PRODUCTION OF STRANGE-PARTICLE RESONANT STATES BY 2.1-BeV/c π^- MESONS*

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In a study of the multiparticle final states produced by K^-+p interactions at 1.15 BeV/c, Alston et al. observed enhancements in the effective-mass distributions for (a) the $\Lambda\pi$ system (Y_1^*, isotopic spin $I=1$) at 1385 MeV[1]; (b) the $K\pi$ system ($K^*, I=\frac{1}{2}$) at 885 MeV[2]; and (c) the $\Sigma\pi$ system (Y_0^*, $I=0$) at 1405 MeV.[3] The deviations from calculated phase-space distributions were attributed to resonant interactions between the particles indicated. Statistical limitations in the data did not permit the determination of the spins or parities for the states involved. Though marked correlations due to production of Y_1^* and K^* have since been observed in several other reactions,[4-6] little additional evidence for the existence of a Y_0^* at 1405 MeV has been reported in the study of reactions in which its production might be expected.[3,6,7] In this Letter we show that the Y_0^* is produced strongly in 2.1-BeV/c π^-+p interactions leading to the final states $(\Sigma^+\pi^-$ or $\Sigma^-\pi^+)K^0$. The distribution of events in the region of the peak suggests that it be identified with a bound $S^{1/2}$ state of the $\bar{K}N$ system. In addition, an enhancement appears in the mass region $M_{\Sigma\pi}=1510$ to 1560 MeV due to production of the $I=0$, 1520-MeV resonant state studied first by Ferro-Luzzi et al.[8] A study of the mass distribution for the $K\pi$ system leads to an observed width $\Gamma=60\pm5$ MeV for the K^*, as compared to the value $\Gamma=16$ MeV reported by Alston et al.[2] Finally, some evidence is presented for the existence of a resonant state of the $K\pi$ system at $M_{K\pi}\simeq730$ MeV.

The data were obtained during a recent exposure of the Lawrence Radiation Laboratory 72-in. hydrogen bubble chamber in which 15 000 pictures with 10 to 20 π^- tracks each were obtained at each of the momenta 2.035 and 2.155 BeV/c. All interactions resulting in the production of a visible hyperon were measured and fitted kinematically with computer programs that adjusted by a least-squares method the measured variables in order to satisfy simultaneously the energy-momentum conservation constraints at the production and decay vertices. Little difficulty was encountered in distinguishing the three-body final states listed in Table I from the other final states produced. After fitting, each event was examined for consistency of the actual track ionization with that expected from the calculated fits.

Table I. Distribution of numbers of events.

Final state	Number observed	Corrected number
(1) $\Lambda\pi^-K^+$	148	222[a]
(2) $\Lambda\pi^0K^0$	26	117[a]
(3) $\Sigma^0\pi^-K^+$	55	82[a]
(4) $\Sigma^+\pi^-K^0$	47	47
(5) $\Sigma^-\pi^+K^0$	142	~152[b]
(6) $\Sigma^-\pi^0K^+$	61	~ 70[b]

[a]The correction is for neutral decay modes only: $\frac{2}{3}$ for states (1) and (3), $\frac{2}{9}$ for state (2).
[b]Nineteen ambiguous events were assigned to states (5) and (6) according to the lower χ^2 value.

At this point it was possible to resolve all but 19 cases of ambiguity between reactions of type (5), in which the K^0 either decayed neutrally or outside the chamber, and type (6). The 19 ambiguous events were assigned to the hypothesis resulting in the lower χ^2, introducing a small error which has no effect upon the present conclusions.[9]

The effective-mass plots for the $\Lambda\pi K$ events are given in Figs. 1 and 3. They are consistent with the dominant production mechanisms

$$\pi^-+p\rightarrow\begin{matrix}Y^*+K\\ \Lambda\ \ +K^*\end{matrix}\rightarrow\Lambda+\pi+K.$$

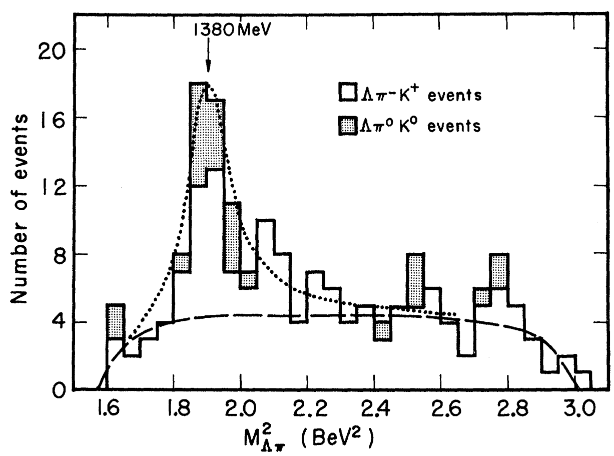

FIG. 1. Distribution in $M_{\Lambda\pi}{}^2$ for the $\Lambda\pi K$ events. The dotted curve represents a fit to a p-wave resonance formula with $E=1385$ MeV and $\Gamma=50$ MeV. The dashed curve reflects the K^* background.

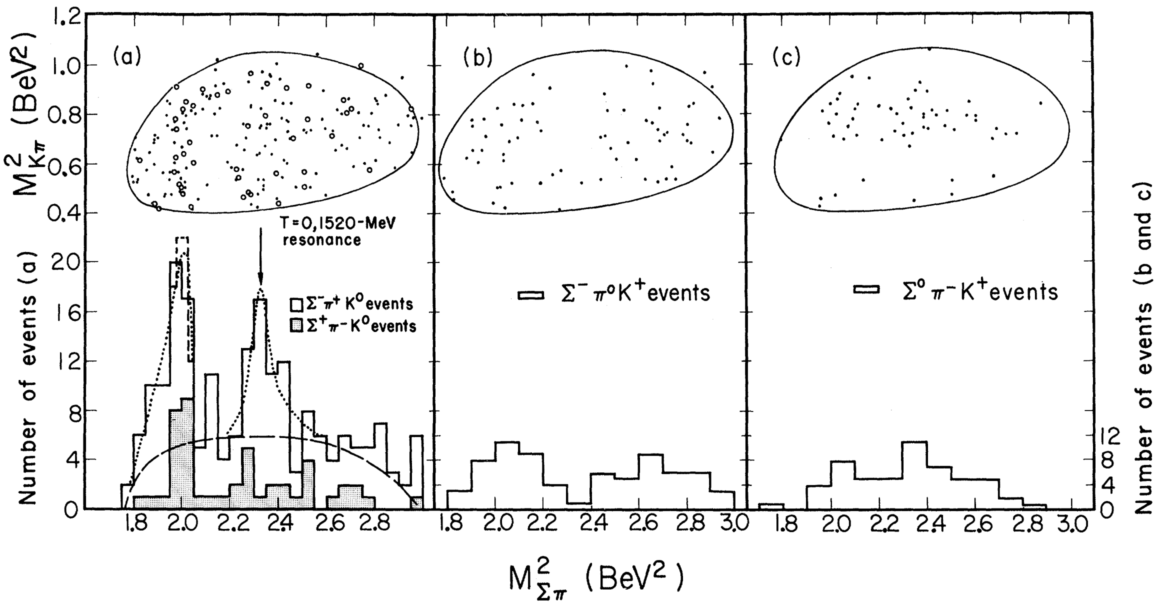

FIG. 2. Distribution in $M_{\Sigma\pi}{}^2$ for the $\Sigma\pi K$ events. In (a) the dashed curve represents the background; the dotted curves are the resonance forms discussed in the text. The area per event is the same in each figure.

In accordance with the tentative spin assignment $J=\frac{3}{2}$ of Ely et al.,[5] the mass distribution in the vicinity of the $Y_1{}^*$ peak has been fitted with a p-wave resonance formula.[10] A satisfactory fit is obtained with $M(Y_1{}^*)=1385$ MeV and full width $\Gamma(Y_1{}^*)=50$ MeV. No significant evidence for a peak at any higher mass is observed.

Examination of the Dalitz plot in Fig. 2(a) for the $\Sigma^{\pm}\pi^{\mp}K^0$ events and its projection on the $M_{\Sigma\pi}{}^2$ axis indicates two regions of enhancement. The lower mass peak occurs at $M_{\Sigma\pi}\simeq 1410$ MeV and appears particularly clearly in the $\Sigma^+\pi^-K^0$ events. No corresponding peak occurs in the $\Sigma^-\pi^0K^+$ or $\Sigma^0\pi^-K^+$ events. On this basis we associate the peak with the $I=0$ resonance reported by Alston et al.[3,11] The asymmetry of the distribution with respect to the peak provides some evidence for the spin of this state. On the Dalitz plot in Fig. 2(a) the density of events appears to fall off slowly in the low-mass region, although on the high-mass side of the peak the enhancement disappears abruptly at the KN threshold, $M_{\Sigma\pi}{}^2=2.05$ BeV.[2] This is in marked contrast to the mass distribution for the $\Lambda\pi$ events associated with the $J=\frac{3}{2}$ $Y_1{}^*$ peak, and suggests the behavior expected for a resonance associated with a bound $S^{1/2}$ state of the KN system.[12,13] The dotted curve in Fig. 2(a) represents a fit to the data based on this model.[14] The full width at half-maximum gives $\Gamma=35\pm 5$ MeV, with the uncertainty arising from both statistical limitations and imprecise knowledge of the background. The second enhancement occurs in the 1510- to 1560-MeV mass region. Ferro-Luzzi et al. have reported the existence of an $I=0$, $D^{3/2}$ resonance at 1520 MeV with $\Gamma=20$ MeV.[8] We obtain an adequate fit to the present data with the values $M(Y_0{}^{**})=1525$ MeV and $\Gamma\simeq 30$ MeV.[15]

The effective-mass distributions for the $K\pi$ systems are given in Figs. 3(a) and 3(b). Plots of several charge configurations have been combined on the assumption that features dependent primarily upon the $K\pi$ effective mass will persist. The $\Sigma^+\pi^-K^0$ events are shown separately, since this is the only case in which the $K\pi$ system is in a pure $I=\frac{3}{2}$ state. We attribute the broad peak in the region $M_{K\pi}\simeq 880$ MeV to K^* production. However, in contrast to the narrow width $\Gamma=16$ MeV observed by Alston et al. for production of this state near the energetic threshold,[2] a fit to this data gives $\Gamma\simeq 60\pm 5$ MeV.[16] Some part of this observed width may result from interference between the amplitudes for Y^* and K^* production, though the width varies little with the charge state studied.

A second peak in the mass distribution occurs at $M_{K\pi}\simeq 730$ MeV. Based on the foregoing evidence that the $Y\pi$ systems tend to be produced in resonant states, a reasonable estimate of the background for the Σ events is shown by the dashed curve in Fig. 3. (Note also the $K\pi$ mass

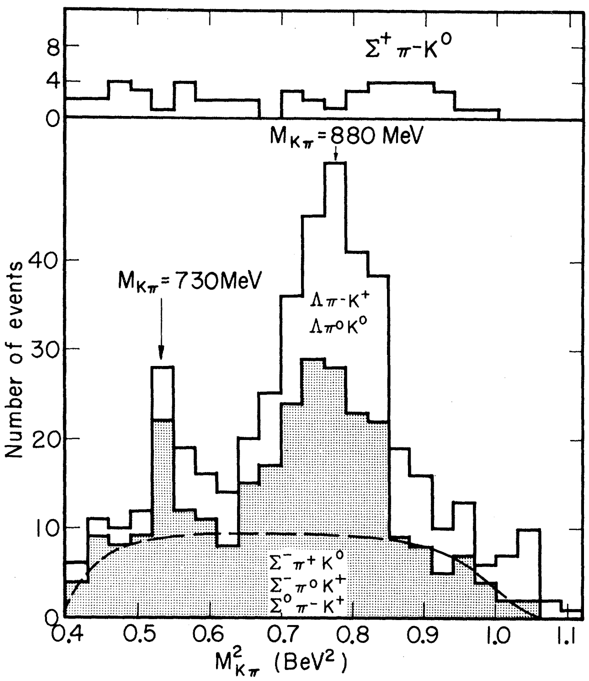

FIG. 3. Distribution in $M_{K\pi}{}^2$ for all events. The dashed curve is the best estimate for the background in the $\Sigma\pi K$ events.

distribution for the $\Sigma^+\pi^-K^0$ events.) The statistical significance of the peak for the combined Σ^- sample thus corresponds to about three standard deviations. Since our mass resolution in this range is less than 10 MeV, it appears likely that there is a resonant $K\pi$ interaction with $M_{K\pi} \simeq 730$ MeV and $\Gamma \leq 20$ MeV. Because of the limited number of events available, no definite assignment of isotopic spin has been possible, though $I = \frac{1}{2}$ is weakly suggested by the lack of any effect in the $\Sigma^+\pi^-K^0$ events. The distribution of events in Fig. 3 indicates that this resonant state is produced predominantly in association with Σ's.

It may be noted that if the strangeness $S = \pm 1$ analog of the ρ meson has mass $m = 730$ MeV[17,18] and binding is due to ρ-meson exchange, its expected decay rate relative to the ρ may be estimated by using the formula

$$\Gamma(K^* \to K\pi) \propto [p^2/(1+p^2R^2)]R^3(p/m)(2J+1),$$

where $p = 160$ MeV is the c.m. momentum, and $R = 1/m_\rho$ is the radius of interaction. The term in brackets represents the effect of the centrifugal barrier; p/m, the phase space; and J, the spin. With a similar expression for the ρ meson, and with $m_\rho = 750$ MeV, and $\Gamma_\rho = 100$ MeV, we obtain $\Gamma(M \to K\pi) = 0.12\ \Gamma_\rho = 12$ MeV. This result suggests that the narrow peak observed in the present data would be consistent with a resonant $K\pi$ state at $M_{K\pi} \simeq 730$ MeV with $J \geq 1$.[19]

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[3]M. Alston, L. Alvarez, P. Eberhard, M. Good, W. Graziano, H. Ticho, and S. Wojcicki, Phys. Rev. Letters 6, 698 (1961).

[4]M. Alston and M. Ferro-Luzzi, Revs. Modern Phys. 33, 416 (1961), summarize the early data on $Y_1{}^*$.

[5]R. P. Ely, Sun-Yiu Fung, G. Gidal, Yu-Li Pan, W. M. Powell, and H. S. White, Phys. Rev. Letters 7, 461 (1961).

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[7]P. Bastien, M. Ferro-Luzzi, and A. H. Rosenfeld, Phys. Rev. Letters 6, 702 (1961).

[8]M. Ferro-Luzzi, R. D. Tripp, and M. B. Watson, Phys. Rev. Letters 8, 28 (1962).

[9]Of the 65 events of types $\Sigma^-\pi^+K^0$ or $\Sigma^-\pi^0K^+$ that had two or more fits with $\chi^2 < 6.0$ (one-constraint class), 46 were resolved by using ionization information. For the 46 events, 27 agreed with lowest χ^2 fit. This suggests that of the 19 unresolved events, about eight are improperly assigned.

[10]We assume that the enhancement on the Dalitz plot is proportional to $(\Gamma/q)[(E-E_0)^2+\Gamma^2/4]^{-1}$ where Γ is $[2(qa)^3/(1+q^2a^2)]\gamma^2$ and q is the momentum of the $Y_1{}^*$ decay product in the $Y_1{}^*$ c.m. system. [See R. Dalitz and D. H. Miller, Phys. Rev. Letters 6, 562 (1961) and M. Gell-Mann and K. M. Watson, Ann. Rev. Nuclear Sci. 4, 219 (1954).] The dotted curve corresponds to the values $a = 1/m_\pi$, $\gamma^2 = 25$ MeV, and $E_0 = 1385$ MeV.

[11]We do not attribute the peak to $Y_1{}^*$ decay since (a) the difference in mean energy is 20 to 25 MeV and (b) the branching fractions for $Y_1{}^*$ decay would give $\Gamma(Y_1{}^{*-} \to$

$\Lambda\pi^-)/\Gamma(Y_1{}^{*-}\to\Sigma^0\pi^-+\Sigma^-\pi^0)\simeq 5$ while $\Gamma(Y_1{}^{*0}\to\Lambda+\pi^0)/\Gamma(Y_1{}^{*0}\to\Sigma^+\pi^-+\Sigma^-\pi^++\Sigma^0\pi^0)\simeq 1.3$ in disagreement with the requirements of charge independence. See also references 3 and 7. The present data are not sufficient to rule out $I=1$ for the resonant state. The absence of a strong effect in the $\Sigma^-\pi^0K^+$ and $\Sigma^0\pi^-K^+$ events could be due to destructive interference between the production amplitudes from the initial $I=\frac{1}{2}$ and $I=\frac{3}{2}$ states of the π^-+p system. If this is so, the resonant state must be produced in π^++p interactions in the same energy range. The absence of any effect would then ensure the assignment $I=0$.

[12]The possibility for resonances of this type was first pointed out by R. Dalitz and S. F. Tuan, Phys. Rev. Letters 2, 425 (1959). The model has been discussed further by R. Dalitz, Phys. Rev. Letters 6, 239 (1961); and Revs. Modern Phys. 33, 471 (1961).

[13]R. L. Shult and R. H. Capps, Nuovo cimento 13, 416 (1962), have emphasized the importance of the $Y_0{}^*$ in the low-energy K^--d absorption reactions.

[14]The enhancement for an S-wave final state is proportional to $(\sin\delta e^{i\delta}/q)^2$. To obtain the correct energy dependence we used $\tan\delta=q[\gamma-\beta^2\kappa/(1+\kappa\alpha)]$. A satisfactory fit to the data is obtained with $\gamma=(248\text{ MeV})^{-1}$, $\alpha=(110\text{ MeV})^{-1}$, and $\beta=(175\text{ MeV})^{-1}$. For the $I=0$ KN system, these values yield a complex scattering length $a+ib=-1.23+i0.75$ F, in reasonable agreement with the (b-) solutions of reference 12, or the type-II solution of William E. Humphrey, Lawrence Radiation Laboratory Report UCRL-9752, 1961 (unpublished); and Ronald R. Ross, Lawrence Radiation Laboratory Report UCRL-9749, 1961 (unpublished).

[15]The peak is composed predominantly of $\Sigma^-\pi^+K^0$ events. Whether this is due to an interference with the K^* background or a nonresonant $I=1$ $\Sigma\pi$ amplitude cannot be determined from the present data.

[16]The narrow width reported in reference 2 has been interpreted as evidence for the existence of a centrifugal barrier in the resonant state of the $K\pi$ system. In addition, M. A. Baqi Bég and P. C. DeCelles [Phys. Rev. Letters 6, 145 (1961)] have favored the assignment $J=I$ by assuming a simple relation between the production cross section and decay width given in reference 2. In view of the width observed in this experiment these arguments are no longer compelling.

[17]M. Gell-Mann, in California Institute of Technology Synchrotron Laboratory Report CTSL-20, 1961 (unpublished) and Phys. Rev. 125, 1067 (1962), has discussed the possibility for the existence of such a particle with $I=\frac{1}{2}$, called the M meson. In this scheme the expected mass is given to lowest order by $m_M=\frac{1}{4}(3m_\omega+m_\rho)=780$ MeV.

[18]Y. Ne'emen, Nuclear Phys. 26, 222 (1961).

[19]The same calculation yields $\Gamma=42$ MeV for the K^* at 885 MeV, so that $J=1$ for this state cannot be ruled out by this argument.

EXPERIMENTAL STUDIES OF THE FORM FACTORS IN $K_{\mu3}{}^+$ AND $K_{e3}{}^+$ DECAY*

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Three-body leptonic decays of K^+ mesons ($K_{\mu3}{}^+\to\mu^++\pi^0+\nu$, $K_{e3}{}^+\to e^++\pi^0+\nu$) provide a fruitful field for the study of strangeness-nonconserving weak interactions. Previous work in this area includes determinations of rates,[1] studies of pion energy spectra and angular correlations in $K_{e3}{}^+$ decay,[2] and investigations of the muon energy spectrum in $K_{\mu3}{}^+$ decay.[3-5] In this Letter we present the results of a detailed analysis of 76 $K_{\mu3}{}^+$ events observed in a 12-inch xenon bubble chamber.[6] In particular, we show that within the framework of the usual V-A Fermi interaction, the muon and electron are coupled identically in three-body leptonic K^+ decay. In addition, we place limits on the magnitudes and possible energy dependence of the "form factors" inherent in the decay process and compare these results to those recently obtained from studies of the $K_{\mu3}{}^+$-muon energy spectrum.[5]

A number of authors[7,8] have shown that under the assumption of vector coupling, the following distribution function holds for either $K_{e3}{}^+$ or $K_{\mu3}{}^+$ decay for the pion momentum and pion-neutrino angular correlation:

$$F(P,\theta)dPd\cos\theta=\frac{P^2(W^2-P^2-m_L{}^2)^2}{E\ (W+P\cos\theta)^4}\left[P^2\sin^2\theta f_V{}^2+\frac{m_L{}^2}{M_K{}^2}(M_Kf_V+(W+P\cos\theta)g_V)^2\right]dPd\cos\theta. \quad (1)$$

Here P is the pion momentum and E is the total