K^+d PARTIAL CROSS SECTIONS AROUND 1 BeV/c*

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We present partial cross sections for K^+d and isospin-0 KN scattering around 1 BeV/c.

The K^+p and K^+d total cross sections, accurately measured by Cool et al.[1] and Bugg et al.,[2] have similarly shaped asymmetric peaks near 1 BeV/c. The K^+p cross section is the isospin-1 KN cross section. The isospin-0 cross section is extracted from the K^+p and K^+d cross sections using approximations the validity and effect of which are not entirely known. The cross section so deduced has a peak, also near 1 BeV/c, that is larger, narrower, and more symmetric than the isospin-1 peak. Peaks in πN and $\bar{K}N$ cross sections are almost always attribted to resonances. However the repercussions of the existence of KN resonances are severe. In particular, all well-established strongly interacting particles and resonances have quantum numbers that permit their classification as quark-antiquark (meson) or triple-quark (baryon) states, and KN resonances will not fit into this scheme.

Bland et al.[3] studied K^+p reactions around 1 BeV/c and found that the peak in the total cross section was due to the rapid increase of the single-pion production cross section near the thresholds for the quasi-two-body channels $K\Delta(1236)$ and $K^*(890)N$. A partial-wave analysis of the reaction $K^+p \to K\Delta$ revealed no rapid variation of any phase. They concluded that there was no evidence requiring or even strongly suggesting a resonance in the K^+p channel.

We have measured some of the K^+d partial cross sections around 1 BeV/c, and calculated most of the others using relations derived from isospin conservation and data from the experiments mentioned above. We also extracted isospin-0 partial cross sections. These lead to a better understanding of the nature of this channel, but are not sufficient to confirm or deny the existence of a resonance.

The results were obtained from a 100 000-picture exposure of the Lawrence Radiation Laboratory 25-in. bubble chamber, filled with deuterium, to a separated K^+ beam at 863, 968, 1211, and 1364 MeV/c. The film was scanned twice for events with a "vee" ($K^0 \to \pi^+\pi^-$ decay) or with more than two outgoing charged tracks. An event with an uneven number of outgoing charged tracks was either a K^+ decay or a K^+d interaction in which the proton in the deuteron was spec-

tator to an interaction on the neutron and did not have enough momentum to make a visible track. In the latter case, the absence of a track constitutes a measurement ipso facto, and in fitting we assigned to the unseen proton a momentum of zero with an uncertainty appropriate to a proton too slow to be visible. Events were measured on the Lawrence Radiation Laboratory flying-spot digitizer or on a Franckenstein, and were processed with the programs SIOUX and ARROW. At these energies, events fitting more than one hypothesis could be resolved unambiguously by looking at track ionization. Failing events were remeasured until their number was reduced to an insignificant level. We found 3166 events with a K^+ and 5504 events with a K^0 in the final state. Cross sections were normalized with 2727 $K^+ \to \pi^+\pi^+\pi^-$ decays. In obtaining cross sections, K^0 events were weighted for decay into neutrals or outside the bubble chamber or too close to the production vertex for the "vee" to be seen as such.

(1) <u>Directly measured cross sections.</u>—The reactions that occur at these energies are the following:

$$K^+d \to KNN \to [K^+pn]$$
$$\to K^0pp$$
$$\to KNN\pi \to [K^+nn\pi^+]$$
$$\to K^0pn\pi^+$$
$$\to K^+pp\pi^-$$
$$\to [K^+pn\pi^0]$$
$$\to K^0pp\pi^0$$
$$\to KNN\pi\pi \to K^0nn\pi^+\pi^+$$
$$\to K^+pn\pi^+\pi^-$$
$$\to K^0pp\pi^+\pi^-$$
$$\to [K^+nn\pi^+\pi^0]$$
$$\to K^0pn\pi^+\pi^0$$
$$\to K^+pp\pi^-\pi^0$$
$$\to [K^+pn\pi^0\pi^0]$$
$$\to K^0pp\pi^0\pi^0. \tag{1}$$

Reactions in which the deuteron is left intact are implicitly included with those with a proton and neutron in the final state. We measured cross sections for the reactions not enclosed in brackets. The reactions are arranged according to the charge states of the pions, for reasons that will become clear. The symbol σ_{c0}, for example, will represent the sum of all cross sections leading to one charged and one neutral pion. Thus the total $K^+d \rightarrow KNN\pi$ cross section is $\sigma_c + \sigma_0$, and the total $K^+d \rightarrow KNN\pi\pi$ cross section is $\sigma_{cc} + \sigma_{c0} + \sigma_{00}$.

Figure 1(a) shows the cross sections we measured. The $K^+d \rightarrow K^0pp$ cross section falls off smoothly with increasing momentum. The single-pion production cross sections rise rapidly until about 1.2 BeV/c and then level off; they all have about the same shape, though they differ in size. The double-pion production cross sections (only the sum of the measured cross sections is shown) are extremely small until 1.2 BeV/c, after which they begin to rise. The thresholds for single- and double-pion production on deuterons
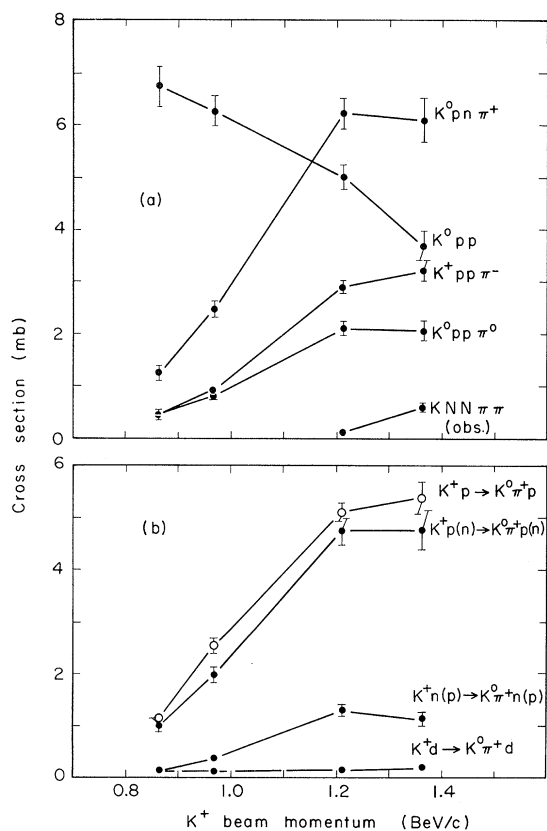

FIG. 1. (a) K^+d partial cross sections measured in this experiment. (b) Components of the $K^+d \rightarrow K^0pn\pi^+$ cross section. Also shown is the $K^+p \rightarrow K^0\pi^+p$ cross section measured by Bland et al. (Ref. 3).

are 0.45 and 0.70 BeV/c. (On free nucleons, the thresholds are 0.51 and 0.81 BeV/c.) The cross sections are small until well above the thresholds. In fact, they remain small until thresholds for K^* and N^* production are approached (see below).

Reactions such as $K^+d \rightarrow K^0pp$, $K^+d \rightarrow K^0pp\pi^0$, and $K^+d \rightarrow K^+pp\pi^-$, with two final-state protons, necessarily involve the neutron in the target deuteron as more than a spectator. To the extent that one nucleon in the deuteron is only a spectator to the interaction of the incident K^+ with the other nucleon (an assumption we shall often make), these reactions take place on the neutron, and the cross sections give a somewhat distorted picture of free-neutron cross sections. In contrast, the $K^0pn\pi^+$ final state can come from interaction of the K^+ with either of the target nucleons (or from $K^+d \rightarrow K^0\pi^+d$). Figure 1(b) shows the division of the $K^+d \rightarrow K^0pn\pi^+$ cross section with the spectator nucleon indicated by parentheses.[4] Also shown is the $K^+p \rightarrow K^0\pi^+p$ cross section measured by Bland et al.[3] The difference between the $K^+p \rightarrow K^0\pi^+p$ and $K^+p(n) \rightarrow K^0\pi^+p(n)$ cross sections is small and is consistent with a rough calculation of the effect of eclipsing and motion of the nucleons within the deuteron.

(2) Isospin conservation and K^+d reactions. —Isospin conservation provides one linear relation between the $KNN\pi$ cross sections and one between the $KNN\pi\pi$ cross sections. The relations are[5]

$$\sigma_c = 2\sigma_0, \tag{2a}$$

$$2\sigma_{cc} = 4\sigma_{00} + \sigma_{c0}. \tag{2b}$$

We can now write the total $KNN\pi$ and $KNN\pi\pi$ cross sections in various ways, eliminating one or another of the constituent parts:

$$\sigma(KNN\pi) = \sigma_c + \sigma_0, \tag{3a}$$

$$= 3\sigma_0, \tag{3b}$$

$$= \tfrac{3}{2}\sigma_c; \tag{3c}$$

$$\sigma(KNN\pi\pi) = \sigma_{cc} + \sigma_{c0} + \sigma_{00}, \tag{4a}$$

$$= 3(\sigma_{cc} - \sigma_{00}), \tag{4b}$$

$$= \tfrac{3}{2}(\sigma_{c0} + 2\sigma_{00}), \tag{4c}$$

$$= \tfrac{3}{4}(\sigma_{c0} + 2\sigma_{cc}). \tag{4d}$$

We have not measured all of either σ_C or σ_0 [see Eq. (1)], nor all of any two of σ_{CC}, σ_{C0}, and σ_{00}. However we can still use the equations to obtain $\sigma(KNN\pi)$ and $\sigma(KNN\pi\pi)$.

To complete σ_C we need the $K^+d \rightarrow K^+nn\pi^+$ cross section. Here if the incident K^+ interacts with only one of the nucleons in the deuteron, it interacts with the proton. In view of the comparison made in Fig. 1(b) we may expect the approximation

$$\sigma(K^+d \rightarrow K^+nn\pi^+) \approx \sigma(K^+p \rightarrow K^+\pi^+n) \qquad (5)$$

to be good to 10 or 20%. The $K^+p \rightarrow K^+\pi^+n$ cross section has been measured by Bland et al.[3] It is small, being never more than one tenth the sum of the other, directly measured parts of σ_C. Since the latter is measured to about 5%, Eq. (5) would have to be wrong by 50% to affect the value of σ_C obtained using it by as much as a standard deviation. Small corrections to the approximation are inconsequential, especially since we double the quoted errors on $\sigma(K^+p \rightarrow K^+\pi^+n)$. Thus with Eq. (5) we complete σ_C, and with Eq. (3c) obtain $\sigma(KNN\pi)$.

Equations (4a)-(4d) for $\sigma(KNN\pi\pi)$ become in-equalities if we put on the right just the measured parts of σ_{CC}, σ_{C0}, and σ_{00}. Since all of σ_{CC} is measured, Eq. (4b) gives an upper limit to $\sigma(KNN\pi\pi)$. The other three inequalities give lower limits, from which we may choose whichever is most restrictive. We then assign to $\sigma(KNN\pi\pi)$ the value midway between upper and lower limits, and fold together half the difference between the limits and the statistical uncertainty on them for an error.

Finally, subtracting the pion production cross sections from the total cross section gives the $K^+d \rightarrow KNN$ cross section. Subtracting the $K^+d \rightarrow K^0pp$ cross section from this gives the $K^+d \rightarrow K^+pn$ cross section (this includes $K^+d \rightarrow K^+d$). Figure 2 shows the results. Also shown are the total-cross-section data from Cool et al.[1] and Bugg et al.[2] and some partial-cross-section data from Slater et al.[6] and Butterworth et al.[7] The most striking feature is the abrupt rise of the single-pion production cross section to 15 mb at 1.2 BeV/c. As this is accompanied by a less precipitous fall of the KNN cross section, the total cross section increases by only about 10 mb. The onset of double-pion production, by which time the single-pion production cross section has leveled off, causes no marked change of the total cross section.
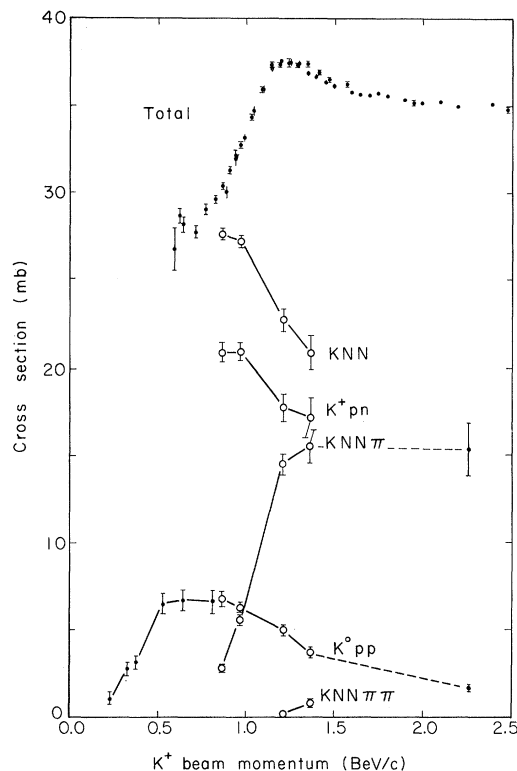
(3) Isospin conservation and K^+N reactions.

FIG. 2. K^+d total and partial cross sections. Total cross sections are from Cool et al. (Ref. 1) and Bugg et al. (Ref. 2). The $K^+d \rightarrow K^0pp$ cross sections at low momenta are from Slater et al. (Ref. 6). The points at 2.26 BeV/c are from Butterworth et al. (Ref. 7).

—There are seven charge states for single-pion production in K^+N reactions:

$$K^+p \rightarrow K^0\pi^+p,$$
$$\rightarrow K^+\pi^+n,$$
$$\rightarrow K^+\pi^0p;$$
$$K^+n \rightarrow K^0\pi^+n,$$
$$\rightarrow K^0\pi^0p,$$
$$\rightarrow K^+\pi^0n,$$
$$\rightarrow K^+\pi^+p; \qquad (6)$$

we use σ_p and σ_n to represent the sums of the K^+p and K^+n cross sections, respectively. There are 11 charge states for double-pion production. Isospin conservation provides one linear relation between the $KN\pi$ cross sections and one between the $KN\pi\pi$ cross sections. The relations are again Eqs. (2), in which the symbols now refer to a different set of reactions but are defined, as before, in terms of the charge states of the pions.

The cross sections for single-pion production

1487

through the isospin-0 and -1 channels are

$$\sigma_1(KN\pi) = \sigma_p,$$ (7a)

$$\sigma_0(KN\pi) = 2\sigma_n - \sigma_p.$$ (7b)

From Eqs. (7b) and (2a) one can obtain

$$\sigma_0(KN\pi) = 3[\sigma(K^+n \to K^0 n^+ n) + \sigma(K^+n \to K^+\pi^- p)$$
$$-\sigma(K^+p \to K^+\pi^0 p)],$$ (8)

in which only three of the seven $KN \to KN\pi$ cross sections appear. The $K^+p \to K^+\pi^0 p$ cross section has been measured by Bland et al.[3] The other two are approximately equal to the $K^+n(p)$ $\to K^0\pi^+ n(p)$ and $K^+d \to K^+ p p \pi^-$ cross sections shown in Fig. 1. To get free-neutron cross sections from these, we have multiplied them at each momentum by the corresponding ratio of the $K^+p \to K^0\pi^+ p$ to $K^+p(n) \to K^0\pi^+ p(n)$ cross sections shown in Fig. 1(b). Although it is not strictly valid to apply to one channel the free-to-bound-nucleon cross-section ratios found in another, the errors on the ratios were probably large enough to encompass channel-to-channel variations, and they were propagated.[8] Figure 3
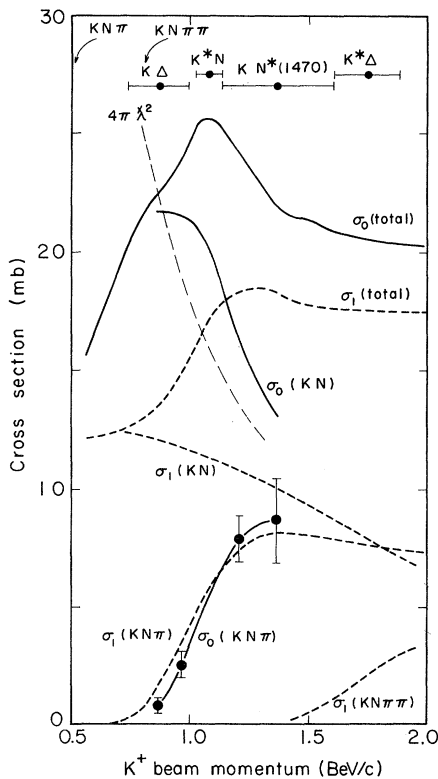

FIG. 3. KN total and partial cross sections. Subscripts indicate isospin. Total cross sections are from Carter (Ref. 9). Isospin-1 partial cross sections are adapted from the compilation of Bland et al. (Ref. 3).

shows the values of $\sigma_0(KN\pi)$ we obtained. Also shown are total cross sections from Carter[9] and isospin-1 partial cross sections adapted from a compilation made by Bland et al.[3] The smooth curve labeled $\sigma_0(KN\pi)$ was subtracted from σ_0(total) to get the elastic scattering cross section $\sigma_0(KN)$. We were not able to extract reliable values of $\sigma_0(KN\pi\pi)$, but even at 1364 MeV/c it is too small to do more than slightly reduce $\sigma_0(KN)$.

We remark that in the region of the peak and below, the values of σ_0(total) that appear in the literature are in only qualitative agreement.[1,2,9] Below 1 BeV/c, even the purely statistical errors amount to 1 or 2 mb, and the elastic cross section is correspondingly uncertain. At low momenta, the total and elastic cross sections are equal, and their qualitative behavior is indicated by the low-momentum limit $\sigma = 4\pi A^2$, where A is the s-wave zero-effective-range scattering length. The lengths $A_0 = 0.04 \pm 0.04$ F[10] and $A_1 = -0.30 \pm 0.01$ F[11] give cross sections $\sigma_0 = 0.2^{+0.6}_{-0.2}$ mb and $\sigma_1 = 11.3 \pm 0.8$ mb. These strikingly dissimilar values make clear that σ_0(total), in contrast to σ_1(total), falls off rapidly at low momenta, as is indicated in Fig. 3.

The rapid increase of $\sigma_0(KN\pi)$ comes at the threshold for the quasi-two-body reaction $KN \to K^*N$. It appears to come at a slightly higher momentum than does the increase of $\sigma_1(KN\pi)$. This is reasonable because the reaction $KN \to K\Delta$, for which the threshold is slightly lower and which is known to be the major part of $\sigma_1(KN\pi)$ in this region,[3] is forbidden to the isospin-0 channel. It is surprising then how similar in magnitude $\sigma_0(KN\pi)$ and $\sigma_1(KN\pi)$ quickly become. The rapid increase of $\sigma_0(KN\pi)$ is accompanied by the turnover of $\sigma_0(KN)$. The latter then falls off quite rapidly, much more so than does $\sigma_1(KN)$. The structure in the isospin-0 channels is clearly associated with the K^* threshold, but further interpretation must await an analysis of the differential distributions in the individual channels.

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[1]R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontic, K. K. Li, A. Lundby, and J. Teiger, Phys. Rev. Letters 17, 102 (1966). We thank Dr. T. F. Kycia for sending us slightly revised results.

[2]D. V. Bugg, R. S. Gilmore, K. M. Knight, D. C. Salter, G. H. Stafford, E. J. N. Wilson, J. D. Davies, J. D. Dowell, P. M. Hattersley, R. J. Homer, A. W. O'Dell, A. A. Carter, R. J. Tapper, and K. F. Riley, Phys. Rev. 168, 1466 (1968).

[3]R. W. Bland, M. G. Bowler, J. L. Brown, G. Goldhaber, S. Goldhaber, V. H. Seeger, and G. H. Trilling, Phys. Rev. Letters 18, 1077 (1967). Final results and a more complete discussion may be found in R. W. Bland, thesis, Lawrence Radiation Laboratory Report No. UCRL-18131, 1968 (unpublished).

[4]The simplest way to make the division is to take the slower nucleon to be the spectator. This overestimates the smaller $[K^+n(p) \to K^0\pi^+n(p)]$ cross section and underestimates the larger; so we have done something better but have not the space here to describe it.

[5]There are three independent isospin amplitudes for the reactions $K^+d \to KNN\pi$ (and $K^+N \to KN\pi$), and six for the reactions $K^+d \to KNN\pi\pi$ (and $K^+N \to KN\pi\pi$). Equations (2a) and (2b) are independent of the relative importance of the amplitudes. It is a lengthy process to derive the relations using Clebsch-Gordan coefficients. The method of Shmushkevich enables one to write them almost at once. See I. Shmushkevich, Dokl. Akad.

Nauk SSSR 103, 235 (1955); N. Dushin and I. Shmushkevich, Dokl. Akad. Nauk SSSR 106, 801 (1956) [translation: Soviet Phys.—Doklady 1, 94 (1956)]; G. Pinski, A. J. Macfarlane, and E. C. G. Sudarshan, Phys. Rev. 140, B1045 (1965).

[6]W. Slater, D. H. Stork, H. K. Ticho, W. Lee, W. Chinowsky, G. Goldhaber, S. Goldhaber, and T. O'Halloran, Phys. Rev. Letters 7, 378 (1961).

[7]I. Butterworth, J. L. Brown, G. Goldhaber, S. Goldhaber, A. A. Hirata, J. A. Kadyk, B. M. Schwarzschild, and G. H. Trilling, Phys. Rev. Letters 15, 734 (1965), and unpublished data of the same authors.

[8]From low to high momentum, the ratios are 1.14 ± 0.14, 1.28 ± 0.11, 1.07 ± 0.06, and 1.12 ± 0.10.

[9]A. A. Carter, Cavendish Laboratory Report No. HEP 68-10, 1968 (unpublished). This uses data from both Refs. 1 and 2.

[10]V. J. Stenger, W. E. Slater, D. H. Stork, H. K. Ticho, G. Goldhaber, and S. Goldhaber, Phys. Rev. 134, B1111 (1964).

[11]S. Goldhaber, W. Chinowsky, G. Goldhaber, W. Lee, T. O'Halloran, T. F. Stubbs, G. M. Pjerrou, D. H. Stork, and H. K. Ticho, Phys. Rev. Letters 9, 135 (1962).

STUDY OF AN $I=0$ $\pi^-\pi^+$ RESONANCE AT A MASS OF 1.06 GeV*

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We have observed a resonance in the $\pi^-\pi^+$ final state with $I=0$, $M = 1.06 \pm 0.015$ GeV, and $\Gamma < 0.07$ GeV; our analysis favors $l \geq 2$. It is produced primarily at a four-momentum transfer squared less than 0.1 GeV^2, and observed most clearly in the region where the cosine of the $\pi\pi$ scattering angle is less than −0.75.

As part of a continuing study of $\pi\pi$ interactions[1-3] we have observed an $I=0$ enhancement at 1.060 ± 0.015 GeV in the $\pi^-\pi^+$ final state. This enhancement appears to be incompatible with the S^*, an $l=0$ effect observed in the $K\overline{K}$ system near threshold,[4,5] which, if interpreted as a resonance, has a width ≥ 0.08 GeV. An enhancement in the $\pi^-\pi^+$ mass spectrum in this mass region has been reported previously.[6,7] This enhancement was particularly evident for events with $\cos\theta$ less than zero[8] (where θ is the angle between the outgoing π^- and the incident π^- in the

di-pion rest system). A review of these experiments is contained in Ref. 8 where the effect was considered to be the $\pi\pi$ decay mode of the S^*. The following analysis is based on data from a Purdue-Notre Dame-Stanford Linear Accelerator Center Collaboration.[9] The reaction channels and numbers of events obtained are

$$\pi^- + p \to \pi^- + \pi^+ + n, \quad 7916 \text{ events}; \tag{1}$$

$$\pi^- + p \to \pi^- + \pi^0 + p, \quad 4979 \text{ events}. \tag{2}$$

The average beam momentum is 4.0 GeV/c and a