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Structure in $\bar{K}N$ and $\bar{K}N$ Total Cross Sections*

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Introduction

Presently known baryon resonances have been discovered using two different methods. In one case the resonance is directly produced by bombarding protons with mesons. In the other case the resonance is produced together with other particles. These two methods are sometimes referred to as formation and production experiments, respectively.

In a formation experiment the search for new resonances is performed by measuring a partial cross section or the total cross section as a function of the momentum of the incoming meson. At the resonance energy the cross sections will show an enhancement, in the best case a peak, sometimes a shoulder.

In general the measurement of an appropriate partial cross section as a function of energy will be more sensitive to the presence of resonances than the measurement of the total cross section, which means that the enhancements will stand out more clearly. On the other hand the relatively poor intrinsic sensitivity of the total cross sections is largely compensated by the simplicity of the total cross section measurements and by the high precisions obtainable.

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Production experiments have been performed mainly with bubble chambers, where one studies the effective mass spectra of many-body particles. Some missing mass experiments have been performed with counters and spark chambers.

It is interesting to note that up to now most of the nucleon isobars were discovered in total cross section measurements, while this is not the case for hyperon resonances. The main reason for this is the fact that adequate pion beams for total cross section measurements are readily obtainable from an accelerator, while kaon beams of sufficient purity and intensity have only recently become available.

I shall be concerned about the measurements of the K^+ -Nucleon total cross sections in the energy region below about 4 GeV/c, which is characterized by the presence of many structures. In particular I shall describe the results of a total cross section experiment of K^+ on hydrogen and deuterium between 1 and 2.4 GeV/c performed at Brookhaven National Laboratory by Cool, Kycia, Leontic, Li, Lundby, Teiger and myself⁽¹⁾. Wilkin solved most of our problems connected with the deuteron. The purpose of this experiment was the search for baryon resonances with large masses. I think it is clear that I am using the word resonance in a rather loose way; it is applied to essentially any structure in any cross section.

Low mass resonances are relatively easy to detect because they usually produce large effects. Instead higher mass resonances show up as broad and non-prominent structures, often overlapping with one another. Bubble chamber experiments are in this case usually limited by statistics, while total cross section experiments are limited by difficulties in interpretation.

If a structure is found in a total cross section measurement, the information which one may obtain from it includes mass, width, and height of the structure. The isotopic spin is determined directly for π^+p and K^+p , while for the other cases one has to measure two cross sections, either changing the incoming particle or changing the target particle. For pions it is easy to measure both π^+p and π^-p total cross sections from which one derives the total cross sections $\sigma_{1/2}$ $\sigma_{3/2}$ in the pure isotopic spin states 1/2 and 3/2. For kaons the simplest solution is that of measuring the cross section off protons and off neutrons bound in the deuteron. In this case problems of nuclear physics in the deuteron limit severely the analysis of the data.

A Breit-Wigner formula is usually assumed for the shape of the resonance as a function of the total energy E in the center of mass:

$$\sigma_T(E) = 4\pi\lambda^2 \frac{(J + 1/2) \cdot x}{[(E_R - E)^2/\Gamma^2 + 1} \quad (1)$$

where $\lambda = \frac{1}{K} = \frac{197.32}{p_{c.m.}}$, K is the wave number, $p_{c.m.}$ is the c.m. momentum,

J, E_R, Γ are the angular momentum, the resonant energy and the full width at half height of the resonance; x is the elasticity defined as

$$x = \frac{Y^* \rightarrow \text{elastic channel}}{Y^* \rightarrow \text{all channels}} \quad (2)$$

Γ and the elasticity are not really constant, but should contain an energy dependence which is neglected in first approximation.

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Experimental

The classical geometry used for a total cross section measurement (Fig. 1) consists of: a) a system of counters to monitor the incoming beam, b) the target where the beam is absorbed, and c) a series of transmission counters which detect the transmitted particles. Several improvements in the technique were made during the last years and it is now easy to achieve precisions of 0.1% in the relative values of measurements at different energies and 1% in the absolute values of the cross sections.

Some of the improvements which made such precision possible are: a) the construction of beams of good optical quality and of high intensity. Partially separated beams are used for kaons and antiprotons. Usable beam intensities are typically 50,000 pions and anywhere between 300 - 30,000 kaons per machine pulse. The momentum resolution of the beams is typically $\pm 1\%$.

b) Refined Cerenkov counters separate electronically wanted from unwanted particles in the beam.

c) Hydrogen and Deuterium targets of a double jacketed design provide long term density stability to 0.03%. The vapor pressure is well fixed and continuously monitored so that hydrogen density is known to about 0.03% while that of deuterium to about 1%.

d) The use of a large number of transmission counters, each subtending a different solid angle, allows an easy extrapolation of the data to zero solid angle.

e) The data taking, which is automated, follows a well-defined pattern designed to minimize fluctuations. At each energy we used the sequence

ε E H H E D D E H H E D D C E ε

where ϵ is an efficiency measurement and E, H, D, C correspond to Empty, Hydrogen, Deuterium, and Carbon targets, respectively.

The main energy dependent correction is due to the increased decay rate of mesons after having lost energy in the targets.

The experimental resolution in our experiment was about 15 MeV in the c.m. (full width at half maximum) essentially constant over energy.

K^- -Nucleon cross sections

Figure 2 shows the K^-p total cross section as a function of the laboratory kaon momentum. The data agree within their errors⁽¹⁻⁴⁾. The statistical standard deviation in the experiment I am describing changed from about 60 μb for energies above 1.5 GeV to about 200 μb at 1 GeV. This was approximately so for both K^+ and K^- on hydrogen and deuterium targets. Three structures are clearly present. The structure around 1 GeV/c was well known, while the other two are new. Note the displaced vertical scale and the smallness of the structures: high precisions are really required to see them!

Figure 3 shows a collection of total and total elastic K^-p data from 0.2 to 20 GeV/c.

Figure 4 shows K^-d data. There is a general agreement with the trend of earlier data, but not with the absolute scale. This is not surprising because the density of liquid deuterium was poorly known. Again three structures are present.

Figure 5 shows a collection of K^-d total cross sections from 0.8 to 20 GeV/c. The amount of data available in the literature is not very extensive.

The K^-p and K^-d total cross sections can be expressed in terms of the total cross sections σ_0 and σ_1 in the isotopic spin states $I=0$ and $I=1$ respectively

$$\sigma_T(K^-p) = \frac{1}{2} (\sigma_0 + \sigma_1) \quad (3)$$

$$\sigma_T(K^-d) = \frac{1}{2} (\sigma_0 + 3 \sigma_1) - \sigma_g \quad (4)$$

where

$\sigma_g = \frac{1}{4\pi} \langle r^{-2} \rangle \{ \sigma_T(K^-p) \sigma_T(K^-n) - \left(\frac{4\pi}{k^2} \right)^2 \text{Re } f_{K^-p}(0) \text{Re } f_{K^-n}(0) \}$ (5) is the Glauber screening correction (5); $\langle r^{-2} \rangle$ is the inverse square of the mean separation of nucleons in the deuteron. We used $\langle r^{-2} \rangle = 0.0423 \text{ mb}^{-1}$. (1) The second term in (5) contains the product of the real parts of the forward scattering amplitudes in K^-p and K^-n scattering.

The determination of σ_0 and σ_1 is complicated by nuclear physics considerations of the deuteron. Besides the limitations inherent in the theoretical picture, for our purposes the complications consist of:

- i) The assumption that the real parts of the forward scattering amplitudes are small enough to be neglected.
- ii) The uncertainty in the value of $\langle r^{-2} \rangle$ which reflects itself in the uncertainty of the absolute value of σ_0 and σ_1 without altering significantly their shapes.
- iii) The assumption that coherent and higher order rescattering effects on the deuteron cross section are small enough to be neglected.
- iv) The effect of Fermi momentum which broadens peaks. It is taken into account by computing a spread out kaon-proton cross section " σ_p " from the experimental values σ_p , then performing the calculations of " σ_1 " and " σ_0 " and finally unfolding the Fermi momentum. " σ_p " is given by:

$$"\sigma_p(s)" = \int \sigma_p(s') |\varphi(q)|^2 d^3q \quad (6)$$

where $s = (p_1 + p_2)^2$, $s' = (p_1 + p_2 - q)^2$; p_1 and p_2 are the four momenta of the kaon and proton, respectively; q is the Fermi momentum of the proton in the deuteron; $\varphi(q)$ is the deuteron wave function. Hulthen and Gaussian wave functions have been used. The σ_0 and σ_1 cross sections computed using the two wave functions with several parameters are not significantly different, apart from the σ_0 cross section around 2.2 GeV/c

v) The possibility of an energy shift of peaks in the deuteron data compared to proton data, due to coherent processes involving the bound state of the deuteron. (6)

It is very important to establish if this energy shift exists because while the enhancements in $\sigma_T(K^-d)$ appear at approximately the same momenta as those in $\sigma_T(K^-p)$, the central values do not correspond in fact exactly, but appear shifted to lower momenta.

We have performed a test of the shifting effect by measuring the total cross sections of $\pi^\pm$ mesons in hydrogen and deuterium. Because of charge symmetry one has

$$\sigma_T(\pi^+d) = \sigma_T(\pi^-d) = \sigma_T(\pi^+p) + \sigma_T(\pi^-p) - \sigma_g \quad (7)$$

Therefore by performing the four measurements the situation is overdetermined and we may check energy shifts in peaks and the adequacy of the Glauber correction.

Figure 6 shows our π^+p and π^+d data. They are preliminary, but they are already adequate to prove that if the shifting occurs it is very small.

It is reasonable to assume that the shifting is also negligible in KN data.

Figure 7 shows the total cross sections in the isotopic spin states $I=0$ and $I=1$.

The $I=0$ curve shows three enhancements; one is the well known $Y_0^*(1815)$ ⁽⁷⁾. The other structures appear at center of mass total energies of (2100 ± 20) and (2340 ± 20) MeV. The last structure is sensitive to the type of deuteron wave function used and to the experimental data above 2.5 GeV/c which have large errors. In spite of these uncertainties the existence of this structure is very probable.

The $I=1$ curve shows three peaks and two shoulders. The peak at 0.95 GeV/c is due to the well known $Y_1^*(1765)$ ⁽⁷⁾. The other two peaks in σ_1 appear at center of mass total energies of (2040 ± 20) and (2260 ± 30) MeV. The $Y_1^*(1765)$ peak seems to be slightly asymmetric; two shoulders, one on each side, are adjacent to the peak. The shoulder at 0.72 GeV/c, which is barely significant because of the large errors in the experimental data available in this energy range, may be due to the well known $Y_1^*(1660)$, which has a small elasticity. The shoulder at 1.26 GeV/c (1915 MeV mass) is about a 5 statistical standard deviation effect. This shoulder falls between the large bumps due to the $Y_1^*(1765)$ and $Y_0^*(1815)$ and is computed as the difference between two large numbers. Its shape and height, but not its position, is sensitive to the deuteron wave function used. A further complication may come from the fact that the thresholds for K^*N and N^*K reactions fall in this same energy region. Therefore it is difficult to establish the existence of this shoulder as conclusively as the other $I=1$ structures.

Table I gives the relevant parameters of the structures found in this total cross section measurement.

It is only after fitting the structures with Breit-Wigner formulae that one finds the considerable overlapping among resonances and that the structures are the tops of the bumps.

In the literature there are some experiments where hyperons with large masses have been observed.

Böck, et al⁽⁸⁾ at CERN, with limited statistics, find indications for narrow hyperon structures of masses (1942 ± 9) , (2097 ± 6) , and (2299 ± 6) in $\bar{Y} Y^*$ final states in a hydrogen bubble chamber exposure to 5.7 GeV/c $\bar{p}$. The first structure should have $I=1$ while the isospins of the others are unknown.

Blanpied, et al⁽⁹⁾, with limited statistics, find indications for hyperon resonances of unknown isotopic spin at (2022 ± 20) and (2245 ± 25) MeV in the photoproduction of K^+ mesons.

Wohl, et al⁽¹⁰⁾ from analysis of the angular distributions in $K^- p \rightarrow \bar{K}^0 n$ as function of incoming momentum find evidence for an $F_{7/2} Y_1^*(2065)$. A similar result is obtained by Stevenson et al⁽¹¹⁾ from an analysis of the angular distributions of $K^- p \rightarrow \Lambda^0 \pi^0$ (they quote a mass of 2050 MeV).

It is difficult to reconcile these data within their stated errors. On the other hand if some of the quoted errors on the masses and on the widths are somewhat underestimated, one may reach a reasonable picture in agreement with the information contained in table I.

All the hyperons described in table I can be located in a plot of Regge trajectories for hyperons as shown in Figure 8.

The $Y_0^*(2100)$ may be a recurrence of the $Y_0^*(1520)$ and therefore have spin $7/2^-$.

The $Y_0^*(2340)$ may be the second recurrence of the Λ and thus have an assignment of $9/2^+$.

The $Y_1^*(2040)$ should have a spin $7/2^+$, according to the Berkeley data, and therefore could be the recurrence of the $Y_1^*(1383)$.

The $Y_1^*(2260)$ could be the recurrence of the $Y_1^*(1765)$ and could have a spin $9/2^-$. It could also be a recurrence of the $Y_1^*(1660)$ whose spin is still unsettled.

The $Y_1^*(1915)$ could be a recurrence of the Σ , in which case it would have spin $5/2^+$.

From the point of view of SU3 the $Y_1^*(1915)$ could be the missing member of the $5/2^+$ baryon octet together with $N_{1/2}^*(1688)$, $Y_0^*(1815)$ and $\Xi^*(1933)$.

K^+ -Nucleon cross sections

Figure 9 shows the K^+p total cross sections^(1,12-15). A structure is clearly evident in the laboratory momentum interval 1.0-1.3 GeV/c

Figure 10 shows a collection of K^+p total and total elastic cross sections from 0.1 to 20 GeV/c. The structure is again apparent and it looks like a step function with an overshoot. The elastic cross section starts falling rapidly after about 1.3 GeV/c.

Figure 11 shows the K^+d total cross sections^(1,12-15). The structure in the 1.0-1.3 GeV/c region is more pronounced than in K^+p and is slightly displaced in momentum.

Figure 12 shows the K^+d data over a larger momentum interval. Again the structure at 1.2 GeV/c is the only significant structure. In Figure 12 the total cross section for K^+n scattering is also given.

The K^+p and K^+d total cross sections can be expressed in terms of the total cross sections σ_0 and σ_1 in the isotopic spin states $I=0$ and $I=1$, respectively.

$$\sigma_T(K^+p) = \sigma_1 \quad (8)$$

$$\sigma_T(K^+d) = \frac{1}{2} (\sigma_0 + 3 \sigma_1) - \sigma_g \quad (9)$$

All previous considerations about the deuteron apply, but the problems are now simpler because one measures directly the $I=1$ cross section and because there is only one significant structure in each of $\sigma_T(K^+p)$ and $\sigma_T(K^+d)$.

The rise in σ_1 above 650 MeV/c may be connected with the increase in the one pion production cross section. Figure 13 shows a collection of bubble chamber data on the reaction $K^+ p \rightarrow K^0 p \pi^+$. (16-20) Just above threshold, the cross section for this channel seems to remain small until the $N_{33}^*(1238)$ threshold is reached. At this point there is a sudden increase and most of the reaction goes through the N_{33}^* resonance. This is shown in Figure 13 which also gives that part of the reaction which goes via the $K^*(890)$ and the sum of the cross sections for the three reactions

The production angular distributions of N_{33}^* at 1.14 GeV/c⁽¹⁹⁾ and at 1.45 GeV/c⁽¹⁷⁾ in the K^+p center of the mass frame is peaked backward, which is characteristic of a vector meson exchange model.⁽²¹⁾

From the available data we cannot arrive at a conclusive interpretation of the structure in the K^+p total cross section. Our results could be interpreted as either being due to threshold phenomena or a resonance with a mass $(1910 \pm 20) \text{ MeV}$.⁽²²⁾ Such a resonance would be a member of the 27 representation. The shape of the σ_1 cross section and the fact that the thresholds for the main inelastic channels

would be rather close to the peak indicate that such a resonance would probably not be describable in terms of a standard Breit-Wigner formula.

The determination of the σ_0 cross section from the K^+p and K^+d data follows the same lines as for the K^-N data. The result of these calculations is shown in Figure 14. For purposes of comparison σ_1 is also displayed. Both σ_1 and σ_0 clearly have a structure at about 1.2 GeV/c. ⁽²³⁾ The σ_0 structure is at a mass of 1865 ± 20 MeV.

It is remarkable that the structure in σ_0 is at approximately the same mass value as the structure in σ_1 . In this momentum interval, the inelastic processes for the $I=0$ system are considerably different from the $I=1$ system, mainly because the N^*K state is not allowed for σ_0 . It may be worth mentioning that the threshold for 2π production is at about the same energy as the N^*K threshold.

Pertinent data available in the literature on K^+ meson charge exchange and elastic scattering off neutrons in deuterium have been studied in a bubble chamber for laboratory momenta below 812 MeV/c. ^(21,24) A phase shift analysis of the data using the impulse approximation requires SP and probably SPD waves. Two sets of phases corresponding to the Fermi Yang ambiguity are obtained. A dispersion relation calculation ⁽²⁵⁾ favors the Yang set which has a large and rapidly rising $I=0$ $P_{1/2}$ phase shift. Lovelace suggested that this phase shift could reach 90° in the momentum region where we find the $I=0$ enhancement. ⁽²⁶⁾ The angular momentum and parity of the state would then be $1/2^+$. From the point of view of SU3, this $Y=2$ state could start an SU3 anti-decuplet together with N_{11}^* (1480).

Conclusion

Table 1 summarizes the properties of the new enhancements observed in K^+N and K^-N total cross sections.⁽¹⁾ A few comments can be made on these results:

- a) The 1-2.5 GeV/c region in $\bar{K}N$ scattering is as complicated as the region below 1 GeV/c;
- b) K^+N scattering exhibits two structures, one in each isotopic spin state;
- c) Heavy baryon resonances have a tendency to come in pairs, one in each isotopic spin state;
- d) The precise measurement of total cross sections is a powerful tool for investigating the existence and determine some of the properties of baryon resonances. Unfortunately, its usefulness for strange particle resonances is limited by the incomplete understanding of the nuclear physics connected with the deuteron.

I would like to express my thanks to many experimental and theoretical colleagues at BNL for help and discussions.

Table I- Parameters of the Strange Baryon Resonances
observed in total cross sections. Values
quoted are preliminary. Symbols are defined
in text.

Notation	S	I	$P_{k \text{ lab}}$ (GeV/c)	W (GeV)	Γ (GeV)	σ_R (mb)	$4\pi\lambda^2$ (mb)	$(J+\frac{1}{2})x$
$Y_0^*(1815)$	-1	0	1.07	1825 ± 20	110	30	16.2	1.85
$Y_0^*(2100)$	-1	0	1.68	2100 ± 20	160	10	8.7	1.15
$Y_0^*(2340)$	-1	0	2.27	2340 ± 20	105	3	5.9	0.51
$Y_1^*(1660)$	-1	1	0.71	1660 ± 20	50	7	30.0	0.23
$Y_1^*(1765)$	-1	1	0.97	1780 ± 20	100	21	18.7	1.12
$Y_1^*(1915)$	-1	1	1.26	1915 ± 20	65	4	12.8	0.31
$Y_1^*(2040)$	-1	1	1.54	2040 ± 20	150	6	9.7	0.62
$Y_1^*(2260)$	-1	1	2.06	2260 ± 20	180	3	4.3	0.70
$Z_0^*(1863)$	+1	0	1.15	1863 ± 20	150	8	14.6	0.55
$Z_1^*(1910)$	+1	1	1.25	1910 ± 20	180	4	12.9	0.31

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Figure Captions

- Fig. 1 The geometry of a total cross section measurement -
 $S_1 - S_{12}$ are scintillation counters; C is a liquid differential Cerenkov counter - The targets are indicated as D_2 , H_2 , Dummy.
- Fig. 2 The K^-p total cross section in the momentum range 0.5-3 GeV/c; error bars represent standard deviations; if the error is smaller than the size of the dot, it is not indicated.
- Fig. 3 The K^-p total and total elastic cross section in the momentum range 0.2-20 GeV/c.
- Fig. 4 The K^-d total cross section in the momentum range 1-2.5 GeV/c
- Fig. 5 The K^-d total cross section in the momentum range 0.8-20 GeV/c
- Fig. 6 π^+p and π^+d total cross sections
- Fig. 7 The total cross sections for the $I=0$ and $I=1$ isotopic spin states for the $\bar{K}N$ system; typical statistical errors for a single point are shown for each structure.
- Fig. 8 Regge trajectory plot for the hyperon resonances
- Fig. 9 The K^+p total cross section up to 3 GeV/c
- Fig. 10 The K^+p total and elastic cross section from 0.1 to 20 GeV/c
- Fig. 11 The K^+d total cross section between 0.7 and 3 GeV/c
- Fig. 12 The K^+d and K^+n total cross sections from 0.1 to 20 GeV/c
- Fig. 13 The cross sections for one pion production: I) for the reaction $K^+p \rightarrow K^0 p \pi^+$; II) for N_{33}^* (1238) production in the $K^0 p \pi^+$; III) for $K^*(890)$ production in $K^0 p \pi^+$; IV) the sum of the cross sections for the three final states $K^0 p \pi^+ + K^+ p \pi^0 + K^+ n \pi^+$.
- Fig. 14 The total cross sections for the $I=0$ and $I=1$ isotopic spin states for the KN system; some typical statistical errors for a single point are shown for the $I=0$ cross section.

FIGURE 1

FIGURE 2

FIGURE 3

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