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

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A splitting in the $K^+\pi^+\pi^-$ mass spectrum in K^+d interactions at 9 GeV/c is observed. We find a mass of 1243 ± 8 MeV/c^2 and a width of $70 \pm {}^{26}_{18}$ for the lower mass state, and a mass of 1344 ± 4 and a width of less than 40 MeV/c^2 for the higher mass state. The isospin of both states is determined to be 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 due to the difficulty of separating diffraction produced[1] resonances from the background processes. Since the background in the Q region (Mass($K\pi\pi$) < 1400 MeV/c^2) predominantly has $J^P = 1^+$ it is possible for $J^P = 1^+$ K^* states[2,3,4] to interfere not only with each other but with the background as well. Goldhaber et al. 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

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experiments have alternately reported substructure and none in the Q spectrum.

We have chosen to extend the Goldhaber experiment by running at the same beam momentum but have used deuterons as targets. Our observed $K^+\pi^+\pi^-$ mass spectrum shows two distinct states upon the broad Q enhancement in both the coherent and deuteron break up channels. Both states are shown to have isospin $I = 1/2$, and spin-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 BNL 80" deuterium bubble chamber to a beam of 9.04 GeV/c K^+ mesons. We have studied the following reactions:

$$K^+d \rightarrow K^+\pi^+\pi^-d \qquad (714\ \text{events}) \qquad (1)$$

$$K^+d \rightarrow K^+\pi^+\pi^-pn \qquad (2060\ \text{events}) \qquad (2)$$

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 the 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 the calculated curve which assumes pure $K^*(890)$ production. 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(c) shows the $K^{*o}\pi^+$ 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] Fig. 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 ± 4 MeV/c^2 and a width of less than 40 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 $K^{*o}\pi^+$ mass from threshold to approximately 1400 MeV/c^2. The properties of this enhancement have been widely studied, and are generally believed to be due to 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 isospin equal to 1/2.

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

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;

$$f(\cos\theta) = 1 + a\,P_1(\cos\theta) + b\,P_2(\cos\theta) \qquad (3)$$

the expectation that the background is a pure S-wave $K^{*o}\pi^+$ state ($J^P = 1^+$) with helicity determined by pomeron 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 we find no evidence for $K^o\pi^+$ decays[12] of the $K_A(1243)$ and $K_A(1344)$, we expect them to belong in the spin 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. 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 MeV/c^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, and 1300-1400 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 $\ell = 1$ 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 $\rho^0 K^+$ 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 equal to 1/2, strangeness equal to +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 equal to one 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 pomeron is a unitary singlet with positive charge conjugation, then SU(3) forbids the production by pomeron exchange of the K^* belonging to the B octet. The current observation of such production is evidence for K^* mixing.[17]

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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 UCRL 8030.
3. Recent studies which have observed substructure in the diffractively produced Q spectrum are:

   G. Goldhaber et al., Phys. Rev. Letters 19, 972 (1967), G. Bassompierre et al., Phys. Letters 26B, 30 (1967), G. Alexander et al. Nucl. Phys. B13, 503 (1969), K. W. J. Barnham et al., Nucl. Phys. B25, 49 (1970).
4. Evidence for non diffractively produced K^*'s in the Q region has come from: C. Astier et al., Nucl. Phys. 10, 65 (1969), D. J. Crennell et al., Phys. Rev. Letters 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. Letters 19, 976 (1967).
6. Events having a final state proton with projected mementum 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). See reference (8) for details.

8. R. F. Holland, Ph.D. Thesis Purdue University. (Unpublished)

9. In approximately 90% of the cases, there were no ambiguity. The remaining cases were resolved by a procedure for testing for energy and momentum balance from the unfitted track data. See reference (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.

12. We have studied the reaction $K^+d \rightarrow pn\, K^0\pi^+$ (2') and find it dominated by $K^*(890)$ and $K^*(1420)$ production. However, the reaction $K^+d \rightarrow d\, K^0\pi^+$ (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 to the known mass and width of the $K^*(890)$. All events described here were first measured on SMP's 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. Letters 22, 1394 (1969), C. Y. Chein et al., Phys. Letters 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 reference (8). The indicated background level in Fig. 1(d) is obtained from a fit to the mass region 1160 to 1380 MeV/c^2.

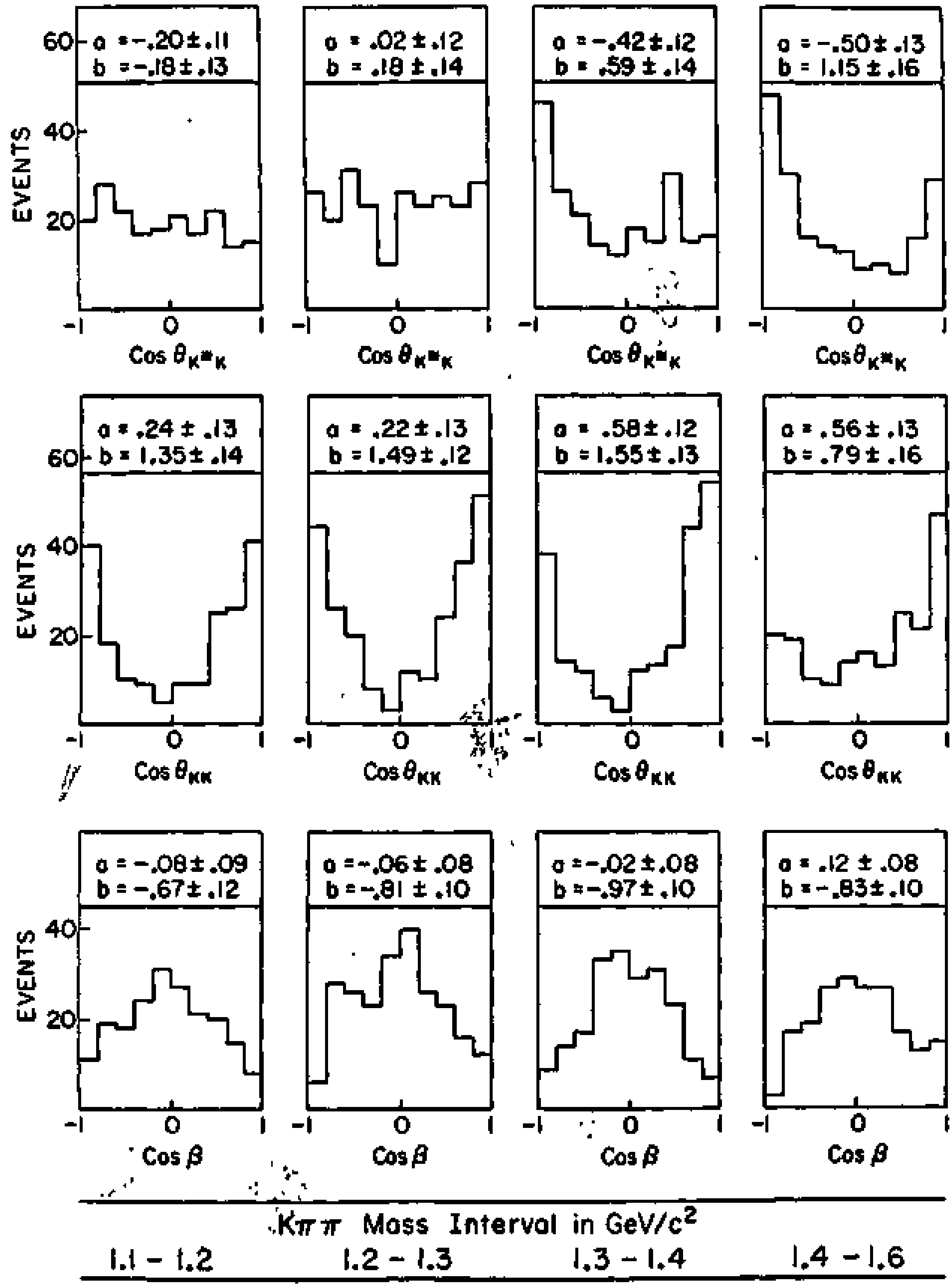
16. We choose not to do a simultaneous fit to all the distributions to set limits on the 2^- assignment because of the difficulty of determining effects of the π^+K^+ ambiguity in reaction (2). We have recently obtained a second exposure of 9 GeV/c K^+d at BNL which will bring our sensitivity to 16 events/μb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

17. R. Gatto and L. Maiani Phys. Letters 26B, 95 (1967).

FIGURE CAPTIONS

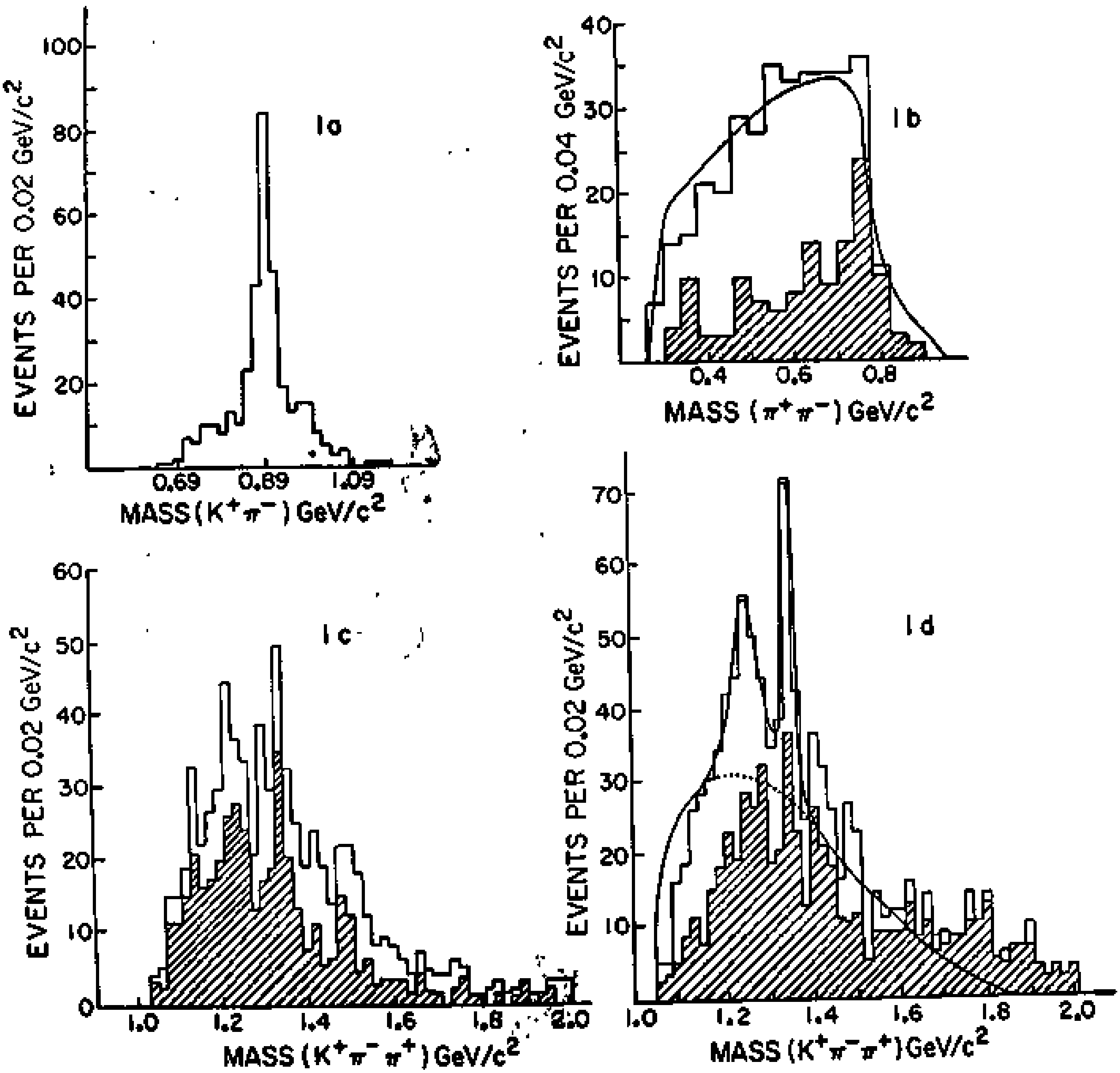
Fig. 1(a) Effective mass distribution of $K^+\pi^-$ for events from reaction (1) in the Q region. (b) Effective mass-distribution of $\pi^+\pi^-$ for the same set of events. Shaded events are for $M(K^+\pi^+\pi^-)$ between 1300 and 1400 MeV/c^2. (c) Effective mass distribution of $K^*(890)^o\pi^+$ from 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 part (c).

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



a = -.20 ± .11
b = -.18 ± .13
a = .02 ± .12
b = .18 ± .14
a = -.42 ± .12
b = .59 ± .14
a = -.50 ± .13
b = 1.15 ± .16
a = .24 ± .13
b = 1.35 ± .14
a = .22 ± .13
b = 1.49 ± .12
a = .58 ± .12
b = 1.55 ± .13
a = .56 ± .13
b = .79 ± .16
a = -.08 ± .09
b = -.67 ± .12
a = -.06 ± .08
b = -.81 ± .10
a = -.02 ± .08
b = -.97 ± .10
a = .12 ± .08
b = -.83 ± .10
EVENTS
60
40
20
-1
0
1
Cos θ_{K^*K}
Cos θ_{KK}
Cos β
$K\pi\pi$ Mass Interval in GeV/c^2
1.1 - 1.2
1.2 - 1.3
1.3 - 1.4
1.4 - 1.6

Figure 1.



1a
EVENTS PER 0.02 GeV/c²
MASS (K⁺π⁻) GeV/c²
1b
EVENTS PER 0.04 GeV/c²
MASS (π⁺π⁻) GeV/c²
1c
EVENTS PER 0.02 GeV/c²
MASS (K⁺π⁻π⁺) GeV/c²
1d
EVENTS PER 0.02 GeV/c²
MASS (K⁺π⁻π⁺) GeV/c²

Figure 2.