Analyzing Power in the Reactions $p+d \rightarrow d+p$ and $p+p \rightarrow d+\pi$ at GeV Energies

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We have used a polarized proton beam to measure the analyzing power for pd backward elastic scattering at incident kinetic energies of 0.68, 1.03, and 1.53 GeV and for the reaction $p+p \rightarrow d+\pi$ at 1.03 GeV. The data indicate that several mechanisms dominate pd backward elastic scattering over this energy range.

The existence of a backward cross-section peak in proton-deuteron elastic scattering from low energies to the GeV energy range has resulted in considerable theoretical speculation as to the scattering mechanism.[1] Kerman and Kisslinger have proposed that N^* components in the deuteron wave function augment the scattering amplitude as a result of nucleon exchange.[2] An alternative approach, which naturally explains the shoulder near $T_p = 600$ MeV in the 180° cross section as a function of energy, has been proposed by Craigie and Wilkin.[3] Their model relates pd backward elastic scattering to the inelastic process $p+p \rightarrow d+\pi$ through a pion-exchange (PE) process. The Craigie-Wilkin model is equivalent to one proposed by Yao[4] and explained in detail by Barry[5] which also relates this latter inelastic reaction to elastic πp scattering. In this combined view, the shoulder in the backward pd cross section as a function of energy is a reflection of the $N^*(1232)$ in the πp s channel.

As is often the case, both models yield reasonable fits to the differential cross-section data. However, they make different predictions for the analyzing power for a polarized proton beam for this reaction. Until recently, no spin-dependent parameters of pd backward elastic scattering had been measured at energies above physical pion threshold. In this Letter, we present analyzing-power data at incident kinetic energies of 0.68, 1.03, and 1.53 GeV, measured with the polarized proton beam at the Argonne National Laboratory zero-gradient synchrotron (ZGS). A recent experiment[6] has measured backward pd elastic scattering analyzing powers at 0.32 and 0.52 GeV. We also report here a measurement of the analyzing power for the reaction $p+p \rightarrow d+\pi$ at $T_p = 1.03$ GeV, which is useful for testing the Craigie-Wilkin model.

This experiment was performed using a single-arm spectrometer, which has been described in detail and diagrammed in previous publications,[7] to detect the forward deuteron from the scattering. The polarized proton beam, with a typical polarization of 70% and a typical intensity of 5×10^8 protons per 500-msec pulse, was incident on a 10-cm liquid-deuterium target. The direction, position, and size of the incident beam were determined by three multiwire proportional chambers read out in an integrated mode. The relative beam intensity was monitored by three telescopes, each consisting of three scintillation counters, which viewed a thin polyethylene target located about 5 m upstream of the deuterium target. The polarization, which was normal to the scattering plane, was determined with an absolute uncertainty of ± 4% by a carbon-target polarimeter located at the point at which 50-MeV protons were injected into the synchrotron. Previous studies have shown no measurable depolarization during the process of acceleration to the energies used in this experiment.[8] The direction of the beam polarization was reversed every pulse in order to eliminate systematic errors due to apparatus drifts. The spectrometer, which detected the forward-scattered deuteron, consisted of four dipole magnets for momentum dispersion and angular selection and seven quadrupole magnets for a large solid-angle acceptance. A small scintillation counter at the intermediate focus of the spectrometer limited the momentum acceptance to ± 1% ($\Delta p/p$). Tests with a hodoscope in this same position indicated a negligible contamination of the pd backward elastic signal within the spectrometer acceptance at all incident energies in this experiment. The reaction $p+p \rightarrow d+\pi$ was also cleanly identified by the kinematics of the forward-scattered deuteron. The desired scattering angle was obtained by adjusting currents in dipoles located both in the primary proton beam and in the spectrometer in the manner described in Ref. 7.

TABLE I. The analyzing power in the reactions $p+d\rightarrow d+p$ at 0.68, 1.03, and 1.53 GeV. The angle θ^* is in the center-of-mass system. The uncertainties are discussed in the text.

θ*	u (GeV/c)^2	Analyzing Power	Error
T_p = 0.68 GeV			
172.3	0.653	0.038	0.010
169.2	0.643	0.072	0.016
166.1	0.630	0.118	0.015
163.0	0.613	0.147	0.015
160.0	0.593	0.199	0.014
156.9	0.570	0.184	0.010
153.8	0.544	0.196	0.014
150.7	0.514	0.257	0.013
147.6	0.482	0.242	0.013
144.6	0.448	0.266	0.012
141.7	0.412	0.295	0.014
138.7	0.373	0.254	0.012
135.7	0.331	0.208	0.010
132.7	0.287	0.163	0.013
129.8	0.241	0.056	0.011
126.9	0.196	0.006	0.016
124.0	0.148	-0.093	0.017
121.3	0.101	-0.197	0.021
118.4	0.050	-0.219	0.017
115.6	-0.001	-0.237	0.022
112.7	-0.055	-0.233	0.017
107.2	-0.161	-0.254	0.016
101.8	-0.268	-0.174	0.017
96.3	-0.379	-0.127	0.016
93.8	-0.429	-0.079	0.015
T_p = 1.03 GeV			
171.7	0.573	0.120	0.014
165.4	0.534	0.130	0.014
159.2	0.475	0.158	0.018
153.0	0.397	0.071	0.018
149.4	0.343	0.055	0.019
146.6	0.296	-0.027	0.018
140.7	0.188	-0.239	0.026
134.3	0.053	-0.388	0.024
128.5	-0.083	-0.400	0.033
122.7	-0.230	-0.299	0.028
111.1	-0.552	-0.092	0.028
103.2	-0.787	-0.079	0.030
T_p = 1.53 GeV			
171.7	0.484	0.018	0.012
168.4	0.458	0.089	0.026
165.0	0.422	0.123	0.043
161.7	0.377	0.173	0.026
158.4	0.325	0.144	0.037
151.9	0.197	0.128	0.041
148.6	0.120	-0.060	0.045
145.3	0.036	-0.094	0.040
142.1	-0.052	-0.258	0.034
132.6	-0.353	-0.226	0.040
126.4	-0.577	-0.110	0.034
114.4	-1.060	0.107	0.031

The data were analyzed by determining at each kinematic point the number of left scatterings (looking downstream) with the incident protons polarized up (and down) normalized to the incident intensity as determined by the relative monitor. The analyzing power was calculated from

TABLE II. The analyzing power data for the reaction $p+p\rightarrow d+\pi^+$ at $T_p=1.03$ GeV.

θ*	u (GeV/c)^2	Analyzing power	Error
163.0	0.446	0.091	0.010
148.8	0.391	0.122	0.010
134.0	0.304	0.173	0.012
117.8	0.179	0.238	0.011
97.8	−0.001	0.226	0.020
90.0	−0.076	0.162	0.020
80.0	−0.171	0.106	0.021
70.0	−0.263	−0.022	0.025
60.0	−0.349	0.020	0.028
38.1	−0.506	0.068	0.021
27.4	−0.561	0.138	0.035

the equation $A=(1/P_B)(N\uparrow-N\downarrow)/(N\uparrow+N\downarrow)$, where P_B is the incident beam polarization and $N_\uparrow$ ($N_\downarrow$) is the normalized number of scatters with the beam polarized up (down). Because of the fast reversal of the incident polarization, no corrections were necessary for random apparatus drifts. No eivdence was found for beam position, size, or angle drifts which were correlated with the incident polarization. The cross sections measured in this experiment agree in shape with previous data,[9] although an absolute normalization could not be obtained, because of an imprecise knowledge of the absolute beam intensity.

The data from this experiment are listed in Table I and shown in Fig. 1 along with the data of Ref. 6 on pd elastic scattering. The error shown in both the table and the figure represent the point-to-point statistical uncertainty; they do not include an overall normalization uncertainty of ± 4% of the analyzing power.

An inspection of the data shows that for incident energies between 0.1 and 1.5 GeV, several different mechanisms dominate pd backward elastic scattering. Below physical pion threshold in the PE process (about 300 MeV), earlier studies[10] have shown that interference between nucleon exchange and single scattering accounts fairly well for the measured analyzing power. In the region of the cross-section shoulder (near 600 MeV), where pion exchange proceeds through $N^*(1232)$ formation in the πp s channel, this mechanism apparently dominates pd backward scattering. This can be seen from the strong similarity between the pd elastic analyzing-power data at 0.68 GeV and the $p+p\rightarrow d+\pi$ analyzing power at 0.59 and 0.72 GeV,[11] as shown in Fig. 2. At 1.0 GeV, the situation has again changed as indicated

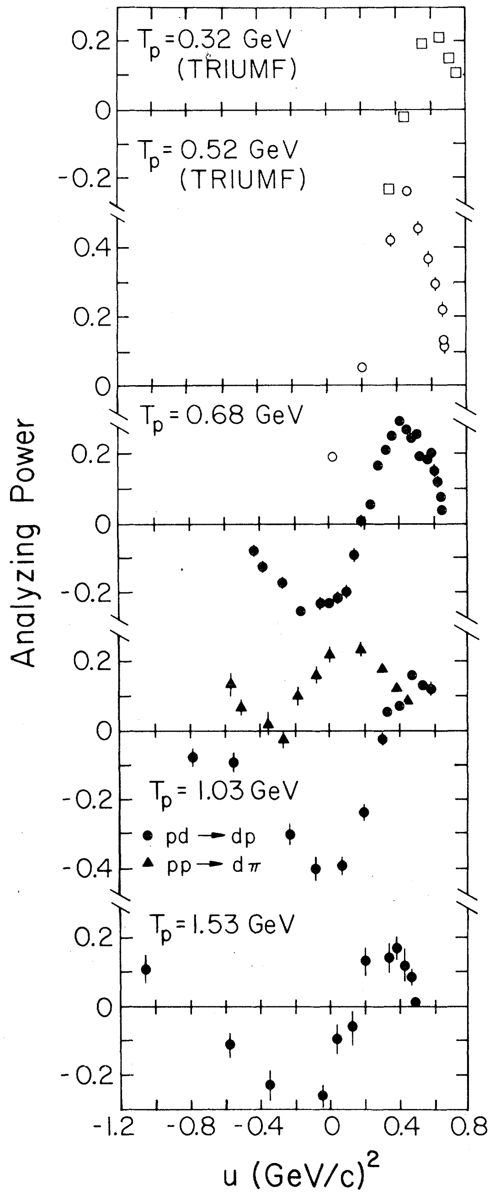

FIG. 1. The analyzing power in the reactions $p+d \to d+p$ at 0.32, 0.52, 0.68, 1.03, and 1.53 GeV and $p+p\to d+\pi$ at 1.03 GeV. Open-symbol data are from Ref. 6 as indicated.

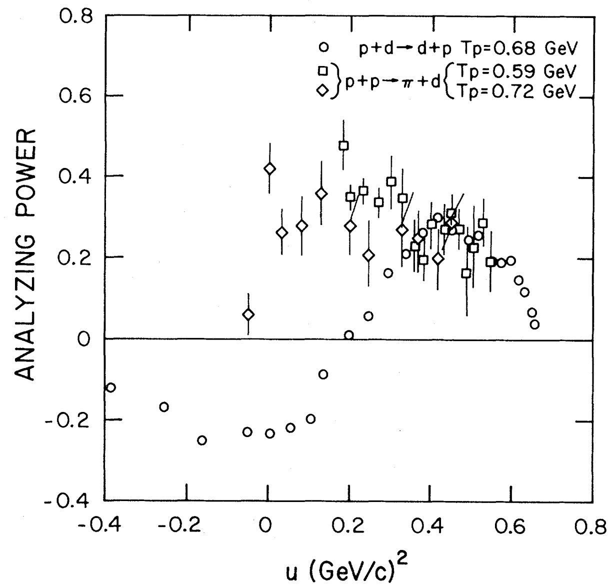

FIG. 2. A comparison of the analyzing power for the reaction $p+d\to d+p$ at 0.68 GeV with A for the reaction $p+p\to d+\pi$ at 0.59 and 0.72 GeV (Ref. 11).

by the dissimilarity of the analyzing-power data for the two reactions. At this higher energy, the reaction $p+p\to d+\pi$ has the larger analyzing power, which is the inverse situation from that found at 500 MeV on the other side of the $N^*(1232)$ resonance by Anderson *et al.*[6] Away from $N^*(1232)$, the triangle graph no longer dominates; the analyzing power at higher and lower energies than the resonance is presumably controlled by the interference between the triangle graph, nucleon multiple scattering, and the nucleon exchange of Kerman and Kisslinger.

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^{12}C-Pion Monopole Scattering

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Inelastic pion excitation of the 0^+ (7.65-MeV) level in ^{12}C is studied using a Kisslinger optical potential in both a distorted-wave impulse approximation and a coupled-channels formalism. In clusion of coupling through the first excited 2^+ state in ^{12}C causes a dramatic suppression of this cross section for pion energies below 75 MeV. This explains the unexpectedly small 0_1^+ cross sections recently observed, and may permit detailed testing of pion-nucleus reaction theories.

Comparison of distorted-wave impulse-approximation (DWIA) calculations of the monopole cross section for the reaction ^{12}C(g.s.)$(\pi^+, \pi^{+\prime})^{12}C^*(0^+$, 7.65 MeV) and the newly obtained inelastic-pion-scattering data[1,2] at 50 MeV demonstrates major inadequacies in the reaction-theory formalism for low pion scattering energies. This glaring disagreement derives from the failure to include contributions to the cross section arising from two-step processes. Interference between the direct monopole and two-step contributions results in a reduction of the cross section by an order of magnitude at 50 MeV and brings the theoretical results into accord with the experimental data.

This failure to explain the 50-MeV monopole scattering data is a somewhat unique exception to the general success of the DWIA approach for inelastic pion scattering. For example, in ^{12}C, which is the most extensively studied nucleus experimentally and theoretically, the 50-MeV inelastic pion scattering to the collective states 2^+(4.44 MeV) and 3^- (9.63 MeV) has been well described by several workers.[2-4]

All of the calculations presented here are obtained using a Kisslinger optical-potential form with an angle transformation of the type used by diGiacomo *et al.*,[5] but without any other corrections. This approach is known to give a good qualitative description of the scattering to collective states of ^{12}C from about 50 to 200 MeV. For the monopole excitation, which is not amenable to a collective-model description, it was necessary to construct a model for ^{12}C based on the measured properties. Transition-charge densities for transitions involving the ground state were obtained from fits to the inelastic electron scattering form factors.[6] The form factor for the transition between excited states was taken to have the same shape as the g.s.-to-2^+ transition but was normalized to reproduce the γ-decay width. The transition densities have the form

$$\rho_{\text{tr}} = \pi^{-3/2} b^{-3} (A + Br^2/b^2 + Cr^4/b^4) e^{-r^2/b^2} \quad (1)$$

with parameters given in Table I.

The breakdown of the DWIA formalism for monopole excitations is obvious only at lower pion energies. From Fig. 1 it can be seen that a DWIA calculation of the monopole excitation in ^{12}C does give a rough description of the data for 150-MeV pions.[7] However, a similar calculation of the direct contribtuion at 50 MeV, shown as the solid line in Fig. 2, predicts a cross section on the order of 1 mb/sr while the observed cross

TABLE I. Parameters of the transition densities.

Transition	A	B	c	b
Diagonal	0.333	0.444	0	1.637
$0_1^+ \leftrightarrow 2_1^+$	0	0.0096	0.1344	1.414
$0_2^+ \leftrightarrow 2_1^+$	0	0.0056	0.0788	1.414
$0_1^+ \leftrightarrow 0_2^+$	−0.0579	−0.1652	0.0815	1.625