Single-Pion Production by 1.96-BeV/c K^+ Mesons*

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Single-pion production by K^+ mesons at a momentum of 1.96 BeV/c is shown to lead predominantly to K^*p and N^*K final states. Study of the dynamics of the reaction shows that the N^*K final state is produced almost entirely via vector exchange, whereas the K^*p final state seems to be produced partly via pion exchange and partly via vector exchange. Numerical values in terms of Gottfried and Jackson's parametrization of the spin-density matrix are given for the K^*p final state. Comparison with similar analyses at energies below and above this experiment indicates that a strong energy dependence of the vector-meson exchange contributes to the K^*p production. We show that the form factors used to fit the vector-meson-exchange contribution to these processes at 3 BeV/c do not fit the data at this energy.

I. INTRODUCTION

SINGLE-pion production by K^+ mesons proceeds via three reactions:

$$K^+ + p \to K^0 + \pi^+ + p\,, \tag{1}$$

$$K^+ + p \to K^+ + \pi^0 + p\,, \tag{2}$$

$$K^+ + p \to K^+ + \pi^+ + n\,. \tag{3}$$

In this note we report on our study of these reactions at an incident K^+ momentum of 1.96 BeV/c. The results indicate that we have observed the phenomenon common to the inelastic channels at high energies: the reaction is dominated by the production of quasi-two-body final states. We find that single-pion production at this energy proceeds mainly via

$$K^+ + p \to K + N^*(1238)\,, \tag{4}$$

or

$$K^+ + p \to K^*(888) + p\,. \tag{5}$$

In reaction (1) both these final states are produced with the largest branching ratio for the decay of each resonance. It is thus perhaps not surprising that this is the dominant reaction in single-pion production. We find that the decay distributions of the particles in channel (4) are in agreement with vector-meson exchange, and in particular with the predictions of a model by Stodolsky and Sakurai.[1] This we have shown earlier,[2] and—as has been observed in other experiments—at lower and higher energy.[3] In channel (5) the K^* is produced predominantly with small momentum transfer, suggesting a peripheral interaction. Analyzing the final-state decay correlation in terms of the K^* spin-density matrix as formulated by Gottfried and Jackson,[4] we find on comparison with other experiments that the vector-meson-exchange contribution to the total cross section increases with energy.

II. EXPERIMENTAL ANALYSIS

The experiment was carried out with the Brookhaven National Laboratory 20-in. hydrogen bubble chamber in the Brookhaven-Yale beam of the Alternating-Gradient Synchrotron. The beam design and performance have been described.[5]

All together, 20 000 frames were exposed to a 1.96-BeV/c separated K^+ beam. The pion contamination was determined to be 0.25%.[6] We found that by scanning the film twice we could achieve a scanning efficiency approaching 100% for the various final states. The events have been measured on a digitized measuring machine (Franckenstein) and processed with the kinematical fitting programs PANG and KICK[7] on the IBM 7090 computer. The events have two topologies.

(a) Two Charged Particles with an Associated Charged Decay of a V^0 in the Final State

An attempt was made to fit the V^0 to the decay modes

$$K^0 \to \pi^+ + \pi^- \quad \text{and} \quad \Lambda^0 \to \pi^- + p\,.$$

No events were found that fitted the Λ^0 decay mode. Each event was then again examined and was accepted if the result of the kinematical fitting was consistent with the bubble density observed on the scan table. No ambiguities were found among events of this topology.

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[1] L. Stodolsky and J. J. Sakurai, Phys. Rev. Letters **11**, 90 (1963); L. Stodolsky, Phys. Rev. **134**, B1099 (1964).

[2] S. Goldhaber, W. Chinowsky, G. Goldhaber, and T. O'Halloran, Bull. Am. Phys. Soc. **8**, 20 (1963); S. Goldhaber, in *Proceedings of the Conference on Fundamental Particle Resonances* (Ohio University Press, Athens, Ohio, 1963), p. 92.

[3] B. Kehoe, Phys. Rev. Letters **11**, 93 (1963); G. B. Chadwick, D. J. Crennell, W. T. Davies, M. Derrick, J. H. Mulvey, P. B. Jones, D. Radojicic, C. A. Wilkinson, A. Battini, M. Cresti, S. Limentani, L. Peruzzo, and R. Santanzelo, Phys. Letters **6**, 309 (1963); E. Boldt, J. Duboc, N. H. Duong, P. Eberhard, R. George, V. P. Henri, F. Levy, J. Poyen, M. Pripstein, J. Crussard, and A. Tran, Phys. Rev. **133**, B220 (1964); M. Ferro-Luzzi, R. George, G. Goldschmidt-Clermont, V. P. Henri, B. Jonejans, D. W. G. Leith, G. R. Lynch, F. Muller, and J. M. Perreau, Nuovo Cimento (to be published).

[4] K. Gottfried and J. D. Jackson, Nuovo Cimento **33**, 309 (1964); Phys. Letters **8**, 144 (1964).

[5] C. Baltay, J. Sandweiss, J. Sanford, H. Brown, M. Webster, and S. Yamomoto, Nucl. Instr. Methods **20**, 37 (1963); J. Leitner, G. Moneti, and N. P. Samios, *ibid.* **20**, 42 (1963).

[6] W. Chinowsky, G. Goldhaber, S. Goldhaber, T. O'Halloran, and B. Schwarzschild, Phys. Rev. **139**, B1411 (1965).

[7] Arthur H. Rosenfeld, editor, Reference Manual for KICK, Lawrence Radiation Laboratory Report UCRL-9099, 1961 (unpublished).

(b) Two Charged Particles in the Final State

Events in this category can be either elastic events, which are kinematically fitted with four constraints, or inelastic, which can be kinematically fitted with one constraint only. Since the one-constraint fits usually give ambiguities in the fitted events, it was necessary to rely on bubble-density criteria to distinguish among the possible final states. To do this, we have limited ourselves to those rolls of film in which the bubble density and contrast made the evaluation of track identity reliable. In selecting the track identity by adding ionization criteria to the kinematic fitting, it was possible to resolve the ambiguities in this topology for 80% of the events. The remaining 20% of this sample of events are selected on the basis of the lowest χ^2 value for the kinematic fitting. These events are found to fall into the different final states in ratios consistent with the unambiguous events. The cross sections are determined by normalizing to the events belonging to topology (a). These have appeared elsewhere.[6]

We used the events from reaction (1) with visible K^0 decays to determine the mass resolution in the experiment as well as to check the entire analysis procedure. We fitted these events by considering the K^0 decay as having occurred at the primary vertex, simulating the reaction $K^+ + p \rightarrow \pi^+\pi^-\pi^+ p$. We then calculated the invariant mass of the appropriate $\pi^+\pi^-$ pair. In order to study the mass resolution for one-constraint fits the π^- track was deleted from the fitting program for this sample of events. The weighted mean value of the K^0 mass for the four-constraint fit is 499.0±0.2 MeV, and for the one-constraint fit 498.0±0.5 MeV. The error quoted in both cases is statistical only. The full width at half-maximum for four-constraint fits is 7.4 Mev, and for one-constraint fits 21.8 MeV. The comparison of the experimental resolution for one-constraint and four-constraint fits is shown in Fig. 1.

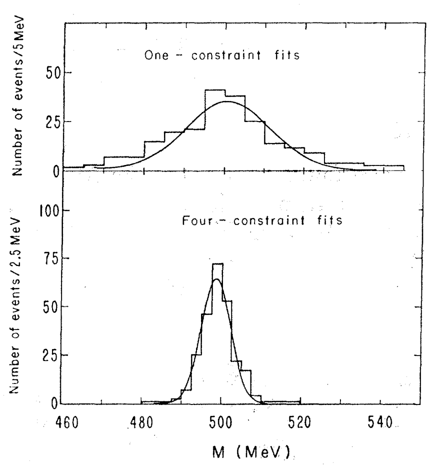

FIG. 1. Invariant mass distribution of the pions from K_1^0 decay. For one-constraint fits, the full width at half-maximum is 21.8 MeV. For the four-constraint fits the full width at half-maximum is 7.4 MeV.

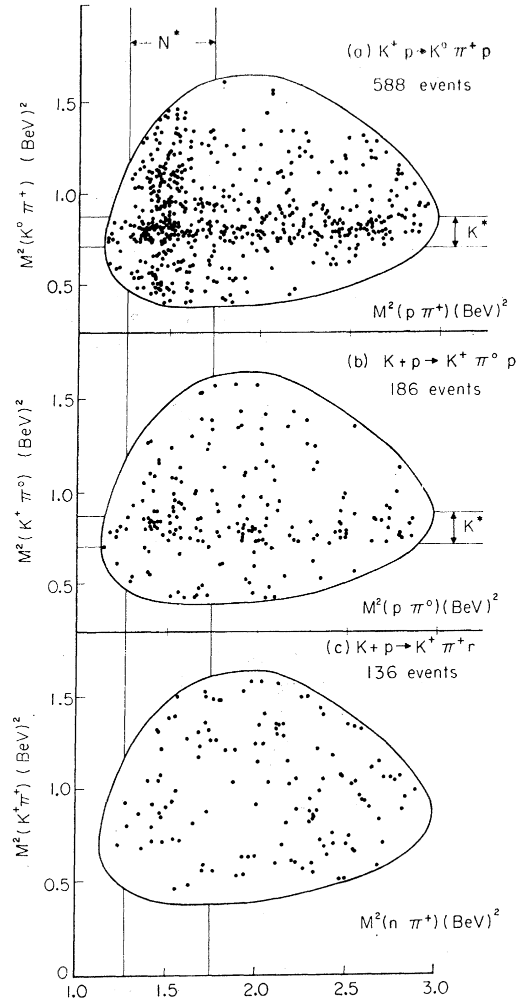

FIG. 2. Dalitz plots for the 3-body final state. The K^* is defined as $840 \leqslant M_{K\pi} \leqslant 940$ MeV. The N^* is defined as $1120 \leqslant M_{p\pi} \leqslant 1320$ MeV.

III. EXPERIMENTAL RESULTS

The Dalitz plots for the three reactions, (1), (2), and (3), are shown in Fig. 2. Reactions (1) and (2) can proceed via the resonant final states K^*p and KN^*, while reaction (3) can proceed only via K^+N^*; nonresonating background also contributes to each. An inspection of the Dalitz plots shows clearly that reactions (1) and (2) are dominated by resonance formation. In order to examine these processes in detail we shall in what follows concentrate on reaction (1).[8]

To separate the events into two final states we have made use of a technique introduced by Eberhard and Pripstein.[9] For each event in one of the resonant bands outside the overlap region of the two resonances we have defined a conjugate mass by reversing the direc-

[8] In this sample of 588 events we find 311 events belonging to topology (a) and 277 to topology (b), which includes 27 ambiguous events.

[9] P. Eberhard and M. Pripstein, Phys. Rev. Letters **10**, 351 (1963).

tion of the particles forming the resonance in the rest system of the resonance. Although this does not change the invariant mass of the resonating pair, it does give another value for the mass of the nonresonating pair. If the resonance is a *pure state*, parity conservation gives the mass-conjugate state an equal probability of being formed. We can now examine the overlap region for possible interferences between the two resonances by removing all events in the overlap region and repopulating this region with the mass-conjugated events. By this procedure we remove 100 events and repopulate the region with 103 events. This result indicates that the interference between the two final states is small, and we neglect it. In our analysis we examine the decay distributions of the K^* and N^* resonances. When we examine the K^* we remove the effect of the N^* events by subtracting the conjugated N^* events (or for N^*, the effect of the K^* by subtracting the conjugated K^*).

We find for reaction (1) that 29% of the final state corresponds to K^*p and 49% to K^0N^*. The remaining 22% of the events in this channel are not associated with a specific resonance formation, and are thus attributed to "phase space." The corresponding cross sections are, respectively, 1.3 ± 0.2, 2.3 ± 0.3, and 1.0 ± 0.2 mb. The cross sections for these channels were obtained by defining the K^* and N^* bands by $840\leqslant M_{K^0\pi^+}\leqslant 940$ MeV and $1120\leqslant M_{p\pi^+}\leqslant 1320$ MeV, respectively.

(a) The Final State K^0N^*; $N^{*++}\rightarrow p\pi^+$

This final state cannot be produced with one-pion exchange without violating parity or angular-momentum conservation at the $KK\pi$ vertex. The simplest process involving a single-particle exchange, therefore, must be a vector-meson exchange. Stodolsky and Sakurai[1] have proposed an analogy between the photoproduction of the N^* and production of an N^* by a virtual ρ meson. This predicts an $M1\rightarrow P_{3/2}$ coupling at the $p\rho N^*$ vertex. (Isoscalar exchange such as an ω is forbidden for this charge configuration.) The distribution W predicted by this model for the angle γ between the normal to the production plane and the direction of the decay pion in the rest frame of the N^* is

$$W(\cos\gamma)=1+3\cos^2\gamma. \qquad (6)$$

The prediction for the Treiman-Yang angle ϕ is

$$W(\phi)=1+2\sin^2\phi. \qquad (7)$$

The experimental distributions are compared with the theoretical predictions in Fig. 3. The shaded area represents the result after the mass-conjugated K^* events which are in the double-resonant region are subtracted. These angular distributions are in good agreement with the proposed model, as has been observed in other experiments.[3]

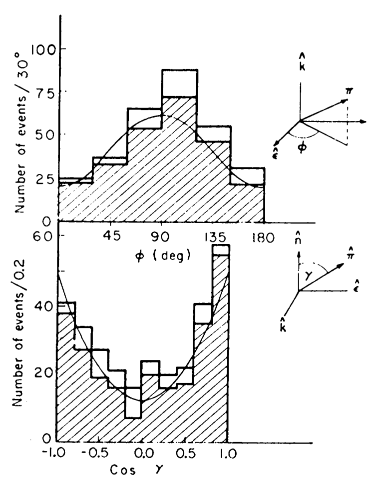

FIG. 3. Decay distributions for the N^* in the rest system of the N^*. Here γ is the angle between the normal to the production plane and the direction of the pion in the N^* rest system. The angle ϕ is the Treiman-Yang angle. The curves shown are the Stodolsky-Sakurai predictions for the angles γ and ϕ.

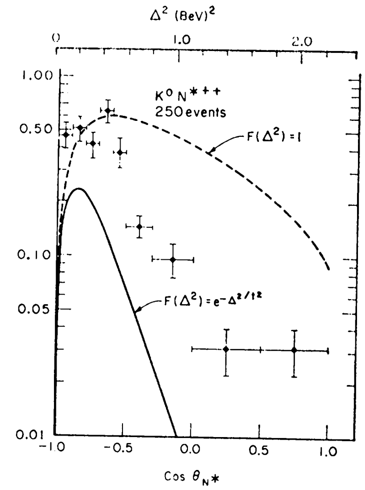

FIG. 4. The N^* differential cross section for the channel $K^++p\rightarrow K^0+N^*$ at 1.96 BeV/c. The curves are calculated by using (8) as described in the text with and without the form factor.

Jackson and Pilkhun,[10] using the Stodolsky-Sakurai model, have calculated the N^*-production differential cross section. It is given by

$$\frac{d\sigma}{d\Omega}=\frac{2q'}{3sq}\frac{g^2}{4\pi}\frac{G^2}{4\pi}\frac{1}{(M_p+M_{N^*})^2}\left|\frac{F(\Delta^2)}{M_\rho^2+\Delta^2}\right|^2 \times\left\{sq^2q'^2\sin^2\theta\left[\frac{3M_{N^*}^2+M_p^2+\Delta^2}{M_{N^*}^2}\right] +\tfrac{1}{4}[(M_p-M_{N^*})^2+\Delta^2][\Delta^2+(M_{K^+}-M_{K^0})^2] \times[\Delta^2+(M_{K^+}+M_{K^0})^2]\right\}, \qquad (8)$$

where $g^2/4\pi$ is the coupling at the meson vertex, $G^2/4\pi$ is the coupling at the baryon vertex, q is the c. m. momentum of the K^+, q' is the c. m. momentum of the K^0, s is the square of the total energy in the c. m. system, and $F(\Delta)^2$ is the form factor.

[10] J. D. Jackson and H. Pilkhun, Nuovo Cimento **33**, 906 (1964); **34**, 1841 E (1964).

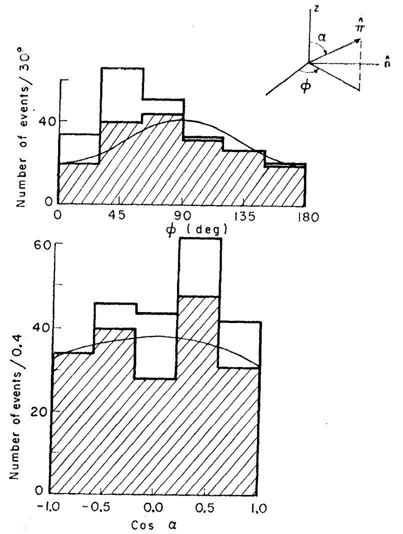

FIG. 5. Decay distributions for the K^* in the rest system of the K^*. The z axis is the direction of the incident K^+. The y axis is the production normal, $\hat{n}$. The curves are the best fits of the spin-density matrix parameters in (10) and (11) of the text.

A good fit to the experimental data[3] at 3 BeV/c was obtained by using (8) with $F(\Delta^2)=\exp(-\Delta^2/t^2)$, $t=0.72$ BeV, and $(g^2/4\pi)(G^2/4\pi)=19$. We have tested whether these same parameters will also fit our data at 1.96 BeV/c. In Fig. 4 we show the differential cross section. The dashed curve corresponds to the evaluation of Eq. (8) without the inclusion of a form factor, i.e., $F(\Delta^2)=1$. The solid curve corresponds to (8) with the parameters used at 3 BeV/c.

It is evident from comparing the dashed curve with the plots of the experimental data in Fig. 4 that some modification of the model expressed by (8) is required. It is also apparent that the form-factor parametrization used to fit the 3-BeV/c experiment does not fit our data. A unique *energy-independent* form factor such as used here is thus not adequate to fit both sets of data.

It has been pointed out[11] that an alternative or perhaps additional modification of the simple peripheral model is called for because of the presence of competing inelastic reactions. These reactions give rise to a damping of the low partial-wave reaction amplitudes. This phenomenon is referred to as the absorption effect. In this paper we have not attempted to include these effects.

(b) The Final State $K^{*+}p$; $K^{*+}\to K^0\pi^+$

This final state can proceed via π, ρ, or ω exchange. The general angular distribution for the decay product in the rest system of the resonance is, in terms of density matrix elements,[4]

$$W(\cos\alpha,\phi)=(3/4\pi)(\rho_{0,0}\cos^2\alpha+\rho_{1,1}\sin^2\alpha -\rho_{1,-1}\sin^2\alpha\cos 2\phi-\sqrt{2}\,\mathrm{Re}\rho_{1,0}\sin 2\alpha\cos\phi)\,, \quad (9)$$

where the z axis is the direction of the incoming K^+ meson in the rest frame of the K^*, and the x-z plane is the plane of production. Integrating over ϕ or $\cos\alpha$, we obtain

$$W(\cos\alpha)=\tfrac{3}{4}[(1-\rho_{0,0})+(3\rho_{0,0}-1)\cos^2\alpha]\,, \quad (10)$$

$$W(\phi)=(1/2\pi)[1-2\rho_{1,-1}+4\rho_{1,-1}\sin^2\phi]\,. \quad (11)$$

In order to determine the parameter $\mathrm{Re}\rho_{1,0}$ of the spin density matrix we average over $\sin 2\alpha\cos\phi$, obtaining

$$\mathrm{Re}\rho_{1,0}=-(5/4\sqrt{2})\langle\sin 2\alpha\cos\phi\rangle\,. \quad (12)$$

If absorption effects are negligible there will be no interference between pseudoscalar and vector exchange, i.e., $\rho_{1,0}=0$. Furthermore $\rho_{0,0}$ then measures the fraction of the total cross section proceeding by one-pion exchange. Best fits to the angular distributions are shown in Fig. 5. The fit has been obtained on the data from which the mass-conjugated N^* events have been removed (shaded in the figure). From these curves we obtain

$$\rho_{0,0}=0.30\pm0.05 \quad\text{and}\quad \rho_{1,-1}=0.18\pm0.07.$$

Furthermore, we find $\mathrm{Re}\rho_{1,0}=0.05\pm0.02$ from the average indicated in Eq. (12). In Fig. 6 is shown the differential cross section for the K^{*+} production decaying by the $K^0\pi^+$ mode. Again the predominance of small momentum transfer indicates a peripheral type of interaction. Neglecting interference effects, one can write the differential cross section as[10]

$$\frac{d\sigma}{d\Omega}=\frac{d\sigma_p}{d\Omega}+\frac{d\sigma_v}{d\Omega}\,, \quad (13)$$

where

$$\frac{d\sigma_p}{d\Omega}=\frac{2q'}{3sq}\frac{g_{K^*}^2}{4\pi}\frac{G^2}{4\pi}\frac{\Delta^2}{4M_{K^*}^2}\times\frac{[\Delta^2+(M_K-M_{K^*})^2][\Delta^2+(M_K+M_{K^*})^2]}{(M_\pi^2+\Delta^2)^2}\,, \quad (14)$$

s is the total energy in the c. m. system, squared, q' is

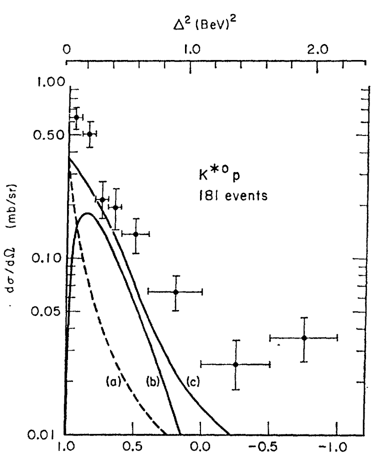

FIG. 6. The differential cross section of the K^*. The curves represent the differential cross section for (a) pion exchange, (b) omega exchange, and (c) the sum of the two contributions.

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[11] N. J. Sopkovich, Nuovo Cimento **26**, 186 (1962); A. Dar, M. Kugler, Y. Dothan, and S. Nussinov, Phys. Rev. Letters **12**, 82 (1964); L. Durand, III, and Y. T. Chiu, *ibid.* **12**, 399 (1964); M. H. Ross and G. L. Shaw, *ibid.* **12**, 627 (1964); K. Gottfried and J. D. Jackson, Nuovo Cimento **34**, 735 (1964).

the c. m. momentum of the K^*, q is the c. m. momentum of the K^+, $g^2K^*/4\pi$ is the $K^+\pi^0K^{*+}$ coupling constant $=0.75$, $G^2/4\pi$ is the $p\pi N$ coupling constant$=15$, Δ^2 is the momentum transfer to the K^*, and

$$\frac{d\sigma_v}{d\Omega}=\frac{q'}{3M_{K^*}^2q}\frac{f^2}{4\pi}\frac{1}{(M_v^2+\Delta^2)^2}\times\left\{\frac{(G_v+G_T)^2}{4\pi}\frac{\Delta^2}{4}[\Delta^2+(M_K-M_{K^*})^2]\times[\Delta^2+(M_K+M_{K^*})^2]+2sq^2q'^2\times\sin^2\theta\left[\frac{G_v^2}{4\pi}+\frac{G_T^2}{4\pi}\frac{\Delta^2}{4M_p^2}\right]\right\}, \quad (15)$$

$f^2/4\pi$ is the KVK^* coupling constant, $G_v^2/4\pi$ and $G_T^2/4\pi$ are the vector-meson–proton coupling constants.

Comparison of the data with the shape of the differential cross section given by these formulas shows a poor fit, indicating the need for inclusion in the calculation of either the effect of absorption in the initial or final state (or both) or of form factors. From the cross section for reaction (1) proceeding by channel (5) and the value we obtained for ρ_{00}, we estimate the partial cross sections of the pseudoscalar and vector-exchange contributions. These are, respectively, 0.4 ± 0.1 and 0.9 ± 0.2 mb. Here we must note that experimentally we know only the integrals over the two differential cross sections and their combined shape, but not the individual shapes. We now attempt to fit the pseudoscalar and vector parts of the cross section by Eqs. (14) and (15) suitably modified by form factors. In the case of the pseudoscalar part we modify Eq. (14) by the introduction of a form factor $|F(\Delta^2)|^2$. Here we use the analytic form $F(\Delta^2)=(\Lambda^2-M_\pi^2)/(\Delta^2+\Lambda^2)$, where $\Lambda^2=0.165$ $(\text{BeV})^2$. This form factor has been used previously to calculate the reaction $K^++p\rightarrow K^*+N^*$, which proceeds mostly via one-pion exchange and has given reasonable fits[12] to the measured cross sections at 1.96 and 3.0 BeV/c. Upon integration of (14) with this form factor, we obtain a total cross section of 0.30 mb, in reasonable agreement with the experimental result. In order to determine the vector meson contribution we have used (15) modified by the form factor,

$$F(\Delta^2)=\exp(-\Delta^2/t_0^2),$$

where

$$t_0^2=0.49(\text{BeV})^2, \quad (f^2/4\pi)\times(G^2_v/4\pi)=12,$$

and $G_T=0$, which, for ω exchange, gave a good fit[13] to the K^* production at 3 BeV/c. Here the integrated cross section is 0.45 mb which is significantly lower than the experimental value of 0.9 ± 0.2 mb. The curves obtained for the pion-exchange and ω-exchange contributions are shown on Fig. 6 also.

We conclude that the vector-exchange form factor used in the parameterization for the 3-BeV/c data does not reproduce our data at 1.96 BeV/c. On the other hand, the form factor and parameterization used for the pseudoscalar exchange in the K^*N^* final state, both at 1.96 and at 3 BeV/c, are in reasonable agreement with our data here.

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[12] G. Goldhaber, W. Chinowsky, S. Goldhaber, W. Lee, and T. O'Halloran, Phys. Letters 6, 62 (1963) [a factor of $\frac{2}{3}$ was omitted in the calculation of the cross section in this reference. The correct value of Λ^2 is 0.165 $(\text{BeV})^2$]; M. Ferro-Luzzi, R. George, Y. Goldschmidt-Clermont, V. P. Henri, B. Jongejans, D. W. G. Leith, G. R. Lynch, F. Muller, and J. M. Perreau, Nuovo Cimento (to be published).

[13] A study of the reaction $K^++n\rightarrow K^{*0}+p$ and $K^++p\rightarrow K^{*+}+p$ at 2.3 BeV/c has shown that the vector exchange mechanism is predominantly isoscalar; S. Goldhaber *et al.*, in *Proceedings of the International Conference on High Energy Physics, Dubna, 1964* (Atomizdat, Moscow, 1965).