University of California

Ernest O. Lawrence Radiation Laboratory

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

Allan A. Hirata, Charles G. Wohl, Gerson Goldhaber, and George H. Trilling

August 23, 1968

Berkeley, California

DISCLAIMER

Submitted to Physical Review Letters

UCRL-18430
Preprint

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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

Allan A. Hirata, Charles G. Wohl, Gerson Goldhaber, and George H. Trilling

August 23, 1968

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

Allan A. Hirata, Charles G. Wohl, Gerson Goldhaber, and George H. Trilling

Department of Physics and Lawrence Radiation Laboratory
University of California, Berkeley, California

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

(1) Introduction. 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 large peak that might have been called a resonance at once were it in a πN or $\bar{K}$N channel. However the repercussions of the existence of KN resonances on classification schemes 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 $K^+p \rightarrow K\Delta$ 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 (Fig. 1), and calculate most of the others using relations derived from isospin conservation and data from the experiments mentioned above (Fig. 2). We also extract isospin-0 partial cross sections (Fig. 3). 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 LRL 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 ($K^0 \rightarrow \pi^+\pi^-$ 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 spectator 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 LRL 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 $K^+ \rightarrow \pi^+\pi^+\pi^-$ 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.

(2) _Directly measured cross sections_. The reactions that occur at these energies are:

$$
\begin{array}{lllll}
K^+d & \to KNN & \to K^+pn & & \\
 & & \to K^0pp & & * \\
 & \to KNN\pi & \to K^+nn\pi^+ & & \\
 & & \to K^0pn\pi^+ & \sigma_c & * \\
 & & \to K^+pp\pi^- & & * \\
 & & \to K^+pn\pi^0 & \sigma_o & \\
 & & \to K^0pp\pi^0 & & * \\
 & \to KNN\pi\pi & \to K^0nn\pi^+\pi^+ & & * \\
 & & \to K^+pn\pi^+\pi^- & \sigma_{cc} & * \\
 & & \to K^0pp\pi^+\pi^- & & * \\
 & & \to K^+nn\pi^+\pi^0 & & \\
 & & \to K^0pn\pi^+\pi^0 & \sigma_{co} & * \\
 & & \to K^+pp\pi^-\pi^0 & & * \\
 & & \to K^+pn\pi^0\pi^0 & \sigma_{oo} & \\
 & & \to K^0pp\pi^0\pi^0 & & *
\end{array}
\qquad (1)
$$

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 marked with an asterisk. The reactions are arranged according to the charge states of the pions, for reasons that will become clear. The symbol σ_{co}, for example, represents the sum of all cross sections leading to one charged and one neutral pion. Thus the total $K^+d \to KNN\pi\pi$ cross section is $(\sigma_{cc} + \sigma_{co} + \sigma_{oo})$, etc.

Figure 1(a) shows the cross sections we measured. The $K^+d \to K^0pp$ cross section falls off smoothly with increasing momentum. The single-pion-production cross sections rise rapidly until about 1.2 BeV/c, 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 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.

(3) 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]:

$$\sigma_c = 2\sigma_o \tag{2a}$$
$$2\sigma_{cc} = 4\sigma_{oo} + \sigma_{co}. \tag{2b}$$

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:

$$\sigma(KNN\pi) = \sigma_c + \sigma_o \tag{3a}$$
$$= 3\sigma_o \tag{3b}$$
$$= \frac{3}{2}\sigma_c \tag{3c}$$

$$\sigma(KNN\pi\pi) = \sigma_{cc} + \sigma_{co} + \sigma_{oo} \quad (4a)$$
$$= 3(\sigma_{cc} - \sigma_{oo}) \quad (4b)$$
$$= \frac{3}{2}(\sigma_{co} + 2\sigma_{oo}) \quad (4c)$$
$$= \frac{3}{4}(\sigma_{co} + 2\sigma_{cc}). \quad (4d)$$

We have not measured all of either σ_c or σ_o [see Eqs. (1)], nor all of any two of σ_{cc}, σ_{co}, and σ_{oo}. However we can still use the equations to obtain $\sigma(KNN\pi)$ and $\sigma(KNN\pi\pi)$.

To complete σ_c we need the $K^+d \to K^+nn\pi^+$ 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

$$\sigma(K^+d \to K^+nn\pi^+) \approx \sigma(K^+p \to K^+\pi^+n) \quad (5)$$

to be good to 10 or 20%. The $K^+p \to K^+\pi^+n$ 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 $\sigma(K^+p \to K^+\pi^+n)$. Thus with Eq. (5) we complete σ_c, and with Eq. (3c) obtain $\sigma(KNN\pi)$.

Equations (4) for $\sigma(KNN\pi\pi)$ become inequalities if we put on the right just the measured parts of σ_{cc}, σ_{co}, and σ_{oo}. 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 $K^+d \to KNN$ cross section. Subtracting the $K^+d \to K^0pp$ cross section from this gives the $K^+d \to K^+pn$ cross section (this includes $K^+d \to K^+d$). 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.

(4) Isospin conservation and K^+N reactions. There are seven charge states for single-pion production in K^+N reactions:

$$\left.\begin{array}{ll} K^+p & \to K^0\pi^+p \\ & \to K^+\pi^+n \\ & \to K^+\pi^0p \end{array}\right\} \sigma_p \qquad \left.\begin{array}{ll} K^+n & \to K^0\pi^+n \\ & \to K^0\pi^0p \\ & \to K^+\pi^0n \\ & \to K^+\pi^-p \end{array}\right\} \sigma_n , \tag{6}$$

where σ_p and σ_n are the sums of the K^+p and K^+n cross sections. There are eleven 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 through the isospin-zero and -one channels are:

$$\sigma_1(KN\pi) = \sigma_p \tag{7a}$$

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

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

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

in which only three of the seven $KN \to KN\pi$ cross sections appear. The $K^+p \to K^+\pi^0p$ 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 $K^+d \to K^+pp\pi^-$ 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 shows the values of $\sigma_0(KN\pi)$ we got. 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 must say 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 with 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 $KN \rightarrow K^*N$. It appears to come at a slightly higher momentum than does the increase of $\sigma_1(KN\pi)$. This is reasonable, because the reaction $KN \rightarrow K\Delta$, 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.

We gratefully acknowledge the contributions made to this experiment by the Bevatron and bubble-chamber crews, by Dr. Howard S. White, Jr. and his staff, and by our scanning and programing groups.

FOOTNOTES AND REFERENCES

*Work supported by the U. S. Atomic Energy Commission.

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, Single Pion Production in the K^+p Channel from 860 to 1360 MeV/c (Ph. D. Thesis), Lawrence Radiation Laboratory Report UCRL-18131 (March 1968).

4. The simplest way to make the division is to take the slower nucleon to be the spectator. This overestimates the smaller [$K^+n(p) \rightarrow K^0\pi^+n(p)$] 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 $K^+d \rightarrow KNN\pi$ (and $K^+N \rightarrow KN\pi$), and six for the reactions $K^+d \rightarrow KNN\pi\pi$ (and $K^+N \rightarrow KN\pi\pi$). Equations (2) 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) [translated by M. Hamermesh, AEC-tr-2270]; N. Dushin and I. Shmushkevich, Sov. 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, The Argand Diagrams of the KN and $\bar{K}$N Forward Scattering Amplitudes, Cavendish Laboratory Report HEP 68-10 (March 1968). 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).

FIGURE LEGENDS

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

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 $K^+d \to K^0pp$ 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).

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

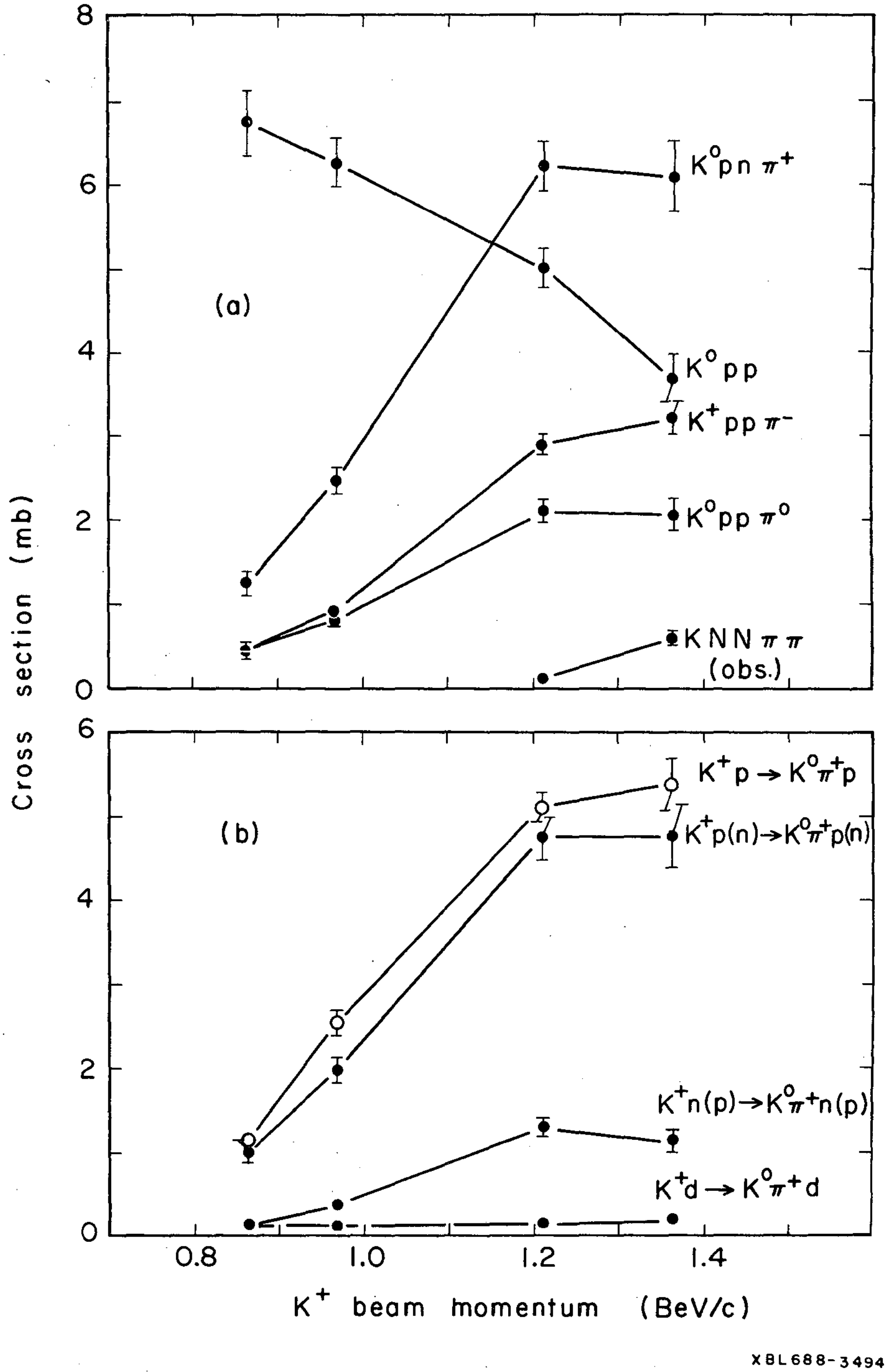

8
6
4
2
0
(a)
K°pn π+
K° pp
K+ pp π−
K° pp π°
K N N π π
(obs.)
6
4
2
0
(b)
K+ p → K° π+ p
K+ p(n) → K° π+ p(n)
K+ n(p) → K° π+ n(p)
K+ d → K° π+ d
0.8
1.0
1.2
1.4
Cross section (mb)
K+ beam momentum (BeV/c)
XBL688-3494

Fig. 1

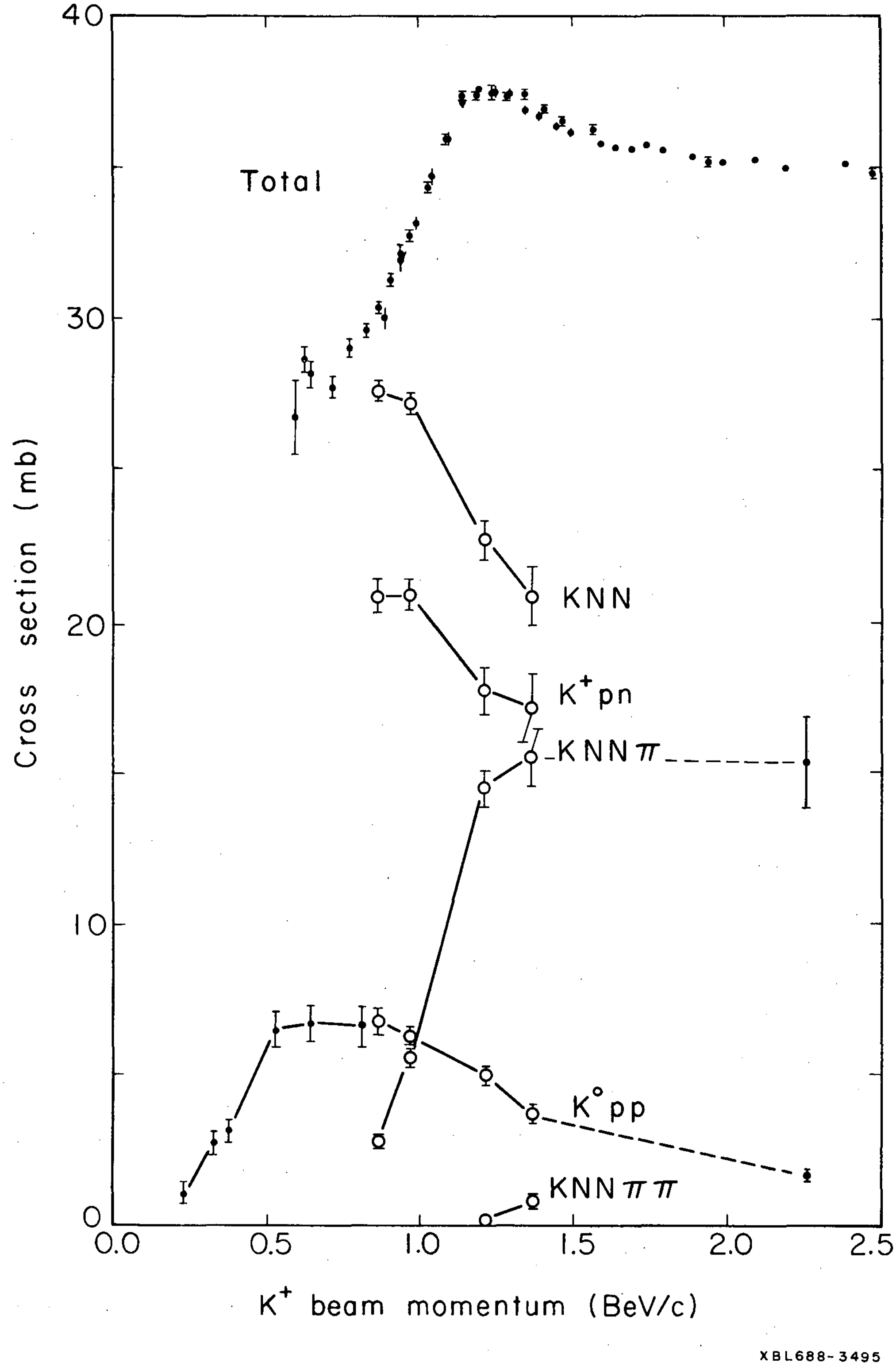
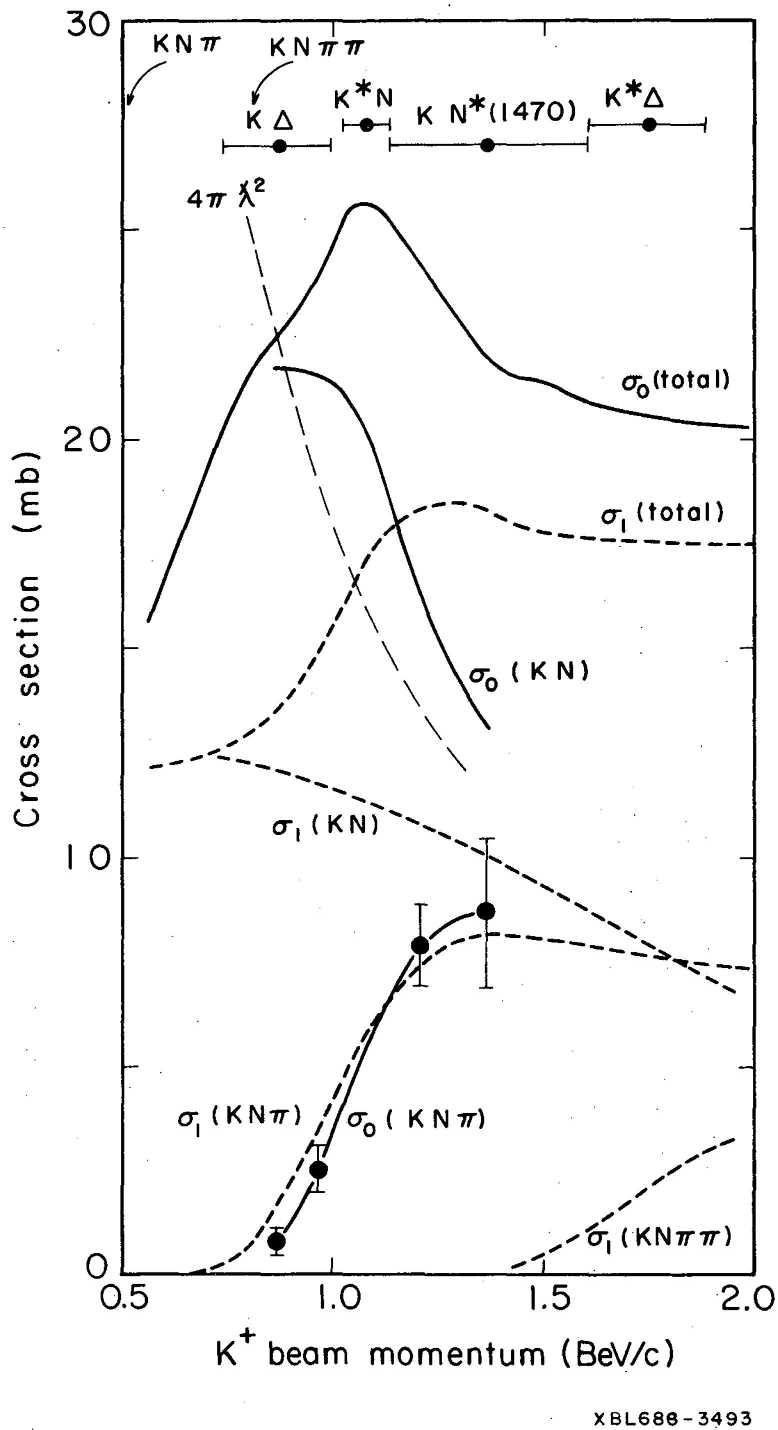

40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
Total
KNN
K+pn
KNNπ
K°pp
KNNππ
Cross section (mb)
K+ beam momentum (BeV/c)
XBL688-3495

Fig. 2



30
20
10
0
0.5
1.0
1.5
2.0
KNπ
KNππ
K Δ
K*N
K N*(1470)
K*Δ
4π ƛ²
σ0(total)
σ1 (total)
σ0 (K N)
σ1 (KN)
σ1 (KNπ)
σ0 (K N π)
σ1 (KNππ)
Cross section (mb)
K+ beam momentum (BeV/c)
XBL688-3493

Fig. 3