[4]For the $f^0(1250)$, see K. Lai et al., private communication, based on 6-BeV/c π^-p studies.

[5]S. Glashow and R. H. Socolow, Phys. Rev. Letters 15, 329 (1965). Additional references are given in this paper.

[6]V. E. Barnes et al., Phys. Rev. Letters 15, 322 (1965).

[7]M. Goldberg et al., Nuovo Cimento 45A, 169 (1966).

[8]P. Dornan et al., Phys. Rev. Letters 19, 271 (1967). References to other studies of $Kn\pi\pi$ final states are given here.

[9]The symbol "K^*" when used without a mass subscript denotes the established resonance at 890 MeV.

[10]The $(1420)^0$ peak appears to be narrower than the $(1420)^-$ peak discussed later, but statistics are too small to consider the difference significant. In any event, since we do not "mix" neutral- and charged-(1420) branching-ratio information, different mass criteria for the peaks are irrelevant.

[11]The background shape in Fig. 1(b) was determined by studying the behavior of mass cuts adjacent to the (1420) peak of Fig. 1(a).

[12]After subtraction of the huge K^* peak, the resultant $M(p\pi)$ spectrum shows a clear N^* peak. The "N^* criteria" are $M(p\pi) = 1235 \pm 75$ MeV and cos($p\pi$ production angle) ≥ 0.9.

[13]J. Badier et al., Phys. Letters 19, 612 (1965); J. Bishop et al., Phys. Rev. Letters 16, 1069 (1966); B. Shen et al., Phys. Rev. Letters 17, 726 (1966).

[14]This value is obtained either from channel (2) alone by fitting with a Breit-Wigner plus phase-space shape, or from a combined plot in which the background is estimated by a smooth curve.

[15]A critique of the limitations inherent in any analysis which makes use of this formula is given in Ref. 7.

[16]See M. Gell-Mann, California Institute of Technology Pasadena Synchrotron Laboratory Report No. CTSL-20 (6) (unpublished); S. Okubo, Progr. Theoret. Phys. (Kyoto) 27, 949 (1962). This yields $|\theta_0| \approx 10°$, $|\theta_1| \approx 30°$. Owing to the small size of the 0^- mixing angle, the effect of mixing between the 0^- decay products of 2^+ mesons is negligible and is thus ignored. See A. MacFarlane and R. H. Socolow, Syracuse University Report No. NYO 3399-4.4, 1965 (unpublished). As is customary, the signs of θ_J are chosen in order to achieve the desired supression of certain decay rates.

[17]Here we make use of the University of California Radiation Laboratory "Minifun" program as revised by M. Sakitt of Brookhaven National Laboratory. We include in $\Delta\Gamma$ the experimental error, all uncertainties, including for example the error in mixing angles, etc. The dependence of the "best fit" solution on X_A, X_B is trivial as long as $X_i \geq 200$ MeV. See Ref. 7.

[18]Chikovani et al., Ref. 1.

[19]The possibility of two separate resonances in the A_2 region has also been discussed by D. R. O. Morrison [Phys. Letters 25B, 238 (1967)] on the basis of excitation function evidence.

EVIDENCE FOR $K^*(1250)$ RESONANCE PRODUCTION IN K^+p INTERACTIONS AT 9 BeV/c †

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We present evidence for $K^*(1250)$ resonance production in K^+p interactions at 9 BeV/c. We observe that the large $K\pi\pi$ mass enhancement in the region 1.1 to 1.5 BeV probably consists of three resonances at the observed masses 1.25, 1.36, and 1.42 BeV above a broad background due primarily to diffraction dissociation.

The $K\pi\pi$ mass enhancement in the region 1.1 to 1.5 BeV has been a phenomenon of great interest and much investigation.[1-7] It has been suggested in an earlier communication that the complex structure in this enhancement observed in K^+p interactions at 4.6 BeV/c consists of at least two resonances, $K^*(1320)$ and $K^*(1420)$, on top of a broad kinematical background produced via the Deck mechanism.[8] In this Letter we wish to present, as preliminary results of a study of K^+p interactions at 9 BeV/c, evidence for the existence of a resonance at 1250 MeV in addition to $K^*(1320)$ and $K^*(1420)$. This resonance may be the same effect as the C meson observed in $\bar{p}p$ annihilations at rest.[9,10] The production rates of these resonances depend sensitively on the momentum transfer to the recoil proton in such a way that the resonance effects are partially separated from the background events and partly from each other for different regions of momentum transfer. In our data the observed masses of the three resonances are 1250, 1360, and 1420 MeV, and full widths at half-maximum are 50, 80, and 80 MeV, respectively. We also speculate that the apparent masses and widths of the peaks depend on the interference effects between resonances of the same spin and parity and possibly with coherent background. Details of an investigation into such effects are described in the following Letter.[11]

Our experiment was carried out in the Brookhaven National Laboratory's 80-inch hydrogen bubble chamber, which was exposed to a 9-BeV/c rf-separated K^+ beam at the alternating gradient synchrotron (AGS). The measurement was performed with the Lawrence Radiation Laboratory's flying spot digitizer (FSD), and the geometric reconstruction and kinematical fitting were accomplished with the program TGVP-SQUAW.[12-14] The beam momentum at the entrance of the chamber is 8950 ± 65 MeV/c, and the upper limit on the pion contamination is 1.3 %.[15]

In the investigation of the $K\pi\pi$ system, we have studied primarily the reactions

$$K^+p \to K^+\pi^+\pi^-p, \quad 2572 \text{ events}; \quad (1)$$

$$K^+p \to K^0\pi^0\pi^+p, \quad 416 \text{ events}. \quad (2)$$

Events have been identified in a computer program utilizing FSD ionization measurements in addition to the kinematical fitting confidence criterion.[16] The present sample is based upon measurements of 34 000 four-pronged events and 6000 two-pronged events with vee.[17] The typical errors of the $K\pi\pi$ mass in the mass region 1.1 to 1.5 BeV are 7 MeV for four-constraint-fit events of Reaction (1) and 15 MeV for one-constraint-fit events of Reaction (2).

In Fig. 1 we show the mass distribution of the positively charged $K\pi\pi$ system for all events in Reactions (1) and (2). The principal feature of this distribution is the broad enhancement in the mass region 1.1 to 1.5 BeV. This enhancement corresponds to a cross section of 0.3 ± 0.1 mb.[18] We wish to point out here that a second enhancement is also observed in the mass region 1.60 to 1.76 BeV which is probably the same effect as the L meson.[19]

In Fig. 2(a) we show the $K\pi\pi$ mass distribution for events of Reactions (1) and (2) combined, with the mass of the $K^+\pi^-$ pair for Reaction (1) and either of the $K\pi$ pairs for Reaction (2) in the $K^*(890)$ mass band or the $\pi\pi$ mass in the ρ-meson mass band.[20] In this graph the events in the N^{*++} band have been removed from the sample. Two mass peaks centered at 1250 and 1400 MeV above a broad background can

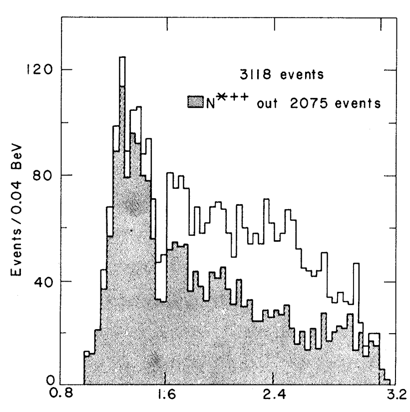

FIG. 1. $M(K\pi\pi)^+$ distribution in 40-MeV intervals for reactions $K^+p \to K^{+,0}\pi^{-,0}\pi^+p$. The shaded histogram corresponds to the same distributions with events in the N^{*++} band removed.

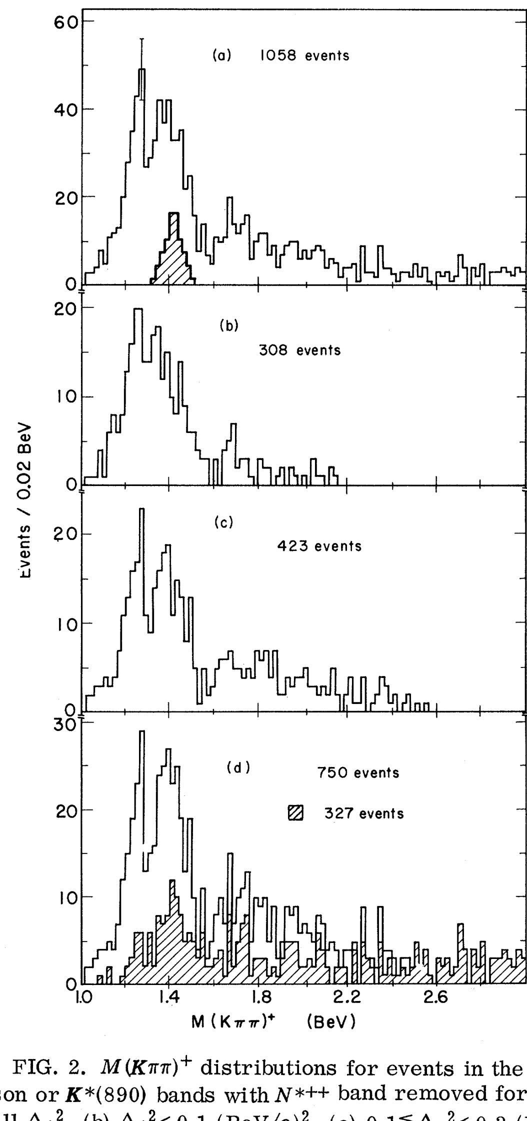

FIG. 2. $M(K\pi\pi)^+$ distributions for events in the ρ meson or $K^*(890)$ bands with N^{*++} band removed for (a) all Δ_p^2, (b) $\Delta_p^2 < 0.1$ (BeV/c)^2, (c) $0.1 \le \Delta_p^2 < 0.3$ (BeV/c)^2, (d) $\Delta_p^2 \ge 0.1$ (BeV/c)^2, and (shaded histogram) $\Delta_p^2 \ge 0.3$ (BeV/c)^2. The shaded area in (a) represents our estimate of the $K^*\pi$ and $K\rho$ decay modes of the $K^*(1420)$.

be clearly distinguished. These two peaks are well resolved by a 60-MeV-wide dip of about 3.2 standard deviations, and are, respectively, 7- and 6-standard-deviation effects above background.

In Figs. 2(b)-2(d) we show various regions of four-momentum transfer to the proton, Δ_p^2. We observe that the $K^*(1420)$ has a Δ_p^2 distribution somewhat wider than those of the $K^*(1250)$ and $K^*(1320)$, and appears clearly for $\Delta_p^2 \geq 0.3$ $(\text{BeV}/c)^2$ in the shaded histogram in Fig. 2(d). We interpret the unresolved peak at 1400 MeV in Fig. 2(a) to consist of two parts: the $K^*(1420)$ and a peak at 1360 MeV, which we believe to be the same as the $K^*(1320)$. The 1360-MeV peak appears most clearly in the region $0.1 \leq \Delta_p^2 < 0.3$.

In accordance with the foregoing discussion we therefore conjecture that the large $K\pi\pi$ mass enhancement in the region 1.1 to 1.5 BeV consists of at least four effects with different momentum-transfer dependence: a broad background peak due to diffraction dissociation, and three distinct resonances. The apparent resonance parameters observed in our experiment are

$$M(K^*(1250)) = 1250 \pm 10 \text{ MeV}, \quad \Gamma(K^*(1250)) = 50 \pm 20 \text{ MeV};$$
$$M(K^*(1320)) = 1360 \pm 10 \text{ MeV}, \quad \Gamma(K^*(1320)) = 80 \pm 20 \text{ MeV};$$
$$M(K^*(1420)) = 1420 \pm 10 \text{ MeV}, \quad \Gamma(K^*(1420)) = 80 \pm 20 \text{ MeV}.$$

As may be noted, the observed mass 1360 MeV is higher than that reported earlier for the $K^*(1320)$.[8,21] We emphasize here that the true parameters of these resonances may depend sensitively on the interference effects among the resonances as well as upon the coherent background, and may be shifted from the values we have observed in the experiment presented here.[11]

In Fig. 3 we show the decay properties of the $K\pi\pi$ system as a function of the $K\pi\pi$ mass for five mass regions defined as (I) 1000-1180 MeV, (II) 1180-1280 MeV, (III) 1300-1400 MeV, (IV) 1420-1500 MeV, and (V) 1600-1760 MeV. Regions II, III, and IV correspond to the (1250), (1360), and (1420) mass bands, respectively. Region I is a control region, and Region V corresponds to the L-meson mass region. The top two rows of five histograms each of Fig. 3 show, respectively, the mass distributions of $(K\pi)^0$ and $\pi\pi$ systems. As may be noted, the main decay mode of the $K^*(1250)$ and $K^*(1320)$ resonances is $K^*(890)+\pi$; however, the $\rho+K$ decay mode is clearly present. We have also studied the five-particle final state $K^+\pi^+\pi^-\pi^0p$ and found no evidence for the $K\omega$ decay mode of the $K^*(1320)$.

To study the angular distributions we select only the $K^*+\pi$ events. As shown in Fig. 3(c), the distributions of the $K\pi$ scattering angle in the $(K\pi)^0$ rest frame, $\cos\alpha$, indicate that for Regions II and III the spin of $K^*(890)$ is aligned in such a way that the z component along the incident direction is zero.[22] This alignment is consistent with the interpretation that the $K^*(1250)$ and $K^*(1320)$ resonances are of $J^P = 1^+$, are produced by Pomeranchuk exchange, and decay mainly by s wave into $K^*(890)+\pi$. The decay angular distributions of $\cos\theta$, where θ is the angle between the odd π^+ and the incident K^+ in the $K\pi\pi$ rest frame, are largely isotropic, consistent with s wave, with possibly a small amount of d-wave contribution for Regions II and III, as shown in Figs. 3(d). Since, in the reaction $K^+p \to K^0\pi^+p$, we observe no evidence for the $K^0\pi^+$ decay of the $K^*(1250)$ and $K^*(1320)$, we conclude that the J^P assignment is not likely to be 1^- or 2^+. Figure 3(e) shows the $K^*(890)$ decay angular distribution of $\cos\xi$, where ξ is the $K^*(890)$ decay angle with respect to the odd-pion direction in the $K^*(890)$ rest frame. The distributions in Regions II and III are isotropic, which implies that the $J^P = 0^-$ assignment is unlikely, since it would predict a $\cos^2\xi$ distribution. Thus the likely J^P assignments for the $K^*(1250)$ and $K^*(1320)$ are 1^+ or 2^-. Although 2^- cannot be excluded, our data favor the assignment of 1^+ for both the $K^*(1250)$ and $K^*(1320)$ resonances. For a quantitative analysis of the angular distributions, interference effects with the $\rho+K$ events and background must be taken into account.

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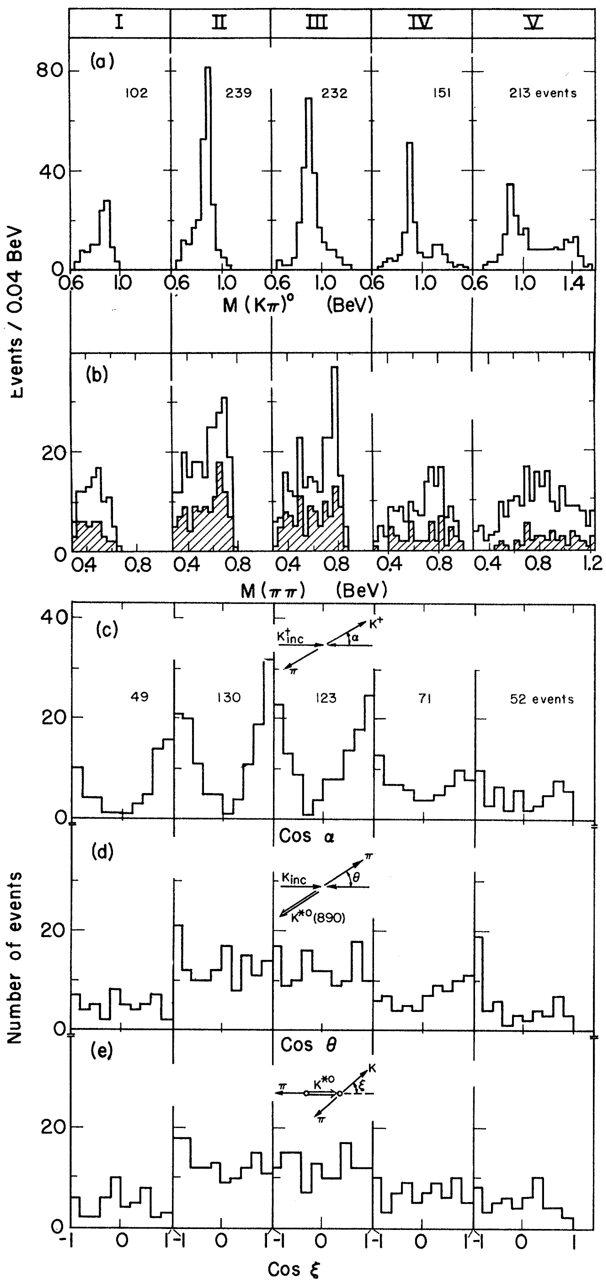

FIG. 3. The decay properties of the $K\pi\pi$ system shown for five $K\pi\pi$ mass regions I-V with N^{*++} band removed. (a) $M(K\pi)^0$; (b) $M(\pi\pi)$, the shaded histograms for events in the $K^{*0}(890)$ band and for $K^{*0}(890)$ events; (c) $\cos\alpha$, where α is the angle between the outgoing K and the incident K^+ in the $(K\pi)^0$ rest frame; (d) $\cos\theta$, where θ is the angle between the odd π^+ and the K^+ in the $(K\pi\pi)^+$ rest frame; (e) $\cos\xi$, where ξ is the angle between the outgoing K and the $K^{*0}(890)$ flight direction in the $K^{*0}(890)$ rest frame.

portant contributions in the earlier stages of the experiment. Finally we acknowledge the valuable support given by our programming and scanning staff, in particular D. Armstrong and E. R. Burns.

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[1]For earlier references on this subject see Gerson Goldhaber, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, 1966 (University of California Press, Berkeley, California, 1967), p. 103.

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[10]This resonance may be the same effect as that observed by Grard et al. and Shen et al. in the five-particle final states. See Ref. 1 for details and references.

[11]G. Goldhaber, following Letter [Phys. Rev. Letters 19, 976 (1967)].

[12]H. Foelsche, J. Lach, J. Sandweiss, and M. Gudzik, Brookhaven Alternating Gradient Synchrotron Report No. HF/JL/JS/MG-1, 1964 (unpublished).

[13]The Berkeley camera system was developed by Duane Norgren and Daniel Curtis. We wish to thank Daniel Curtis for his contribution during the exposure at the AGS.

[14]F. T. Solmitz, A. D. Johnson, and T. B. Day, Three-View Geometry Program, Alvarez Group Programming Note No. P-117 (unpublished); O. I. Dahl, T. B. Day, and F. T. Solmitz, SQUAW, Alvarez Group Programming Note No. P-126 (unpublished).

[15]The pion contamination of the K^+ beam is consistent with zero. The upper limit of 1.3% is a conservative estimate from a study of the elastic scattering events.

[16]The projected measured bubble density of the track

with proton interpretation is compared with that expected in all views. Tracks with interpretations other than proton are not used, since at our incident energy the K, π ambiguity is in most cases difficult to resolve.

[17]A comparison with visual identification indicates a maximum possible misidentification of 3% for Reactions (1) and (2).

[18]This enhancement was called the Q effect by the authors of Ref. 2. The quoted cross section, for the enhancement with N^{*++} removed, is estimated from Reactions (1) and (2) separately and corrected for invisible K^0 decays and FSD efficiencies.

[19]J. Bartsch et al. [Aachen-Berlin-CERN-Imperial College (London)-Vienna Collaboration], Phys. Letters 22, 357 (1966).

[20]The $K^*(890)$ mass band is defined from 860 to 940 MeV, whereas the ρ-meson band is defined from 650 to 850 MeV. The N^{*++} band is defined from 1160 to 1320 MeV.

[21]To avoid confusion in nomenclature we refer to the peak observed here at 1360 MeV as the $K^*(1320)$.

[22]It was observed in the study of $K^+p \to K^{+,0}\pi^{-,0}\pi^+p$ at 4.6 BeV/c (Ref. 8) that the $K^*(1320)$ resonance was mainly associated with the equatorial region of $\cos\alpha$. That observation is quite contrary to our data at 9 BeV/c, which indicate that both the $K^*(1250)$ and $K^*(1320)$ have $\cos^2\alpha$ shape distributions in the $K\pi$ scattering angle. One possible explanation for this difference is that the production mechanisms of the $K^*(1250)$ and $K^*(1320)$ may be a sensitive function of incident energy, giving rise to different decay angular distributions. This can also give rise to the energy dependence of the phase between the two resonance amplitudes, as described in Ref. 11. Without invoking the interference between these two resonances, it is difficult to account for all the different observations by various experimental groups at different incident momenta and the fact that the $K^*(1250)$ production rises extremely slowly with incident momentum far above its kinematical production threshold.

INTERFERENCE PHENOMENA ASSOCIATED WITH BOSON RESONANCE PRODUCTION*

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It is suggested that the peculiar variation in structure observed in the $K\pi\pi$ mass enhancement in the region 1.1 to 1.4 BeV as a function of incident momentum could be primarily due to interference between two resonances with the same J^P values.

As mentioned in the previous Letter,[1] the structure of the very large enhancement observed in the $K\pi\pi$ system in the mass region 1.1 to 1.5 BeV has shown distinct and statistically significant differences for various incident momenta. The $K\pi\pi$ enhancement can be separated into two parts: the $K^*(1420)$, and the region roughly between 1.1 and 1.4 BeV recently called the "Q enhancement."[2] We wish to suggest here that the observed variation in structure in the Q enhancement is primarily due to interference effects between two adjacent resonances with equal spin and parity. In addition, a coherent background term is probably also present and must be taken into account.[3] As has been suggested,[1] $J^P = 1^+$ is the most likely value for both K^* resonances as well as for the background.[3,4]

In general a mass distribution corresponds to an average over all decay angular distribution. Thus K^*'s with different J^P values, such as a 1^+ K^* and the 2^+ $K^*(1420)$, will not give an interference effect in the $K\pi\pi$ mass distributions. However, two K^*'s with equal J^P values will add coherently.

In what follows we consider a very simple model corresponding to the coherent addition of two resonances together with a third added incoherently.[5] Here we express each resonance by a Breit-Wigner amplitude and allow an arbitrary phase between two of them.

Let $B_k = \frac{1}{2}\Gamma_k/(E_k - E - i\frac{1}{2}\Gamma_k)$, with $k = 1$, 2, and 3, correspond to the Breit-Wigner amplitude for each of these resonances; then the resulting mass distribution can be expressed as

$$d\sigma/dM \propto (|a_1B_1 + B_2e^{i\varphi}|^2 + |a_3B_3|^2)P,$$

where E_k and Γ_k are the resonant masses and widths, respectively, φ is a relative phase angle, and a_1 and a_3 relative amplitudes, all of which must be determined from experiment, and P is a phase-space factor. As an illustration, this expression was evaluated for $E_1 = 1250$ MeV, $\Gamma_1 = 50$ MeV; $E_2 = 1320$ MeV, $\Gamma_2 = 80$ MeV; $E_3 = 1420$ MeV, $\Gamma_3 = 90$ MeV; $a_1 = 1$; $a_3 = 2^{-1/2}$; and values of φ from 0 to $9\pi/5$ in ten equal steps. Figure 1 shows the resulting