PROBLEMS WITH DEUTERIUM

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INTRODUCTION

The complete knowledge of the antinucleon-nucleon system ($\bar{N}N$) requests the study of both the I = 0 and I = 1 isospin channels.

An increasing number of experiments have been performed in the last years on the antiproton-proton system ($\bar{p}p$) which is a mixture of the I = 0 and I = 1 states.

The antiproton-neutron system ($\bar{p}n$) is a pure I = 1 isospin state but the absence of a free-neutron target makes much more complicated the study of this channel.

By charge conjugation the $\bar{p}n$ system is equivalent to the antineutron-proton system ($\bar{n}p$) but in this case the experimental difficulties in building up an $\bar{n}$ beam have not allowed up to now a real improvement. In fact the $\bar{n}p$ interaction has been studied with the bubble chamber technique in a two-steps process [1] ($\bar{p}p \rightarrow \bar{n}p\pi^-$, $\bar{n}p \rightarrow$ elastic and total) with very poor statistics.

Only very recentely some results on the $\bar{N}N$ interactions have been published using an antideuterium beam at Serpoukov [2], but, of course, the problem of the free-antineutron interaction is not resolved in this way.

Therefore the main source of information on the $\bar{N}N$ system in the pure I = 1 state is at the moment the study of the $\bar{p}$-deuterium interaction ($\bar{p}d$), since the deuterium is the simplest and weakest bound proton-neutron system. However the difficulties encountered when working with a deuterium target have been in most of the cases understimated and not all the effects due to the bound nucleon have been studied extensively [3]. In fact while the shadow or Glauber effect [4] has been deeply analysed the three following complications have received much less attention:

a) the Fermi motion

b) the dependence of the cross section on the nucleon mass

c) the interaction between the incident particle and the entire deuteron.

Practically all the existing $\bar{p}d$ data have been analyzed in the spirit of the Impulse Approximation (IA) and a suitable factor for the Glauber screening correction has been applied for the partial and total cross section computations.

In this paper the validity of the IA for the $\bar{p}d$ case will be briefly discussed in the first part. In the two following sections recent counter data on the $\bar{p}d$ total cross section will be analyzed and the criteria for studying particular final states will be reported, when the experiments with bubble chambers will be discussed. At the end the difficulties in extracting the free-neutron cross sections will be considered in some details taking as a reference a recent analysis of the K^+-nucleon system, where the situation is easier because of the spin zero of the incident K^+ and the possibility of making a phase shift analysis.

1. THE IMPULSE APPROXIMATION

The criteria for the applicability of this method for the $\bar{p}d$ case has been studied by P.E. Nemirovskii et al. [5].

It is well known that three main requirements must be fulfilled, [6] i.e.

I) The incident particle never interacts strongly with two constituents of the system at the same time. And this is verified because of the large deuteron radius ($R \simeq 4$ fm) compared to the range of the $\bar{p}N$ forces ($r \simeq 1$ fm).

II) The amplitude of the incident wave falling on each constituent (nucleon) is nearly the same as if that constituent were alone (the transparency assumption). If the wavelength $\lambda\!\!\!^{-}$ of the scattered particle is small compared with R, this condition may be written in the following way

$$\frac{\lambda\!\!\!^{-}}{R^2}\left(\frac{\sigma}{4\pi}\right)^{1/2} << 1$$

If R = 4 fm and the formula $\sigma = \frac{85 \cdot 8}{\beta}$ mb [7]) (β is the $\bar{p}$ velocity in the laboratory system) gives the magnitude of the $\bar{p}p$ and $\bar{p}n$ total cross sections, this limit may be expressed as $\gamma = \frac{\lambda}{\sqrt{\beta}}$ 0.052 << 1 (λ in Fermi). As an example for an $\bar{p}$ incident in the laboratory system of 0.5 GeV/c γ = 0.063 and for 0.2 GeV/c γ = 0.22.

III) The binding forces between the constituents of the system are negligible during the decisive phase of the collision, when the incident particle interacts strongly with the system. And this is true if $\lambda << R$.

Therefore the IA may be applied to the $\bar{p}d$ interaction even at low energies: in II) it has been shown that for a momentum of 0.5 GeV/c ($\simeq$ 0.13 GeV of kinetic energy) the correction is of the order of 6%.

But the effect of the Fermi motion at low energy may be very important: this effect in two extreme situations has been made evident in the plot of λ (the relative $\bar{p}$-particle target wavelenght) of Fig. 1; here the nucleon target momentum p_N of 0.3 GeV/c has the beam direction and the same (p_N = +0.300) or the opposite (p_N = -0.300) versus of the beam; since the deuteron mass is considered to be conserved, the nucleon target is taken off-mass shell.

Nevertheless the diffraction theory [4]) cannot be applied to the complete range where the IA is trustworthy. In fact it has been shown in a convincing fashion that the standard Glauber formula

$$\sigma_{ad} = \sigma_{an} + \sigma_{ap} - 2\,\sigma_{ap}\,\sigma_{an}\,C$$

where σ_{ad}, σ_{an} and σ_{ap} are the $\bar{p}d$, $\bar{p}p$ and $\bar{p}n$ absorption cross sections and C is a positive constant does not work because of their large values also at relatively high energy [8]).

Moreover at very low energy (0.050-0.100 GeV of the incident $\bar{p}$) some theoretical calculations give the impossible result that C be negative [5]).

In these cases the correct prescription, which saves the unitarity, is the following: compute the elastic amplitude from the Glauber theory and from it both the elastic and total cross sections (through the optical theorem); the absorption cross section is then the difference between them.

A comment about the formula

$$\sigma_{td} = \sigma_{tp} + \sigma_{tn} - \delta\sigma$$

(where σ_{td}, σ_{tp} and σ_{tn} are now the $\bar{p}d$, $\bar{p}p$ and $\bar{p}n$ total cross sections, and $\delta\sigma$ is the Glauber cross section defect) may be useful at this point: assuming the Glauber theory all the effects due to the bound two-nucleon system are considered to be summarized in $\delta\sigma$. This term is zero if we take into account only the contribution from the single scattering, but in this case the unitarity is violated because the imaginary part of the amplitude at zero degrees cannot be represented in the form of a sum of amplitudes for the free particles, each of them satisfaying separately the unitarity condition.

2. THE TOTAL $\bar{p}d$ CROSS SECTION

In Fig. 2 the $\bar{p}d$ total cross section is shown [9-14]). If explicitely given by the authors, also the $\bar{p}n$ total cross section is plotted.

In a high-precision [12]) transmission experiment the $\bar{p}p$ and $\bar{p}d$ total cross sections have been measured between 1.00 and 3.30 GeV/c and the authors give the pure isospin total cross sections σ_0 and σ_1.

The computation of the these cross sections has been carried-out in the following way:

The total cross section formula has been written as

$$\sigma_{\bar{p}d} = "\sigma_{\bar{p}p}" + "\sigma_{\bar{p}n}" - \delta\sigma$$

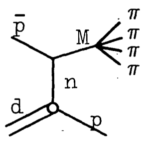
Here $$\delta\sigma = \frac{\langle r^{-2}\rangle}{4\pi}\left\{2\,"\sigma_{\bar{p}p}"\,"\sigma_{\bar{p}n}"\,(1-\rho_p\rho_n) - \frac{1}{2}\left["\sigma_{\bar{p}p}"^2(1-\rho_p^2)+"\sigma_{\bar{p}n}"^2(1-\rho_n^2)\right]\right\}$$

is the Glauber-Wilkin cross section defect where ρ_p (ρ_n) is the ratio of the real to imaginary part of the forward scattering amplitude for the $\bar{p}p$($\bar{p}n$) scattering. The "$\sigma_{\bar{p}p}$" and "$\sigma_{\bar{p}n}$" are the $\bar{p}p$ and $\bar{p}n$ total cross section smeared out over the Fermi motion.

The procedure for the extraction of the free-neutron cross section is rather compli-

TABLE I

$\bar{p}d$ annihilation at rest

Reaction	I A	p spectrum	Comments	Authors
$\bar{p}d \to$ all	assumed	Hulthèn [16] large tail	20% simultaneous $\bar{p}pn$ interactions	Chinowsky [15] 1966
$\bar{p}d \to p_s\ \pi^- \varphi_-$ $\varphi \to K\bar{K}$	assumed $p_s < 0.250$			Gray [17] 1966
$\bar{p}d \to p_s + (n\pi)$	assumed $p_s < 0.250$	Hulthèn, normalization 0.12 - 0.18, large tail	28% proton visible and stopping in the chamber	Bettini [18] 1967
$\bar{p}d \to p_s\ \pi^-\pi^-\pi^+$	assumed $p_s < 0.150$	Hamada - Johnson [20] up to 0.200 okey	If the proton has large momentum, it cannot be treated as a spectator	Anninos [19] 1968
$\bar{p}d \to \bar{N}\ N\ N$ $[\pi^- p]$ $[\Lambda^0 K^+ + (n\pi)]$	no 3-body reaction	84% okey Hulthèn 16% no Hulthèn	Rescattering not possible or not sufficient $\to$ $\to$ 3 body	Bizzarri [21] 1969
$\bar{p}d \to p_s K\bar{K} + (n\bar{n})$	assumed $p_s < 0.250$			Bettini [22] 1969
$\bar{p}d \to p_s\ \omega\pi^-$ $p_s\ \omega\pi^-\pi^0$ $p_s\ \omega\pi^-\pi^-\pi^+$	assumed $p_s < 0.150$			Bizzarri [23] 1970
$\bar{p}d \to p + M$ $M \to n\pi$		Hulthèn okey .150-.200	Efficiency for identifying protons by ionization unity up to 0.800	Gray [24] 1971

cated and, as yet, a little arbitrary. Moreover for the $\bar{p}N$ case ρ_n is taken equal to ρ_p, because of lack of data on this quantity, and $<r^{-2}>$ is not well known.

Nevertheless the result seems reliable if the $\bar{p}N$ cross-section is reasonably smooth or better if the $\bar{p}N$ cross-sections do not vary rapidly because of the presence of sharp resonances.

If the conditions for the extraction of the free-neutron cross section from deuterium and hydrogen data is supposed to be fulfilled, the pure isospin total cross section are then

$$\sigma_1 = \sigma_{\bar{p}n}$$
$$\sigma_0 = 2 \cdot \sigma_{\bar{p}p} - \sigma_{\bar{p}n} \qquad (1)$$

where $\sigma_{\bar{p}p}$ and $\sigma_{\bar{p}n}$ are the total free-target $\bar{p}p$ and $\bar{p}n$ cross sections.

In Fig. 3 a compilation of all the existing data on σ_0 and σ_1 is shown; if not given by the authors they have been computed from formula (1) propagating the errors.

3. BUBBLE CHAMBER EXPERIMENTS

In Table I and II the present situation is summarized.

Table I deals in the $\bar{p}d$ experiments at rest while in Table II the $\bar{p}$ in flight are considered. The following general comments can be drawn:

a) The $\bar{p}d$ annihilation at rest with a proton (p_s) in the final state can be explained as an $\bar{p}n$ annihilation provided that the p_s momentum be less than 0.150-0.200 GeV/c.
In about 20% of the cases the $\bar{p}d$ annihilation is better explained as a 3-body interaction.

b) Almost all the $\bar{p}d$ annihilation in flight experiments have assumed the simple IA. There is some evidence that the old prescription for cooking the deuterium (momentum spectator less than momentum not spectator, momentum spectator less than 0.25 GeV/c) seems not to work properly even at high energies (see for example the 5.5 GeV/c experiment [37,31,36,38]).

4. THE EXTRACTION OF FREE-NEUTRON CROSS SECTIONS

A) From the experimental point of view:

I) In a recent K^+p and K^+d experiment [41]) the same reaction has been measured in hydrogen and in deuterium:

$$K^+p \rightarrow K^0 p \pi^+ \qquad (2)$$

$$K^+p(n) \rightarrow K^0 p \pi^+(n) \qquad (3)$$

The parentheses denote the spectator nucleon defined with the two conditions

$$p_n < 0.250$$

$$p_n < p_p$$

These two cross sections are shown in Fig. 4 together with previously measured data. The cross section for reaction (2) is systematically larger than that of reaction (3) by an average factor $R = 1.26 \pm 0.04$.

Therefore in this case the standard Glauber correction factor $R = 1.12$, often used in the literature, does not work.

II) In Fig. 5 the $\bar{p}p$ and $\bar{p}n$ annihilation cross sections measured in the 0.050-0.200 GeV intervall of the incident $\bar{p}$ kinetic energy are shown (full-point) from a $\bar{p}d$ experiment [42]).

The data shown that these two cross section are not equal.

In the same figure the $\bar{p}p$ annihilation cross section from an $\bar{p}p$ experiment is shown [7]) (open points): the lack of the shadow in this case is apparent.

Therefore it is evident that some caution is necessary in the extraction of free-neutron cross sections, since the effects of the bound nucleon seem to be strongly dependent on the particular channel and on the particular energy range.

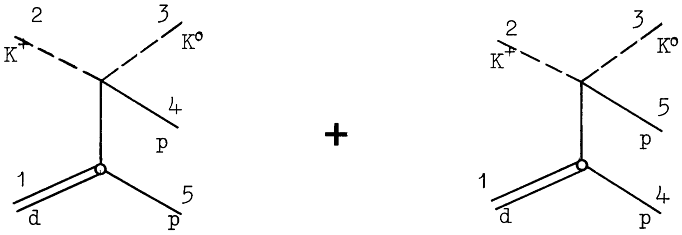
B) From the theoretical point of view:

If the main point of interest is the extraction of the free-neutron cross section (and not the coherent reaction, in which there is a deuteròn in the final state) then only the 'elastic incoherent" break-up reaction has been studied in some details. A process is here called "elastic incoherent" if it is of the type

$$xd \rightarrow y\, NN$$

where x is a hadron, NN a nucleon pair, and y is or x or the charge-exchanged particle of x (for example $\pi^-d \rightarrow \pi^-pn$, $K^+d \rightarrow K^0pp$, $\bar{p}d \rightarrow \bar{p}\, pn$ etc.).
The results of a particular analysis on the $K^+d \rightarrow K^0pp$ reaction [43]) are reported here, just to understand all the difficulties.

The deuteron break-up in the $K^+d \rightarrow K^0pp$ case has been described by means of the impulse approximation, assuming that the two following Feynman graphs, obtained one from the other by interchanging the two nucleon lines, describe the process:



The charge exchange differential cross section in the lab. frame, where the deuteron is at rest, can be expressed by means of the K-nucleon free amplitudes in the following way:

$$\frac{d\sigma}{d\Omega_{3\,lab}} = \frac{1}{m_1 p_2}\int d^3p_5 \left\{ |\Psi_5-\Psi_4|^2 \left[\frac{1}{4}|f_1-f_0|^2 + \frac{1}{6}|g_1-g_0|^2\right] + |\Psi_5+\Psi_4|^2\left[\frac{1}{12}|g_1-g_0|^2\right]\right\} \frac{p_3^3}{E_5[p_3^2(E_3+E_4) - E_3\vec{p}_3\cdot(\vec{p}_2-\vec{p}_5)]} \tag{4}$$

where we label the particles following, for example, the first of the two diagram.

The kinematical variables i.e. $\vec{p}_i$ and E_i, are all defined in the lab. frame while the standard no spin-flip and spin-flip amplitudes in I=1 and 0 state, $f_{1(0)}$ and $g_{1(0)}$, are defined in the c.m. of the K^+-N system. $\Psi_{5(4)}$ is equal to $S_{34(35)}^{1/2}\ \psi(-\vec{p}_{5(4)})$ where $\psi(-\vec{p}_i)$ is the deuteron wave function in the momentum space and $S_{34(35)}^{1/2}$ is the total energy of the K-nucleon system in their c.m. frame.

The amplitudes $f_{1(0)}$ and $g_{1(0)}$ depend on $\vec{p}_5$ through S_{34}, S_{35} and $\cos\vartheta^*$. If we suppose that the dependence of $f_{1,0}$ and $g_{1,0}$ on $\cos\vartheta^*$, S_{34}, S_{35} is slow we can evaluate them for

$$S_{34} = S_{35} = S'$$

$$\cos\vartheta^* = \cos\vartheta'$$

where the primed quantities are obtained considering the struck nucleon at rest in the target. Under this assumption it is also possible to give the cross section in the approximate K^+-N c.m. frame just by multiplying $d\sigma/d\Omega_{3\,lab}$ by the jacobian of the transformation from the K^+-N lab. frame to the K^+-N c.m.frame (if we suppose the nucleon at rest in the target this jacobian does not depend on $\vec{p}_5$).

With these hypothesis equation (4) becomes

$$\frac{d\sigma}{d\Omega^*}_{c.e.} = \left[\frac{1}{4}|f_1-f_0|^2 + \frac{1}{6}|g_1-g_0|^2\right] I_{ppt} + \left[\frac{1}{12}|g_1-g_0|^2\right] I_{pps} \tag{5}$$

Where I_{ppt} and I_{pps} are the so called deuteron weight factors for the proton-proton final charge state and respectively triplet and singlet spin state [44]. Now $I_{ppt} = I_0 - J_0$ and $I_{pps} = J_0 + J_0$, and

$$I_0 \pm J_0 = \frac{S_{12}}{2m_1 p_2}\ \frac{d\Omega_3}{d\Omega^*}\int d^3p_5 \frac{|\psi(-\vec{p}_5) \pm \psi(-\vec{p}_4)|^2}{E_5[p_3^2(E_3+E_4) - E\vec{p}_3\ (\vec{p}_2-\vec{p}_5)]}\, p_3^3$$

The behaviour of I_{pps} for two different momenta are given in Fig. 6; as can be seen, in the high energy limit, this result is coherent with the closure approximation.

In Fig. 7.a and 7.b the behaviour of the function that must be integrated for the $I_0 \pm J_0$ computation is shown for two different values of $\cos\vartheta_3^*$. The spectator shoulder and the quasi-elastic peak are apparent. In the second case the interference between the two single scatterings is visible.

Finally the charge exchange differential cross section in deuterium can be expressed as

$$\frac{d\sigma}{d\Omega^*} = \left|\frac{f_1-f_0}{2}\right|^2 (I_0 - J_0) + \left|\frac{g_1-g_0}{2}\right|^2 (I_0 - \frac{J_0}{3})$$

but even when the $K^+n \to K^0p$ differential cross section is derived from the $K^+d \to K^0pp$ data [45], nevertheless the $K^+n \to K^0p$ cross section on the free-neutron is not obtainable because of the lack of knowledge of the f_1, f_0 and g_1, g_0. Therefore this free-neutron cross section will be a by-product for example of a complete phase shift analysis in which the amplitudes will be fitted directly to the deuteron data rather than to free-nucleon data [46].

5. CONCLUSION

The era in which the deuterium was considered as an easy device for the extraction of free neutron cross sections seems definitively ended.

From a naive experimental point of view it is possible to say that there is no fundamental difficulty in the particle-deuterium analysis.

From a phenomenological point of view the extraction of particle free-neutron cross-section largely depends upon the type of observations that are made, but in general becomes more and more complicated.

If we are interested in angular distributions or Dalitz plots form the $\bar{p}n$ annihilations the situation seems reasonably good if the momentum of nucleon spectator is less than ~ 0.2 GeV/c. On the contrary the absolute values depend from the proton spectator distribution. And in this distribution there are two discontinuity points, at about 0.1 GeV/c and at about 0.3 GeV/c. Between 0 and ~ 0.1 GeV/c the proton is not visible and the events are practically with 2 constraints. Between ~ 0.1 and ~ 0.3 GeV/c the proton stops in the chamber and the events are really with 4 constraints. Above ~ 0.3 GeV/c the proton does not stop in the chamber and therefore its identification becomes difficult.

At the end from a theoretical point of view the situation is very far from the satisfaction. The large tail of high momentum spectators has not been explained up now. And this may be due either to insufficiencies in the deuteron wave function or to the failure of the simple impulse approximation.

FIGURE CAPTIONS

Fig. 1 - The relative $\bar{p}$-particle target wavelength λ versus p_{lab} (laboratory incident momentum), T_{lab} (laboratory incident kinetic energy) and μ ($\bar{p}$-nucleon at rest invariant mass). The effect of the Fermi motion is shown (see text). R and r are approximately the deuteron radius and the range of the $\bar{p}N$ forces.

Fig. 2 - $\bar{p}d$ and $\bar{p}n$ total cross sections versus laboratory incident momentum p_{lab}.

Fig. 3 - $I = 0$ (σ_0) and $I = 1$ (σ_1) cross sections for the $\bar{p}N$ system versus laboratory incident momentum p_{lab}.

Fig. 4 - The cross sections $K^+p \rightarrow K^0 p \pi^+$, $K^+d \rightarrow K^0 p \pi^+ (n)$ and $K^+d \rightarrow K^0 n \pi^+ (p)$ versus laboratory incident momentum. The cross sections for the last two reactions are the raw data, after the cuts on the spectator nucleon in parenthesis [41]).

Fig. 5 - $\bar{p}p$ and $\bar{p}n$ annihilation + charge exchange cross sections as measured in hydrogen [7]) (open points) and in deuterium (full point) [42]).

Fig. 6 - $I_0(\vartheta^*)$ and $J_0(\vartheta^*)$ for two different K^+ momenta (see text).

Fig. 7 - Behaviour of the function to be integrated for the $I_0 \pm J_0$ computation for: a) $\cos \vartheta_3^* = 0$ and b) $\cos \vartheta_3^* = 0.9$. In the b) case the saddle of the interference between the quasi-elastic peak and the spectator shoulder is apparent. (see text).

TABLE II

$\bar{p}d$ interaction in flight

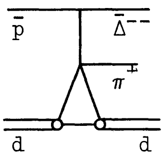
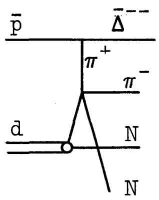
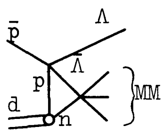
Reaction	I A	p spectrum	Comments	Authors
1.96 GeV/c $\bar{p}d \to p_s p \bar{p} \pi^-$ ($\bar{p}n \to \bar{N}^{*--} p$)	assumed $p_s < p_{ns}$	Hulthèn okey up to 0.2 $p_s < 0.2$	Effective mass $\bar{p}\pi^-$ independent of the choice of the spectator	Bacon [25] 1965
2.80 GeV/c $\bar{p}d \to p_s p \bar{p} \pi^-$ ($\bar{p}n \to \bar{N}^{*--} p$)	"	"	"	Bacon [26] 1967
$\bar{p}d \to \bar{p}\ p n$ $\{\bar{p}p \to \bar{p}p,\ \bar{p}n \to \bar{p}n\}$ 1.65 GeV/c	assumed	Hulthèn okey (up to?) $N_s < 0.150$		Berryhill[27] 1968
$\bar{p}d \to n_s \bar{p} p \pi^+ \pi^-$ ($\bar{p}\pi^+\pi^-$) ($p\pi^+\pi^-$) 2.80 GeV/c	assumed	$p_n < 0.250$		Bacon [28] 1969
$\bar{p}d \to p_s \bar{p} n\ \pi^- \pi^+$ $p_s \bar{p} p\ \pi^- \pi^+$ $p_s \bar{n} p\ \pi^- \pi^-$ 2.80 GeV/c	assumed	$p_s < p_{ns}$ $p_s < 0.250$	$\sigma = \sigma$(measured)×1.12 (the Glauber correction factor)	Bacon [29] 1970
$\bar{p}d \to p_s\ \bar{p}p\pi^-$ ($\bar{p}n \to \bar{p}p\ \pi^-$) (variation with the $\bar{p}n$ c.m.s.) 5.5 GeV/c	~ assumed discussed	Hulthèn okey even in the high momenta $p_s < p_{ns}$ $p_s > 0.100$	plot of cos ϑ_{sp}-isotropy; no I A validity (!) but compensation between various effects; Glauber correction $\langle r^{-2} \rangle = 0.042$ mb^{-1}	Braun [30] 1970
$\bar{p}d \to \bar{p}d\ \pi^+\pi^-$ 5.5 GeV/c	assumed + f.s.i.  		Scatter diagram (cos ϑ_{pn}, p_n/p_p)	Braun [31] 1970
pd → 1,2 prongs ($\bar{p}n \to \bar{p}n$) 3.5 GeV/c	assumed	Hulthèn okey 0.1 - 0.2	only 2 prongs; scatt. lab. angle > 5°; range < 2 cm; equal-mass scatt. test; $\langle r^{-2} \rangle = 0.027$ mb^{-1}	Reynolds [32] 1970
$\bar{p}d \to \bar{p}d\ \pi^+\pi^-$ $\bar{p}pn\ \pi^+\pi^-$ $\bar{p}d\ \pi^+\pi^-\pi^0$ $K^-d\ \bar{\Lambda}$ $K^-pn\ \bar{\Lambda}$ $K^-d\ \bar{\Lambda}\ \pi^0$ 7.0 GeV/c			visible positive prong; proton-neutron collinearity and mass test [34]	Antich [33] 1971

TABLE II (cont.)

Reaction	I A	p spectrum	Comments	Authors
$\bar{p}d \to p_s \pi^+\pi^-\pi^-$ ($\bar{p}n \to \pi^+\pi^-\pi^-$) 1.0-1.6 GeV/c	assumed $p_s < 0.150$	McGee [36] okey up to 0.2	unfolding Fermi motion	Bettini [35] 1971
$\bar{p}d \to p_s \pi^+\pi^-\pi^-\pi^\circ$ ($pn \to \pi^+\pi^-\pi^-\pi^\circ$) 5.5 GeV/c	assumed	Hulthèn okey 0.10-0.28		Braun [37] 1971
$\bar{p}d \to p_s \bar{p}\, \pi^+\pi^- n$ 5.5 GeV/c		No Hulthèn	$p_s < 0.28$; accumulation for $\cos \vartheta_p > 0$; $p_n < p_p$ removal too large; $1 < p_n/p_p < 2$	Braun [38] 1971
$\bar{p}d \to \Lambda + MM$ ($\Lambda\bar{\Lambda}, \Sigma^\circ\bar{\Lambda}, \bar{\Sigma}^\circ\Lambda$)n 1.26-1.67 GeV/c			No $\bar{p}$ annihilation on the entire deuteron	Camerini [39] 1971
$\bar{p}d \to \vec{\bar{p}}d$ 1.6 -2.0 GeV/c			Glauber theory ~ okey (no secondary maximum)	Ming Ma [40] 1971

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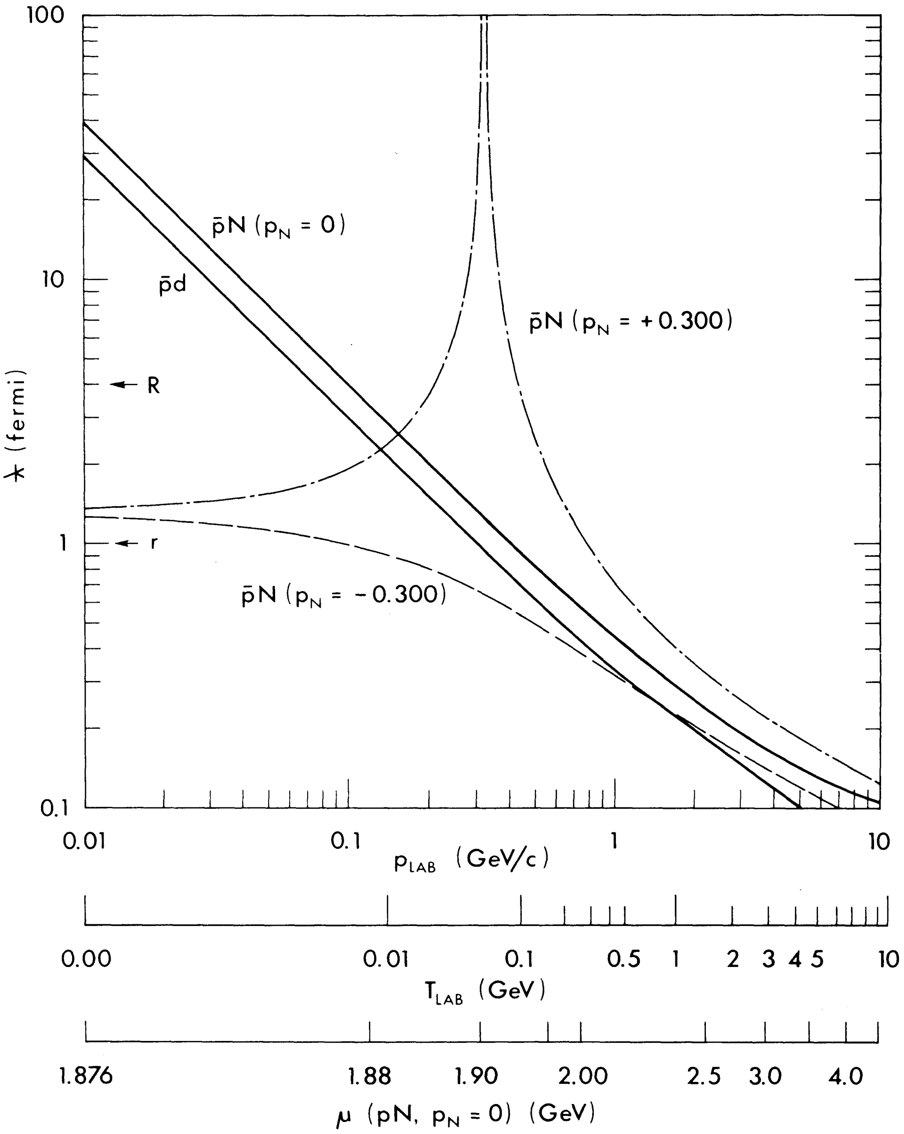


100
10
1
0.1
ƛ (fermi)
R
r
p̄N (p_N = 0)
p̄d
p̄N (p_N = +0.300)
p̄N (p_N = −0.300)
0.01
0.1
1
10
p_LAB (GeV/c)
0.00
0.01
0.1
0.5
1
2
3
4
5
10
T_LAB (GeV)
1.876
1.88
1.90
2.00
2.5
3.0
4.0
μ (pN, p_N = 0) (GeV)

Fig. 1

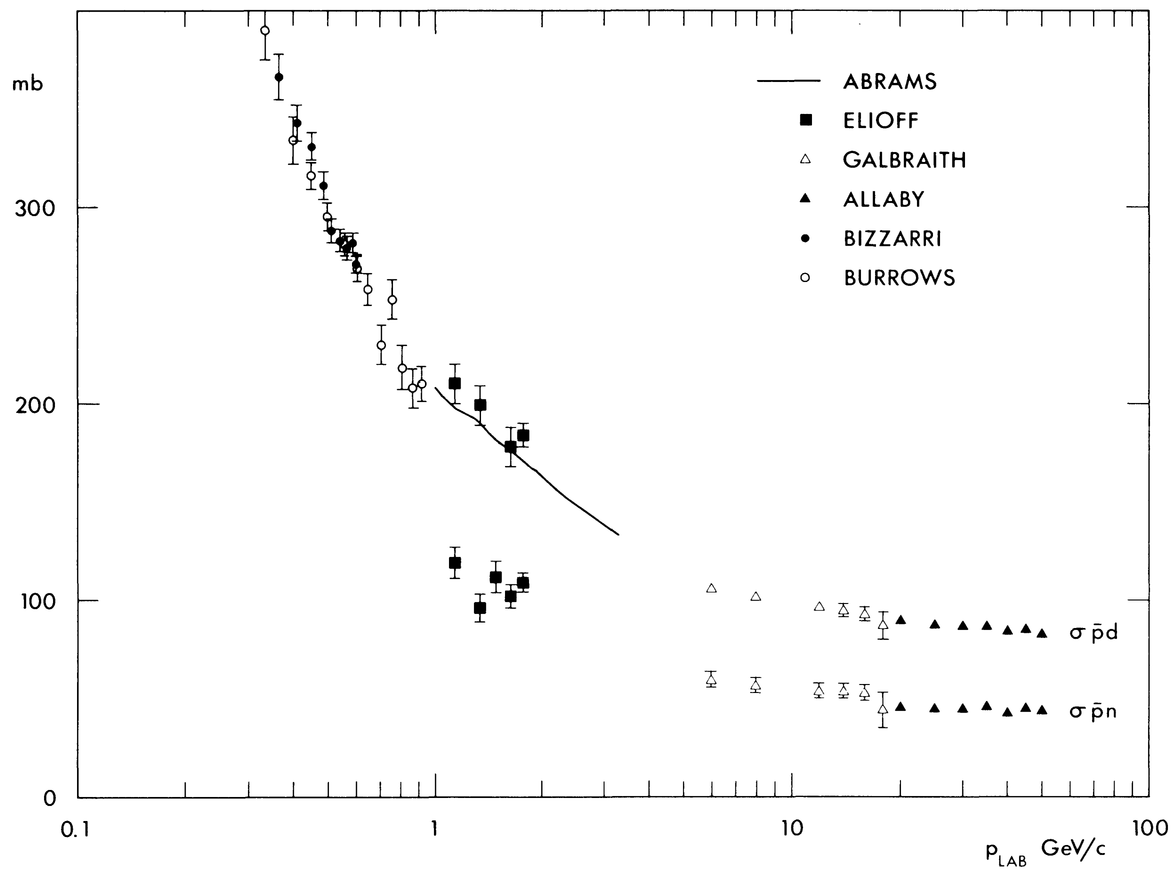
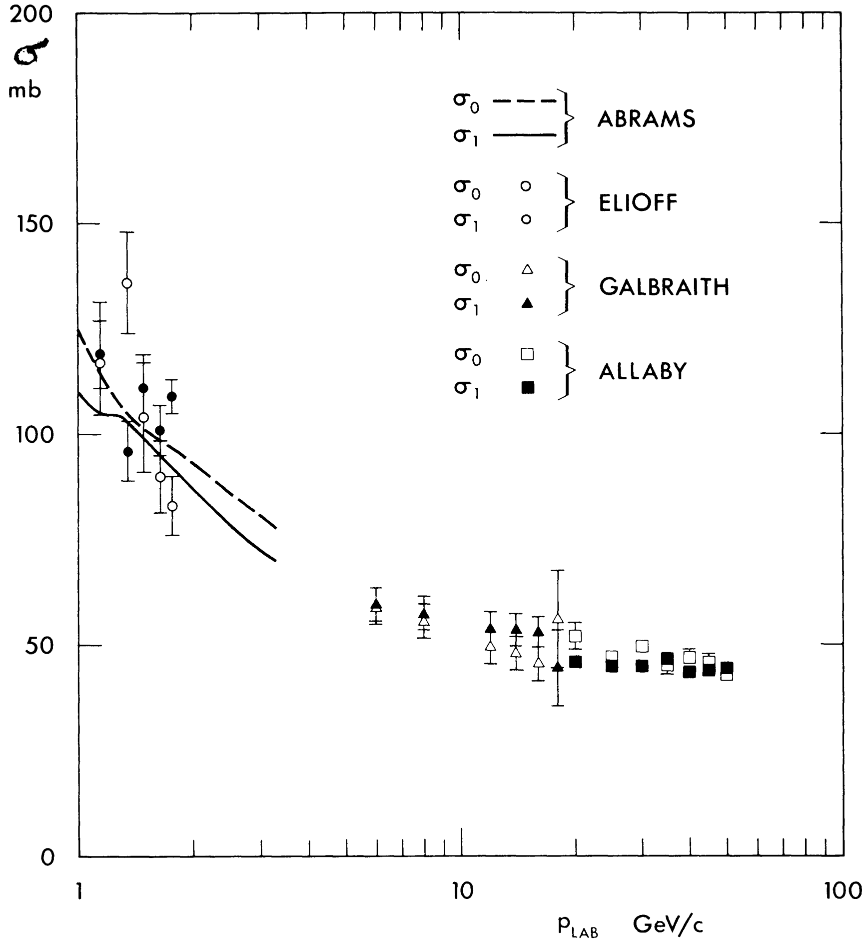
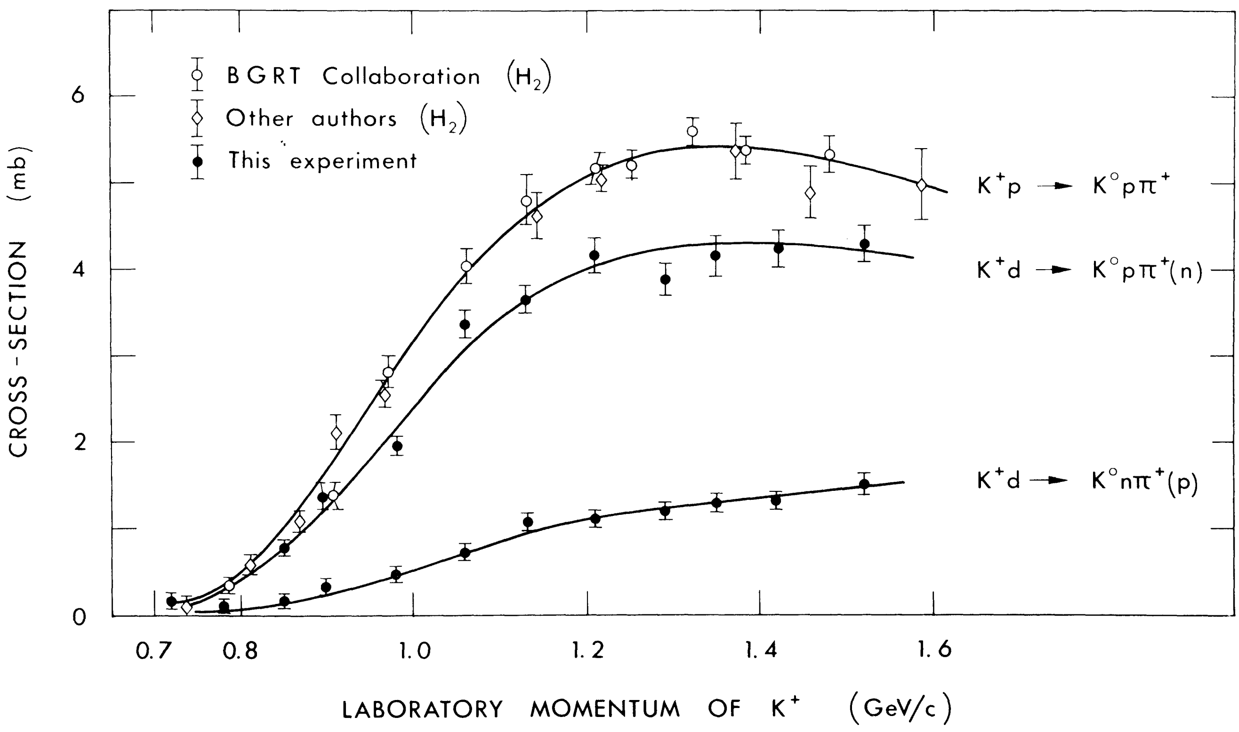

mb
ABRAMS
ELIOFF
GALBRAITH
ALLABY
BIZZARRI
BURROWS
300
200
100
0
0.1
1
10
100
p_{LAB} GeV/c
$\sigma\,\bar{p}d$
$\sigma\,\bar{p}n$

Fig. 2



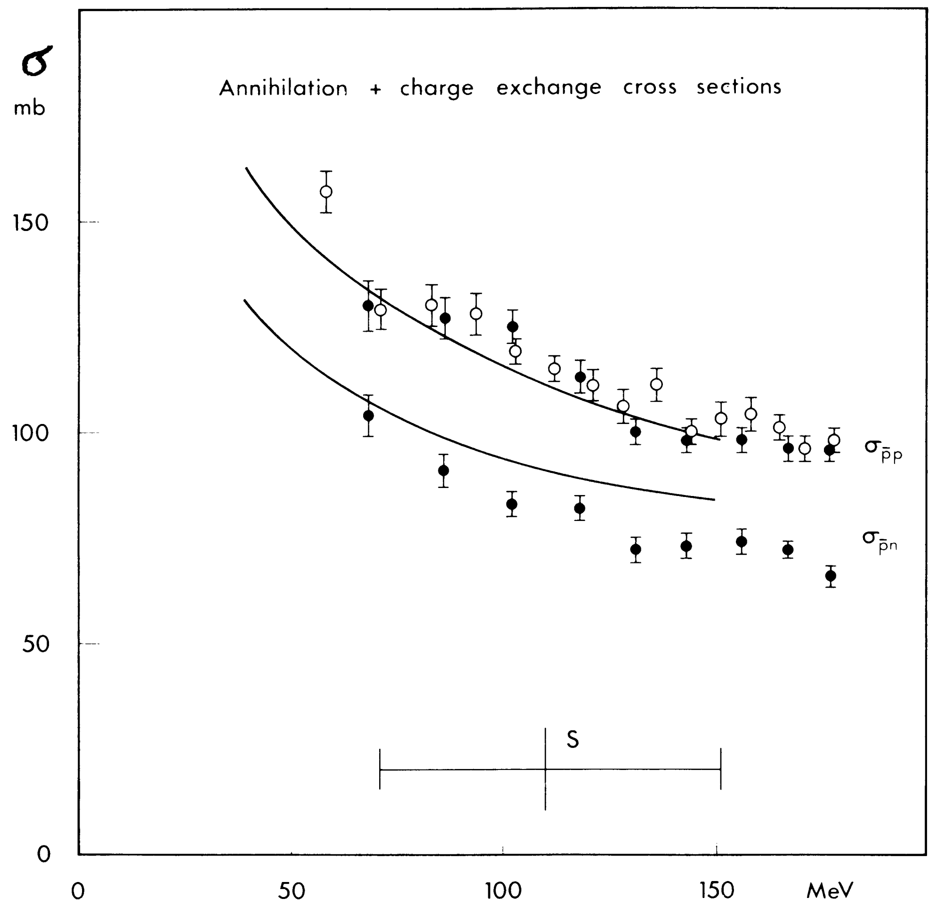
200
σ
mb
150
100
50
0
1
10
100
p_{LAB} GeV/c
σ0
σ1
ABRAMS
σ0
σ1
ELIOFF
σ0
σ1
GALBRAITH
σ0
σ1
ALLABY

Fig. 3



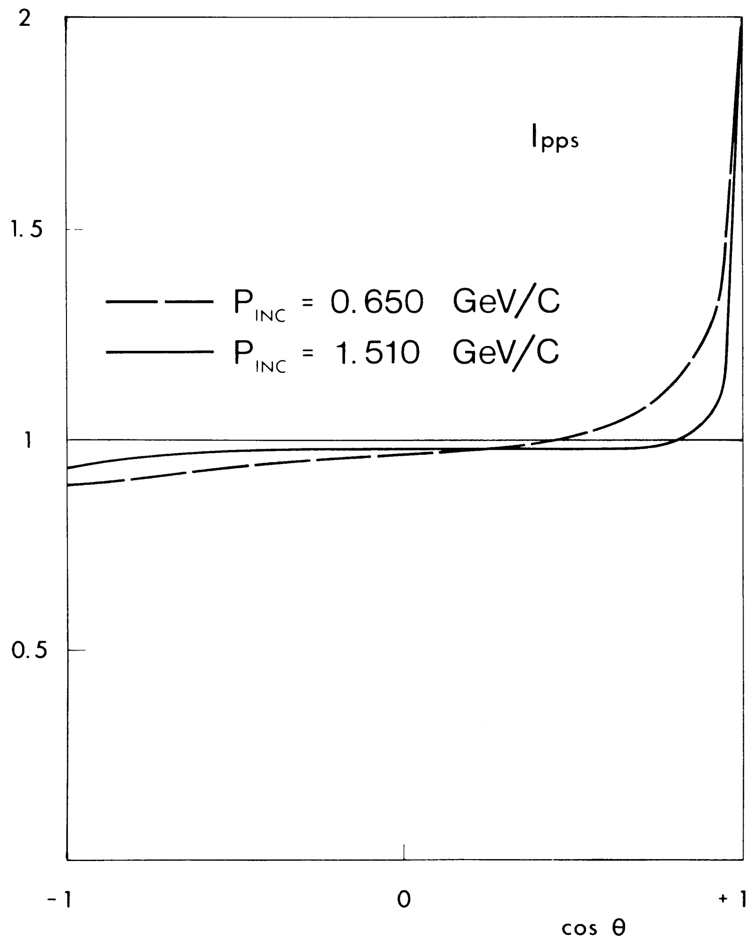
B G R T Collaboration (H_2)
Other authors (H_2)
This experiment
CROSS - SECTION (mb)
6
4
2
0
0.7
0.8
1.0
1.2
1.4
1.6
LABORATORY MOMENTUM OF K^+ (GeV/c)
$K^+p \rightarrow K^\circ p\pi^+$
$K^+d \rightarrow K^\circ p\pi^+(n)$
$K^+d \rightarrow K^\circ n\pi^+(p)$

Fig. 4



σ
mb
Annihilation + charge exchange cross sections
150
100
50
0
0
50
100
150
MeV
$\sigma_{\bar{p}p}$
$\sigma_{\bar{p}n}$
S

Fig. 5



2
1.5
1
0.5
I_{pps}
P_{INC} = 0.650 GeV/C
P_{INC} = 1.510 GeV/C
-1
0
+1
cos θ

Fig. 6

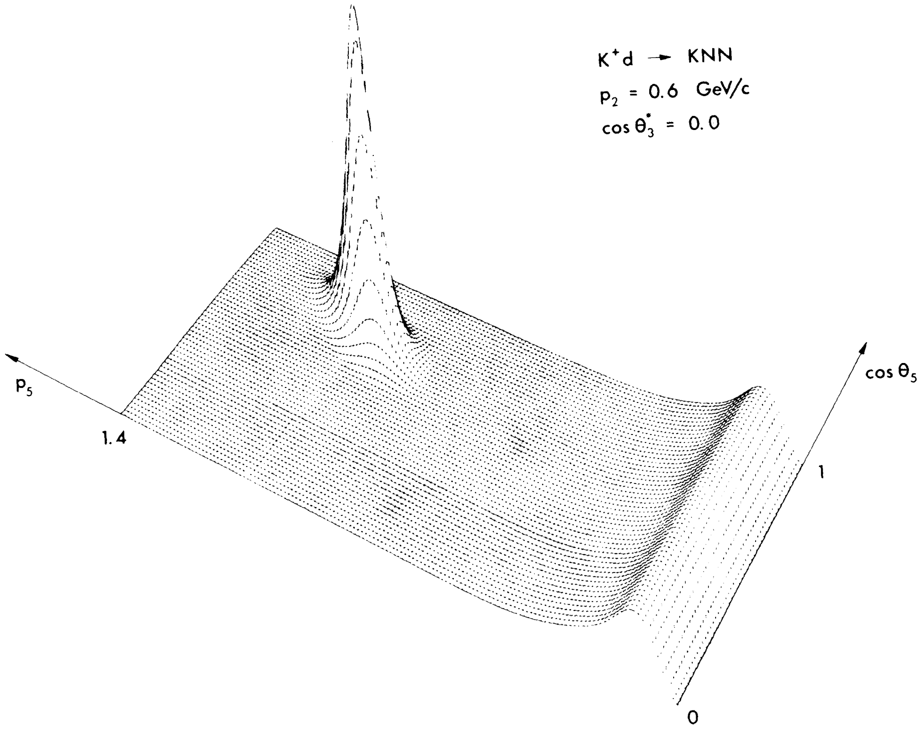

K⁺d → KNN
p₂ = 0.6 GeV/c
cos θ₃* = 0.0
cos θ₅
p₅
1.4
1
0

Fig. 7a

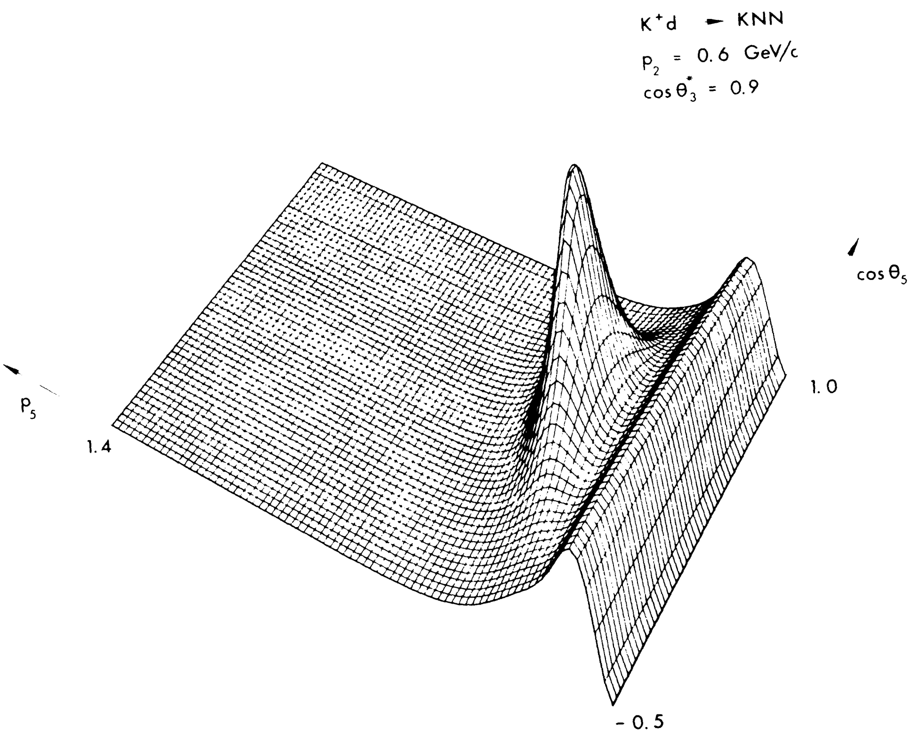

K⁺d → KNN
p₂ = 0.6 GeV/c
cos θ₃* = 0.9
cos θ₅
p₅
1.4
1.0
- 0.5

Fig. 7b

DISCUSSION AND COMMENTS

Mr. Bizzarri : For small enough momenta of the spectator proton (say below 150 MeV) impulse approximation for $\bar{p}n$ annihilations should work quite well. There is then a tail of energetic protons (15 to 20%) which is not accounted for by impulse approximation but it could be due for instance to 3-body ($\bar{N}NN$) annihilations.

After all, from the deuteron wave function, we have a probability of 10 to 15% of finding both nucleons inside the interaction volume.

There are however two difficulties:

1) The direction of the low momentum spectator proton is unknown and this could cause troubles in fitting;

2) The absolute normalization is unknown since we do not know how to estimate the loss of energetic spectators: by means of the deuteron wave function or using the experimental proton spectrum.

These difficulties in normalization are clear in two examples shown by Castelli: $\bar{p}d$ annihilations for 0.4 to 0.6 GeV/c and $K^+d \to K^0\pi^+p\ (n_s)$.

I should like to point out however that these cross-section excess or defects are not rapidly varying with momentum and therefore this uncertainty in the absolute cross-sections should not prevent detection of resonances by formation experiments.