Analyzing Powers and Partial Wave Decomposition of $pn \rightarrow pp(^1S_0)\pi^-$ at Low Energies

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Analyzing powers for $\vec{p}n \rightarrow pp(^1S_0)\pi^-$ were measured at beam energies 353, 404, and 440 MeV by extracting the quasifree process from $\vec{p}d \rightarrow ppp\pi^-$. Partial wave amplitude analysis yields a significant contribution from the isospin 1, s-wave channel. This contribution is relatively much larger than that expected from theoretical models which have been successful in describing the isospin 1, s-wave channel behavior of $pp \rightarrow pp\pi^0$ cross sections at threshold. [S0031-9007(99)08633-0]

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The fundamental processes of intermediate energy physics involve the NN, $N\pi$, and $NN\pi$ systems. The $NN \leftrightarrow NN\pi$ process connects two of these systems and provides the fundamental basis for both pion production and pion absorption. Not only does this process contribute to our understanding of the role of the pion in nuclear physics, but it is also important for studying the onset of inelasticities in nucleon-nucleon scattering. It is thus important to acquire an understanding of the amplitude structure of the $NN \leftrightarrow NN\pi$ process.

The only $NN \leftrightarrow NN\pi$ process whose amplitudes are well known is that of the $pp \leftrightarrow d\pi^+$ reaction [1]. The main reasons are experimental; all particles in this reaction are charged, and both proton and deuteron targets are available. The wealth of data characterizing this reaction has facilitated a great deal of theoretical study, with much progress [2] thus far.

The $pp \leftrightarrow d\pi^+$ reaction proceeds through a pure σ_{10} channel where the subscripts refer to the initial and final NN isospin states [3]. The other possible isospin channels, the σ_{11} and the σ_{01} channels, are less well known because the reactions they describe involve neutral particles as well as three-body final/initial states. As a result, there are no partial wave amplitude (PWA) analyses available for these channels which are extracted purely from experimental observables, and, consequently, theoretical understanding is much less developed.

One of the most straightforward reactions to consider for investigating the σ_{11} and σ_{01} channels is the $pn \leftrightarrow pp(^1S_0)\pi^-$ reaction which proceeds entirely through these lesser known and weaker channels. Even though $pn \leftrightarrow pp(^1S_0)\pi^-$ experiments are intrinsically more difficult than those of $pp \leftrightarrow d\pi^+$, the amplitude structure is simpler, involving only two independent spin amplitudes if the final pp state is restricted to the $(^1S_0)$ state (the "diproton"); whereas the $pp \leftrightarrow d\pi^+$ process has six independent spin amplitudes. The latter requires, if pionic d waves or higher are considered, measurement of many different types of spin observables in order to unravel the amplitude structure [1]; in contrast, unraveling the amplitude structure of the former can be attempted with only measurements of the differential cross section and one spin observable.

For $l_\pi \leq 2$, the 2 spin amplitudes decompose into five possible partial wave amplitudes. These are listed in Table I. The isospin channel of each amplitude is shown as well. Note that the intermediate $N\Delta$ state is not expected to contribute significantly for any of these amplitudes. The $N\Delta$ is forbidden for the σ_{01} $I = 0$ amplitudes, and for the σ_{11} $I = 1$ amplitudes, the dominant $N\Delta$ amplitudes seen in $pp \leftrightarrow d\pi^+$ which correspond to $^1D_2$ and $^3F_3$ initial NN states, are absent due to J-parity considerations. Thus the $pn \leftrightarrow pp(^1S_0)\pi^-$ reaction is expected to be particularly sensitive to weak nonresonant pion processes.

The traditional approach to studying the $pn \leftrightarrow pp(^1S_0)\pi^-$ process has been measurements of the absorption reaction ^{3}He$(\pi^-, pn)n$ [4–8], where the π^- is assumed to be absorbed onto a $pp(^1S_0)$ diproton within the ^{3}He nucleus. However, the ^{3}He nuclear environment is not so trivial [9]. The signature of this reaction is the angular correlation of the outgoing proton-neutron pair. Thus far, only differential cross sections have been obtained. A polarization measurement of the outgoing proton would take a prohibitive amount of time. Although a partial wave analysis has been attempted

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TABLE I. Allowed transitions and amplitudes for $pn \to pp(^1S_0)\pi^-$ for $l_\pi \leq 2$. I_i, I_f designate the initial and the final state NN isospin, respectively.

Transition	Amplitude	$\sigma_{I_iI_f}$
$^3P_0 \to {}^1S_0 s_0$	a_{Ps}	σ_{11}
$^3S_1 \to {}^1S_0 p_1$	a_{Sp}	σ_{01}
$^3D_1 \to {}^1S_0 p_1$	a_{Dp}	σ_{01}
$^3P_2 \to {}^1S_0 d_2$	a_{Pd}	σ_{11}
$^3F_2 \to {}^1S_0 d_2$	a_{Fd}	σ_{11}

[8,10], it relies on NN scattering phase shifts [11] to fix the relative phase angles of the amplitudes (Watson's theorem).

An alternative to measurements of the absorption process is extraction of the $pn \to pp(^1S_0)\pi^-$ production reaction from the quasifree process $pd \to ppp\pi^-$. As the deuteron is lightly bound, the nuclear environment complications are reduced considerably. As polarized proton beams are available the relevant spin information can be easily extracted by measuring the analyzing power, A_{N0}. A $pp(^1S_0)$ state can be selected by requiring both protons to enter a small solid angle detector with nearly the same momentum. Final state interactions in the $pp(^1S_0)$ state enhance the number of such events. An earlier experiment based on this reaction was reported by Ponting *et al.* [12], describing analyzing power measurements at $T_p = 400$ MeV. In the current work, this previous experiment was repeated with an improved apparatus at $T_p = 353$, 403, and 440 MeV over a greater angular range and both double differential cross sections and analyzing powers were obtained. The analyzing powers are presented in this paper along with the first partial wave analysis of the σ_{01} and σ_{11} channels extracted from experimental data alone. All data for this PWA came from this single experiment and hence are internally consistent. The cross section data are presented in a separate paper [9].

The experiment was carried out at the TRIUMF Cyclotron Laboratory using a polarized proton beam and a liquid deuterium target. The negative pions were detected in the quad-quad-dipole (QQD) magnetic spectrometer [13] while the diprotons were detected in a 1 m × 1 m hodoscope [8]. An acceptable event required a good QQD signal together with signals from two of the counters from the hodoscope. The beam polarization was typically 70% and was cycled between "up" and "down" during measurements. It was monitored by an in-beam polarimeter [14] located upstream of the experimental area.

The hodoscope provided positional information for the two protons while their momenta were obtained by time-of-flight measurements. The QQD yielded both the momentum and the trajectory of the π^-. Thus there was enough redundancy to determine the incident beam energy as well as the spectator proton momentum and direction. The reaction signal was identified by the event distribution of the calculated beam energy peaking at the cyclotron beam energy. The observed spectator momentum distribution was consistent with the expected distribution based upon a Reid soft core wave function [15] of the deuteron. The $(^1S_0)pp$ content of the data was enhanced by a cut placed on ΔP, the difference in the proton momenta in the $pp\pi$ c.m. system. The measured A_{N0} was, within statistical accuracy, the A_{N0} at $\Delta P = 0$. Further details of the experimental apparatus and data reduction are provided in the paper describing the cross section measurements [9].

The event sample used when computing analyzing powers had restrictive cuts placed on it to reduce background to a minimum. As A_{N0} is obtained from an event ratio, elimination of some good events in suppressing the background does not affect the result as long as the cuts on both polarization directions are identical. To test the stability of the A_{N0} against restrictive cuts, two independent analyses were used to extract the results. The first had relatively loose cuts and was applied to the 353 and 403 MeV data. The second had very restrictive cuts and was applied to the 403 and 440 MeV data. The A_{N0} at 403 MeV, calculated from both procedures, were consistent within the errors associated with the difference in the sample sizes.

As a test of the experimental method, the analyzing power of $\vec{p}p \to d\pi^+$ was measured by extracting the quasifree process from $\vec{p}d \to nd\pi^+$ at 353 MeV. The comparison with the analyzing powers measured in the free process [16] shows good agreement (Fig. 1).

For each event, the c.m. angle between the incident proton and the outgoing pion was calculated. This variable has a broad range at each spectrometer setting due to Fermi motion of the struck neutron. This permitted splitting the data from each QQD setting into three measurements of the analyzing power A_{N0} at three different c.m. angles. Although there was also a broad spread in $T_{\rm c.m.}$ (the total $pp\pi$ c.m. energy minus the masses of the pion and two protons), this was of little consequence as

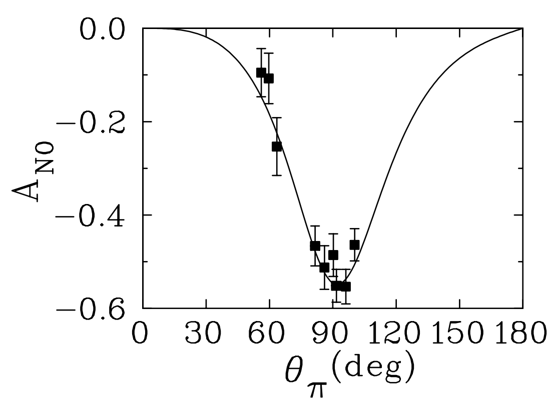

FIG. 1. Quasifree $pp \to d\pi^+$ analyzing power at 353 MeV (points) compared to the free $pp \to d\pi^+$ analyzing power (solid curve).

the A_{N0} displayed little dependence on $T_{\text{c.m.}}$. A_{N0} was computed by

$$A_{N0} = \frac{(Y_\pi)_\uparrow - (Y_\pi)_\downarrow}{P_\uparrow (Y_\pi)_\downarrow + P_\downarrow (Y_\pi)_\uparrow}. \quad (1)$$

The arrows indicate the polarization direction at which normalized pion yields, Y_π, and beam polarization values, P, were measured. The resulting analyzing powers are shown in Fig. 2 and listed in Table II with respect to the central $T_{\text{c.m.}}$ of the three beam energies. At all three energies, the analyzing power crosses zero at $\approx 67°$ and is sharply changing between the extreme values of -1 and $+1$ within an angular range of $\pm 13°$ of this value. These results are consistent with those of Ponting *et al.* [12] except the zero-crossing angle of Ponting's data is larger by 4°. The $T_{\text{c.m.}}$ 70 MeV data ($T_p = 440$ MeV) show a

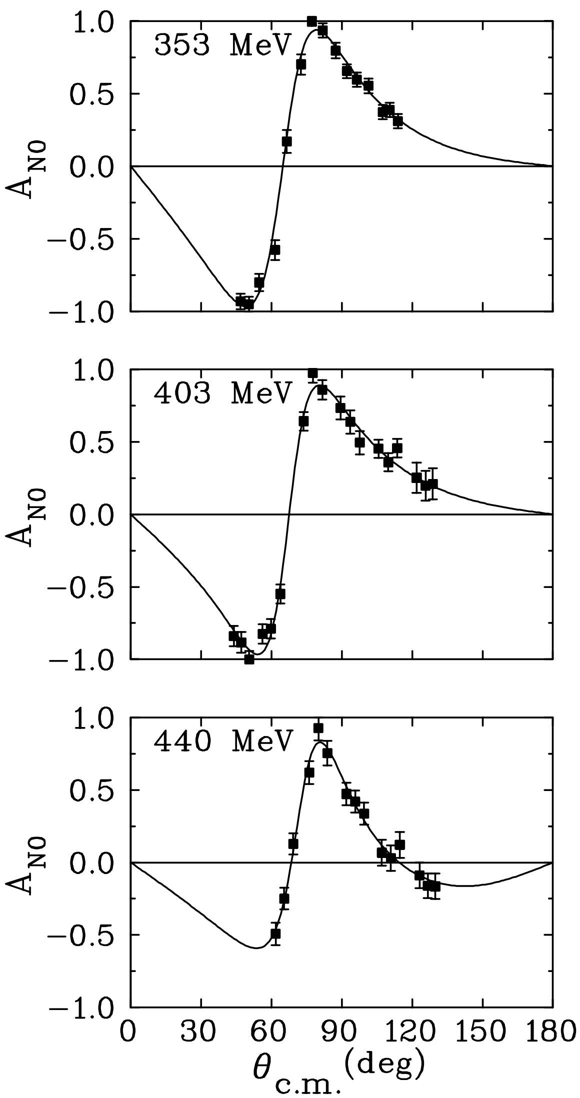

FIG. 2 Analyzing powers for $pn \to pp(^1S_0)\pi^-$ from this experiment (points). The partial wave amplitude fit for $l_\pi \leq 2$ from the solution set (set text) is the solid curve.

second zero crossing at 114°. This can happen only with a sufficient contribution from pion d waves.

The partial wave expansion for $pn \to pp(^1S_0)\pi^-$ was constructed by modifying the procedure developed by Gell-Mann and Watson [3]. The expansion was fitted to both the A_{N0} and the cross section [9] data and included all the amplitudes in Table I. The d wave amplitudes, although quite small, can be extracted by this analysis because their presence is manifested through interference with the dominant s and p waves.

The fitting procedure used to extract partial wave amplitudes produced more than one solution at each energy [17]. Some solutions were unrealistic such as one which involved large d waves at the lowest $T_{\text{c.m.}}$ energy. The possibility of such ambiguities in the amplitude analysis for this process was pointed out by Gal [18]. In order to select an appropriate physical set of solutions, a continuity procedure was used. The total change in each amplitude on the argand plot was calculated from energy to energy. The changes were summed to give a total amplitude change for each solution set. All possible solution sets were formed, and the set which had the minimum total amplitude change was chosen. This procedure assumes that there are no strong resonant structures present.

At $T_{\text{c.m.}} = 31$ MeV there was no significant improvement in the χ^2/ν between the fit restricted to s and p waves and that allowing s, p, and d waves. This indicated that the d-wave contribution is small as should be the case at a near-threshold energy. At $T_{\text{c.m.}} = 55$ and

TABLE II. Quasifree $pn \to pp(^1S_0)\pi^-$ analyzing power, A_{N0}, as a function of the center of mass production angle of the π^-, θ^*_π, at $T_{\text{c.m.}} = 31$ MeV ($T_p = 353$ MeV), $T_{\text{c.m.}} = 55$ MeV ($T_p = 403$ MeV), and $T_{\text{c.m.}} = 70$ MeV ($T_p = 440$ MeV).

$T_{\text{c.m.}} = 31$ MeV		$T_{\text{c.m.}} = 55$ MeV		$T_{\text{c.m.}} = 70$ MeV	
θ^*_π (deg)	A_{N0}	θ^*_π (deg)	A_{N0}	θ^*_π (deg)	A_{N0}
46.8	−0.93(5)	43.9	−0.84(7)	61.8	−0.49(7)
50.4	−0.95(5)	47.1	−0.88(7)	65.4	−0.25(7)
54.7	−0.80(6)	50.5	−1.00(6)	69.3	0.13(7)
61.5	−0.58(7)	56.2	−0.82(6)	76.1	0.62(7)
66.5	0.17(7)	59.8	−0.79(6)	80.0	0.93(8)
72.6	0.70(7)	63.8	−0.55(6)	83.8	0.75(8)
77.2	1.00(3)	73.6	0.64(6)	91.9	0.47(7)
81.9	0.94(5)	77.6	0.98(6)	95.7	0.42(7)
87.4	0.80(5)	81.7	0.86(6)	99.5	0.34(7)
92.1	0.66(4)	89.4	0.73(7)	107.0	0.07(7)
96.4	0.60(5)	93.6	0.64(7)	110.9	0.03(7)
101.4	0.55(5)	97.6	0.49(7)	114.7	0.12(7)
107.4	0.37(4)	105.6	0.45(5)	123.1	−0.09(6)
110.4	0.39(4)	109.8	0.36(5)	126.6	−0.16(6)
113.9	0.31(4)	113.6	0.46(5)	129.8	−0.17(6)
		121.9	0.25(8)		
		125.7	0.20(8)		
		128.8	0.21(8)		

TABLE III. Relative contributions for $pn \leftrightarrow pp(^1S_0)\pi^-$ from partial wave amplitude analysis (PWAA) of the data for $l_\pi \leq 2$; from partial wave amplitude analysis using Watson's theorem (WATSON) for $l_\pi \leq 1$; and the coupled channel model with heavy meson exchange (HME) (Ref. [19]) and without (no HME) (Ref. [20]). d wave represents the combined contribution from the a_{Pd} and a_{Fd} amplitudes.

Solution	a_{Ps}	a_{Sp}	a_{Dp}	d wave
31 MeV				
PWAA	0.36(2)	0.24(3)	0.40(2)	0.013(8)
WATSON	0.36(2)	0.25(4)	0.39(3)	
HME	0.15	0.23	0.62	0.0021
No HME	0.020	0.26	0.72	0.0025
55 MeV				
PWAA	0.23(6)	0.37(28)	0.38(23)	0.018(25)
HME	0.12	0.22	0.66	0.0046
No HME	0.0067	0.25	0.74	0.0052
70 MeV				
PWAA	0.11(6)	0.57(9)	0.28(10)	0.041(29)
HME	0.11	0.22	0.67	0.0073
No HME	0.0029	0.24	0.74	0.0082

70 MeV d waves were required to fit the data. This suggested an alternative procedure to pick the most likely solution set. Calculate the change in each amplitude on the argand plot at each energy between the solution set and the s- and p-wave solution and choose the set with the minimum total summed amplitude change. This procedure picked the same solution set as did the continuity procedure described above.

As a check on the physical reality of the chosen solution set, an additional s and p wave fit only at $T_{\text{c.m.}} = 31$ MeV was further constrained by NN scattering phases (Watson's theorem) using the method of Piasetzky *et al.* [10]. It can be argued that at this near-threshold energy Watson's theorem should be valid. The lowest energy member of the chosen solution set matched this constrained fit in both amplitude and phase (see WATSON in Table III).

The resulting partial wave solution set is shown in Fig. 2 as the solid lines. The fraction of the total cross section contributed by each partial wave is presented in Table III for the three energies studied here. The errors are given within the brackets. The sizable strength of the s-wave pion channel indicates that short-range effects have to be included in the theoretical understanding of the process. However, present models such as the coupled channels model (CCM) [19,20] still fail to provide sufficient s-wave strength even when heavy meson exchange (HME) [21,22] is included. It is noted that HME or another mechanism such as off-shell rescattering [23] has been successful in describing the isospin 1, s-wave channel behavior of $pp \to pp\pi^0$ cross sections at threshold [24].

It is apparent in Table III that the CCM model with HME suggests a larger contribution from the a_{Dp} amplitude than what we obtain. There does exist another solution set which has a larger a_{Dp} contribution, but it shares the same $T_{\text{c.m.}} = 31$ MeV solution and then grows sizably in a_{Dp} strength with energy. In contrast, the CCM model's a_{Dp} strength is fairly stable. However, the other solution cannot be ruled out as at $T_{\text{c.m.}} = 55$ MeV there is a large correlation uncertainty between a_{Sp} and a_{Dp} which is reflected in the large uncertainties seen in these parameters. Thus, except for $T_{\text{c.m.}} = 31$ MeV the relative strengths of the a_{Sp} and a_{Dp} are still somewhat uncertain. However, the relatively large a_{Ps} strength is fixed by the A_{N0} zero-crossing angle and the angle of the minimum in the cross section [9] data.

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