Analyzing-Power Measurement in $\vec{p}n \rightarrow \pi^- pp(^1S_0)$: Pion Absorption by Quark Clusters?

C. Ponting,[1] D. A. Hutcheon,[2] M. A. Moinester,[2,3] P. L. Walden,[2] D. R. Gill,[2] R. R. Johnson,[1,2] F. Duncan,[1] G. Sheffer,[2] P. Weber,[1] V. Sossi,[1] A. Feltham,[1] M. Hanna,[1] R. Olszewski,[1] M. Pavan,[1] F. M. Rozon,[1] M. Sevior,[1] D. Ashery,[3] R. P. Trelle,[1] H. Hahn,[3] and B. Mayer[4]

[1]*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada V6T 2A6*
[2]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*
[3]*Raymond and Beverly Sackler Faculty of Exact Sciences, School of Physics and Astronomy, Tel-Aviv University, 69978 Ramat Aviv, Israel*
[4]*Département de Physique Nucléaire–Moyenne Énergie, Centre d'Études Nucléaires de Saclay, 91191 Gif-sur-Yvette, France*
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We have measured analyzing powers in $d(\vec{p},\pi^- pp)p$ at a beam energy of 400 MeV and laboratory pion detector angles of 35° and 43°. The π^- and two of the outgoing protons were detected in coincidence in a geometry which selected the quasifree two-body reaction $pn \rightarrow \pi^- pp(^1S_0)$. The analyzing-power data combined with $^3\mathrm{He}(\pi^-,pn)n$ differential cross sections allow determination of the transition amplitudes. The results indicate a significant contribution from a very short-range part of the nucleon-nucleon interaction.

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The two-body mechanism $\pi^- pp \rightarrow pn$ is a fundamental process of pion absorption and production, and can give information on states not accessible through absorption on the well-studied $T=0$, $S=1$ deuteron. In contrast to $\pi^+ d \rightarrow pp$, which is mediated by intermediate $N\Delta$ states, the $\pi^- pp(^1S_0) \rightarrow pn$ reaction is dominated by partial-wave channels which cannot involve a Δ.[1,2] This suppression of the usually dominant long-range Δ mechanism increases the potential sensitivity to other contributions, for example, absorption on a six-quark cluster.

Study of pion absorption on an $L=0$, $S=0$, $T=1$ nucleon pair has been done mainly via the $^3\mathrm{He}(\pi^-,pn)n$ reaction, with complete kinematics permitting extraction of the quasifree $\pi^- pp \rightarrow pn$ cross section.[1,3] At low energies, absorption on an isovector pair, $\pi^- pp \rightarrow pn$, has 10–20 times smaller cross section than absorption on the isoscalar pair in $\pi^+ d \rightarrow pp$. Qualitatively similar results for the isovector-isoscalar ratio have been drawn from tensor analyzing powers T_{20} in $pd \rightarrow {}^3\mathrm{He}\pi^0$ (Ref. 4).

Recently, Piasetzky *et al.*[2] carried out a partial-wave analysis of the $\pi^- pp(^1S_0) \rightarrow pn$ angular distributions extracted from $T_\pi = 63$-MeV $^3\mathrm{He}(\pi^-,pn)n$ data of Aniol *et al.*[1] Assuming that only *s*- and *p*-wave pions contribute at this energy, only three complex amplitudes are required to describe all observables of the reaction; their quantum numbers are listed in Table I. The analysis yielded two possible solutions for the transition amplitudes. Both solutions had approximately 93% of the total cross section from absorption of *p*-wave pions ($T=0$ channel, no Δ), and were distinguished by the way this strength was divided between $^{2S+1}L_J = {}^3S_1$ and $^3D_1$ for the final-state *pn* pair (Table I). The two solutions can be distinguished experimentally by their dramatically different polarization of the final-state protons.

There exist several calculations of the $\pi^- pp(^1S_0) \rightarrow pn$ cross section in meson-exchange models with nucleon-isobar intermediate states.[5,6] None of these gives an accurate reproduction of both shape and magnitude of the differential cross sections; the paper of Maxwell and Cheung[6] presents a partial-wave decomposition which is given in Table I. Miller and Gal[7] used a bag model in which all of the quasifree reaction $\pi^- pp(^1S_0) \rightarrow pn$ on ^{3}He occurred in a central six-quark cluster region. They obtained fair agreement with the shape and good agreement with the magnitude of the cross section (albeit with sensitive dependence on the bag radius). They found the transition to a $^3S_1$ *pn* final state to be dominant (Table I), in contrast to the results of Maxwell and Cheung, where the $^3D_1$ is the dominant state.

It is therefore of great interest to measure the polarization of the final-state proton in pion absorption on the diproton, since it will not only allow the complete determination of the absorption amplitudes but may also provide a signature for the direct absorption of pions by a six-quark cluster. Because direct measurement of proton polarizations in $^3\mathrm{He}(\pi^-,pn)n$ is very time consuming, one might equivalently measure the analyzing power with a neutron beam for the time-reversed reaction $pn \rightarrow \pi^- pp(^1S_0)$. The desired $^1S_0$ configuration may be

TABLE I. Relative strengths of transition amplitudes $\pi^- pp(^1S_0) \rightarrow pn$.

l_π	J^π	T	$^{2S+1}L_J$ (*pn*)	Expt. solution "S"	Expt. solution "D"	Theoretical quark[a]	Theoretical meson[b]
0	0^-	1	$^3P_0$	0.07	0.07	0.02	0.00
1	1^+	0	$^3S_1$	0.52	0.09	0.87	0.02
			$^3D_1$	0.41	0.84	0.11	0.98

[a] Reference 7. [b] Reference 6.

isolated, thanks to the strong $^1S_0$ final-state interaction, by selecting events in which the relative momentum between the two protons, *P*, is very small. A Monte Carlo simulation described below showed that selection of events with low (<100 MeV/*c*) relative proton momentum strongly suppresses the higher *pp* partial waves relative to the desired $^1S_0$ state. Instead of a neutron beam, one can use a polarized proton beam incident on a deuterium target and kinematically select the quasifree $pn \to pp(^1S_0)\pi^-$ reaction. Many orders of magnitude in beam intensity are gained, at the cost of some complications due to the presence of a "spectator" proton.

We have measured the analyzing power in the $d(\vec{p},\pi^- pp)p$ reaction. The momenta of the π^- and two of the protons were measured in a geometry suitable for a quasifree $pn \to pp(^1S_0)\pi^-$ process. The experiment was carried out using a 400-MeV polarized proton beam on beam line 1B of TRIUMF. The target was liquid deuterium in an upright cylinder 5 cm in diameter. Pions were detected to the left of the beam in a 16-msr quadrupole dipole spectrometer (the TRIUMF "QQD" spectrometer[8] with its front quadrupole removed) which had wire chambers before and after the dipole, permitting momentum determination, traceback to the target, and rejection of $\pi \to \mu\nu$ decays in flight. Measurement of time of flight through the spectrometer eliminated contamination due to electrons. Data were taken with the spectrometer set at 35.3° and at 43.5° to the beam. The diprotons were detected to the right of the beam in a segmented array of ΔE and E counters spanning 4° to 21° horizontally and $\pm 7°$ in the vertical. The ΔE counters were a 2×2 matrix of 3-mm-thick plastic scintillators which, together with scintillators and wire chambers of the pion spectrometer, formed the hardware trigger. The *E* counters were an array of seven vertical NaI bars, 51 mm thick, having phototubes at each end, thus providing both position and energy-loss information.[9] A 2×2 array of plastic scintillators vetoed events in which particles passed through the NaI bars.

Beam polarization was typically 70%, and was monitored by an in-beam polarimeter upstream of the experimental cave. Beam polarization was cycled between "up" and "down" at the ion source; dead time of the data acquisition system was determined separately for each polarization state. The position of the beam on target was reconstructed from the data, and found to be the same within 1 mm for the "up" and "down" polarization states. Beam intensity, typically 100 pA, was monitored by the summed count rates of the polarimeter arms. At this current, the single-bar NaI singles rates were less than 60 kHz, which limited pile up in the analog-to-digital converter's (ADC's) to a few percent. Piled-up events were rejected by using pile-up gates on the faster ΔE scintillators and by comparing NaI signal sizes for early, normal, and late gates of the charge-integrating ADC's.

Data analysis required that the proton pair (1) have between 40- and 128-MeV kinetic energy for each particle, (2) have a computed separation of at least 25 mm (to eliminate scattering of a single particle from one bar to a neighbor bar), and (3) show the appropriate energy loss in the corresponding ΔE scintillator(s). The tests for a valid π^- were that it passed through the spectrometer, originated in the target, did not decay in flight, and had the correct time of flight. The pion and the proton pair had to originate in the same rf burst of primary beam. Of events which survived the above-mentioned cuts, fewer than 1% were accidental coincidences. All these events are from the $d(p,pp\pi^-)p$ reaction: Target windows contain only 4% of the number of neutrons in the liquid deuterium and we observed no contribution from windows in a plot of binding energy of struck neutrons. Details of the hardware and analysis are provided in Ref. 10.

The finite acceptance of the diproton detector (in particular, the minimum angle of 4° with respect to the beam) determines the detection efficiency. In order to check this acceptance for the final-state (*pp*) *S* and *P* waves, we carried out a Monte Carlo simulation which included the geometric acceptance and resolution of our detectors. It was based on a quasifree impulse approximation of the free $np \to \pi^- pp$ reaction, the spectator momentum being distributed according to the Hulthen[11] wave function of the deuteron. For the elemental process, we used Handler's amplitudes,[12] which fit bubble-chamber data for the $np \to \pi^- pp$ reaction around 410 MeV. The amplitudes included the effects of the $^1S_0$ final-state interaction, as shown in Fig. 2 of Ref. 12. From this input we carried out a Monte Carlo simulation of the $d(p,pp\pi^-)p$ reaction, determining the accepted events as a function of various parameters such as the spectator-proton momentum (Fig. 1) or the relative momentum between the final-state protons (Fig. 2). In a test run the spectrometer polarity and the electronic trigger were changed to detect quasifree $pp \to d\pi^+$ events; we obtained an analyzing power of -0.02 ± 0.05 at $\theta^*_\pi = 61°$, in excellent agreement with the measurements of Mathie *et al.*[13] on the free reaction. This measurement further supports our use of the quasifree reaction in deuterium to study an elemental process.

Figure 1(a) shows the observed yield of events as a function of spectator momentum P_s, along with the prediction of the Monte Carlo simulation. The horizontal error bar indicates a typical uncertainty in calculated P_s due to random errors of measurement for a single event. The yield vanishes as the spectator momentum approaches zero due to the $P^2_{\rm spec}$ phase-space factor. In Fig. 1(b) the analyzing power A_y is shown as a function of a cut placed on P_s; the analyzing powers are constant for spectator momenta up to 90 MeV/*c*, and somewhat lower above. The shape of the simulated quasifree yield is essentially that of the Hulthen distribution cutoff at high momenta by detector acceptance. This same form is seen in the data, although with a small shift (from 48

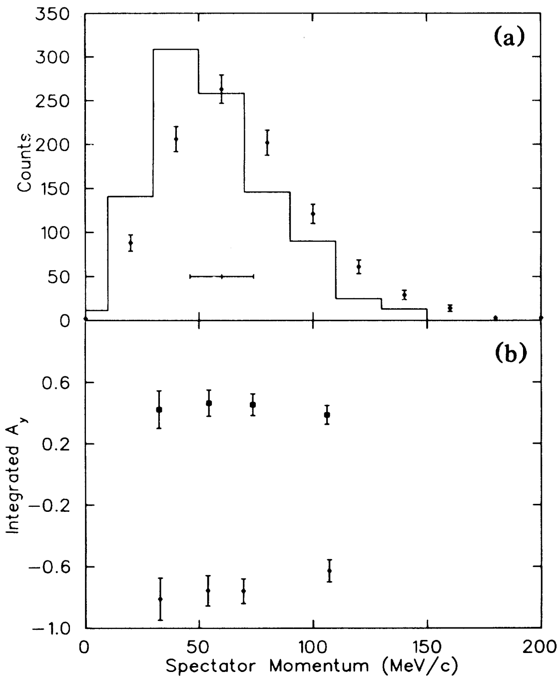

FIG. 1. (a) Comparison of the observed momentum distribution of "spectator" protons with that from a Monte Carlo simulation of the quasifree reaction $pn \rightarrow \pi^- pp$. The pion detector angle was 43.5°. The horizontal error bar indicates the resolution of our detector system. (b) Analyzing power A_y, for events having spectator momenta below the value P_s, as a function of P_s at pion detector angles 35.3° (diamonds) and 43.5° (squares).

to 59 MeV/c) in position of the maximum and in the yields at high P_s. Possible systematic errors in determining P_s as well as a background due to nonquasifree mechanisms could account for the observed shift. An example of such a mechanism is the breakup of a four-particle final state in which the momentum distributions of the four final particles follow four-body phase space. In this case the simulation yields a P_s distribution centered at 100 MeV/c with a width of 100 MeV/c, significantly different from the observed distribution. The constancy of A_y up to $P_s = 90$ MeV/c supports the picture of dominance by a quasifree process. The shift in A_y above 90 MeV/c may be a sign that other processes are becoming important, and we have excluded from subsequent analysis all events of $P_s > 90$ MeV/c.

Because of the Fermi momentum within the deuteron, the laboratory beam energy does not completely determine the effective c.m. energy and π^- angle of the free $pn \rightarrow \pi^- pp$ reaction. The equivalent beam energy for our data set had a mean value of 410 MeV and a width of ± 22 MeV. We verified from the present data that this range does not affect our results, as we obtain the same analyzing power for different equivalent beam energies. This is expected because the pion isovector cross

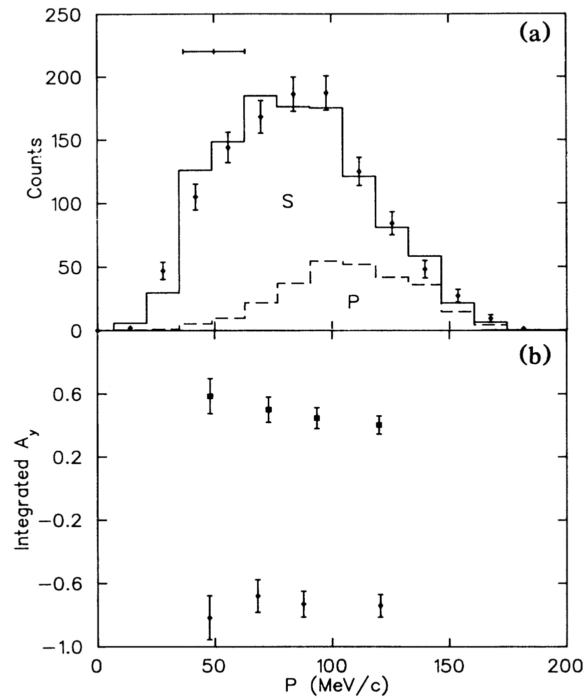

FIG. 2. (a) The distribution of P, the difference in momentum of the two detected protons in the center-of-mass system for spectrometer angle 43.5°. The horizontal bar indicates the resolution of our detector system. The lines show the Monte Carlo predictions, the upper line being the total yield and the lower line marking the division into S- and P-wave couplings of the diproton. (b) The analyzing power as a function of a cut on P representing all the events up to the value P at pion detector angles 35.3° (diamonds) and 43.5° (squares).

section (corresponding here to S wave) does not vary rapidly with energy (Ref. 1), and because the P-wave contribution is much suppressed.

The key to selection of the ${}^1S_0$ diproton state is restriction to small values of P, the difference between the momenta of the detected protons in the center of mass. Our Monte Carlo simulation showed that for the P range of our experiment, the bars accepted roughly 10% of the S-wave and 0.3% of the P-wave diprotons associated with detected pions, resulting in a factor of 30 enhancement of S-to-P-wave events. In Fig. 2(a) we see good agreement of observed and Monte Carlo yields as a function of P. We found [Fig. 2(b)] that the analyzing power (mainly associated with S wave) does not vary significantly with P, although it is somewhat lower in the highest P range at 43.5°. In order to minimize any P-wave contribution, we imposed a condition $P < 110$ MeV/c on the 35.3° data set and $P < 100$ MeV/c at 43.5°. The P-wave yield within these cutoffs should be negligible.

The diproton-pion center-of-mass frame was determined for each event and in this frame the c.m. angle be-

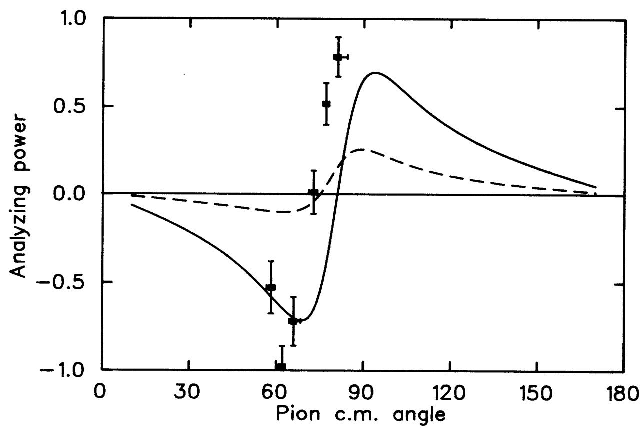

FIG. 3. Analyzing powers at $T_p = 400$ MeV for the reaction $d(\vec{p},\pi^- pp)p$. The horizontal error bars represent the width of distributions within bins of pion c.m. angle, the vertical error bars are statistical uncertainties. The solid and dashed lines are the predictions from the two partial-wave solutions, "S" and "D," with dominant np states $^3S_1$ and $^3D_1$, respectively.

tween the incident proton and the pion was found. The measured analyzing powers were binned with respect to this variable, which has a broad range at each spectrometer angle due to Fermi motion of the struck neutrons. The measured analyzing powers are shown in Fig. 3, where the data at the smallest and largest three angles correspond to the laboratory angles of 35.3° and 43.5°, respectively. The curves "S" and "D" are the analyzing powers predicted by the two possible sets of partial-wave amplitudes (Table I) consistent with the 63-MeV differential-cross-section data and $np \rightarrow np$ phase shifts. We used the same procedures as described by Piasetzky *et al.*,[2] except for the choice of np elastic scattering parameters. Instead of the solution of Bugg *et al.*,[14] we have used the more recent solution C400 of Arndt.[15,16]

Our analyzing-power data clearly favor solution "S," the one with the large amplitude for the $^3S_1$ np state. Inclusion of higher partial waves in the amplitude set could alter the solution, but as argued in Ref. 2, such partial waves should be strongly suppressed by the pion centrifugal barrier. If only pion s and p waves are present, the product of cross section for the absorption process times the proton polarization is of the form

$$\frac{d\sigma}{d\Omega}(\theta)P(\theta) = B_1 P_1^1(\theta) + B_2 P_2^1(\theta),$$

where the P_L^1 are associated Legendre polynomials. From the present experiment and the $T_\pi = 63$ MeV results of Aniol *et al.*,[1] we find $B_1 = 15.4 \pm 4$ μb/sr and $B_2 = -19.9 \pm 5$ μb/sr, with $B_2/B_1 = -1.25 \pm 0.11$.

It has been suggested by Vigdor *et al.*[17] that analyzing powers of the elemental process $pn \rightarrow pp\pi^-$ could be deduced from data on $A(p,\pi^-)B$ in which the residual nucleus was left in a highly excited (continuum) state. Citing (p,π) data for ^{14}C, ^{18}O, and ^{27}Mg targets, the authors of Ref. 17 concluded that the analyzing powers of $pn \rightarrow \pi^- pp(^1S_0)$ would be positive at all angles. The present data contradict their conclusions.

In Table I we observe that the quark-cluster model has most of the transition strength in the $^3S_1$ np amplitude and almost none in the $^3D_1$, which is not surprising since that model assumes contributions solely for separations < 0.85 fm. In the meson-exchange model, where longer-range interactions (including the nucleon-nucleon tensor force) are possible, it is the $^3D_1$ configuration which dominates. The experimentally preferred solution "S" has roughly equal strength in $^3S_1$ and $^3D_1$ np states; this suggests that a model with significant contributions from both short- and long-range interactions is needed, for example, a quark-cluster model with suitable matching to a tail contribution from meson exchanges.

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