$\langle Y_l^0 \rangle$ moments, we omit the superscript m in $B_V^{\lambda\lambda'}$

[6]Since the effect of δ_0^3 appears as the s- and p-wave interference, it is desirable to study the sign of δ_0^3 in the $K\pi$ mass region where both s- and p-wave amplitudes are dominant.

[7]It is most unlikely that the sign of δ_0^3 could change in going from $t \sim 0.3$ GeV^2 to the pion pole.

[8]C. Lovelace, in *Proceedings of a Conference on the ππ and Kπ Interactions at Argonne National Laboratory, 1969,* edited by F. Loeffler and E. Malamud (Argonne National Laboratory, Argonne, Ill., 1969), p. 562.

[9]T. G. Trippe *et al.*, Phys. Lett. 28B, 203 (1968).

[10]P. E. Schlein, in *Proceedings of a Conference on the ππ and Kπ Interactions at Argonne National Laboratory, 1969,* edited by F. Loeffler and E. Malamud (Argonne National Laboratory, Argonne, Ill., 1969), p. 446; P. Antich *et al.*, *ibid.*, p. 508; W. DeBaere *et al.*, CERN Report No. CERN/D. Ph. II/PHYS. 69-17, 1969 (unpublished); P. Herquet and T. Trippe, CERN Report No. CERN/D. Ph. II/PHYS. 70-29, 1970 (unpublished).

[11]For $K\pi$ masses less than 1.1 GeV, both solutions give a χ^2 per degree of freedom of 0.9, whereas for $K\pi$ masses above 1.1 GeV, the χ^2 per degree of freedom is 1.9 for the first solution and 6.8 for the second solution. Since the model is more uncertain at the high masses, the χ^2 test may not be a reliable discriminator.

[12]This ambiguity in δ_0^1 arises because A^I is parametrized as $\sin(\delta_l^{2I}) \exp(i\delta_l^{2I})$.

[13]F. Muller, private communication.

[14]G. Kane, in *Experimental Meson Spectroscopy,* edited by C. Baltay and A. H. Rosenfeld (Columbia U. Press, New York, 1970); G. C. Fox *et al.*, "The Charge Exchange Production Mechanism for $K^*(890)$" (to be published).

Evidence for Splitting in the Q Region of $K^+\pi^+\pi^-$ Mass*

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We observe a splitting in the $K^+\pi^+\pi^-$ mass spectrum in K^+d interactions at 9 GeV/c. We find a mass of 1243 ± 8 MeV/c^2 and a width of 70_{-18}^{+26} for the lower mass state, and a mass of 1344 ± 8 and a width of less than 60 MeV/c^2 for the higher mass state. The isospin of both states is determined to be $\frac{1}{2}$. The results can be interpreted as evidence for the mixing of two $J^P = 1^+$ K^* states.

While one of the principal successes of hadron physics has been the classification of resonances into SU(3) representations, no $J^P = 1^+$ multiplets are as yet well defined. This situation is partially due to the difficulty of separating diffraction-produced[1] resonances from the background processes. Since the background in the Q region [$M(K\pi\pi) < 1400$ MeV/c^2] predominantly has $J^P = 1^+$, it is possible for $J^P = 1^+$ K^* states[2-4] to interfere not only with each other but with the background as well. Goldhaber, Firestone, and Shen, whose 9-GeV/c K^+p experiment presented strong evidence[3] for substructure in the Q region, also proposed a model for interference effects.[5] Subsequent experiments have alternately reported substructure and no substructure in the Q spectrum.

We have chosen to extend the Goldhaber experiment by running at the same beam momentum but using deuterons as targets. Our observed $K^+\pi^+\pi^-$ mass spectrum shows two distinct states upon the broad Q enhancement in both the coherent and the deuteron-breakup channels. Both states are shown to have isospin $I = \frac{1}{2}$, and spin and parity $J^P = 1^+$ is preferred for both.

The data discussed here are from a 4.3-event/μb per nucleon exposure[6] of the Brookhaven National Laboratory 80-in. deuterium bubble chamber to a beam of 9.04-GeV/c K^+ mesons. We have studied the reactions

$$K^+d \to K^+\pi^+\pi^- d \quad \text{(714 events)} \tag{1}$$

and

$$K^+d \to K^+\pi^+\pi^- pn \quad \text{(2060 events)} \tag{2}$$

in the four-prong topology where a clear separation of Reactions (1) and (2) is possible.[7,8]

In Reaction (1) where the kinematic fit has four constraints, we readily distinguish the K^+ from π^+ track.[9] In Fig. 1(a) the $K^+\pi^-$ effective-mass spectrum from Reaction (1) is shown for events in the Q region. It is completely dominated by the $K^*(890)$. The unshaded histogram in Fig. 1(b) shows the $\pi^+\pi^-$ effective-mass spectrum from Reaction (1) for events in the Q region. It is well described by a Monte Carlo–calculated $\pi^+\pi^-$ effective-mass spectrum (solid curve) which assumes a peripherally produced Q decaying solely to $K^*(890)\pi$. Unfortunately, in Reaction (2) no separation of the K^+ and π^+ tracks is possible on the basis of either fit or ionization information. However, by examining the two-particle effective-mass spectrum of the π^- with each of the positive tracks (assigned the K^+ mass) one obtains the true $K^+\pi^-$ spectrum added to an equal-sized distribution of misassigned events. This spectrum (not shown) is likewise consistent with nearly pure $K^*(890)$ production. Consequently, events from Reaction (2) were selected by choosing the combination giving the smaller difference between the $K^+\pi^-$ effective mass and the K^* mass of 892 MeV/c,[2] and requiring in all cases that this mass difference be less than 40 MeV/c^2.[10]

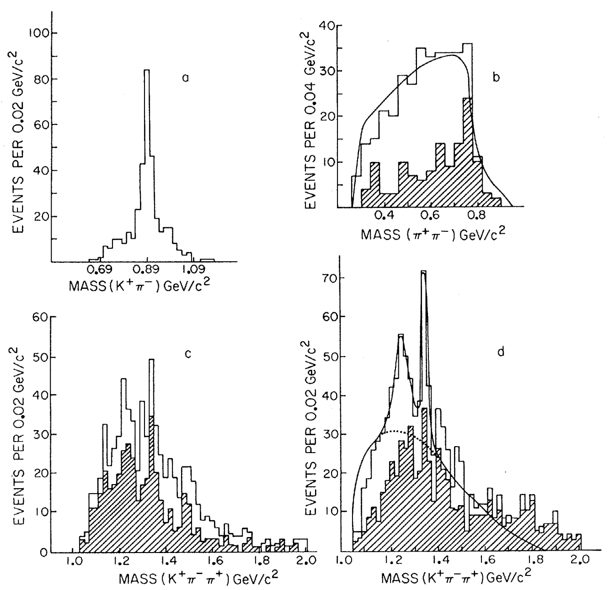

FIG. 1. (a) Effective-mass distribution of $K^+\pi^-$ for events from reaction (1) in the Q region. (b) Effective-mass distribution of $\pi^+\pi^-$ for the same set of events. Shaded events are for $M(K^+\pi^+\pi^-)$ between 1300 and 1400 MeV/c^2. (c) Effective-mass distribution of $K^*(890)^0\pi^+$ from Reaction (2). Shaded events are restricted to $|t| \leq 0.12$ GeV/c^2. (d) The sum of all coherent events [Reaction (1), shaded] and the shaded events from (c).

Figure 1(c) shows the $K^{*0}\pi^+$ mass spectrum[11] for Reaction (2). The shaded region of the spectrum has the requirement that the $K^*\pi$ be produced at a four-momentum transfer $|t| \leq 0.12$ (GeV/c)^2 to obtain events in a t region comparable to those of Reaction (1) and to suppress $K^*(1420)$ production.[12] Figure 1(d) shows the combined spectra of all $K^+\pi^+\pi^-$ events from Reaction (1) (shaded) added to the selected sample of events shaded in Fig. 1(c). Background and resonance-fit curves are shown. One sees two clear enhancements above the background curve. The lower peak can be represented by a simple Breit-Wigner shape with a mass of 1243 ± 8 MeV/c^2 and a width (unfolding our resolution[13]) of 70^{+26}_{-18} MeV/c^2. The upper peak has a mass of 1344 ± 8 MeV/c^2 and a width of less than 60 MeV/c^2 at 90% confidence level. The fits assumed no interference between the enhancements or with the background.

The background under the peaks is a broad enhancement in $K^{*0}\pi^+$ mass from threshold to approximately 1400 MeV/c^2. The properties of this enhancement have been widely studied, and are generally believed to be the result of a kinematic effect[14] related to diffraction dissociation of the K^+. The background curve in Fig. 1(d) is from a typical[15] multi-Regge calculation of this effect. Both peaks deviate by more than five standard deviations from any reasonable background curve. We shall denote them by $K_A(1243)$ and $K_A(1344)$. Due to their production in Reaction (1) they can both be assigned an isospin equal to $\frac{1}{2}$.

The differential production cross section is extremely peripheral not only for Reaction (1), where the deuteron form factor serves as a limiting factor, but for Reaction (2) as well. Fitting the differential cross section of events in the Q region by the form $A\exp(B|t|)$, we obtain values of $B = 25.5 \pm 2.5$ (GeV/c)$^{-2}$ for Reaction (1) and $B = 9.5 \pm 2.0$ (GeV/c)$^{-2}$ for Reaction (2), in the $|t|$ range 0.03 to 0.14 (GeV/c)^2.

As a framework for analysis of the spins and parities of the $K_A(1243)$ and $K_A(1344)$ we shall first consider a model for the background amplitude. With each of the angular distributions $f(\cos\theta)$ normalized to the form

$$f(\cos\theta) = 1 + aP_1(\cos\theta) + bP_2(\cos\theta), \qquad (3)$$

the expectation that the background is a pure S-wave $K^{*0}\pi^+$ state ($J^P = 1^+$) with helicity determined by Pomeranchukon exchange has the following consequences: The $\cos\theta_{K^*K}$ distribution should be flat, where θ_{K^*K} is the angle between the beam and the K^* in the Q rest frame; the $\cos\theta_{KK}$ distribution should be $\cos^2\theta_{KK}$ (a equal to zero, and b equal to 2), where θ_{KK} is the angle between the beam kaon and the produced kaon in the $K^*(892)$ rest frame; the β distribution should be $\sin^2\beta$ (a equal to zero, and b equal to -1), where β is the angle between the normal to the $K^+\pi^+\pi^-$ decay plane and the beam direction in the Q rest frame.

Since diffraction dissociation is their apparent production mechanism, and since we find no evidence for $K^0\pi^+$ decays[12] of the $K_A(1243)$ and $K_A(1344)$, we expect them to belong in the spin-and-parity series 0^-, 1^+, 2^-, etc. To make assignments from this series we have examined the angular distributions shown in Fig. 2 and their moments. The distributions represent the total sample of events in Fig. 1(d) in the mass range 1100-1600 MeV/c^2. The separate distributions for Reactions (1) and (2) were not measurably different. Maximum-likelihood values for a and b from each angular distribution are shown above it. Higher-order coefficients were not required.

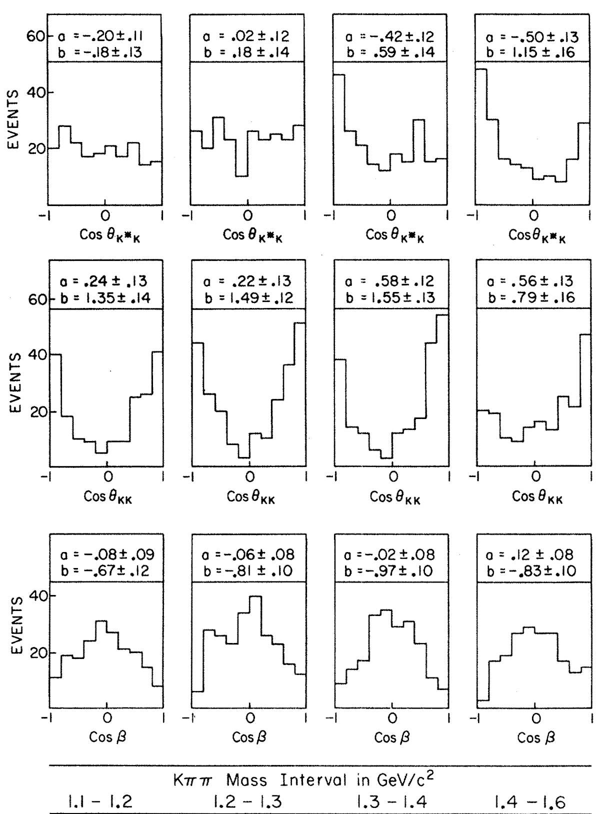

FIG. 2. Decay angular distributions and their expansion coefficients for four regions in $K^+\pi^+\pi^-$ effective mass.

In these distributions the region below 1200 MeV/c^2 should describe the diffraction background, the regions 1200-1300 and 1300-1400 MeV/c^2 could be expected to show some effects of the resonances, and the region 1400-1600 MeV/c^2 to show any possible $K^*(1420)$ effects and describe the background above the Q. The $\cos\theta_{K^*K}$ distribution is quite flat between 1100 and 1300 MeV/c^2 and becomes increasingly asymmetric between 1300 and 1600 MeVc^2. The $\cos\theta_{KK}$ distribution is nearly a pure $\cos^2\theta_{KK}$ function below 1400 MeV/c^2 with an increasing forward-backward asymmetry. Finally, the β distribution is nearly pure $\sin^2\beta$ over the complete mass range.

Hence, we find that not only the background region 1100-1200 MeV/c is well described by our $J^P=1^+$ diffraction-production model, but the resonance regions 1200-1300 are also well described by it. We can rule out $J^P=0^+$ assignments because of the $K^*\pi$ decay mode, and can rule out $J^P=0^-$ because of the anisotropy of the $\cos\beta$ distributions. If one of the states had the quantum numbers $J^P=2^-$ (or 1^-), it would decay into $K^*\pi$ in at least an $l=1$ orbital wave. We see no effect of such an orbital wave in the $\cos\theta_{K^*K}$ distribution corresponding to a single mass region. We consequently favor the $J^P=1^+$ assignment.[16] The only physical characteristic of a resonance mass region different from adjacent regions is the observed ρ^0K^+ production in the mass range 1300-1400 MeV/c^2. This ρ^0 signal is shown in the shaded portion of Fig. 1(b). The shifting to lower mass of the ρ^0 peak is due to its being a decay product of a relatively low-mass object.

In summary, evidence is presented for two isospin-$\frac{1}{2}$, strangeness-+1 mesons which are observed to decay predominantly to $K^*(890)\pi$. They appear to have the same spin and parity as the broad $J^P=1^+$ background upon which they are produced. It is natural to associate them with the octets whose isospin-1 members are the A_1 ($J^{PC_n}=1^{++}$) and B ($J^{PC_n}=1^{+-}$), where C_n denotes the charge-conjugation quantum number of the neutral states. If one assumes that the Pomeranchukon is a unitary singlet with positive charge conjugation, then SU(3) forbids the production by Pomeranchukon exchange of the K^* belonging to the B octet. The current experiment may be considered as evidence for K^* mixing.[17]

We wish to thank the physicists and technicians at Brookhaven National Laboratory for their assistance during the exposure, and the engineers, technicians, programmers, and scanners at Purdue and the University of California at Davis for their untiring efforts. We would especially like to thank Professor R. L. McIlwain, Jr., for his aid and advice in maintaining the Purdue measuring system at its high level, and Professor J. A. Gaidos for his multi-Regge calculations.

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[1]M. L. Good and W. D. Walker, Phys. Rev. 120, 1857 (1960).

[2]The Particle Data Group has collected evidence for two K^*'s in the Q region, the $K_A(1240)$ or C, and K_A (1280-1360). See N. Barash-Schmidt *et al.*, Phys. Lett. 33B, 1 (1970).

[3]Recent studies which have observed substructure in the diffractively produced Q spectrum are G. Goldhaber, A. Firestone, and B. C. Shen, Phys. Rev. Lett. 19, 972 (1967); G. Bassompierre *et al.*, Phys. Lett. 26B, 30 (1967); G. Alexander *et al.*, Nucl. Phys. B13, 503 (1969); K. W. J. Barnham *et al.*, Nucl. Phys. B25, 49 (1970). See also the recent review article by A. Firestone, in *Experimental Meson Spectroscopy*, edited by C. Baltay and A. H. Rosenfeld (Columbia U. Press, New York, 1970), p. 229.

[4]Evidence for nondiffractively produced K^*'s in the Q region has come from C. Astier *et al.*, Nucl. Phys. B10, 65 (1969); D. J. Crennell *et al.*, Phys. Rev. Lett. 19, 44 (1967); A. R. Erwin *et al.*, Nucl. Phys. B9, 364 (1969); J. M. Bishop *et al.*, Nucl. Phys. B9, 403 (1969).

[5]G. Goldhaber, Phys. Rev. Lett. 19, 976 (1967).

[6]Events having a final-state proton with projected momentum greater than 430 MeV/c were excluded. The events were analyzed with the TVGP and SQUAW set of programs.

[7]While most events that were assigned to Reaction (1) also had an acceptable fit to Reaction (2), the converse was not true. One was able to make a clean separation by examining the p-n effective mass from the fit to Reaction (2). For details see R. F. Holland, thesis, Purdue University (unpublished).

[8]Holland, Ref. 7.

[9]In approximately 90% of the cases there were no ambiguities. The remaining cases were resolved by a procedure for testing for energy and momentum balance from the unfitted track data. See Ref. 8.

[10]We estimate that this technique gives the correct combination for more than 80% of the included events. The K^* requirement eliminates an apparent nK^* threshold enhancement due to misidentified π^+'s from $N^*(1238)^+$ decays.

[11]Reaction-(1) events with $M(d\pi^+) < 2.2$ GeV/c^2 and Reaction-(2) events with $M(n\pi^+) < 1.3$ GeV/c^2 are excluded to eliminate d^* and $N^*(1238)$ signals. These cuts excluded 85 and 278 events, respectively, but do not alter our conclusions.

[12]We have studied the reaction

$$K^+d \to pnK^0\pi^+ \qquad (2')$$

and find it dominated by $K^*(890)$ and $K^*(1420)$ production. However, the reaction

$$K^+d \to dK^0\pi^+ \qquad (1')$$

is much rarer with $K^*(1420)$ production suppressed by an order of magnitude compared to Reaction (2′). This phenomenon makes Reaction (1) ideal for a search for a $J^P=1^+$ state near 1420 MeV/c^2. A $|t|$ cut at 0.12 GeV/c^2 reduces $K^*(1420)$ production in Reaction (2′) [and consequently in Reaction (2)] by a factor of 2. The $K^0\pi^+$ spectrum shows no enhancements in the Q region other than the $K^*(1420)$.

[13]The $M(K^+\pi^+\pi^-)$ mass resolution (full width at half-maximum) is less than 10 MeV/c^2 for 50% of the events in Fig. 1(d). We have checked this by studying the $M(K^+\pi^-)$ spectrum and comparing it with the known mass and width of the $K^*(890)$. All events described here were first measured on scanning and measuring projectors and remeasured on precision microscopes to obtain the greatest possible resolution. Absolute mass determinations were tested in a study of unfitted K_1^0 decays from various production channels.

[14]M. S. Farber *et al.*, Phys. Rev. Lett. 22, 1394 (1969); C. Y. Chien *et al.*, Phys. Lett. 29B, 433 (1969); and references cited in these.

[15]The matrix element for generating this curve is from a multi-Regge expression for $K^*\pi$ production where the final-state pion diffractively scatters from the nucleon target. See Ref. 8. The indicated background level in Fig. 1(d) is obtained from a fit to the mass region 1160 to 1380 MeV/c^2.

[16]We choose not to do a simultaneous fit to all the distributions to set limits on the 2^- assignment because of the difficulty of determining effects of the π^+K^+ ambiguity in Reaction (2). We have recently obtained a second exposure of 9-GeV/c K^+d at Brookhaven National Laboratory which will bring our sensitivity to 16 events/μb per nucleon and allow us to do a spin and parity analysis with a pure sample of Reaction (1).

[17]R. Gatto and L. Maiani, Phys. Lett. 26B, 95 (1967).