Scattering of Protons by Deuterium from 1.0 to 2.0 BeV†

E. COLEMAN,* R. M. HEINZ,‡ O. E. OVERSETH, AND D. E. PELLETT§
University of Michigan, Ann Arbor, Michigan
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The differential cross sections for proton-deuteron elastic scattering at high momentum transfers have been measured at incident proton kinetic energies from 1 to 2 BeV in a counter experiment. The differential cross sections for backward elastic scattering at incident kinetic energies of 1.0, 1.3, and 1.5 BeV have been measured for values of the cosine of the center-of-mass proton scattering angle ($\cos\theta^*$) from -0.5 to -0.9, which corresponds to values of the four-momentum transfer squared ($-t$) from 2.6 to 5.0(BeV/c)^2. A backward peak is observed, and the cross section decreases rapidly with increasing energy. At 2.0 BeV, the forward elastic differential cross section has been measured for $-t$ from 0.44 to 1.54(BeV/c)^2, or $\cos\theta^*$ from 0.875 to 0.565. A shoulderlike departure from the forward diffraction peak is observed.

I. INTRODUCTION

RECENTLY, a considerable amount of theoretical effort has been devoted to studying nucleon-deuteron interactions.[1–7] Nucleon-deuteron scattering is of importance because it provides an examination of our understanding of the bound state of strongly interacting particles and increases our understanding in the use of deuterium as a free-nucleon target. The paucity of experimental differential cross sections at high energies has resulted in most theoretical models being compared with intermediate-energy data below 500 MeV where the distinction between different deuteron wave functions and dynamical approaches cannot be fully examined. One expects the finer details of the deuteron wave functions and the deuteron form factor to depend upon the small radial components whose effects can only be observed for larger momentum transfer.

At the onset of this experiment, little experimental work had been done on nucleon-deuteron scattering at high momentum transfers. Bayukov *et al.*[8] had measured a single point of the elastic proton-deuteron differential cross sections at 0.715, 1.0, and 3.66 BeV. The proton-deuteron elastic differential cross section at 0.660 BeV was reported by Leksin.[9] In the present experiment the elastic differential cross sections for incident proton kinetic energies of 1.0, 1.3, and 1.5 BeV have been measured for center-of-mass scattering angles ($\cos\theta^*$) from -0.5 to -0.9 corresponding to four-momentum transfer squared ($-t$) from 2.6 to 5.0 (BeV/c)^2. For 2.0-BeV protons, the differential cross sections were measured for $\cos\theta^*$ from 0.875 to 0.565, corresponding to values of $-t$ from 0.44 to 1.54 (BeV/c)^2, since small-angle data existed at this energy.

One of the primary motivations for this experiment was to provide data for a test of the one-nucleon-exchange model. We had previously studied the reaction $p+p\rightarrow d+\pi^+$ at comparable energies,[10] and interpreted our data in terms of a one-nucleon-exchange model.[11] This model gives agreement with the data if a hard core is used in the deuteron wave function. Backward proton-deuteron elastic scattering appeared to be a good candidate to proceed via a one-nucleon-exchange mechanism and hence data of the reaction were of interest to test the model and provide information on the deuteron wave function. Preliminary results of this experiment have been published elsewhere.[12]

II. EXPERIMENTAL ARRANGEMENT

The measurements were taken in a scintillation counter experiment using an external proton beam at the Brookhaven cosmotron. The differential cross sections expected were of the order of a μb/sr so the counter logic must be able to select the backward elastic-scattering events from a background 10^4 times more intense. To do this we (1) detected both the proton and deuteron, (2) momentum-analyzed the deuteron, and (3) determined the time of flight of the deuteron over a 40-ft flight path. This served to over-

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* Present address: School of Physics, University of Minnesota, Minneapolis, Minnesota.
‡ Present address: Physics Department, Indiana University, Bloomington, Indiana.
§ Present address: Physics Department, University of California, Davis, California.
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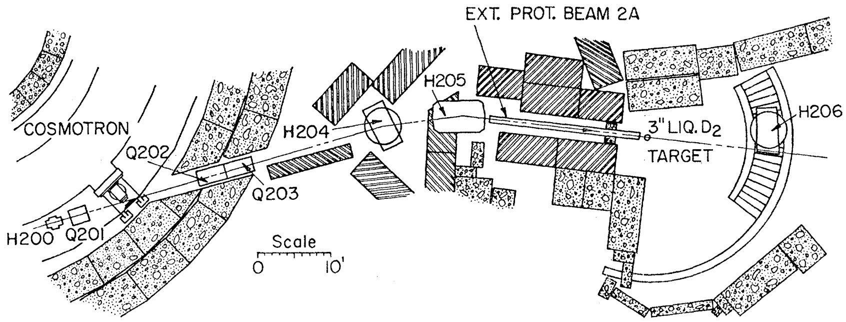

FIG. 1. External proton beam at the cosmotron used in this experiment.

constrain the determination and kept the background due to accidental counts to less than 10% for even the most difficult points.

An external beam was designed for the cosmotron to bring an intense beam of protons to a good focus with small angular divergence at the target. The beam layout is shown schematically in Fig. 1. Bending magnet H200 removed the energy dependence of the beam exit angle from the cosmotron and also contained a collimator between the pole faces to restrict the beam spot size at the target. Quadrupoles Q201, Q202, and Q203 focused the beam to a maximum beam spot size of 1.5 in. in diameter at the target with an angular divergence less than 1.5 mrad. The bending magnets H204 and H205 guided the beam along the axis defined by the center of the target and the center of the C counter. The beam was contained in vacuum pipes up to the deuterium target and totally enclosed in shielding. In the experimental area (Fig. 2) the beam passed unshielded to the beam stop. A maximum intensity of 10^{10} protons/pulse in this beam kept background radiation levels in all parts of the building well within safe limits.

The energy of the protons of the beam was determined by two methods. The first consisted of measuring the rf accelerating frequency and the radius of the internal beam at ejection; the second consisted of measuring the radius of the circulating beam and the magnetic field of the cosmotron at ejection. These methods determined the beam energy to ± 0.05 BeV.

The experimental area is shown in Fig. 2. Two counter telescope arms pivoted about a point beneath the center of the target. The deuterium target was a cylinder 5 in. long and 3 in. in diameter. A theodolite mounted on top

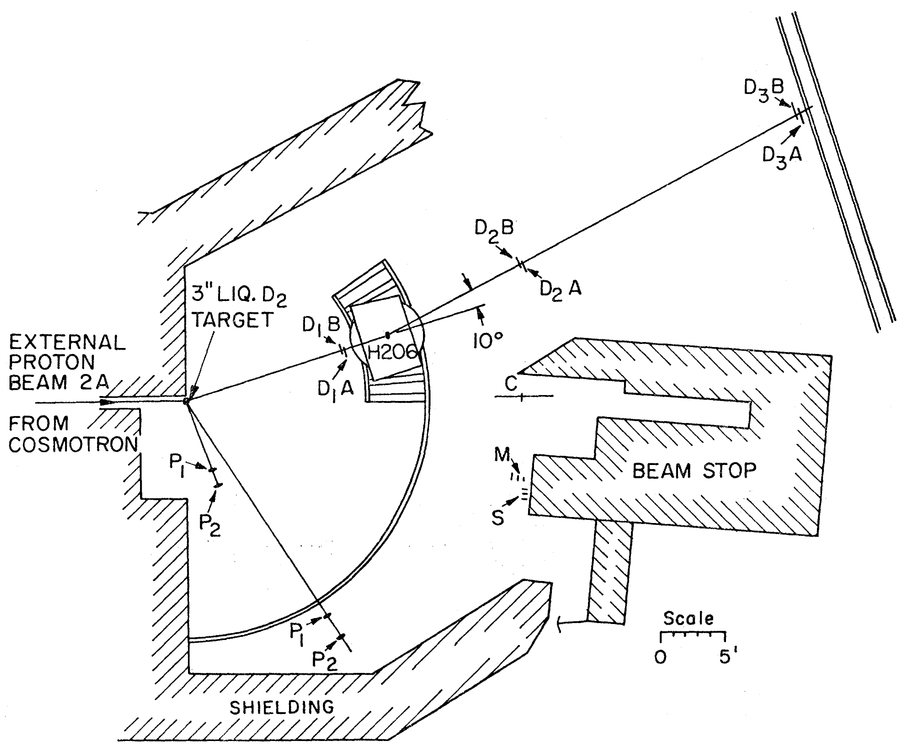

FIG. 2. Schematic diagram of the experimental area and apparatus.

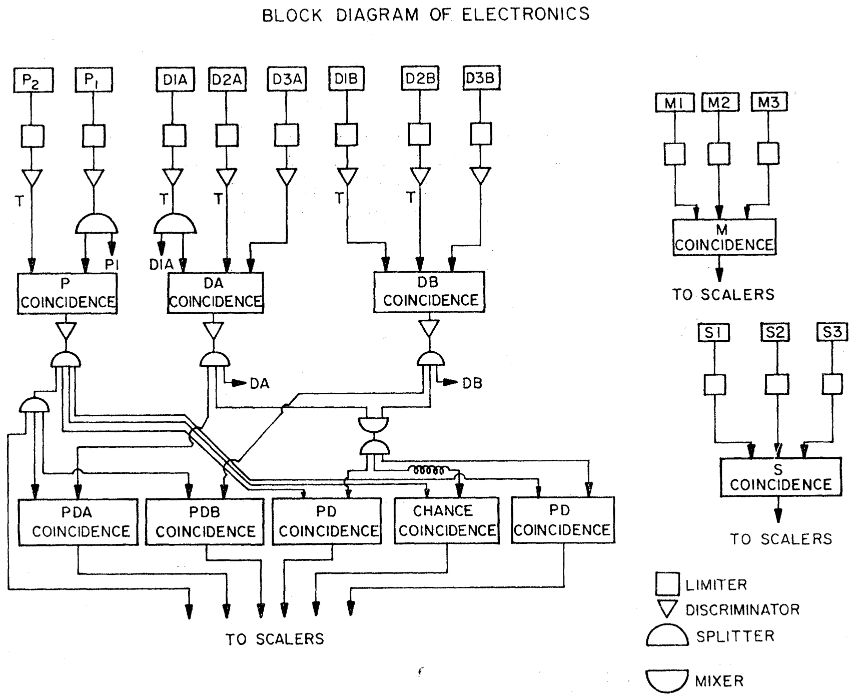

FIG. 3. Schematic diagram of the electronic logic.

of the pivot post was used to determine the polar angles of the scattered particles.

The first counter of the P telescope determined the solid angle of acceptance. In backward scattering of the incident proton, the shorter arm was used. The angle between this telescope and the beam line was varied by rotating the I beam, which was connected to the pivot under the theodolite and rolled on a leveled steel platform. The longer arm was used to detect the scattered deuteron in the forward scattering measurements. This arm was varied by rolling the I beam along a circular rail located 19 ft from the target. The counter holders also could be moved radially along the I-beam arms.

The deuteron (proton) in backward (forward) scattering of the incident proton was detected by two overlapping telescopes consisting of three counters each. These counters constituted the D telescopes and were referred to as D1A, D2A, D3A and D1B, D2B, D3B. The D1 and D2 counters were supported by a motorized carriage, which also supported a bending magnet H206 between them. H206 deflected the particles passing through D1 by $\pm 10°$ to provide momentum separation of the desired elastically scattered particles from quasi-elastic events and reaction products. The 18×36-in. H206 attained a maximum flux density of 15.3 kG with a 10.5-in. gap. The momentum resolution of the system was increased by the use of the two overlapping counter telescopes. The 40-ft flight path between D1 and D3 counters provided a time-of-flight criterion which the scattered particle was required to satisfy. The angle of the D1 counters was adjusted by moving the motorized carriage until the center of the overlapping portion was aligned with the vertical cross hair of the theodolite. The overlap of the D counters was determined from multiple Coulomb scattering in the target, and any previous counters. Time of flight plus the momentum analysis provided complete separation of desired particles from background up to a momentum of 2.4 BeV/c.

The dimensions of the scintillators are given in Table I. The D3 counter had a photomultiplier at each end of the scintillator. A block diagram of the electronic logic is outlined in Fig. 3. Counters P1 and P2 were put into a twofold coincidence (called P). Counters D1A, D2A, and D3A were put into three-fold coincidence (DA), as were D1B, D2B, and D3B (DB). The signature of an event was a coincidence between P and DA or between

TABLE I. Counter dimensions.

Counter	Width×height×thickness (in.)
P1	3.5×5 ×$\frac{1}{8}$
	2.5×3 ×$\frac{1}{8}$
	2.0×1 ×$\frac{1}{8}$
P2	5 ×7 ×$\frac{1}{2}$
	4 ×2 ×$\frac{1}{2}$
D1A	5.5×8 ×$\frac{1}{2}$
D1B	5.5×8 ×$\frac{1}{2}$
D2A	13 ×19 ×$\frac{3}{8}$
D2B	13 ×19 ×$\frac{3}{8}$
D3A	17 ×30 ×$\frac{1}{2}$
D3B	17 ×30 ×$\frac{1}{2}$
C	8 diam ×$\frac{1}{2}$
M	1 ×1 ×$\frac{1}{4}$
S	1.5×1.5×$\frac{3}{8}$

P and DB or both within 8 nsec. Variable delay cables were inserted between the counters and coincidence circuits to compensate for the unequal flight times. A gating circuit prevented the recording of events whenever an anomalously large incident flux density occurred via a trigger pulse from the in-beam C counter. Pulses from each channel were split to provide scalar records of the P coincidences, the C coincidences, and their combinations. Accidental coincidences were continuously monitored by delaying a portion of the pulse from the D channels by 50 nsec with respect to the coincidence time for a real event. These chance events were held to less than 10% of the actual events by regulating the beam intensity. Two scalars were used to record the events to provide evidence of any malfunction of the scalars.

Two sets of monitor counters were used for normalization. A three-counter telescope M looking at the deuterium target at 11° to the beam line was used to monitor the beam during target full runs. A second monitor telescope S looked at interactions caused by the incident beam in the in-beam counter C. This monitor was sensitive to beam drift off the axis and was also used to normalize the target-empty runs.

III. EXPERIMENTAL PROCEDURE

The equipment was calibrated and checked out by first filling the target with hydrogen and observing several forward elastic scattering angles where yield was high. At these points we ran timing curves and magnet current curves, examined the effect of going off kinematic angle settings, and confirmed wire orbiting measurements and that the counters were properly oversized. On later runs with deuterium we occasionally also ran such checks, but low counting rates made this difficult except for the larger cross-section points. Having gained confidence in the apparatus the target was filled with deuterium and the background elastic scattering measurements were made.

For each point in the differential cross section the P telescope and the carriage supporting magnet H206 with the D1 and D2 counters were positioned using the the theodolite centered under the deuterium target. The P counter was moved radially inward toward the target so that the maximum rate would be obtained considering the sizes of the D counters. These distances had been calculated from the computer program used in designing the counter sizes and checks were made at several points that there were no losses by sliding the P counters to a greater distance from the target, or using a smaller P1 counter, and observing no change in the differential cross section measured. The D3 counter array was slid on Teflon pads along the parallel I beams to the position determined by wire orbiting and checked during the hydrogen target tests.

Runs were made for each angle with the deuterium target alternately full and empty. The target was bombarded until the desired statistical accuracy was obtained and the results were recorded and printed out from the scalars. For the empty target measurements, the S monitor telescope determined when the same number of protons had passed through the target as in the previous target-full run. Consistency checks were made for several angles at each energy and the results were reproducible to within statistical uncertainties.

Several times during the measurement of the differential cross section at each energy, polyethylene foils were irradiated for normalization purposes. These 4-mil foils were mounted on the downstream end of the target and irradiated by a beam of $(1\text{–}5)\times10^9$ protons per pulse for 1 to 3 min. The C^{11} activity induced in the foil through the reaction $C^{12}(p,pn)C^{11}$ was used to calibrate the monitor telescopes where the C^{11} activity was measured by detecting the γ rays produced by annihilation of the positrons emitted by the C^{11} atoms. Values for the cross section for the reaction in our energy range were interpolated from the data of Poskanzer *et al.* and Cumming *et al.*[13] In this way F/M and F/S were determined as standard ratios for target-full and target-empty runs, respectively, where M is the number of coincidences in the M telescope and S is the number of coincidences in the S telescope during irradiation of the foil by F protons. Statistical errors in counting, and other uncertainties cause an uncertainty in the absolute calibration of $\pm8\%$. Three or more foils were irradiated at each energy, and the normalizations agreed within 4%.

IV. CORRECTIONS TO THE DATA

While traversing the target, counters, and air, a small percentage of the scattered protons and deuterons were lost due to nuclear interactions. For the energy and angular range investigated here, the deBroglie wavelength was sufficiently small to allow the use of a modified geometrical cross section

$$\sigma_{dA}=\sigma_{dN}A^{2/3} \quad \text{and} \quad \sigma_{PA}=\sigma_{PN}A^{2/3}$$

for deuterons and protons, respectively, on a nucleus of mass number A. The energy dependence of the proton-nucleon, and deuteron-nucleon cross sections was taken into account using the data of Chen *et al.*[14] The probability of an event surviving nuclear absorption, assuming the probabilities of surviving the P and D channels to be stochastically independent, varied from 0.91 to 0.93 depending upon the energy and angle. The effect of nuclear absorption was tested by placing a slab of Lucite before the P1 counter and measuring the differential cross section at several points.

Counter efficiency showed no significant departure from $99\%\pm1\%$ since most counters were small, or if

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TABLE II. Backward proton-deuteron elastic scattering.

$\cos\theta^*$	$d\sigma/d\Omega_{c.m}$ (μb/sr) 1.0 BeV	1.3 BeV	1.5 BeV
−0.900			2.05±0.21
−0.895		4.50±0.33	
−0.885	12.99±0.42		
−0.875	10.93±0.36	4.07±0.35	1.73±0.17
−0.850	8.80±0.29	3.47±0.26	1.06±0.12
−0.825	7.99±0.26	3.39±0.23	
−0.800	6.82±0.22	2.22±0.11	0.76±0.08
−0.750	4.52±0.15	1.49±0.15	0.63±0.06
−0.700	3.30±0.11	1.08±0.11	0.49±0.04
−0.650	2.84±0.09	1.00±0.10	0.30±0.03
−0.600	2.70±0.12	0.80±0.08	0.34±0.03
−0.550	2.15±0.13	0.56±0.06	0.29±0.03
−0.500	1.99±0.09	0.66±0.06	0.29±0.03
−0.460		0.50±0.05	

large, had a phototube at each end. In this experiment each beam pulse was typically 150 msec long, and the singles rate on the most active counter was usually less than 8×10^4 particles per pulse. Since the time resolution of the logic circuitry was 8 nsec, the dead-time correction was less than 1%.

The sizes of the counters were designed to eliminate loss of events due to multiple Coulomb scattering. This requirement was checked during the experimental run by substituting a smaller P1 counter for the original P1 defining counter at several angles. No significant difference was measured between using the smaller solid angle, which would confine the corresponding particles in the D channel to a smaller portion of the D counters and thus minimize losses. This technique could not be applied to determine losses by the P1 counter itself, but to a first approximation, the number of particles scattered out of coincidence with the P telescope is equal to those scattered into the telescope. Less than 1% of the coincidences are estimated to have been lost through multiple Coulomb scattering.

Independent particles in the deuteron and proton channels may produce pulses which would be recorded as an event if they occurred within a short time interval. These accidental coincidences were continuously monitored by recording the coincidences between the P and D channels when they were 50 nsec out of true coincidence. The length of this delay cable was varied over a range of 30 nsec with no appreciable difference in the percentage of accidentals for a given run. For a full target, the percentage of accidental events was always kept below 10% by adjusting the beam intensity. The average percentage of recorded events for an empty target to events with a full target for all runs was 1.3%, caused primarily by interaction with the Mylar windows of the target. The number of events for each point of the differential cross section was corrected for background events by subtracting 1.3%. The accidental coincidences were directly subtracted from the PD coincidences.

TABLE III. Forward proton-deuteron elastic scattering at 2.0 BeV.

$\cos\theta^*$	$-t$ (BeV/c)^2	$(d\sigma/d\Omega)_{c.m.}$ (μb/sr)
0.875	0.44	78.09±2.52
0.850	0.53	64.65±1.94
0.800	0.71	51.55±1.55
0.750	0.88	36.42±1.09
0.700	1.06	22.79±0.68
0.650	1.24	12.18±0.37
0.600	1.41	7.11±0.21
0.565	1.54	4.97±0.15

V. RESULTS AND DISCUSSION

The differential cross sections are tabulated in Tables II and III, and are shown graphically in Figs. 4 and 5. The error bars are those due to counting statistics and range from 3% to 10%. The error in the absolute values of the differential cross section is 10%, of which 8% is due to normalization error and 2% is due to the error in the Jacobian for transforming the solid angle from the laboratory system to the center-of-mass system which was introduced by the uncertainty in the beam energy.

The backward differential cross sections were found to have the following form:

$$\frac{d\sigma}{d\tau}=e^{(a+b\tau+c\tau^2)}\frac{\mu\text{b}}{(\text{BeV}/c)^2},$$

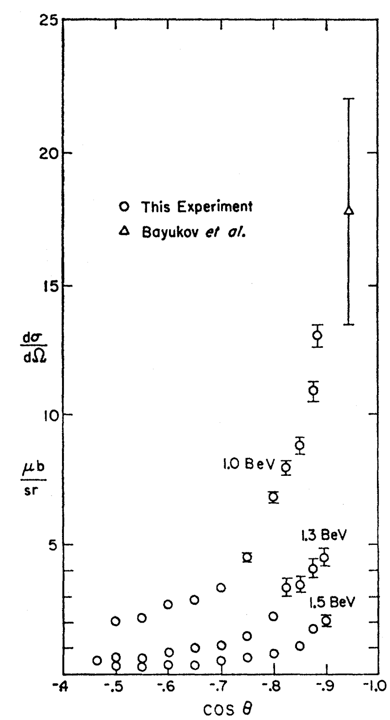

FIG. 4. Backward proton-deuteron elastic cross-section measurements.

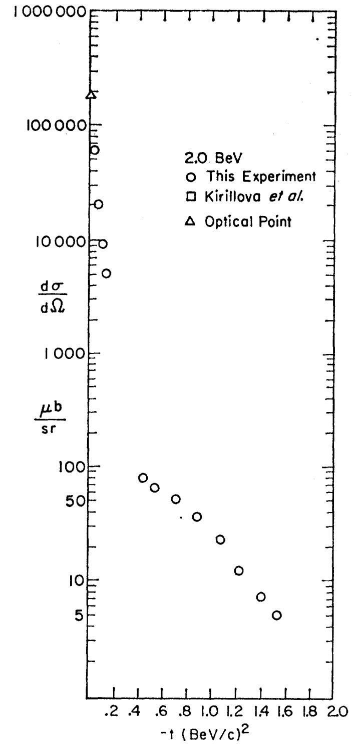

FIG. 5. Forward proton-deuteron elastic cross-section measurements at 2.0 BeV.

where τ equals the four-momentum transfer minus the four-momentum transfer at 180°. A χ^2 test of the powers of τ up to the fourth power specified a quadratic as the best fit. The values of a, b, and c determined by the least-squares procedure are given in Table IV.

The backward peak is much broader than the forward peak at these energies, and its slope is comparable to the forward nucleon-nucleon slope for the same energies. The magnitude of the backward peak displays a strong energy dependence. From 1.0 to 1.5 BeV, the extrapolated values of the backward point ($\cos\theta^* = -1.0$) decreased by a factor of ten.

The backward peak may be interpreted as due to a one-nucleon-exchange mechanism. The one-nucleon- exchange Feynman diagram for this interaction using the proton-neutron-deuteron vertex function of Blankenbecler, Goldberger, and Halpern[15] yields a peak in the backward direction which agrees with the angular dependence of the experimental data. The effectiveness of various proton-neutron-deuteron vertex form factors may be examined by comparing their predictions in the high momentum transfer region. It is found that the usual vertex form factors obtained from the Fourier transforms of the deuteron wave functions yield differential cross sections with a slope which is much too steep. This suggests that the high momentum components are more probable than present deuteron wave functions allow. The effect of including a hard core causes the differential cross section to turn over in the backward direction, which is not observed up to $\cos\theta^* = -0.90$. A theoretical discussion of the one-nucleon-exchange mechanism in this reaction will be given in a separate paper.[16]

In the forward direction the present experiment observed a broad shoulder in the differential cross section for four-momentum transfer ($-t$) greater than 0.5 $(\text{BeV}/c)^2$ at 2.0-BeV incident proton kinetic energy. The dependence of the shoulder on an exponential in $-t$ is only half of the dependence exhibited by the diffraction peak measured by Kirillova *et al.*[17] The standard impulse approximation agrees well with the experimental data for $-t$ less than 0.13 obtained by Kirillova *et al.*, but it does not give a satisfactory interpretation of the data above four-momentum transfers of 0.5 $(\text{BeV}/c)^2$. The magnitude and slope of the experimental data for $0.5 \leq |-t| \leq 1.5$ $(\text{BeV}/c)^2$ have been determined quite accurately as manifestations of the incident proton being successively scattered by both constituents of the deuteron.[1] Because of the interference between single scattering and double scattering, a dip occurs in the predicted differential cross section which has no apparent correspondence in the experimental data. The dip is sensitive to the sign and magnitude of the real parts of the nucleon-nucleon amplitudes. The ratio of the real part to the imaginary part of the proton-proton scattering amplitude α_{pp} was determined by Kirillova *et al.* to equal -0.12 ± 0.07 at 2.0 BeV. Using a single-scattering approximation and their proton-deuteron scattering data, Zolin *et al.*[18] determined the ratio of the real part to the imaginary part of the neutron-proton scattering amplitude α_{np} to equal 0.2 ± 0.4. From existing proton-proton data and the proton-deuteron data of this experiment, the ratios of the real to the imaginary parts of the forward scattering amplitudes are shown[1] to be negative for both proton-neutron and proton-proton interactions in contrast to

TABLE IV. Coefficients in exponential fit.

Kin. energy T_p (BeV)	a	b $(\text{BeV}/c)^{-2}$	c $(\text{BeV}/c)^{-4}$
1.0	−4.97	6.48	−3.54
1.3	−3.58	4.47	−1.49
1.5	−2.66	4.68	−1.82

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the single-scattering approximation made with the earlier data.

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Measurement of $\pi^- p$ Elastic Scattering at 180°*

S. W. Kormanyos,† A. D. Krisch, J. R. O'Fallon,‡ and K. Ruddick§
The Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan

AND

L. G. Ratner
Particle Accelerator Division, Argonne National Laboratory, Argonne Illinois
(Received 21 July 1967)

We have measured the differential cross section for $\pi^- p$ elastic scattering at 180° in steps of 0.10 GeV/c or less in the region P_0=1.6 to 5.3 GeV/c. We detected elastic scattering events, from protons in a liquid H_2 target, with a double spectrometer consisting of magnets and scintillation counters in coincidence. The incident π^- beam was counted by scintillation counters. The cross section was found to have considerable structure. This may be interpreted as interference between the resonant amplitudes and the nonresonant or background amplitude. Very strong destructive interference occurs around P_0=2.15 GeV/c, where the cross section drops almost two orders of magnitude in passing through the N^*(2190). Another interesting feature of the data is a large narrow peak in the cross section at P_0=5.12 GeV/c, providing firm evidence for the existence of a nucleon resonance with a mass of 3245±10 MeV. This N^*(3245) has a full width of less than 35 MeV, which is about 1% of its mass. From this experiment we were able to determine the parity and the quantity $\chi(J+\frac{1}{2})$ for each N^* resonance, where χ is the elasticity and J is the spin of the resonance.

1. INTRODUCTION

In recent years many high-energy physics experiments have investigated the existence and properties of resonances. Traditionally the mass, width, and isotopic spin have been studied in total-cross-section measurements. These resonances caused structure in total cross sections from which certain properties of the resonances could be deduced. The spins and parities have traditionally been determined from angular distributions in elastic scattering.

In this experiment a different technique was employed to study the properties of resonances. We measured a differential elastic cross section at 180° as a function of energy. Because of the interference of the resonances with the background, quite a bit of structure was present in the cross section. From the data we were able to determine the parity and the quantity $\chi(J+\frac{1}{2})$ for various N^* resonances. This method of studying resonances appears to be more sensitive than studying the total cross section.

We have measured[1,2] the differential cross section for $\pi^- p$ elastic scattering at 180° in steps of 0.10 GeV/c or less in the region P_0=1.6 to 5.3 GeV/c. This experiment was done at the zero-gradient synchrotron ZGS at Argonne National Laboratory. The differential cross section for $\pi^- p$ elastic scattering in the backward hemisphere has been measured in other experiments.[3–9] However, essentially none of them have taken measurements as far back as 180°.

There is considerable structure in the cross section.

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† Present address: Bendix Aerospace Systems Division, Ann Arbor, Michigan.

‡ Present address: Department of Physics, Saint Louis University, Saint Louis, Missouri.

§ Present address: Department of Physics, University of Minnesota, Minneapolis, Minnesota.

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