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Pion Absorption on the Diproton

E. Piaseetzky, D. Ashery, and M.A. Moinester
Raymond and Beverly Sackler Faculty of Exact Sciences,

School of Physics and Astronomy,

Tel-Aviv University, Ramat Aviv 69978, Israel

G.A. Miller

Department of Physics, University of Washington,
Seattle, Washington 98195

A. Gal(a)

TRIUMF, Vancouver, B.C., Canada V6T 2A3

Abstract

A partial-wave analysis of recent low-energy pion absorption data on a diproton (1S_0) in ^3He is supplemented by proton-neutron final-state interaction phase shifts and mixing parameters, yielding a model-independent determination of the absorption amplitude. Several possible amplitudes describe the existing angular distribution, but these can essentially be distinguished by a polarization measurement.

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Absorption on two nucleons provides the simplest reaction for pion absorption in nuclei.¹ Its theoretical study offers challenging insights into the intermediate-range coupling between NN and $\text{N}\Delta$, NN^* modes,^{2,3} and/or the short-range coupling between NN and six-quark cluster modes.^{4,5} Pion absorption on the deuteron has been studied for over three decades, being the most accessible elementary absorption process. The $J^\pi = 1^+$ character of the deuteron introduces a multitude of amplitudes which requires measurement of differential cross sections and many spin observables⁶ in order to establish the absorption mechanism. This program has not yet been completed.

Studying pion absorption on a pair of $T=1$ nucleons provides different information. Experimental studies of π^- absorption by ^3He at rest,⁷ low energies⁸ ($T_\pi < 85$ MeV) and at higher energies⁹ have been reported. The use of complete kinematics allows one to obtain cross sections for π^- absorption on the proton pair. These two protons are in a 1S_0 bound state, which we call a diproton. Reference 8 gives the angular distribution of the emitted pn pair, analogous to the pp pair emitted in the π^+d reaction. The $J^\pi = 0^+$ nature of the diproton restricts drastically, through angular momentum and parity selection rules, the number of contributing partial-wave amplitudes. In the present Letter we show that, by incorporating the constraints of unitarity for the outgoing pn pair, the analysis of the angular distribution⁸ determines the absorption amplitude up to a discrete multiplicity of solutions. This multiplicity can be largely resolved by measuring the polarization of one of the outgoing nucleons.

Expressions for the

$$\pi^- + (pp)^1S_0 \rightarrow p + n \quad (1)$$

transition amplitudes for incoming pion angular momentum $\ell=0,1,2$ are given in Table I. The partial-wave amplitudes $A, \dots, E$ depend on energy only. The $S=0 + S=1$ spin-flip nature of the absorption on diproton limits the reaction amplitude F to the form (disregarding isospin indices)

$$F = \vec{\sigma} \cdot \vec{V}, \quad \vec{V} = f(\cos\theta) \hat{p} + g(\cos\theta) \hat{k} \quad (2)$$

where $\hat{\sigma} \equiv 1/2(\hat{\sigma}_2 - \hat{\sigma}_1)$, $\cos\theta = \hat{k} \cdot \hat{p}$ and the amplitudes f and g depend on energy. The differential cross section, parametrized as $\Lambda A_n P_n(\cos\theta)$, is given by

$$\frac{d\sigma}{d\Omega} = |\vec{V}|^2 = |f|^2 + |g|^2 + 2 \operatorname{Re}(f g^*) \cos\theta, \quad (3)$$

with f and g derived from Table I:

$$f = (A-D-E) + 3C \cos\theta + 5E \cos^2\theta, \quad g = (B-C) + (3D-2E) \cos\theta. \quad (4)$$

We now restrict the discussion to $\ell=0,1$ (low energy) so that $D=E=0$.

The determination of the five parameters (leaving out an overall phase) which make the complex amplitudes A, B, C requires two further conditions beyond the given⁸ nonzero angular-distribution coefficients A_0, A_1, A_2 .

We begin by ignoring the relatively weak pion-nuclear interaction in the initial state, as was done in a related context.¹⁰ Under these circumstances, we can employ Watson's theorem.¹¹ This allows one to use pn elastic-scattering phase shifts and mixing parameters to determine the phases of A, B, C . At the relevant energies the pn interaction is still dominated by elastic scattering and the use of Watson's theorem is justified. The $3P_0$ final-state amplitude assumes then the form

$$A = t^{(0)} \exp(i\delta^{(0)}) \quad (5)$$

in terms of the $3P_0$ phase shift $\delta^{(0)}$ and a real parameter $t^{(0)}$. Since

the $3S_1$ and $3D_1$ final states (and $3P_2-3F_2$ when $\ell=2$ is included) are mixed by the tensor force, the corresponding amplitudes $B \equiv F_1^{(0)}$, $C \equiv -2^{-1/2} F_1^{(2)}$ are expressed in terms of two real parameters $t_\alpha^{(1)}, t_\beta^{(1)}$ as follows:

$$F_J^{(J-1)} = \cos e_J \exp(i\delta_\alpha^{(J)}) t_\alpha^{(J)} - \sin e_J \exp(i\delta_\beta^{(J)}) t_\beta^{(J)} \\ F_J^{(J+1)} = \sin e_J \exp(i\delta_\alpha^{(J)}) t_\alpha^{(J)} + \cos e_J \exp(i\delta_\beta^{(J)}) t_\beta^{(J)}, \quad (6)$$

where $\delta_\alpha^{(J)}, \delta_\beta^{(J)}$ are the Blatt-Biedenharn (BB) phase shifts and e_J are the BB mixing angles.¹¹ The amplitudes A, B and C depend now on three real unknowns. These are determined from Eq. (3) (cf. also Eq. (4) for $D=E=0$) by invoking the fitted Legendre coefficients for the 62.5 Mev data⁸ and solving the appropriate equations numerically. In doing so, the tabulated¹² bar phase shifts and mixing angles for $T_L = 425$ Mev were transformed into the BB corresponding quantities.

Two solutions were found for the pion-absorption amplitudes A, B, C as displayed in the first two lines in Table II (the other solutions, with $\ell=2$ included, are discussed below). These two solutions share a common value for A (through $t^{(0)}$), which leads to a unique and large value for the $(T_f=0)$ fraction [recall that $T_f = (1+(-1)^\ell)/2$ through conservation laws]:

$$P_{\ell=1} = \frac{\sigma(T_f=0)}{\sigma(T_f=0) + \sigma(T_f=1)} = \frac{|B|^2 + 2|C|^2}{|A|^2 + |B|^2 + 2(|C|^2 + |D|^2) + 4/3|E|^2}. \quad (7a)$$

The solutions differ in the values found for B, C (through $t_\alpha^{(1)}$ and $t_\beta^{(1)}$). Hence, the $(L_f=0)$ fraction for $\ell=1$,

$$P_{L=0}/P_{\ell=1} = \frac{\sigma(L_f=0)}{\sigma(L_f=0) + \sigma(L_f=2)} = \frac{|B|^2}{|B|^2 + 2|C|^2}, \quad (7b)$$

is determined up to a two-fold ambiguity. This, almost complete determination of the pion-absorption partial-wave amplitudes, is due to incorporating the restrictions of unitarity in the pn final-states. Without it, the values of $P_{\ell=1}$ and $(P_{\ell=0}/P_{\ell=1})$ are free to vary within the shaded area drawn in Fig. 1. The results of the earlier analysis⁸ and the one constrained by final-state interaction (FSI) both show dominance of the $\ell=1$, $T_f=0$ channel where the $\Delta(1232)$ cannot play any role through NA intermediate states. The present calculations give two solutions in this dominant exit channel, which yield the same differential cross section.

We note that the two solutions are roughly obtained from each other by applying the transformation $f' = f + 2g \cos\theta$, $g' = -g$.

To assess the effects of the π -nuclear initial-state interaction (ISI) on these results we extend Eqs. (5),(6) by multiplying their r.h.s. by $\exp(i\delta_0)$, $\exp(i\delta_1)$, respectively, where δ_ℓ are the $\pi^-(pp)$ elastic phase shifts. For example, Eq. (5) is modified as follows:

$$A = \exp(i\delta_0) \tau^{(0)} \exp(i\delta^{(0)}) . \quad (8)$$

This approximation is similar to the distorted-wave approximation in nuclear physics, but does not follow from Watson's theorem because the coupling to πNN breakup channels causes δ_ℓ to be complex.¹³ Although the breakup cross section is over an order of magnitude larger than that for absorption, the effect of these channels on absorption should be small because the low-energy pion-nuclear interaction is weak enough so that $\text{Im } \delta_\ell$ is very small. The phases δ_ℓ were approximated in the present study by twice the π^-p phase shifts, averaged over the singlet-spin configuration of the diproton. This must involve an overestimate, because the pp form factor will cut the additivity assumed. We extracted

the πN phase shifts at 62.5 MeV from Ref. 14 to derive $\delta_0=6.7^\circ$, $\delta_1=2.9^\circ$. The effect of these ISI causes the numerical results for the first two solutions in Table II to change by no more than a few percent.

We now turn to spin observables and discuss measurements in which the polarization of one of the emitted nucleons is measured. The asymmetry, $\Delta^{(1)} \equiv \sigma(+)-\sigma(-)$ between spin up and spin down along $\hat{n} = \hat{k} \times \hat{p}$ for an emitted nucleon, is given by (cf. Eq. (2))

$$\frac{d\Delta^{(1)}}{d\Omega} = 2 \text{Im}(V_y V_x^*) = 2 \text{Im}(fg^*) \sin\theta . \quad (9)$$

The vector polarization is perpendicular to the reaction plane, $\vec{P} = P_n \hat{n}$, with P given by $P = (d\Delta^{(1)}/d\Omega)/(d\sigma/d\Omega)$. The polarizations predicted for each of the ($\ell=0,1$) two solutions of Table II are shown in Fig. 2a. The shaded areas reflect the approximation involved in considering the pion-nuclear ISI, between neglecting it altogether or adopting the estimate specified above. It is evident that vector-polarization measurements can resolve the duplicity of solutions. We note that Solution 1 which has the more dramatic polarization effect is the one corresponding to a large value of $P_{\ell=0}/P_{\ell=1}$, (cf. Fig. 1) i.e. approximately equal contributions from the $\ell=0$ and $\ell=2$ partial waves in the exit channel.

We now discuss the effects of adding the $\ell=2$ pion-nuclear initial wave into the absorption analysis. The additional amplitudes D, E (cf. Table I) are expressed in terms of two real parameters $t_\alpha^{(2)}$ and $t_\beta^{(2)}$ as given by Eq. (6), where $D=F_2^{(1)}$ and $E=-(3/2)^{-1/2} F_2^{(3)}$. The total of five real parameters $t^{(0)}$, $t_\alpha^{(1)}$, $t_\beta^{(1)}$, $t_\alpha^{(2)}$ and $t_\beta^{(2)}$ are determined by using Eqs. (3) and (4) with the reported⁸ values of A_0, A_1, A_2 and setting

$A_3=A_4=0$. Three additional solutions, with variable but substantial fraction $P_{\lambda=2}$ for absorption cross section from the $\lambda=2$ entrance channel, were found and are listed in Table II as Solutions 3,4,5. Solution 3 roughly corresponds to interchanging f and g in the amplitude Eq. (2) for Solution 1. This operation keeps the absorption angular distribution, Eq. (3), invariant. It interchanges the intensities of absorption to 3P_0 and 3S_1 and transfers the sizable 3D_1 intensity into the 3P_2 (new) channel. The FSI conditions (5),(6) do not allow a similar solution to develop from Solution 2. The vector polarization associated with Solution 3 is shown in Fig. 2b; it is similar to the one associated in Fig. 2a with Solution 1.

Solutions 4,5 are approximately obtained from Solutions 1,2, respectively, by the transformation $f' = g + 2f \cos\theta$, $g' = -f$, which also keeps the cross section, Eq. (3), invariant. It transfers the sizable 3D_1 intensity dominantly into the 3F_2 (new) channel. The polarization associated with each of these solutions, as shown in Fig. 2b, is dramatically different from the other three, with opposite signs in the backward hemisphere, and therefore can be readily identified. In fact, if observed, a sizable contribution from the $\lambda=2$ partial wave would be established.

With $P_{\lambda=1}$ assuming an exceedingly small value for Solutions 3-5 (cf. Table II), a dominance of the $T_f=1$ channels which may be coupled to NA intermediate states emerges. However, with both $\lambda=0$ and $\lambda=2$ pion partial waves allowed for $T_f=1$, it is inconceivable that the $\lambda=2$ contribution should be appreciable at these low energies; in fact, pion centrifugal-barrier arguments would limit such a contribution to almost two orders of magnitude below the $\lambda=0$ contribution. Hence, based on NA dynamics alone,

the $\lambda=2$ channels are not expected to play a significant role in the absorption process. Identification of a significant $\lambda=2$ contribution may signal other dynamics for particular final states (e.g. 3F_2), such as dibaryon structure.

In conclusion, it is possible to determine (up to a duplicity) the low-energy transition amplitudes for $\pi^-(pp)$ absorption by assuming $\lambda=0,1$ and using the constraints of unitarity. The remaining duplicity can be resolved by measurements of the polarization of one of the emitted nucleons. If such a measurement is performed, a model-independent determination of the absorption partial-wave amplitudes will be possible. Dynamical models which are designed to describe pion absorption on a $T=1$ nucleon pair will have a very complete set with which to compare their amplitude predictions.

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Table I. Quantum numbers and amplitudes involved in the π^- absorption reaction (1) for $l \leq 2$. The pion cm momentum is $\vec{k}$ and the nucleons' cm momentum is $\vec{p}$. The operators are defined as $\vec{\sigma} = 1/2(\vec{\sigma}_2 - \vec{\sigma}_1)$, $\vec{t} = 1/2(\vec{t}_2 - \vec{t}_1)$ in terms of the nucleon Pauli spin and isospin matrices, respectively, and $T_{-1} = (T_x - iT_y)/2^{1/2}$ in terms of the nucleons' total isospin $\vec{T} = 1/2(\vec{T}_1 + \vec{T}_2)$.

$l(\pi^- 2N)$	$^3L_F; J_F^{\pi}; T_F$	$\pi^-(pp)^1S_0 \rightarrow (pn)$ amplitude
0	$^3P_0; 0^-; 1$	$A\vec{\sigma} \cdot \vec{p} \ T_{-1}$
1	$^3S_1; 1^+; 0$	$B\vec{\sigma} \cdot \vec{k} \ \tau_{-1}$
	$^3D_1; 1^+; 0$	$C\vec{\sigma} \cdot (3\hat{p}(\hat{k} \cdot \hat{p}) - \hat{k}) \tau_{-1}$
2	$^3P_2; 2^-; 1$	$D\vec{\sigma} \cdot (3\hat{k}(\hat{k} \cdot \hat{p}) - \hat{p}) T_{-1}$
	$^3F_2; 2^-; 1$	$E\vec{\sigma} \cdot (5\hat{p}(\hat{k} \cdot \hat{p})^2 - \hat{p} \cdot 2\hat{k}(\hat{k} \cdot \hat{p})) T_{-1}$

Table II. Solutions for the partial-wave amplitudes t of reaction (1) obtained by fitting to the pn angular distribution⁸ ($A_0=55$, $A_1=45$, $A_2=89$ in units 10^{-4} fm²) at $T_L=62.5$ MeV. P indicates the absorption fractions. The FSI parameters used are $\delta^{(0)}=-20.0^\circ$, $\epsilon_1=19.4^\circ$, $\delta^{(1)}=-3.93^\circ$, $\delta^{(1)}_g=-27.8^\circ$, $\epsilon_2=-7.28^\circ$, $\delta^{(2)}_a=18.54^\circ$, $\delta^{(2)}_g=0.02^\circ$.

$t^{(0)}$	$t_{\alpha}^{(1)}$	$t_{\beta}^{(1)}$	$t_{\alpha}^{(2)}$	$t_{\beta}^{(2)}$	$P_{\ell=1}$	$P_{\ell=2}$	
10^{-2} fm					%		
1	1.91	-3.70	6.12	0	0	93.4	—
2	1.92	0.20	7.15	0	0	93.3	—
3	3.97	-1.61	0.82	4.22	0.57	5.9	65.6
4	5.55	1.12	1.53	-0.25	-3.20	6.5	37.6
5	2.36	1.17	1.60	-0.37	-4.76	7.1	82.8

Figure Captions

1. Region of allowed solutions (shaded area) in the ($1-P_{\ell=1}$), $P_{\ell=0}/P_{\ell=1}$ plane for the π^- -absorption reaction (1) at 62.5 MeV, assuming $\ell(\pi^-N)=0,1$. This region replaces the one in Fig. 14 of Aniol et al.⁸ due to the current definitions of the absorption fractions in Eqs. (7). The points mark the two solutions found in the present work (cf. Table II) by incorporating the constraints of unitarity.
2. Vector polarization along the normal to the reaction plane for a nucleon emitted in the π^- -absorption reaction (1), as calculated (Eq. (9) and following text) for the five solutions of Table II.
 - (a) The shaded area for each of the solutions 1 (solid) and 2 (dash), with $\ell=0,1$ only, is bounded by polarization curves obtained by ignoring or considering the pion-nuclear ISI as explained in the text.
 - (b) Polarization curves for Solutions 3,4 (solid) and 5 (dash), with $\ell=2$ included.

Fig. 1

Fig. 2