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Evidence for an Additional Resonance in the Region of the $K^*(1420)$ †

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We have observed an additional K^* resonance on the low-mass side of the $K^*(1420)$ in the reaction $K^+n \to K^+\pi^-p$ at 12 GeV/c. This resonance has parameters $M \approx 1370$ MeV and $\Gamma < 150$ MeV, and is probably produced by a pion-exchange mechanism with $J^P = 0^+$; but the alternative hypotheses of a $J^P = 1^-$ or a $J^P = 2^+$ resonance cannot be ruled out at this time.

The Stanford Linear Accelerator Center (SLAC) 82-in. bubble chamber was exposed to an rf-separated 12-GeV/c K^+-meson beam.[1] Approximately 500 000 exposures were taken, of which about 85% have been analyzed to date. The experimental details have been reported previously.[2,3]

The film has been scanned for all three-pronged events or four prongs with at least one track which stops in the bubble chamber. The events were measured on the Lawrence Radiation Laboratory flying-spot digitizer, and were reconstructed and kinematically fitted in the program SIOUX.

The spectator proton (assumed to be the slower proton in the laboratory frame) has a momentum distribution in agreement with that expected from the Hulthén wave function for momenta less than 300 MeV/c, and is isotropic in the laboratory frame. For the subsequent analysis only events with $p_{\text{spect}} < 300$ MeV/c are accepted. There are 6419 such events for the reaction $K^+d \to K^+\pi^-pp$, of which 67% are three prongs and 33% are four prongs. The cross section for this reaction is 400 ± 8 μb, where the quoted error reflects statistical uncertainties only.[4]

Data analysis.—Figure 1 shows the Dalitz plot for the reaction $K^+n \to K^+\pi^-p$. The outstanding features of this plot include (1) a large low-mass enhancement in the $p\pi^-$ system, which is associated with several N^* resonances[5]; (2) a $K^*(890)$ band; (3) a $K^*(1420)$ band; (4) a striking depletion of events in a band with $M^2(K^+\pi^-) \sim 2.4$ GeV^2; (5) an excess of events distributed along a band with $M^2(K^+\pi^-) \sim 3$ GeV^2; and (6) a general lack of background events, particularly the absence of any diagonal mass band corresponding to a

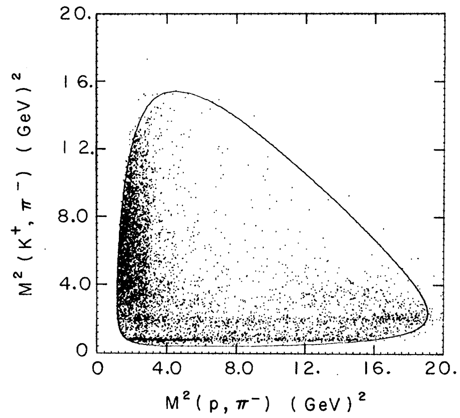

FIG. 1. Dalitz plot, $M^2(K^+\pi^-)$ vs $M^2(p\pi^-)$.

$M^2(pK^+)$ enhancement. The Dalitz plot shows that, although there is perhaps some $K^*(1420)N^*$ and $K^*(890)N^*$ interference, the N^* band is not continuous. The depletion of events in a band with $M^2(K^+\pi^-) \sim 2.4$ GeV^2 cuts right across the N^* band, and in addition the lower-mass portion of the N^* band does not persist down to the region between the $K^*(890)$ and $K^*(1420)$. Moreover, the well-known asymmetry in the $K^*(890)$ decay angular distribution, which appears on the Dalitz plot as an asymmetric population density along the $K^*(890)$ band, is not associated with the N^*; i.e., the high-density region of the $K^*(890)$ band is approximately the region with $M^2(p\pi^-) < 7$ GeV^2, whereas the region attributable to the N^* is only the region with $M^2(p\pi^-) < 3$ GeV^2.

Figure 2(a) shows the mass distribution $M(p\pi^-)$ in which the N^* enhancement is very clear. Figure 2(b) shows the mass distribution $M(K^+\pi^-)$ in which the dominant features are the $K^*(890)$, the $K^*(1420)$, and a higher-mass enhancement above 1.6 GeV. This enhancement is due in part to reflections of the N^* peak, but there is evidence for an enhancement in this region when the N^* events are removed, at $M(K\pi) \cong 1.8$ GeV [see also Fig. 2(d)].

Evidence for an additional resonance.—In the $K^+\pi^-$ mass distribution we observe an unusually broad signal from 1.3 to 1.5 GeV which appears at first sight to be due to the $K^*(1420)$ with fitted parameters $M = 1413 \pm 5$ MeV and $\Gamma = 143 \pm 12$ MeV. We note however that the character of the $K\pi$ decay angular distribution changes sharply at 1.4 GeV. Figures 3(a) and 3(b) show the $\cos\theta$ distributions in $(K^+\pi^-)$ mass regions, where θ is the Jackson angle. The distribution in $\cos\theta$ for the high-mass region, 1.4 to 1.5 GeV, is just that angular distribution expected from the decay of a

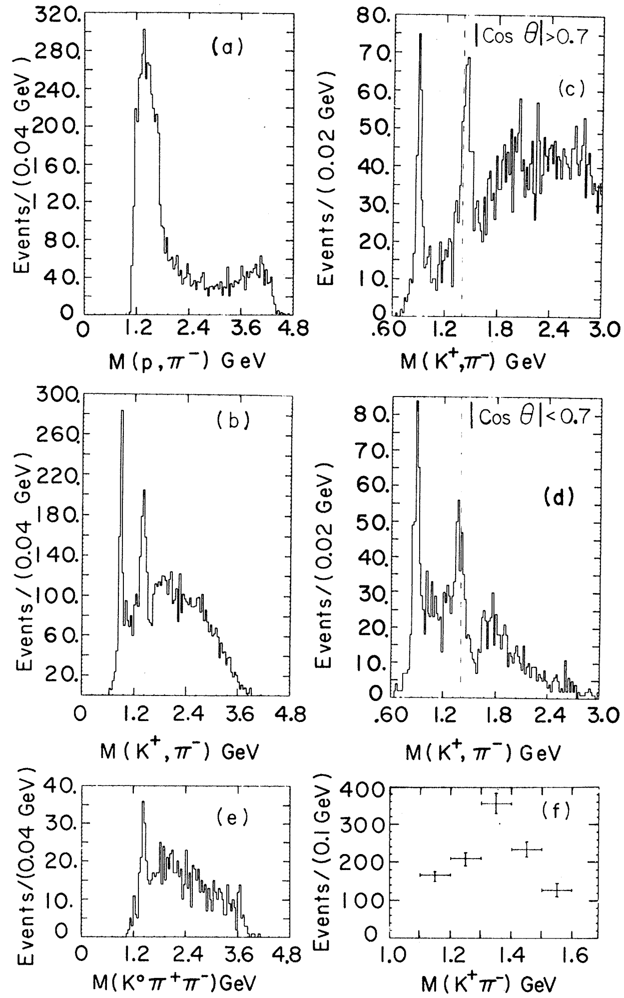

FIG. 2. Distributions in (a) $M(p\pi^-)$, and $M(K^+\pi^-)$ for (b) all events, (c) events with $\cos\theta$ in the polar region, and (d) events with $\cos\theta$ in the equatorial region. (e) $M(K^0\pi^+\pi^-)$ for the reaction $K^+n \to K^0\pi^+\pi^-p$, and (f) S-wave events as a function of $K^+\pi^-$ mass.

$J^P = 2^+$ resonance produced by pion exchange. There is no evidence for a significant asymmetry, and the distribution may be fitted with D waves with a substantial S-wave background. The $\cos\theta$ distribution for the low-mass region, 1.3-1.4 GeV, however, requires no powers of $\cos\theta$ greater than 2 to achieve an excellent fit. The parameters for the fits to the angular distributions in Legendre polynomials,

$$\sum_{n=0}^{N} a_n P_n(\cos\theta),$$

are $(a_1/a_0) = 0.38 \pm 0.1$ and $(a_2/a_0) = 0.69 \pm 0.11$ in the region $1.3 < M(K\pi) < 1.4$ GeV with $\chi^2 = 13.3$ for 17 degrees of freedom; $(a_1/a_0) = -0.01 \pm 0.11$, $(a_2/a_0) = 1.84 \pm 0.11$, $(a_3/a_0) = -0.19 \pm 0.13$, (a_4/a_0)

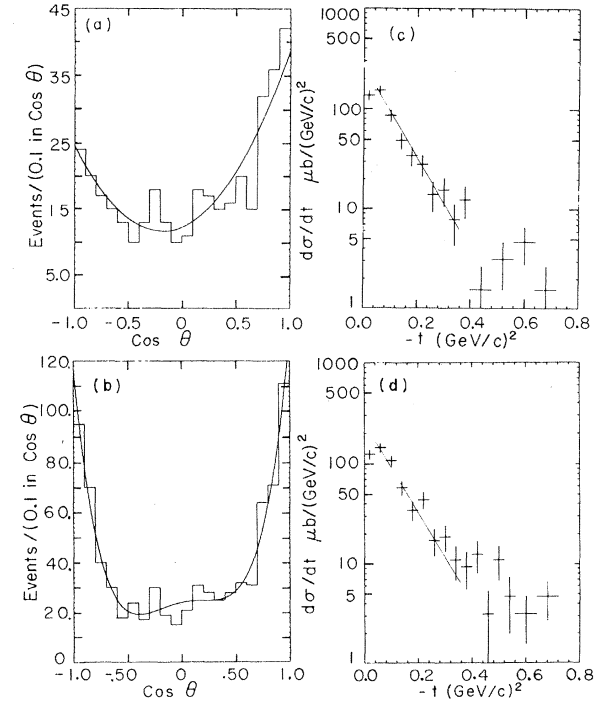

FIG. 3. Distributions in $\cos\theta$ for all events with $M(K^+\pi^-)$ in the range (a) 1.3-1.4 GeV, (b) 1.4-1.5 GeV; and $d\sigma/dt$ vs t for all events with $M(K^+\pi^-)$ in the range (c) 1.3-1.4 GeV, (d) 1.4-1.5 GeV. The solid curves in (a) and (b) are the distributions expected from the fits to the data with the parameters as listed in the text. The straight lines in (c) and (d) are the results of fits by functions of the form $d\sigma/dt = Ae^{Bt}$ with $B = 11.0 \pm 0.4$ $(\mathrm{GeV}/c)^{-2}$ and $B = 9.6 \pm 0.4$ $(\mathrm{GeV}/c)^{-2}$ in the 1.3- to 1.4-GeV and 1.4- to 1.5-GeV regions, respectively.

$= 1.06 \pm 0.15$ in the region $1.4 < M(K\pi) < 1.5$ GeV with $\chi^2 = 19$ for 15 degrees of freedom. In order to demonstrate the inconsistency of the angular distributions in the two mass regions, we have tried to fit the angular distribution, expected from the fit to the entire region 1.3-1.5 GeV renormalized to the actual number of events in each region, to the observed angular distributions. This fit has a confidence level of 0.0005 in the 1.3- to 1.4-GeV region and 0.0001 in the 1.4- to 1.5-GeV region; thus the two angular distributions are clearly inconsistent.

We have considered the effect of the low $(p\pi^-)$ mass enhancement on the angular distributions. If we subtract the events attributable to this N^* enhancement, the character of the angular distributions is not significantly changed.

As an alternative way of presenting the data we plot the $K\pi$ mass distribution for two regions of $\cos\theta$ [see Figs. 2(c) and 2(d)]: $|\cos\theta| > 0.7$ (polar region), and $|\cos\theta| < 0.7$ (equatorial region). In the polar region the "$K^*(1420)$ peak" is fitted with parameters $M = 1439 \pm 5$ MeV, $\Gamma = 105^{+13}_{-12}$ MeV, but in the equatorial region the parameters are $M = 1373^{+6}_{-5}$ MeV, $\Gamma = 150^{+5}_{-14}$ MeV. This large (66-MeV) shift in the central value of the "$K^*(1420)$ peak" with decay angle is obvious from Figs. 2(c) and 2(d).

The possibility that a sharp change at 1.4 GeV in the character of the exchange mechanism producing a *single* resonance is responsible for this effect is unlikely in view of the fact that a *single* resonance, produced by two different exchange mechanisms, e.g., π and ρ exchanges, would show a decay angular distribution characteristic of the particular mix of exchange mechanisms, but that distribution is not expected to be a function of $(K^+\pi^-)$ mass, as is the case here.

Other decay modes. —In a search for possible alternative decay modes of the $K_N^*(1370)$, we have studied the charge-exchange reaction $K^+n \to K^0\pi^+\pi^-p$, in which the K^0 decays visibly in the bubble chamber. In the $K^0\pi^+\pi^-$ mass distribution, shown in Fig. 2(e), the $K^*(1420)$ signal is particularly clean and has been fitted with parameters $M = 1440 \pm 5$ MeV, $\Gamma = 109 \pm 24$ MeV. These parameters are very consistent with the parameters obtained for the fit in the polar region in the reaction $K^+n \to K^+\pi^-p$ [see Fig. 2(b)]. There is thus no evidence for any $K^0\pi^+\pi^-$ peak on the low-mass side of the $K^*(1420)$, and hence the $K_N^*(1370)$ has no strong three-body decay mode and is probably not associated with the structure in the Q at about this mass.[6]

Discussion of the $J^P = 0^+$ hypothesis. —If we assume pion exchange and normalize to the number of observed events in each mass region, we calculate an average of 356 ± 27 S-wave and 19 ± 6 D-wave events in the 1.3- to 1.4-GeV region, and 234 ± 20 S-wave and 191 ± 22 D-wave events in the 1.4- to 1.5-GeV region. The amount of D wave in the 1.3- to 1.4-GeV region is entirely consistent with that expected from the tail of a Breit-Wigner centered at 1440 MeV with width 100 MeV. The distributions in φ, the decay azimuth in the Jackson frame, are consistent with being flat throughout in the $K^*(1420)$ region. Aside from the effects of the crossing N^* bands, an admixture of as little as 1% P wave to the S and D waves is sufficient to entirely explain the observed asymmetry in this region. These calculations ignore any possible effects of absorption, but include all relevant interference terms.

In Fig. 2(f) we show the number of S-wave events in each region as a function of $K^+\pi^-$ mass.

The rise in the S wave in the region 1.3- to 1.4-GeV is more than four standard deviations above the level in the two neighboring regions. The data are thus consistent with a D-wave resonance of $M \sim 1439$ MeV, $\Gamma < 105$ MeV and an S-wave resonance of $M \sim 1370$ MeV, $\Gamma < 150$ MeV.[7] The apparent absence of a three-body decay mode for $K_N^*(1370)$ favors the $J^P = 0^+$ interpretation since such a resonance cannot decay into three pseudoscalars.

Discussion of the $J^P = 1^-$ hypothesis. —The data in the region 1.3-1.4 GeV may be fitted entirely with S and P waves ignoring any D-wave tail of the $K^*(1420)$, with an average of 247 ± 40 S-wave and 128 ± 20 P-wave events. Because of the intrinsic ambiguity between a P wave and an S-D interference term, the actual amount of P wave present is unknown. Thus there is no conclusive evidence for a resonant P wave, although this possibility cannot be ruled out. Antich *et al.*[8] have previously suggested the presence of a $J^P = 1^-$ state, or at least an increase in the 1^- contribution to background, in the vicinity of the $K^*(1420)$ in the reaction $K^+p \to K^+\pi^-\Delta^{++}$ at 5.5 GeV/c. In addition, the presence of a large S-wave signal has been observed at the $K^*(1420)$ in the similar reaction $K^+p \to K^+\pi^-\Delta^{++}$ at 9 GeV/c,[9] and at the f^0 in the reaction $\pi^+p \to \pi^+\pi^-\Delta^{++}$ at 8 GeV/c,[10] although in neither case was there strong evidence for an appreciable P-wave amplitude.

Discussion of the $J^P = 2^+$ hypothesis. —If the $K_N^*(1370)$ were $J^P = 2^+$, its spin-density-matrix elements have been calculated by the method of moments to be $\langle\rho_{00}\rangle = 0.45 \pm 0.05$, $\langle\rho_{11}\rangle = 0.23 \pm 0.02$, and $\langle \text{Re}\rho_{1-1}\rangle = -0.06 \pm 0.05$. The other spin-density-matrix elements, e.g., ρ_{22}, are consistent with zero. As in the $J^P = 0^+$ case, the expected angular distribution is symmetric in $\cos\theta$, and therefore a small P-wave background must be invoked to explain the asymmetry. The angular distribution, folded about $\cos\theta = 0$ to eliminate the asymmetry, may be fitted with the distribution expected from the spin-density-matrix elements, but the confidence level for this fit is less than 5%. However this fit may be markedly improved by the addition of a substantial S-wave background. Furthermore, the expected distribution in the Treiman-Yang angle φ differs only weakly from isotropy, and within the present statistics no discrimination between the various hypotheses may be made on the basis of the φ distribution. The similarity of the t distributions in the two regions [see Figs. 3(c) and 3(d)] suggests similar production mechanisms and argues to some extent against the substantial vector exchange, which is required to explain the observed angular distribution with a $J^P = 2^+$ object.

Conclusion. —In conclusion we have observed strong evidence for an additional resonance on the low-mass side of the $K^*(1420)$, $K_N^*(1370)$ with $M \approx 1370$ MeV and $\Gamma < 150$ MeV. This resonance is probably $J^P = 0^+$ and is produced by pion exchange, but the alternative hypotheses of a $J^P = 1^-$ resonance produced by pion exchange or a $J^P = 2^+$ resonance produced by a mixture of pion and vector exchanges cannot be ruled out at this time.

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