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ABSTRACT

It is suggested that the broad $K^*(890)\pi$ enhancement from 1.15 to 1.55 BeV is a complex phenomenon consisting of at least three parts: kinematic enhancement via the Deck mechanism, a possible new K^* resonance at 1320 MeV, and an alternate decay mode of the $K^*(1430)$. It is further speculated that the A_1, $K^*(1320)$, D and E mesons could be the members of a nonet.

Evidence for a $K^*(1320)$ Resonance[†]

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In a study of the reactions:

$$K^+p \rightarrow K^0\pi^0\pi^+p \qquad (1)$$

$$K^+p \rightarrow K^+\pi^-\pi^+p \qquad (2)$$

at 4.6 BeV/c, we find that the $K^*(890)\pi$ enhancement[1-5] in the mass region 1.15 to 1.55 BeV is a complex phenomenon with definite structure probably consisting of at least three distinct effects:

(a) a broad kinematic enhancement (e.g., Deck effect)[6]

(b) indications of a new resonance – $K^*(1320) \rightarrow K^*(890) + \pi$ or $\rho + K$

(c) an alternate decay mode of the $K^*(1430)$ resonance into $K^*(890) + \pi$.

In our preliminary data for this phenomenon[2, 3] we found all the ear marks of a kinematic enhancement, i.e., (i) alignment of the K^* (as expected for one-pion exchange),[7] (ii) isotropy of the Treiman-Yang angle at the K^* vertex, (iii) "narrow" $\Delta^2(K^*)$ distribution, and (iv) angular distribution at the nucleon vertex consistent with elastic π^+p scattering. However, with improved statistics we have established a sharp and distinct peak at $M(K^*\pi) = 1320 \pm 10$ MeV, $\Gamma = 80 \pm 20$ MeV which appears too narrow and too far off the leading edge of the enhancement to be caused by the Deck effect. Furthermore, we find by confining ourselves to narrow $K^*\pi$ mass bands that the alignment of the K^* changes distinctly and that the $\Delta^2(K^*)$ distribution broadens considerably as the $K^*\pi$ mass traverses the "1320-MeV" region. We also find that a considerable fraction of the 1320-MeV peak tends to decay into $K\pi_a\pi_b$ in a configuration such that the K and π_a form a K^*, while π_a and π_b form a ρ. The question whether the "$K^*(1320)$ phenomenon" is a kinematic enhancement or meson is thus resolved in that <u>both</u> features appear to be present. By comparison with the reaction

$$K^+p \rightarrow K^0\pi^+p, \tag{3}$$

we find that our observed ratio

$$R = [K^*(1430) \rightarrow K^*(890) + \pi]/[K^*(1430) \rightarrow K + \pi] \tag{4}$$

is consistent with the value R = 0.6 predicted by Glashow and Socolow.[8]

Our experiment was carried out in the Brookhaven National Laboratory's 80-in. bubble chamber exposed to a 4.6-BeV/c separated K^+ beam at the A. G. S. The analysis was carried out primarily with the Lawrence Radiation Laboratory's Flying Spot Digitizer (FSD).

We have analyzed 669 events of reaction (1), 2324 events of reaction (2), and 429 events of reaction (3), as well as 150 events of the reaction

$$K^+p \rightarrow K^0\pi^+\pi^+n. \tag{5}$$

Reactions (1), (2), and (3) all lead to $K^*(890)$ and $K^*(1430)$ production. Figure 1 shows the triangle plot for reaction (2) as well as the $K\pi$ mass projections for reactions (2) and (3). In Fig. 2 we show the $K^*\pi$ mass distribution in 20-MeV intervals for reactions (1) and (2) combined. Here the appropriate N^* was removed in each case.[9] Two distinct mass peaks centered at 1320 and 1430 MeV on top of a broad enhancement can be clearly distinguished. The shaded region corresponds to the estimated contribution from the $K^*(1430)$ resonance.[10] The number of $K^*(1430)$ events decaying via the $K^*\pi$ mode were estimated from our observed

$K^*(1430)$ production rate in reaction (3) and the ratio (4) by use of the appropriate Clebsch-Gordan coefficients. The curve shown in Fig. 2 corresponds to the calculations by Maor and O'Halloran for the Deck mechanism.[11] The curve is normalized to the experimental height at 1220 MeV – the computed position of the kinematic peak in the $K^*\pi$ mass distribution. It is noteworthy that this kinematic mass peak lies about 100 MeV below our observed peak at 1320 MeV. Figure 3, a and b gives the same distribution for reactions (1) and (2) separately. In Fig. 3, c and d we illustrate another feature of the $K^*(1320)$ peak. Here in Fig. 3c we have taken out the ρ band $[M(\pi\pi) = 680$ to 840 MeV$]$. As may be noted, the $K^*(1320)$ peak nearly disappears in this case. Figure 3d shows the complementary information corresponding to the selection of events in the ρ band which then gives a strong $K^*(1320)$ peak. This evidence suggests that the $K^*(1320)$ peak has a decay mechanism leading to a large extent to both $K^* + \pi$ and $\rho + K$ in the final state. At first sight this result makes it tempting to consider the $K^*(1320)$ as a consequence of simultaneous K^* and ρ formation. However on a more careful consideration of the range of $K\pi\pi$ masses that can be formed, there is no obvious reason why this type of phenomenon should give rise to such a sharp peak in the $K\pi\pi$ system.[12] We are thus inclined to consider our result as evidence for a resonance, with the simultaneous K^* and ρ formation a consequence of either constructive interference between the two decay channels or final-state interaction among the three bosons. This feature is very reminiscent of the proponderance of double-K^* formation in the decay of the E(1420) meson to $K\bar{K}\pi$,[13] although in that instance the situation is complicated by the presence of a $K\bar{K}$ enhancement.

A further property of the $K^*(1320)$ peak is illustrated in Fig. 3, e and f. Here we made use of the K^* alignment expected for the Deck mechanism to partially separate it from the $K^*(1320)$ peak. Let us consider the $K\pi$ scattering angle α_{KK} in the K^* center of mass. Alignment of the K^* on the OPE model corresponds to an angular distribution of the form $\cos^2\alpha_{KK}$. Thus to select events corresponding preferentially to the Deck effect, we consider the $K^*\pi$ mass distribution for the "polar" events, i.e., with the restriction $|\cos\alpha_{KK}| \geq 0.8$. This gives a sample containing ~1/2 of these events. Similarly the restriction $|\cos\alpha_{KK}| < 0.8$ which selects the "equatorial" events gives a sample depleted, by a factor of ~2, of events corresponding to the Deck effect. Figure 3, e and f shows the $K^*\pi$ mass distribution with the above two complementary restrictions imposed. The curves are the same as that in Fig. 2 with only the factor 1/2 in the normalization. As may be noted by comparison with the calculated curves, the events in Fig. 3e correspond primarily to the Deck effect, while Fig. 3f shows the $K^*(1320)$ above a considerably reduced background. The applicability of such a partial separation depends of course on differences in the K^* alignment for the two effects considered. That such differences indeed exist is illustrated in Fig. 4a, where we show the distribution in $\cos\alpha_{KK}$ for various cuts in the $K^*\pi$ mass. As may be noted the two intervals with mass below the $K^*(1320)$ band show a strong $\cos^2\alpha$ component consistent with the kinematic enhancement hypothesis. The character of the distribution changes distinctly as we reach the $K^*(1320)$ band. This is also true of the corresponding $\Delta^2(K^*)$ distribution shown in Fig. 4b. In Fig. 4c we show the $\Delta^2(p)\left[= \Delta^2(K^*\pi)\right]$ distribution. As may be noted this distribution peaks at low Δ^2 values in the region of the 1320 MeV mass band.

To obtain information on the I spin of the $K^*(1320)$, we have looked for a $K^{*+}\pi^+$ enhancement in reaction (5). No such enhancement occurs in the 1320 MeV mass band.[14] This indicates that $K^*(1320)$ is a $T = 1/2$ state. We have also looked for the $K^*(1320)$ decay into $K^+ + \omega$. For the rate of this decay mode, we find a limit of $6^{+4}_{-6}\%$ of that of the $K^*\pi$ decay mode.

Having established the above factual features we now indulge in some pure speculations. In view of the similarity between the phenomena observed here and the A_1, A_2 phenomena, it is tempting to interpret the A_1 also as a resonance[15] belonging to the same SU(3) octet as the $K^*(1320)$.

The building up of a new nonet around the A_1 has been very popular during the past two years, and we do not attempt to refer here to all the papers on this subject. Applying the Gell-Mann-Okubo formula in the mass-squared form to the A_1 and $K^*(1320)$ gives a mass for the isotopic singlet member of the octet of $M_8 = 1390$ MeV. Our association of the $K^*(1320)$ rather than C (1215) with the A_1 has the merit that the A_1 and $K^*(1320)$ are produced in the same pseudoscalar + baryon → A_1 nonet + baryon reaction, while C (1215) has been observed only in $\bar{p}p$ annihilations at rest.[16] The D(1286)[17] and E(1420)[13, 17] could then conceivably be the two isotopic singlets that complete the A_1 nonet. Both of these are produced via pseudoscalar + baryon reactions as well as in $\bar{p}p$ annihilations. If we accept this hypothesis, it gives a mixing angle for the two singlets of $\theta = 28 \pm 8$ deg. Following the procedure of Glashow and Socolow,[8] we can compute the expected decay rates for the various members of the postulated A_1 nonet assuming a decay into vector + pseudoscalar. The resulting decay widths are given in Table I.

As to the spin-parity value for the A_1 nonet, we have no new information at present. The values 1^+ and possibly 2^- have been most often considered and are consistent with the available data. The decay widths in Table I have been computed for a phase space of the form p/M^2, which implies an s-wave decay for the A_1 nonet, i.e., $J^P = 1^+$.

There is one flaw in this argument, namely, the D mass lies below threshold for decay into K^*K. Thus the simple phase space form we have used is not applicable to the D meson. To account for the observed D decay width - if it is indeed as broad as stated - one would have to invoke the presence of SU(3) breaking effects, namely the $K\bar{K}$ interaction for which evidence exists in the D and E meson decays.

We wish to thank R. Shutt and the 80-in. bubble chamber crew at Brookhaven National Laboratory; the AGS crew and D. Rahm for helping with our run at Brookhaven; the FSD crew under H. S. White and our own scanning and computing staff at Berkeley; and J. Dash, S. Hagopian, and W. S. Little, who participated in various stages of the experiment. We also wish to thank H. J. Lipkin and S. Meshkov for helpful discussions.

FOOTNOTES AND REFERENCES

† Work done under the auspices of the U. S. Atomic Energy Commission.

‡ Now at Imperial College, London, England.

** John S. Guggenheim fellow. Deceased.

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3. G. Goldhaber and S. Goldhaber, "The A_1 and $K^{**}(1320)$ Phenomena-Kinematic Enhancements or Mesons?", Proceedings -- Fourth Anniversary Symposium, Institute of Mathematical Science, Madras, India, January 1966; Lawrence Radiation Laboratory Report UCRL-16744, March 1966 (unpublished).
4. W. De Baere, J. Debaisieux, P. Dufour, F. Grard, J. Houghebaert, L. Pape, P. Peeters, F. Verbeure, R. Windmolders, T. A. Filippas, R. George, Y. Goldschmidt-Clermont, V. P. Henri, B. Jongejans, W. Koch, G. R. Lynch, D. W. G. Leith, F. Muller, and J. M. Perreau, "The Enhancement $(K\pi\pi)$ Around 1270 MeV/c^2 in the Reaction $K^+p \rightarrow KN\pi\pi$ at 3.0, 3.5, and 5 GeV/c," paper presented at Oxford International Conference on Elementary Particles, September 1965.

5. J. Bishop, A. T. Goshaw, A. R. Erwin, M. A. Thompson, W. D. Walker, A. Weinberg, Phys. Rev. Letters 16, 1069 (1966). These authors have studied the $K^*\pi$ mass distribution in the five-particle reaction $K^+p \to K^0\pi^+\pi^-\pi^+p$ and observed a peak at 1300 MeV. In our data we also find indications of such a peak, however at the lower mass value of 1280 MeV. We do not see any evidence for $K^*(1320)$ decaying into a $K\pi$ system; an upper limit for the ratio $K\pi/K^*\pi$ is $< 0.15 \pm 0.15$.

6. R. T. Deck, Phys. Rev. Letters 13, 169 (1964).

7. K^* without further mass indication is used in this paper to refer to $K^*(890)$.

8. S. L. Glashow and R. H. Socolow, Phys. Rev. Letters 15, 329 (1965).

9. We select events which satisfy the following criteria: for reaction (2), $M(K^+\pi^-)$ in K^{*0} band (840 to 940 MeV) with $M(\pi^+p)$ outside N^{*++} band (1120 to 1320 MeV); for reaction (1), either $M(K^0\pi^0)$ in K^{*0} band with $M(\pi^+p)$ outside N^{*++} band or $M(K^0\pi^+)$ in K^{*+} band with $M(\pi^0p)$ outside N^{*+} band.

10. For the $K^*(1430)$ contribution we employed a simple Breit-Wigner shape centered at 1430 MeV with $\Gamma = 80$ MeV. This is shown both as the shaded insert in Fig. 2 and how it would affect the distribution if subtracted out.

11. U. Maor and T. A. O'Halloran Jr., Phys. Letters 15, 281 (1965). We are grateful to Drs. Maor and O'Halloran for supplying us with the calculation at 4.6 BeV/c.

12. Note however that in a seminar presented at the Latin-American School of Physics, Caracas, Venezuela, July 1966, C. Sommerfield reported on work by F. S. Chen-Cheung and himself on calculations of overlapping resonances in the Lee model. This work shows that - at least in the framework of the Lee model - two such overlapping resonance bands can give rise to a kinematic enhancement in the three particle system without actually producing a three particle resonance. It is not clear at present how this effect might translate into a realistic physical situation. On the other hand C. Schmid (CALT 68-85 — unpublished) has shown that triangle diagrams corresponding to overlapping resonances do not produce an enhancement in the three particle system. This is based on the fact that the triangle diagram interferes destructively with the corresponding diagram without rescattering.

13. R. Armenteros, D. N. Edwards, T. Jacobsen, L. Montanet, J. Vandermeulen, C. D'Andlau, A. Astier, P. Baillon, J. Cohen-Ganouna, C. Defoix, J. Siaud, and P. Rivet, CERN preprint (1965).

14. For a T = 3/2 state we would expect a peak of ~ 100 events in the $K^{*+}\pi^{+}$ mass range 1.28 to 1.36 BeV. Experimentally we observe ~ 2 events.

15. We are thus speculating here that the A_1 also consists of a sharp <u>bona fide</u> resonance peak sitting on a broad background due to the Deck effect. The difference between the $K^{*}(1320)$ and the case of the A_1 is that the A_1 peak (it it is indeed a meson) is sitting right on top of the peak in the broader distribution due to the Deck mechanism. It is this feature of the presence of a peak in the kinematic enhancement as well as a resonance <u>at the same mass</u> which has made interpretation of the A_1 phenomenon so complicated.

16. R. Armenteros, D. N. Edwards, T. Jacobsen, L. Montanet, A. Shapiro, J. Vandermeulen, C. D'Andlau, A. Astier, P. Baillon, J. Cohen-Ganouna, C. Defoix, J. Siaud, C. Ghesquiere, and P. Rivet, Phys. Letters 9, 207 (1964); N. Barash, J. Steinberger, T. H. Tau, L. Kirsch, and P. Franzini, in XII International Conference on High Energy Physics at Dubna (Atomizdat, Moscow, 1966), p. 587.

17. D. H. Miller, S. U. Chung, O. I. Dahl, R. I. Hess, L. M. Hardy, J. Kirz, and W. Koellner, Phys. Rev. Letters 14, 1074 (1965); C. D'Andlau, A. Astier, M. Della Negra, L. Dobrzynski, S. Wojcicki, J. Barlow, T. Jacobsen, L. Montanet, L. Tallone, M. Thomas, A. M. Adamson, M. Baubillier, J. Duboc, M. Goldberg, E. Levy, D. N. Edwards, and J. E. A. Lys, Phys. Letters 17, 347 (1965).

18. A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, and M. Roos, Rev. Mod. Phys. 37, 633 (1965).

Table I. Decay rates via vector plus pseudoscalar mesons for the A_1 nonet hypothesized in the text.

Resonance	Decay mode	Experimental decay rate, Γ (MeV)	Matrix element	P/M^2	Predicted Γ (MeV)
$A_1(1080)$	$\rho\pi$	~ 125[a]	$4H^2$	0.205	125 input
$K^*(1320)$	$K^*\pi$	80±20[b]	$1.5H^2$	0.193	44
	ρK		$1.5H^2$	0.11	26
	ωK	$6\pm^{4}_{6}$[b]	$1.5\sin^2\theta_1 H^2$[c]	0.089	9
D(1286)	"$K^*\bar{K}$"[d]	40±10[a]	$6\sin^2\theta H^2$	---[d]	---[d]
E(1420)	$K^*\bar{K}$	60±10[a]	$6\cos^2\theta H^2$	0.076	56[e]

a. From compilation by Rosenfeld et al., reference 18.

b. This experiment.

c. The ω-ϕ mixing angle, θ_1, is taken to be 40 deg.

d. The D mass lies below threshold for $K^*\bar{K}$ production. The simple phase-space estimate is thus not applicable.

e. A mixing angle of ~ 20 deg is obtained by using the Gell-Mann–Okubo formula linear in mass. This value of the mixing angle predicts a decay rate of ~ 60 MeV for $E \rightarrow K^*\bar{K}$.

FIGURE LEGENDS

Fig. 1.(a) Triangle plot of $M(\pi^+p)$ vs $M(K^+\pi^-)$ for the reaction $K^+p \to K^+\pi^-\pi^+p$. The two bands correspond to the $K^{*0}(890)$ and $N^{*++}(1236)$; (b) The projections in $M(K^+\pi^-)$. The hatched histogram corresponds to events in the N^{*++} band. (c) $M(K^0\pi^+)$ distribution for the reaction $K^+p \to K^0\pi^+p$. The shaded histogram corresponds to events outside the N^{*++} band.

Fig. 2. Invariant mass distribution of $M(K^*\pi)$ in 20-MeV intervals for events in the reactions $K^+p \to K^+\pi^-\pi^+p$ and $K^+p \to K^0\pi^0\pi^+p$ with K^* selected but complementary N^* removed. The curve is the contribution due to Deck mechanism, normalized to our data.

Fig. 3. (a) and (b) $M(K^*\pi)$ distributions in 40-MeV intervals for the above reactions separately. (c) and (d) $M(K\pi\pi)$ distributions for events outside the N^* band with $M(\pi\pi)$ respectively outside and inside the ρ band. The shaded histograms correspond to events with K^* selection in addition. (e) and (f) $M(K^*\pi)$ distribution for K^* events outside the N^* band with $|\cos\alpha_{KK}| \geq 0.8$ and $|\cos\alpha_{KK}| < 0.8$ respectively. The curves correspond to the curve in Fig. 2 reduced by a factor of 2. The arrows in this figure indicate 1320 MeV and 1430 MeV respectively.

Fig. 4. For various mass regions of $K^*\pi$ as specified, (a) the distribution of $\cos\alpha_{KK}$ in the K^* rest frame; (b) distribution of the momentum transfer to the K^*; (c) distribution of the momentum-transfer to the $K^*\pi$ system.

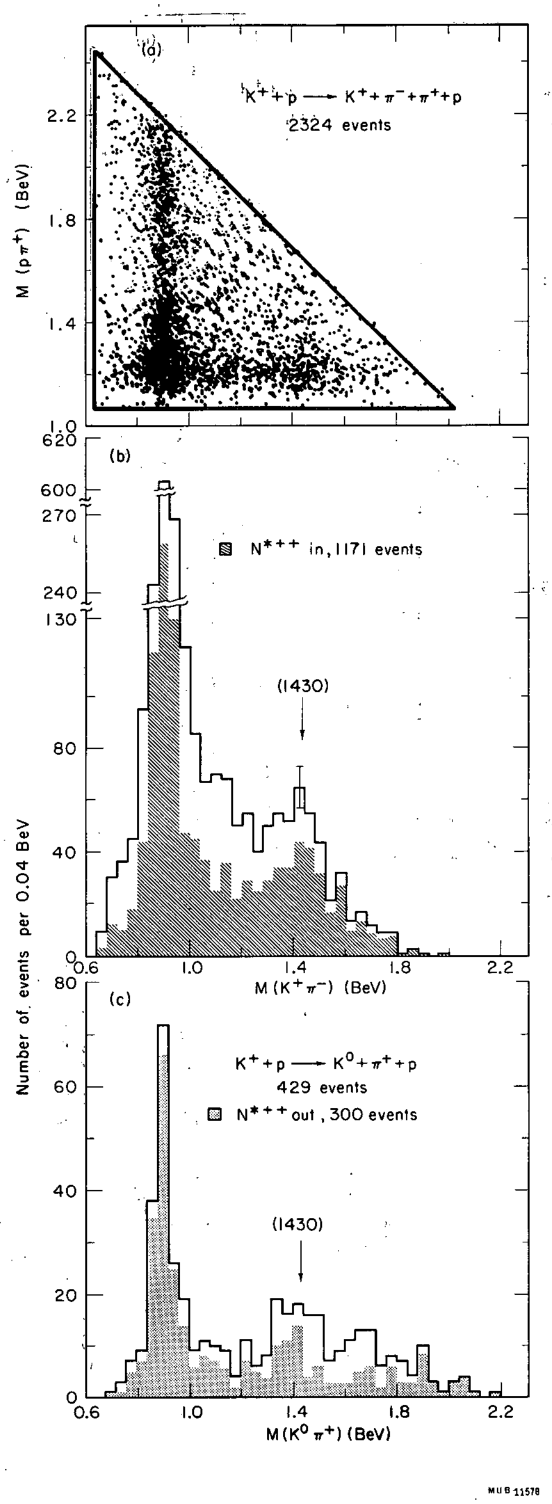
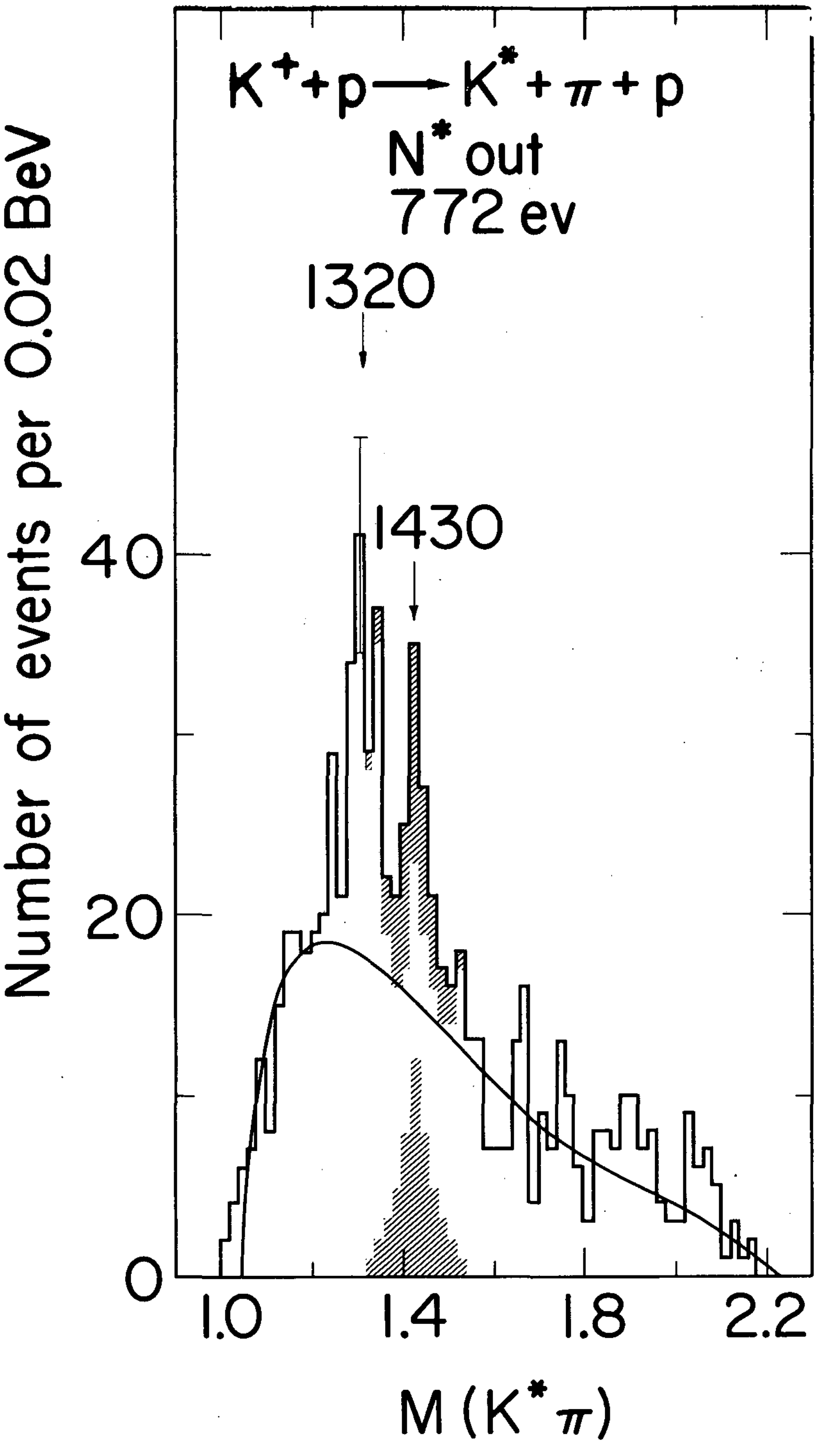

(a)
K⁺+p ⟶ K⁺+π⁻+π⁺+p
2324 events
M (pπ⁺) (BeV)
2.2
1.8
1.4
1.0
(b)
620
600
270
240
130
80
40
0
N*⁺⁺ in, 1171 events
(1430)
0.6
1.0
1.4
1.8
2.2
M (K⁺π⁻) (BeV)
Number of events per 0.04 BeV
(c)
80
60
40
20
0
K⁺+p ⟶ K⁰+π⁺+p
429 events
N*⁺⁺ out, 300 events
(1430)
0.6
1.0
1.4
1.8
2.2
M(K⁰ π⁺) (BeV)
MUB 11578

Fig. 1.



MUB-11577A

Fig. 2.

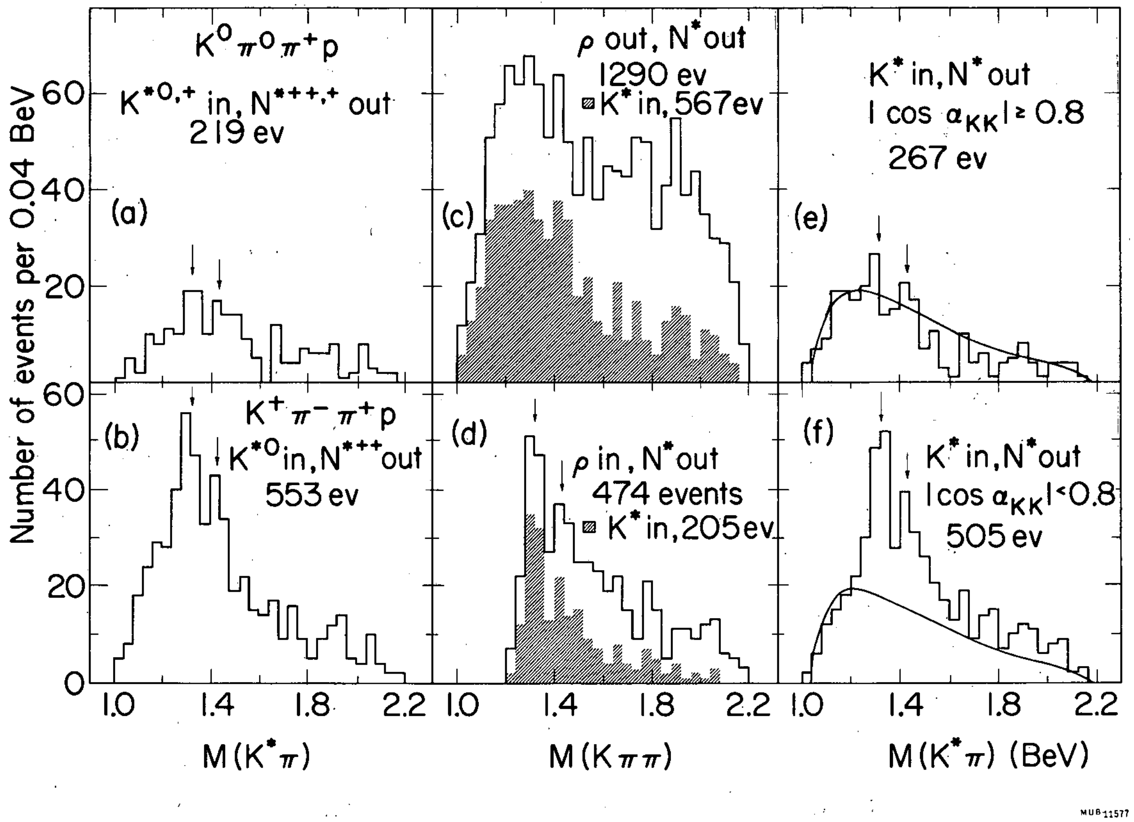

Number of events per 0.04 BeV
0
20
40
60
$K^0\pi^0\pi^+p$
$K^{*0,+}$ in, $N^{*++,+}$ out
219 ev
(a)
(b)
$K^+\pi^-\pi^+p$
K^{*0}in, N^{*++}out
553 ev
ρ out, N^*out
1290 ev
▨ K^* in, 567ev
(c)
(d)
ρ in, N^*out
474 events
▨ K^* in, 205ev
K^* in, N^* out
$|\cos\alpha_{KK}| \geq 0.8$
267 ev
(e)
(f)
K^* in, N^*out
$|\cos\alpha_{KK}| < 0.8$
505 ev
1.0
1.4
1.8
2.2
$M(K^*\pi)$
$M(K\pi\pi)$
$M(K^*\pi)$ (BeV)
MUB-11577

Fig. 3.

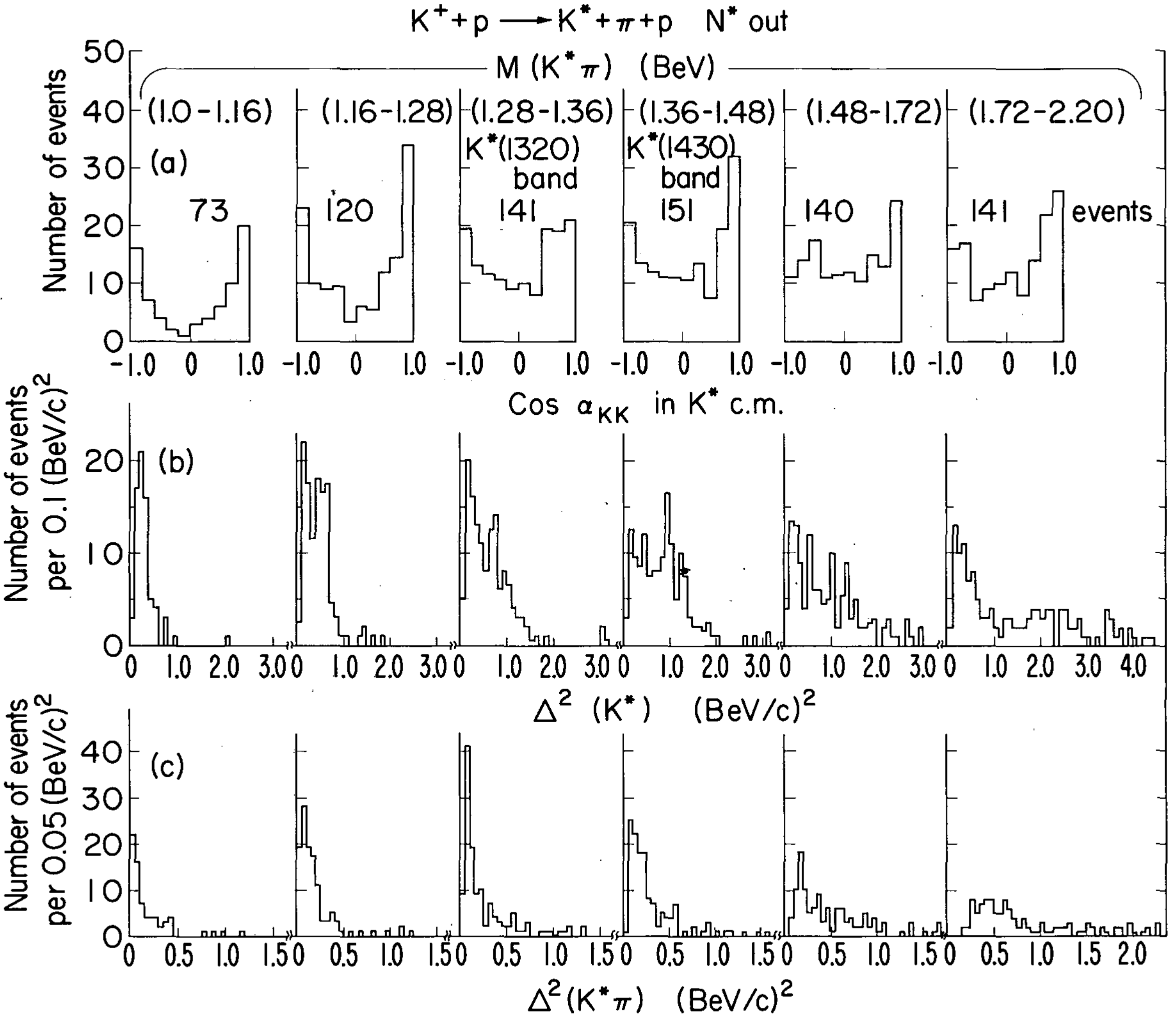

K⁺+p → K*+π+p N* out
M (K*π) (BeV)
(1.0-1.16)
(1.16-1.28)
(1.28-1.36)
K*(1320) band
(1.36-1.48)
K*(1430) band
(1.48-1.72)
(1.72-2.20)
(a)
73
120
141
151
140
141
events
Number of events
Cos α_KK in K* c.m.
(b)
Number of events per 0.1 (BeV/c)²
Δ² (K*) (BeV/c)²
(c)
Number of events per 0.05 (BeV/c)²
Δ²(K*π) (BeV/c)²
MUB 11576

Fig. 4.