Proton-Deuteron Elastic Scattering Cross Section at 17.1-MeV Center-of-Mass Energy*

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The absolute differential elastic scattering cross section of deuterium for 25.7-MeV protons was measured for laboratory scattering angles from 15° to 165°. A solid-state lithium-drifted silicon detector was used with a 1024-channel pulse-height analyzer to identify the scattered protons and recoil deuterons. A sealed deuterium gas target with thin windows was used. The data have been corrected for nuclear reactions in the detector. The absolute accuracy of the cross-section measurement is estimated to be 4%.

I. INTRODUCTION

THE elastic scattering of protons by deuterons is of particular interest because it involves only three nucleons and is therefore the next simplest nuclear system after the two-nucleon system. Existing data on the elastic scattering cross section[1–8] are available only at rather widely spaced energies and some of it near the minimum cross section is of rather poor quality. Few, if any, measurements have been made within 5 MeV of the bombarding energy of the present measurement, and particular care has been taken to obtain accurate measurements near the minimum cross section.

A 25.7-MeV proton beam from the University of Colorado 132-cm variable energy cyclotron was momentum analyzed by two 45° bending magnets and focused at the center of a 90-cm scattering chamber. After passing through the deuterium-filled gas cell located there, the beam emerged from the scattering chamber and was collected by a Faraday cup located behind the chamber, which was connected to a current integrator. A solid-state silicon particle detector and a slit system which defined the target volume (Fig. 1) were mounted on a tray pivoted at the center of the scattering chamber. Pulses from the solid-state detector were pulse-height analyzed by a Nuclear Data ND-160 analyzer. In general the spectrum consisted of an elastic proton peak, a recoil deuteron peak, a proton continuum from deuteron breakup, and a low-energy neutron background. The data were analyzed to determine the number of counts in the proton and deuteron peaks and from these the elastic scattering cross section was calculated. At some center-of-mass angles, the cross section is determined independently by the proton and by the deuteron peaks.

II. EXPERIMENTAL PROCEDURE

The cyclotron beam is transported to the scattering chamber by a system of focusing and bending magnets which includes two 45° bends providing momentum anlysis of the beam. The energy of the beam was measured in the scattering chamber by the crossover technique[9,10] and found to be 25.7±0.1 MeV. From other experiments at this laboratory the energy spread

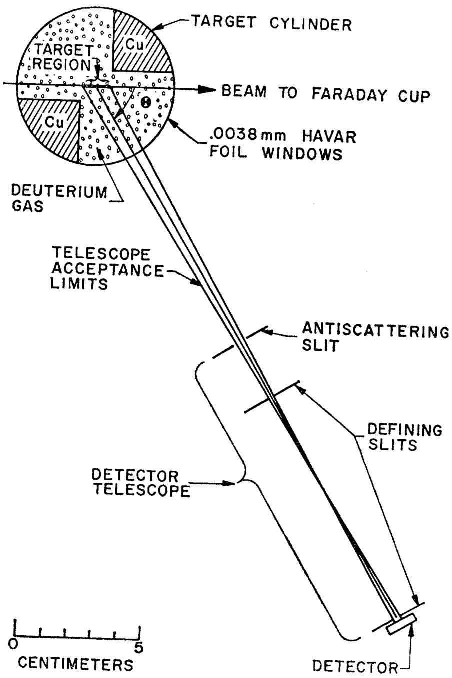

FIG. 1. The experimental geometry. The sealed gas target contained deuterium gas at approximately atmospheric pressure. Rotating the target 90° in the plane of the scattering permitted the telescope to make observations in the other two quadrants. The function of the antiscattering slit was to reduce the flux of extraneous particles incident on the first defining slit.

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of the beam is known to be less than 50 keV. After passing through the scattering chamber, the beam was stopped in a Faraday cup and the current was integrated by use of a current-to-frequency converter and a scaler.[11] Channel zero of the pulse-height analyzer was used as the scaler so that the recorded charge was automatically corrected for analyzer dead time. The beam was focused on a 1.6- by 4.8-mm slit located 5 m ahead of the scattering chamber. A magnetic quadrupole triplet lens focused the transmitted beam at the center of the scattering chamber with unit magnification without any additional slits. The geometry was such as to limit the angular divergence of the beam to a cone of 0.35° half-angle.

The deuterium target (Fig. 1) consisted of a volume milled out of a short copper cylinder which was closed with 3.8-μm Havar foil sealed on with Hysol 1c epoxy. The target was evacuated, flushed, and filled to a pressure of approximately 1 atm while in a vacuum. The 3.2-mm copper filling tube was pinched off forming a cold weld and sealing the target. The temperature and pressure were measured just before sealing the target and the density of the gas was calculated. Two years after sealing the target a small hydrogen and carbon contamination has been noticed by the elastic proton scattering which it produces. It is presumed that this comes from hydrocarbon molecules from the epoxy. After taking the data with the sealed target (two years after sealing) its deuterium density was compared to an unsealed target whose pressure and temperature were monitored. By alternately observing protons scattered from the two targets at 32.5°, it was determined that the density of the sealed target had decreased by 4±1% since it was sealed. The final density was used and a probable error of 3% was assigned to the density.

A 5200-μm lithium-drifted silicon particle detector produced at this laboratory[12] was used to observe particles emerging from the target at forward angles. At angles larger than 124° where the reaction products had low energy, an Ortec 385-μm surface-barrier silicon detector was used in order to decrease the neutron background. Some data are available on silicon detector efficiency,[13] and a correction for detector efficiency was made. The maximum correction was less than 2%. The resolution of the detectors was such that the width of the deuteron and proton peaks in the pulse-height spectrum was determined by kinematic broadening due to the finite angular acceptance of the slit system.

The particle telescope (Fig. 1) consisting of the slit system and the detector was mounted on a movable tray in the scattering chamber. The slits defined the target region along the beam and the region of the detector which was used. Laboratory cross sections were calculated from the expression

$$d\sigma/d\Omega = nrl\sin\theta/(N\rho wvh),$$

where n is the number of counts produced when N protons pass through the target, ρ is the number density of the target nuclei, w and v are the widths of the defining slits and l is their separation, h is the height of the last defining slit, r is its distance from the center of the target, and θ is the scattering angle.

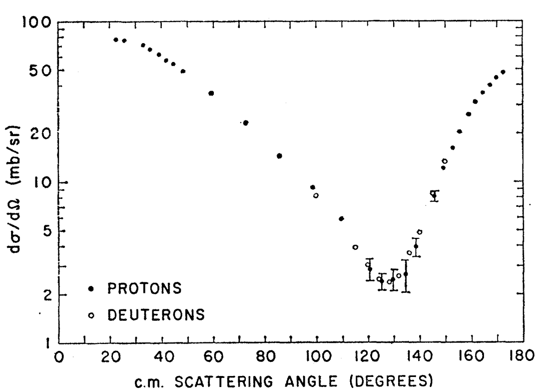

FIG. 2. Proton-deuteron center-of-mass differential elastic scattering cross section as a function of c.m. scattering angle at a c.m. energy of 17.1±0.07 MeV. The errors shown are the relative errors due to statistics and uncertainty of background subtraction. Points without error bars have errors smaller than the point size. In addition, a systematic probable error of 4% applies to the absolute value of all of the points. Some of the points (solid circles) were obtained by observing the scattered protons and the others (hollow circles) by observing the recoil deuterons. The mean proton bombarding energy was 25.7 MeV.

III. RESULTS

The cross sections obtained by this experiment (at 25.7 MeV) are consistent with cross sections measured at 20.57 MeV[2] and 31.0 MeV[6] elsewhere. The results are tabulated in Table I and plotted in Fig. 2. The errors quoted are the relative errors arising from statistics and background subtraction uncertainties. In addition, the absolute value of the cross section has a probable error estimated to be 4%. Primary sources of this error are: beam integrator calibration (1%), geometrical measurements (2.1%), and the deuterium gas density in the sealed target (3%). The cross section in the vicinity of 130° c.m. can be measured by observing either the recoil deuterons or the scattered protons, at different laboratory angles. It is evident that the measurement made by observing the deuterons is much the better measurement. This is due to the better signal-to-background ratio at forward angles because of higher

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TABLE I. Proton-deuteron differential elastic scattering cross section as a function of angle. The c.m. energy of 17.1 MeV corresponds to an incident proton energy of 25.7 MeV. Most of the values were obtained by observing the scattered protons; however, at some angles, the cross section was best measured by observing the recoil deuterons. "$(d\sigma/d\Omega)_{lab}$" is the laboratory cross section for scattering protons and is not given where deuterons were observed. "c.m. angle" is the c.m. scattering angle.

Particle observed	Lab angle (degrees)	c.m. angle (degrees)	$(d\sigma/d\Omega)_{lab}$ (mb/sr)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)
p	15.0	22.6	173 ±1.7	77.6 ±0.8
p	17.5	26.3	168 ±1.7	76.5 ±0.8
p	22.0	33.0	154 ±1.5	71.7 ±0.7
p	24.0	36.0	142 ±1.4	66.7 ±0.7
p	26.0	38.9	132 ±1.3	62.8 ±0.6
p	28.0	41.8	120 ±1.2	57.7 ±0.6
p	30.0	44.7	112. ±1.1	54.5 ±0.5
p	32.5	48.4	98.4 ±1.0	48.9 ±0.5
p	40.0	59.1	67.5 ±0.7	35.8 ±0.4
p	50.0	72.9	39.0 ±0.4	23.1 ±0.23
p	60.0	86.0	21.4 ±0.2	14.5 ±0.14
p	70.0	98.4	11.6 ±0.12	9.24±0.09
d	40.0	99.8		8.22±0.08
p	80.0	109.8	6.13±0.06	5.83±0.06
d	32.5	114.8		3.91±0.04
d	30.0	119.8		3.02±0.03
p	90.0	120.3	2.46±0.41	2.85±0.47
d	28.0	123.8		2.45±0.02
p	95.0	125.2	1.89±0.23	2.42±0.29
d	26.0	127.9		2.39±0.02
p	100.0	129.8	1.73±0.27	2.47±0.39
d	24.0	131.9		2.61±0.03
p	105.0	134.2	1.67±0.40	2.64±0.62
d	22.0	135.9		3.60±0.04
p	110.0	138.3	2.25±0.30	3.95±0.53
d	20.0	139.9		4.81±0.05
d	17.5	144.9		8.42±0.08
p	120.0	145.9	3.79±0.77	8.13±0.62
p	125.0	149.4	5.12±0.05	12.1 ±0.12
d	15.0	149.9		13.2 ±0.13
p	130.0	152.7	6.28±0.06	16.2 ±0.16
p	135.0	155.9	7.29±0.07	20.4 ±0.20
p	140.0	158.9	8.65±0.09	26.1 ±0.26
p	145.0	161.8	9.68±0.10	31.3 ±0.3
p	150.0	164.6	10.4 ±0.10	35.5 ±0.4
p	155.0	167.3	11.0 ±0.11	39.8 ±0.4
p	160.0	169.9	11.8 ±0.12	44.3 ±0.4
p	165.0	172.5	12.2 ±0.12	47.7 ±0.5

particle energy, larger $d\Omega'/d\Omega$, and larger effective target thickness. The angular resolution as measured by the rms deviation from the quoted scattering angle is 0.6°, and the probable error in the scattering angle measurement is 0.3°.

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