations of particles in the final state. Despite the fact that the observed two-body and quasi-two-body differential cross sections suggest a peripheral production mechanism (as shown below), the M^2 distributions show a tendency to follow phase space. The smooth curves on the M^2 distributions are the results of phase-space calculations normalized to the observed number of events unless otherwise stated.

All distributions discussed include events ambiguous among two or more production hypotheses. Since the ambiguity rate is rather small, this raises no serious problems.

The M^2 distributions are uncorrected for geometric and neutral decay mode losses; the spectra remain qualitatively unchanged when these corrections are made. All quoted cross sections in the body of the paper, in the figures, and in Tables I and II, do include all such corrections however.

A. Baryon States of Strangeness $S=-2$

It has been noted in lower-energy experiments[10] that Ξ's tend to be produced in the forward (beam) direction in K^-p collisions. The differential cross sections for Ξ^-K^+ and $\Xi^-K^{*+}(890)$ at 4.25 BeV/c (see Fig. 1) show the same behavior, and may be understood qualitatively as evidence for baryon exchange mediating the peripheral production process. There is reasonable agreement with an exponential falloff in the forward direction.

ΞK production has been observed[11] to decrease (well above threshold) with laboratory beam momentum P_K as

$$\sigma(\Xi)\sim 1/P_K^4.$$

The cross section at 4.25 BeV/c for Ξ^-K^+ (see Table I) is consistent with that found at lower energies, reduced by such a falloff. If the $\Xi^*(1530)K$ state is produced by a similar production mechanism, then the expected[12] cross section at 4.25 BeV/c would be approximately 2–3 μb for either charge mode. Our data, based on the Ξ^- decay mode of the resonance, are consistent with such an estimate.

While production of $\Xi^*(1530)$ and K in a quasi-two-body mode is observed to be low, final states which have extra pions are more copiously produced. The largest $\Xi^*(1530)$ cross section appears in the four-body states $\Xi K\pi\pi$ (~ 12 μb). In Fig. 2(a) we show the distribution of $M^2(\Xi\pi)^{0,-}$ from the five-body states $\Xi K\pi\pi\pi$ which has the largest signal above background. The $\Xi^*(1530)^0$, as observed in decays via $\Xi^-\pi^+$ in these states, has a mass and width of

$$M=1533.6\pm4.8 \text{ MeV},\quad \Gamma=13.2\pm5.7 \text{ MeV}$$

estimated from a Gaussian ideogram of the data.

[9] B. B. Culwick, Brookhaven National Laboratory Internal Report No. BC-05-2-G, 1964 (unpublished).

[10] See, for example, G. W. London, R. R. Rau, N. P. Samios, S. S. Yamamoto, M. Goldberg, S. Lichtman, M. Primer, and J. Leitner, Phys. Rev. **143**, 1034 (1966).

[11] D. R. O. Morrison, Phys. Letters **22**, 528 (1966); invited paper at Stony Brook Conference on High Energy Two-Body Reactions, 1966 (unpublished).

[12] This estimate uses a $\Xi^{*0}K^0$ cross section of 56 ± 11 μb and a $\Xi^{*-}K^+$ cross section of 22 ± 7 μb, both observed at 2.24 BeV/c (see Ref. 10).

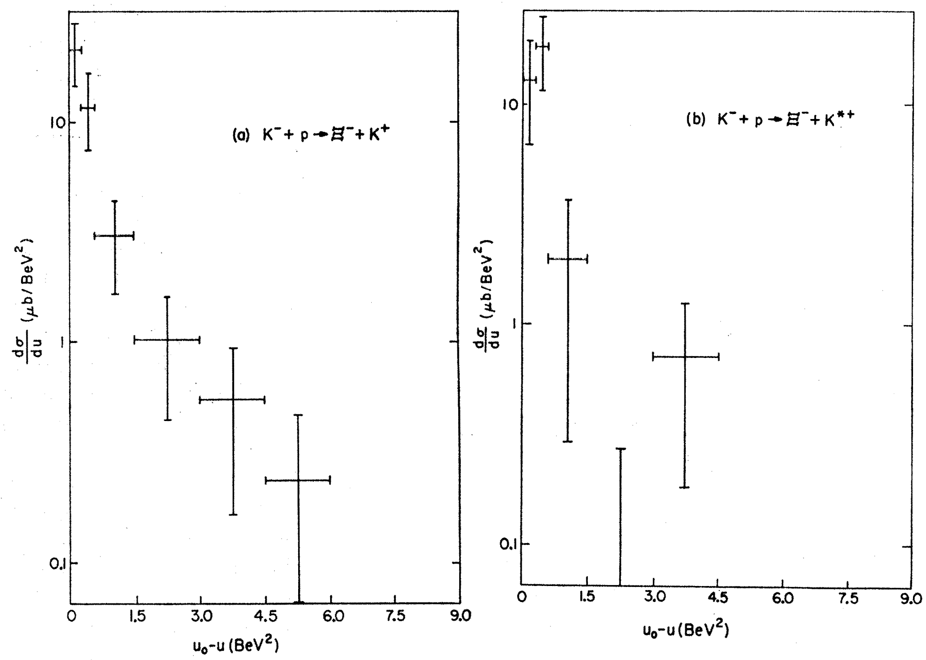

FIG. 1. Differential cross sections for two-body Ξ^- production processes: (a) $K^-p \rightarrow \Xi^-K^+$, 26 events; (b) $K^-p \rightarrow \Xi^-K^*(890)^+$, 38 events. ($u$ is the squared four-momentum transfer from the K^- to the Ξ^-, while u_0 is the value of u when the angle between the K^- and the Ξ^- is 0°.)

TABLE I. Cross sections of final states. The number of observed events listed include the apportioned ambiguous events (see text).

Final state	No. of observed events	Cross section (μb)	Final state	No. of observed events	Cross section (μb)
Ξ^-K^+	26.2	15.4±3.0	$K^-pK_1^0K_1^0\pi^0$	2.0	0.9±0.6
Ξ^0K^0	5.0	10.5±5.5	$\Sigma^+\pi^-K_1^0K_1^0\pi^0$	2.0	1.5±1.1
$\Xi^-K^+\pi^0$	24.1	12.8±2.5	$\Sigma^-K^-K^0\pi^+\pi^+$	2.0	1.6±1.2
$\Xi^-K^0\pi^+$	47.6	19.4±2.8	$\Sigma^-K^+\bar{K}^0\pi^+\pi^-$	2.0	1.6±1.2
$\Sigma^+K^-K^0$	4.0	3.6±1.8	$\Sigma^0K_1^0K_1^0\pi^+\pi^-$	3.0	1.4±0.8
$\Sigma^-K^+\bar{K}^0$	15.0	11.8±3.2	$\Lambda K_1^0K_1^0\pi^+\pi^-$	4.0	2.1±1.1
$\Sigma^0K_1^0K_1^0$	11.8	5.6±1.7	$\Lambda K_1^0K_2^0\pi^+\pi^-$	~4	2.8±1.8
$\Lambda K_1^0K_1^0$	18.1	8.4±2.0	$\Lambda K^+\bar{K}^0\pi^-\pi^0$	8.0	7.4±2.6
$\Lambda K_1^0K_2^0$	~63	30.0±4.3	$\Lambda K^-K^0\pi^+\pi^0$	13.2	12.4±3.6
$\Xi^-K^+\pi^-\pi^+$	32.0	15.0±2.7	$\Xi^-K^0\pi^+\pi^-\pi^+\pi^0$	2.0	1.5±1.1
$\Xi^-K^0\pi^+\pi^0$	34.2	28.8±5.0	Missing-mass events		
$\Xi^0K^0\pi^+\pi^-$	20.0	29.6±4.8	Ξ^-K^++MM	23.0	11.4±2.2
$nK_1^0K_1^0K_1^0$	2.0	1.4±1.0	Ξ^0K^0+MM	13.0	15.3±4.3
$K^-pK_1^0K_1^0$	3	1.4±0.8	$\Xi^-K^0\pi^+$+MM	~15	5.9±3.7
$\Sigma^+K^-K^0\pi^0$	6.6	6.0±2.3	$\Xi^-K^+\pi^-\pi^+$+MM	5.0	2.0±0.9
$\Sigma^+\pi^-K_1^0K_1^0$	4.0	2.9±1.5	$\Xi^0K^0\pi^+\pi^-$+MM	13.0	13.3±3.7
$\Sigma^+\pi^-K_1^0K_2^0$	~12	8.9±2.7	$\Xi^-K^0\pi^+\pi^-\pi^+$+MM		0
$\Sigma^-K^+\bar{K}^0\pi^0$	8.2	7.6±2.4	$K_1^0K_1^0K_1^0$+MM	1.0	0.8±0.8
$\Sigma^-\pi^+K_1^0K_1^0$	1.0	0.6±0.6	$K^-pK_1^0K_1^0$+MM	1.0	0.5±0.5
$\Sigma^-\pi^+K_1^0K_2^0$	~34	15.3±2.5	$\Sigma^+\pi^-K_1^0$+MM	3.0	
$\Sigma^0K^+K^0\pi^-$	8.0	7.4±2.8	$\Sigma^+K^-K^0$+MM	1.0	1.4±1.4
$\Sigma^0K^-K^0\pi^+$	19.9	20.4±5.0	$\Sigma^+\pi^-K_1^0K_1^0$+MM	1.0	0.6±0.6
$\Lambda K_1^0K_1^0\pi^0$	10.0	7.3±2.3	$\Sigma^+\pi^-K_1^0$+MM	4.0	
$\Lambda K^+\bar{K}^0\pi^-$	26.5	25.2±4.8	$\Sigma^-K^+\bar{K}^0$+MM	~0.2	~0.2
$\Lambda K^-K^0\pi^+$	25.5	26.2±5.2	ΛK_1^0+MM	123.0	
$\Xi^-K^+\pi^+\pi^-\pi^0$	38.8	16.1±2.6	$K_1^0K_1^0$+MM	20.0	9.3±2.1
$\Xi3K^0\pi^+\pi^-\pi^+$	16.2	5.4±1.3	$\Lambda K_1^0K_1^0$+MM	7.0	5.2±2.0
$nK^-\pi^+K_1^0K_1^0$	2.0	0.9±0.6	$\Lambda K^-K^0\pi^+$+MM	~4	~4
$nK^+\pi^-K_1^0K_1^0$	1.0	0.5±0.5	$\Lambda K^+\bar{K}^0\pi^-$+MM	~2	~2
$\pi^-pK_1^0K_1^0K_1^0$	2.0	~1	Total Ξ^-	276.0	131.4±8.7

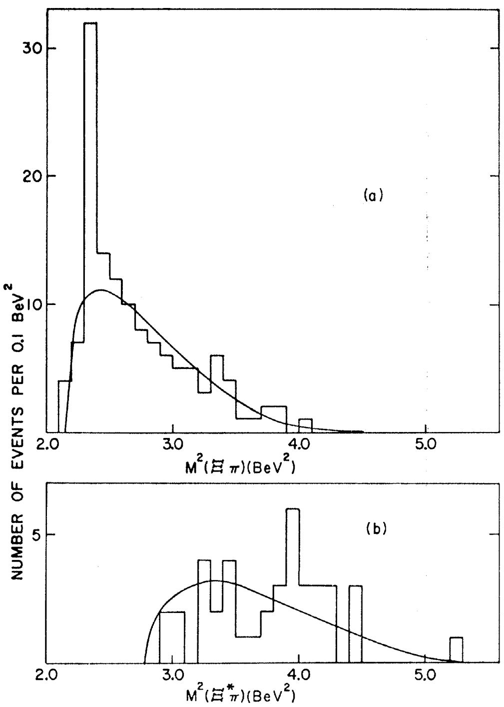

FIG. 2. Effective mass-squared (M^2) distributions from five-body Ξ^- states: (a) $M^2(\Xi^-\pi^+)+M^2(\Xi^-\pi^0)$, 65 events plotted twice; (b) $M^2(\Xi^{*0}\pi^{0,-})$, 14 events ($\Xi^{*0}\pi^-K^+\pi^0$ plotted twice), and 12 events ($\Xi^{*0}\pi^-K^0\pi^+$ plotted once). The Ξ^{*0} is defined by the limits $2.3\leq M^2(\Xi^{*0})\leq 2.4$ BeV^2.

Lower-energy experiments[13,14] have indicated the possible existence of higher Ξ^* resonances at 1705, 1815, and 1933 MeV corresponding to $M^2=2.9$, 3.3, and 3.7 BeV^2. From the rapid falloff in two-body processes, ΞK or Ξ^*K, we do not expect to see two-body production reactions of these higher Ξ^*'s within the statistics of this experiment. Evidence from the multi-body Ξ states indicates no significant evidence for a $\Xi\pi$ decay mode of any of these enhancements. The $\Xi K\pi\pi\pi$ states appear to show an enhancement near 2.0 BeV in the $\Xi^*(1530)\pi$ system; although the effect [see Fig. 2(b)] may be related to the $\Xi^*(1933)$, the enhancement is not strong enough to demand a resonance interpretation. In summary, we find no definite evidence for any higher Ξ^* states decaying to $\Xi\pi$ or $\Xi\pi\pi$.

Ξ's also have been observed to decay via $\Lambda\bar{K}$ (but not $\Sigma\bar{K}$, $\Lambda\bar{K}\pi$, etc.). A narrow 2.5-standard-deviation enhancement (seven events in a bin where two events are expected from phase-space considerations) appears in the region of the $\Xi^*(1815)$ in the distributions of $M^2(\Lambda\bar{K})$ from the states $\Lambda K_1{}^0K^\pm\pi^\mp$. This is the only positive evidence bearing on a $\Lambda\bar{K}$ mode of a Ξ^*.

[13] J. Badier, M. Demoulin, J. Goldberg, B. P. Gregory, C. Pelletier, A. Rouge, M. Ville, R. Barloutaud, A. Leveque, C. Leveque, C. Louedec, J. Meyer, P. Schlein, A. Verglas, D. J. Holthuizen, W. Hougland, and A. G. Tenner, Phys. Letters **16**, 171 (1965).

[14] G. A. Smith and J. S. Lindsey, in Proceedings of Second Topical Conference on Resonant Particles, Athens, Ohio, 1965 (unpublished).

We have investigated all M^2 distributions in the observed final states which have baryon number $B=+1$ and strangeness $S=-2$, but have found no evidence for Ξ^* production other than that cited above. In particular, our final data show no enhancement at 2270 MeV, contradicting the preliminary evidence[2] for a $\Xi^*(2270)$. Although, as would be expected, two standard deviation enhancements abound in these $S=-2$ distributions, only an enhancement at 2225 MeV, with a width of about 25 MeV, appears in more than one distribution. This effect appears in the distribution of $M^2(\Xi^-\pi^-\pi^0)$ in the final state $\Xi^-\pi^-\pi^0\pi^+K^+$ (implying $T\geq\frac{3}{2}$), see Fig. 3(a), and in the distribution of the mass recoiling from the K^+ in the Ξ^- events which are consistent with the production of two or more neutral pions (implying $T\leq\frac{3}{2}$), see Fig. 3(b). The curve in Fig. 3(b) is the phase-space distribution appropriate to the hypothesis that the missing mass is composed of two π^0 mesons. This hypothesis gives an upper limit to the phase space in the region of the enhancement. Since the total evidence for this $T=\frac{3}{2}$ effect is 24 events where phase space predicts 12 events, a resonance interpretation of the enhancement is by no means necessary.

In conclusion, cross sections of known Ξ^*'s appear to be small at 4.25 BeV/c (see Table II) and no convincing evidence can be presented for the existence of new Ξ^*'s. The Ξ^* data are consistent with a very rapid decrease in the two-body production cross sections as the beam momentum increases, as already noted for the ΞK production cross section.

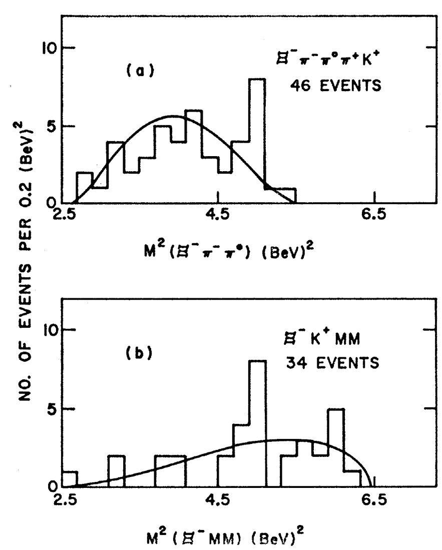

FIG. 3. Distributions showing an $S=-2$ baryon-state enhancement in the region of 2225 MeV: (a) Mass squared for the combination $\Xi^-\pi^-\pi^0$ from the final state $\Xi^-\pi^-\pi^0\pi^+K^+$. (b) Mass squared for the combination Ξ^-MM from the final state Ξ^-K^+MM. The curve is the phase-space distribution for $\Xi^-\pi^0\pi^0$ from $\Xi^-K^+\pi^0\pi^0$. While an admixture of three- and four-π^0 states is expected, the two-π^0 state is probably predominant and gives an upper limit to the phase-space distribution in the region of 2225 MeV (4.95 BeV^2).

B. Y^* Production

We have observed production of the low-lying Y^*'s: $Y_1^*(1385)$, $Y_0^*(1405)$, and $Y_0^*(1520)$. These resonances are seen recoiling from a $K\bar{K}$ combination in four-body final states. Although the number of events is rather small, the $Y_1^*(1385)^+$ in the state $\Lambda\pi^+K^0K^-$ appears to be produced in a backward direction, while the Y_1^*-$(1385)^-$ appears to be forward in the state $\Lambda\pi^-\bar{K}^0K^+$. These tendencies are in agreement with other experiments which indicate that exchanges with $|\Delta Q|=2$ appear to be suppressed (the result of this experiment apparently generalizes the earlier observations which were based on two-body reactions).

In the final states $\Sigma^\pm\pi^\mp K^0\bar{K}^0$, resonance production is copious [$Y_0^*(1405)$, $Y_0^*(1520)$, $K^*(890)$, and $\phi(1020)$]. As can be seen from Figs. 4(a) and 4(b), the double resonance state $Y_0^*\phi$ is produced peripherally in qualitative agreement with a K and K^* exchange production mechanism. The differential cross section for the states $Y_0^*(1405)\phi$ and $Y_0^*(1520)\phi$ is seen to be similar to that of $\Lambda\phi$ [see Fig. 6(a)].

We find no evidence for $N\bar{K}$, ΞK, and $YK\bar{K}$ decay modes of Y^* resonances. We also see no sign of higher Y^*'s such as the 1760 or 1820.

C. K^* Resonances

Production of the $K^*(890)$ is seen in almost every state in which a $K\pi$ combination exists, and comprises

TABLE II. Cross sections of intermediate resonant states. Quoted errors include statistical effects and uncertainties in background estimation.

Intermediate state	Observed final states	Cross section in observed final states (μb)
$\Xi^*(1530)^0K^0$	$\Xi^-\pi^+K^0$	2.0 ± 0.9
$\Xi^*(1530)^-K^+$	$\Xi^-\pi^0K^+$	0.5 ± 0.5
$\Xi^*(1530)^0K^0\pi^0$	$\Xi^-\pi^+K^0\pi^0$	4.7 ± 2.5
$\Xi^*(1530)^-K^0\pi^+$	$\Xi^-\pi^0K^0\pi^+$, $\Xi^0\pi^-K^0\pi^+$	11.6 ± 6.2
$\Xi^*(1530)^0K^+\pi^-$	$\Xi^-\pi^+K^+\pi^-$	-0.2 ± 0.6
$\Xi^*(1530)^0K^0\pi^+\pi^-$	$\Xi^-\pi^+K^0\pi^+\pi^-$	3.8 ± 1.3
$\Xi^*(1530)^0K^+\pi^-\pi^0$	$\Xi^-\pi^+K^+\pi^-\pi^0$	3.5 ± 1.6
$\Xi^*(1705)^0K^0$	$\Xi^-\pi^+K^0$	1.5 ± 1.1
$\Xi^*(1705)^-K^+$	$\Xi^-\pi^0K^+$	-0.2 ± 0.4
$\Xi^*(1815)^0K^0$	$\Lambda\bar{K}^0K^0$	1.5 ± 1.6
$\Xi^*(1815)^-K^0\pi^+$ $+\Xi^*(1815)^0K^+\pi^-$	$\Lambda K^-K^0\pi^++\Lambda\bar{K}^0K^+\pi^-$	5 ± 3
$\Lambda\phi$	$\Lambda K_1{}^0K_2{}^0$	17.2 ± 3.0
$\Sigma^\pm\pi^\mp\phi$	$\Sigma^\pm\pi^\mp K_1{}^0K_2{}^0$	10.3 ± 2.5
$Y_0^*(1405)K^0\bar{K}^0$	$\Sigma^\pm\pi^\mp K^0\bar{K}^0$	5 ± 2
$Y_0^*(1520)K^0\bar{K}^0$	$\Sigma^\pm\pi^\mp K^0\bar{K}^0$	4 ± 2
$Y_1(1385)^\pm(K\bar{K})^\mp$	$\Lambda\pi^-\bar{K}^0K^+$, $\Lambda\pi^+K^0K^-$	5 ± 2
$K^*(890)^+\Xi^-$	$K^0\pi^+\Xi^-$, $K^+\pi^0\Xi^-$	12.1 ± 3.4
$K^*(890)^+\Xi^-\pi^0$	$K^0\pi^+\Xi^-\pi^0$	7.2 ± 4.6
$K^*(890)^0\Xi^-\pi^+$	$K^0\pi^0\Xi^-\pi^+$, $K^+\pi^-\Xi^-\pi^+$	8.7 ± 5.0
$K^*(890)^+\Xi^0\pi^-$	$K^0\pi^+\Xi^0\pi^-$	13.1 ± 7.2
$K^*(890)^0\Xi^-\pi^+\pi^0$	$K^+\Xi^-\pi^-\pi^+\pi^0$	1.4 ± 3.3
$K^*(890)^+\Xi^-\pi^-\pi^+$	$K^0\pi^+\Xi^-\pi^-\pi^+$, $K^+\pi^0\Xi^-\pi^-\pi^+$	7.8 ± 3.4

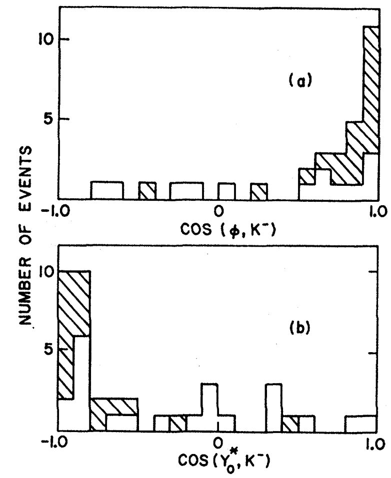

FIG. 4. Angular distributions from the states $\Sigma^\pm\pi^\mp K^0\bar{K}^0$ (in the overall K^-p center-of-mass system): (a) Production angular distribution of ϕ mesons, 31 $\phi\Sigma^\pm\pi^\mp$ defined by the condition $1.0\leq M^2(K_1{}^0K_2{}^0)\leq1.1$ BeV². Shaded events fall within a Y_0^* band (defined below), 18 events. (b) Production angular distribution of Y_0^* hyperons, $Y_0^*(1405)$ and $Y_0^*(1520)$, 40 events defined by the conditions $1.8\leq M^2(\Sigma\pi)\leq2.1$ BeV² or $2.3\leq M^2(\Sigma\pi)\leq2.5$ BeV², respectively. Shaded events fall in the ϕ band (see above), 18 events.

10–40% of the cross section for such states. The $K^*(890)$ appears most copiously in the two-body state Ξ^-K^{*+}, where both the $K^0\pi^+$ and the $K^+\pi^0$ decay modes of the $K^*(890)$ are observed. The measured mass and width of the $K^*(890)$ in this state are

$$M=900\pm16 \text{ MeV},\quad \Gamma=65\pm19 \text{ MeV}$$

in good agreement with currently accepted values. As shown in Fig. 1(b), there is a marked similarity between the differential cross sections for production of Ξ^-K^*-$(890)^+$ and for Ξ^-K^+ [Fig. 1(a)]. The simplest production mechanism is baryon exchange which predicts a forward Ξ^- peaking; for the observed reactions the isospin of the baryon must be 0 or 1 (with $T_z=0$), and hypercharge $Y=0$.

There is some indication of possible production of the $\kappa(725)$ in the three- and four-body states. The magnitude of the enhancements does not preclude the possibility of a statistical fluctuation. No K^* of mass higher than the 890 was seen.

D. ϕ Meson

The ϕ meson, decaying via the mode $K_1{}^0K_2{}^0$, is copiously produced in the states $\Lambda\phi$ and $\Sigma\pi\phi$ (we have already noted the $Y_0^*\phi$ production). In the $\Lambda\phi$ events the mass resolution of the $K\bar{K}$ pair is about 4 MeV, so these events provide a good sample with which to determine the mass and width of the ϕ.

The particular chain of reactions with which we are concerned is

$$\begin{array}{l} K^- + p \to \Lambda \quad + \quad \phi \\ \qquad\qquad \searrow \qquad\quad \searrow \\ \qquad\qquad p+\pi^- \quad K_1{}^0 + K_2{}^0 \\ \qquad\qquad\qquad\qquad \searrow \\ \qquad\qquad\qquad\qquad \pi^+ + \pi^- . \end{array} \tag{1}$$

Contamination from Ξ^0-production processes and π-induced reactions can be shown to be negligible.

As a means of estimating and reducing the possible contamination of events of type (1) by events in which a Σ^0 (rather than a Λ) is produced, we have utilized the square of the mass recoiling from the $\Lambda K_1{}^0$, $M_{\text{recoil}}{}^2$. The distribution of that quantity for all zero-prong $\Lambda K_1{}^0$ events is shown in Fig. 5(a). The shaded events on that figure are those which fit the process $K^- + p \to \Lambda + K_1{}^0 + K^0$ (unseen). Using Monte Carlo techniques we have generated the shape of the expected distribution from Σ^0 production. This distribution, with a normalization which represents an upper limit to the contribution is shown by the smooth curve on the figure.

We have based our determination of the ϕ mass on those events which (i) have a successful fit to the $\Lambda K_1{}^0(K^0)$ production hypothesis, (ii) satisfy $1.02 \leq M_{K_1{}^0K^0}{}^2 \leq 1.06$ BeV², and (iii) have $M_{\text{recoil}}{}^2 \leq 0.26$ BeV². (This last criterion reduces the expected Σ^0 contribution to less than one event and the resulting distortion of the ϕ mass to a value well within our quoted error.)

The $M_{K_1{}^0K^0}{}^2$ spectrum in the ϕ region for those events satisfying criterion (i) above is shown in Fig. 5(b) and the Gaussian ideogram of the 24 events satisfying all three criteria is shown in Fig. 5(c). The measured value[15] of the ϕ mass is then

$$M_\phi = 1021.5 \pm 0.8 \text{ MeV}.$$

The width of the ϕ meson was measured using the same sample of events by comparing the observed distribution with a Monte Carlo calculation. We find

$$\Gamma_\phi = 1.8_{-1.5}^{+3.0} \text{ MeV}.$$

The most precise previous measurement[16] of the mass and width of the ϕ meson has been performed in a study of the final state $K^+K^-\pi^+\pi^-$ arising from $\bar{p}p$ interactions at rest. This study utilized only those events where both K mesons come to rest in the chamber through energy loss by ionization, and used the range-energy relation to obtain precise values of the $K^\pm$ momenta. The result of this measurement was $M_\phi = 1018.6 \pm 0.5$ and $\Gamma_\phi = 3.4 \pm 1.7$. While the width measurements are consistent, the discrepancy in the value of the ϕ mass is significant. Since the Q value of the

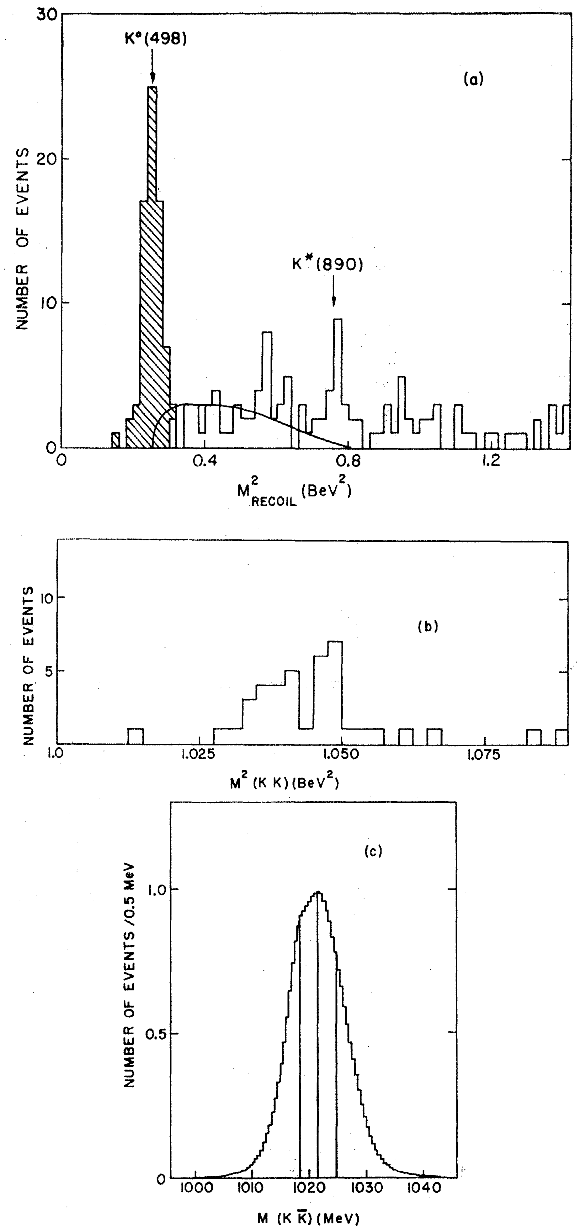

FIG. 5. Distributions from zero-prong events with a visible $\Lambda \to p\pi^-$ decay and one (and only one) visible $K_1{}^0 \to \pi^+\pi^-$ decay: (a) Distribution of the mass squared recoiling from the $\Lambda K_1{}^0$ events. The shaded events fit the hypothesis $K^-p \to \Lambda K^0 \bar{K}^0$ events. (b) Distribution of $M^2(K\bar{K})$ for events which fit $\Lambda K\bar{K}$ in the vicinity of the ϕ meson. (c) Gaussian ideogram of 24 events which satisfy the criteria i, ii, and iii described in the text. The vertical lines on this figure mark the quartiles of the observed distribution.

[15] The error in the mass was estimated from a Monte Carlo calculation of the distribution of the median using the observed measurement errors and a range of widths Γ from 0 to 10 MeV. For these values of Γ, the standard deviation in the median was measured to be approximately 0.7 MeV, and independent of Γ. The uncertainty of the chamber magnetic field (taken as 0.5%) contributes a ϕ mass error of ~0.2 MeV, and the effects of small variations of $M^2(K\bar{K})$ limits used in the analysis (1.02 to 1.06 BeV²) contributed an uncertainty of less than 0.1 MeV. The final result, $M_\phi = 1021.5 \pm 0.8$ MeV, uses the value 497.87 MeV for the K^0 mass and 1115.58 for the Λ mass, taken from the compilation of A. H. Rosenfeld *et al.*, Rev. Mod. Phys. **39**, 1 (1967). Variations of the K^0 and Λ masses consistent with their quoted uncertainties, 0.16 and 0.10 MeV, respectively, produce changes in the ϕ mass substantially less than the 0.8-MeV error quoted.

[16] D. C. Miller, Columbia University Report No. 237, Nevis Report No. 131 (Ph.D. thesis, 1965) (unpublished).

$\phi \to K_1^0K_2^0$ decay is only $\sim$20 MeV, the ϕ mass is rather insensitive to the chamber magnetic field (the mass is lowered only 0.2 MeV if the field is lowered by 0.5%). We have no explanation for this discrepancy.

The ϕ mesons produced in the two-body state $\Lambda\phi$ are seen to have an angular distribution characteristic of a peripheral mechanism [see Fig. 6(a)] indicating that K or K^* exchange may be important in the production mechanism. It has been noted[11] that two-body reactions which apparently proceed through strange exchange obey an approximate momentum dependence of

$$\sigma \sim 1/P_{\mathrm{in}}^2,$$

where P_{in} is the incident-beam laboratory momentum. A logarithmic graph of the available $\Lambda\phi$ cross-section data[10,17–21] is shown in Fig. 6(b); the slope of the straight line is 1.5, in reasonable agreement with exponents indicated by other reactions which can proceed through K or K^* exchange.

E. Other Meson Resonances

Enhancements in the $K\bar{K}$ system aside from the ϕ meson have already been reported[8] by this experiment; these include the $f^*(1515) \to K_1^0K_1^0$ and a $K_1^0K_2^0$ effect at 1590±45 MeV. The existence of a $K_1^0K_2^0$ decay mode of a resonance requires $C=P=-1$ and therefore J odd. No other $S=0$ meson production is significant; there exists perhaps a hint of ω production in the $\Xi^-K^+\pi^+\pi^-\pi^0$ final state.

F. Cross Sections

Tabulated below are the cross sections observed for the various final states, Table I, and for resonance production, Table II, observed at 4.25 BeV/c. Ambiguous events were apportioned to the various hypotheses in the ratio of the unambiguous events. An exception to this procedure was the handling of events consistent with both Ξ^0 and Λ or Σ^0 production leading to an observed Λ decay. These events, while individually compatible with the Ξ^0 hypothesis, produced distributions consistent with up to 100% Λ or Σ^0 production and inconsistent with a significant fraction of Ξ^0 production. All such events were treated as Λ or Σ^0 events. As noted earlier the ambiguity rate was low, making the systematic error introduced by the apportionment scheme small.

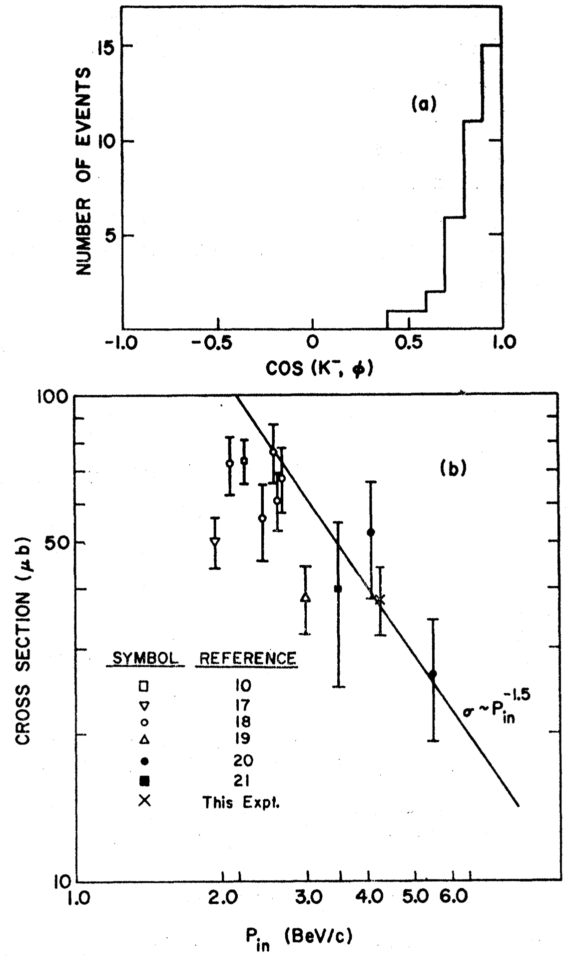

FIG. 6(a) Production angular distribution of the ϕ meson from the final state $\Lambda K\bar{K}$, 36 events. The ϕ events satisfy the conditions $1.025 \leq M^2(K\bar{K}) \leq 1.060$ BeV². (b) Dependence of the $K^-p \to \Lambda\phi$ cross section upon the incident K^- beam momentum (in the laboratory) P_{in}. Only the ϕ decay into $K\bar{K}$ is used for this tabulation. The straight line, $\sigma \sim P_{\mathrm{in}}^{-1.5}$, is meant to represent the behavior of the cross section well above threshold.

All channels were corrected for the requirements on fiducial volume, length, and projected angle. Geometric and neutral decay mode corrections were also made to allow for unseen events. The cross sections are computed from an incident flux of 5.3 events/μb.

The cross sections for the various final states include the contributions from intermediate resonance formation. The errors in resonant cross sections include estimated uncertainties in the subtraction of background. The total Ξ^- cross section is based on only those Ξ^- decays for which a charged Λ decay is observed. Only one Ω^- has been found on the film, no other candidates or ambiguities exist.

IV. SUMMARY AND CONCLUSIONS

The observed cross sections are small. The $\Xi^*(1530)$ is the only hypercharge-(-1) baryon resonance with

[17] P. Schlein, W. E. Slater, L. T. Smith, D. H. Stork, and H. K. Ticho, Phys. Rev. Letters **10**, 368 (1963).

[18] J. S. Lindsey and G. A. Smith, Phys. Rev. **147**, 913 (1966).

[19] J. Badier, M. DeMoulin, J. Goldberg, B. P. Gregory, C. Pelletier, A. Rouge, M. Ville, R. Barloutaud, A. Leveque, C. Louedec, J. Meyer, P. Schlein, A. Verglas, D. J. Holthuizen, W. Hougland, J. C. Kluyver, and A. G. Tenner, Phys. Letters **17**, 337 (1965).

[20] J. Mott, R. Ammar, R. Davis, W. Kropac, F. Schweingruber, M. Derrick, T. Fields, L. Hyman, J. Luken, and J. Simpson, Phys. Rev. Letters **18**, 355 (1967).

[21] Birmingham-Glasgow-London (I.C.)-Oxford-Rutherford Collaboration, Phys. Rev. **152**, 1148 (1966).

an appreciable cross section, but appears most strongly in multibody final states which are difficult to treat in a quantitative way.

Other meson and baryon resonances are observed, but only in the observed quasi-two-body states are the production mechanisms amenable to analysis. These two-body states (ΞK, ΞK^*, $\Lambda\phi$, $Y_0^*\phi$) are peripheral, indicating the importance of single-particle-exchange mechanisms.

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Proton-Neutron Triple Scattering at 425 MeV. I*

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The proton-neutron triple scattering parameters P, D, R, and A have been measured at lab angles of 20°, 30°, and 42° at 425-MeV incident proton energy. Polarized protons were scattered from neutrons in deuterium, and the final proton polarization was measured with a carbon plate wire-spark-chamber system. The recoil neutrons were detected. p-p quasielastic scattering from deuterium was also studied at 30° and 42° as a check on the impulse approximation.

I. INTRODUCTION

THIS paper represents the first in a planned series of experiments applying wire-spark-chamber techniques to the study of proton-neutron triple scattering at 425 MeV. A polarized proton beam was scattered from neutrons in deuterium, and the final transverse proton polarization was analyzed by scattering from carbon. A polarimeter with six wire spark chambers and an on-line computer recorded the azimuthal scattering distribution from the carbon. This polarimeter has been previously used in p-p triple-scattering studies at the same energy.[1] A complete discussion of the wire-chamber system and the computer programs can be found in Ref. 1. The apparatus was modified for p-n scattering by using a liquid deuterium target and counting the recoil neutrons with a large-volume plastic scintillator shielded by an anticoincidence counter.

High-energy p-n triple-scattering data are very scarce. Except for measurements of R at 600 MeV, only the differential cross section and polarization have been measured at energies above 210 MeV.[2] The knowledge of isoscalar ($I=0$) amplitudes in nucleon-nucleon scattering is therefore limited. The phenomenological situation has recently been discussed by MacGregor, Arndt, and Wright,[3] who performed a phase-shift fit to existing data at 425 MeV. These authors emphasized the qualitative nature of the $I=0$ phase shifts obtained. This experiment was undertaken to improve the knowledge of the isoscalar nucleon-nucleon interaction.

II. EXPERIMENTAL PROCEDURE

The final proton spin after p-n scattering can be expressed in the same form as for p-p scattering, using the polarization P and the Wolfenstein parameters D, A, R, A', and R'. Thus,

$$\langle\boldsymbol{\sigma}\rangle I_p(\theta,\phi)=I_0(\theta)[(P+D\langle\boldsymbol{\sigma}_i\cdot\hat{n}_i\rangle)\hat{n}_f+(A\langle\boldsymbol{\sigma}_i\cdot\hat{k}_i\rangle+R\langle\boldsymbol{\sigma}_i\cdot\hat{s}_i\rangle)\hat{s}_f+(A'\langle\boldsymbol{\sigma}_i\cdot\hat{k}_i\rangle+R'\langle\boldsymbol{\sigma}_i\cdot\hat{s}_i\rangle)\hat{k}_f]. \quad (1)$$

This equation is written in the laboratory frame. P, D, A, R, A', and R' are functions of the laboratory scatter-

* Work supported in part by the United States Atomic Energy Commission under Contract No. AT(11-1)-881, COO-881-192, and in part by the National Science Foundation.

[1] P. Limon, L. Pondrom, S. Olsen, P. Kloeppel, R. Handler, and S. C. Wright, Phys. Rev. **169**, 1026 (1968). There are some errors in this paper. In Eq. (3) the right-hand side should be multiplied by $\hat{n}$. In Eq. (6) each ϵ_D equation should be multiplied on the right by P_3.

[2] A complete listing of p-n data with references as of April, 1968 has been made by M. H. MacGregor, R. A. Arndt, and R. M. Wright, Lawrence Radiation Laboratory Report No. UCRL-50426 (unpublished).

[3] M. H. MacGregor, R. A. Arndt, and R. M. Wright, Phys. Rev. **173**, 1272 (1968).