Elastic Scattering of 40-Mev Protons by Deuterons*

JOHN H. WILLIAMS AND MORTON K. BRUSSEL†
School of Physics, University of Minnesota, Minneapolis, Minnesota
(Received December 9, 1957)

Measurements of the differential cross section for elastic scattering of 40-Mev protons by deuterons over the range of proton laboratory angles from 4° to 164° are reported. The results for angles greater than 90° were obtained by observing the recoil deuterons emitted in the forward direction. The cross section exhibits a sharp minimum at 7° and a broad minimum at approximately 110°.

I. INTRODUCTION

THE proton-deuteron elastic scattering process presents one of the simplest "many-body" problems of nuclear physics which should be soluble by a detailed theory. Some of the basic information required by such theories in attacking this problem in the energy region here investigated exists from our earlier knowledge of the elastic scattering of 40-Mev protons by protons[1] and of 40-Mev neutrons by protons.[2] On the other hand, the question as to whether precise descriptions of such "many-body" problems can be given on the basis of two-body forces has occupied a great deal of attention.[3] The measurements reported here on the differential cross section for elastic scattering of 40-Mev protons by deuterons, on which there existed no previous observations, were undertaken in the hope that they might stimulate and serve to check theoretical interpretations of the three-body problem.

Earlier observations on the elastic scattering of protons by deuterons have been made at equivalent proton energies (laboratory) of from 0.25 to 5.25 Mev by several workers,[4–11] at 9.7 Mev by Allred *et al.*,[12] at 20.6 Mev by Caldwell and Richardson,[13] and at 32 Mev by Ashby.[14] Only for the case of 20.6-Mev protons was a sufficiently large range of angles investigated to reveal all the details of the behavior of the differential cross section as a function of angle.

* Work supported in part by the U. S. Atomic Energy Commission.
† Present address: Brookhaven National Laboratory, Upton, New York.
1 L. H. Johnston and D. A. Swenson (to be published).
2 Hadley, Kelly, Leith, Segrè, Wiegand, and York, Phys. Rev. **75**, 351 (1949).
3 H. A. Bethe, Phys. Rev. **103**, 1353 (1956).
4 H. B. Burrows *et al.*, Proc. Roy. Soc. (London) **A209**, 489 (1951).
5 R. F. Taschek, Phys. Rev. **61**, 13 (1942).
6 L. Rosen and J. C. Allred, Phys. Rev. **82**, 777 (1951).
7 K. B. Mather, Phys. Rev. **88**, 408 (1952).
8 Karr, Bondelid, and Mather, Phys. Rev. **81**, 37 (1951).
9 Rodgers, Leiter, and Kruger, Phys. Rev. **78**, 656 (1950).
10 Sherr, Blair, Kratz, Bailey, and Taschek, Phys. Rev. **72**, 622 (1947).
11 Brown, Freier, Holmgren, Stratton, and Yarnell, Phys. Rev. **88**, 253 (1952).
12 Allred, Armstrong, Bondelid, and Rosen, Phys. Rev. **88**, 433 (1952).
13 D. O. Caldwell and J. R. Richardson, Phys. Rev. **98**, 28 (1955).
14 V. J. Ashby, University of California Radiation Laboratory Report UCRL-2091, 1953 (unpublished).

II. APPARATUS

The second section of the three-stage Minnesota proton linear accelerator provides a beam of 39.85±0.20 Mev protons. For observations of the protons scattered in the angular range 20° to 90° the apparatus employed was similar to that described in detail in an earlier report by us,[15] except that the scattering chamber containing the deuterium gas target was only five inches in diameter. For observations in the angular range 4° to 20° the incident protons, after coasting through the unexcited third section of the accelerator, were magnetically deflected through 20°, collimated to a beam of $\frac{1}{2}$-inch diameter and entered a deuterium-filled chamber specifically designed to investigate scattering at such small angles. This apparatus will be described in a forthcoming paper by L. H. Johnston and D. A. Swenson on the scattering of 40-Mev protons by protons.

NaI(Tl) detectors mounted behind collimating slits and antiscattering baffles served to detect the scattered protons and recoil deuterons. The over-all angular definition was approximately ±2° in the range 50° to 90°, ±1° in the range 20° to 50°, ±0.5° in the range 4° to 20°.

Conventional electronic circuits amplified the output of these detectors and the resulting signals were recorded on a twenty-channel pulse-height analyzer.

Appropriate attention was given to the other experimental details of importance in measurements of differential cross sections with a gaseous target. For example, gas pressure, temperature, and purity were accurately determined, tests of efficiency of current collection in a well-designed Faraday cup were made, the calibration of the current integrator was established to within an accuracy of less than one percent, and geometry factors such as the zero of the angular scale, slit sizes, thicknesses, and distance were accurately known.

III. EXPERIMENTAL PROCEDURE

To obtain information on the D(p,p)D elastic scattering cross section, it is possible to observe both the scattered proton and the recoil deuteron. Such observations are complicated by the concurrent process

15 M. K. Brussel and J. H. Williams, Phys. Rev. **106**, 286 (1957).

of deuteron breakup resulting in a continuous spectrum of protons with energies up to within 2.2 Mev of the elastically-scattered proton group. If, as in the present experiments, the particles are detected by a thick NaI(Tl) crystal and distinguished only by the total energy absorbed by that crystal, a further complication arises from the fact that a small percentage of the protons suffer neutron-producing nuclear reactions in the crystal. These few protons are consequently recorded as lower energy pulses than are truly representative of the energy of the incoming particle. The correction to the measured *elastic* scattering cross section due to this latter effect is small, decreasing from 1.9% for 40-Mev protons to approximately 0.5% for 10-Mev protons,[16] which is approximately one tenth of the number of truly inelastic protons observed at an angle of 16°.

A typical number *vs* pulse-height spectrum of the particles recorded with the instrumentation described above (the observations were made at 16° with respect to the direction of the incident beam) is shown in Fig. 1. At this angle the recoil-deuteron peak is clearly separated from the elastically-scattered protons and can be seen to lie on a background of protons arising from the two processes of deuteron breakup and nuclear reactions in the scintillation detector. The curve of Fig. 1 shows that the D(p,pn)H process contributes appreciably to the total cross section for 40-Mev protons incident on deuterons but no attempt will be made in this paper to report on the details of this reaction. Rather, we wish to extract information from experimental data of the type shown in Fig. 1 on the elastic D(p,p)D process by measuring both the numbers of recoil deuterons and elastically scattered protons. Further work on the breakup reaction is planned.

The procedure employed in determining the number

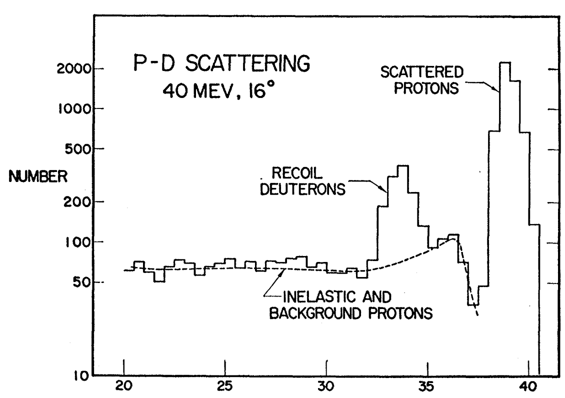

FIG. 1. Number of recorded pulses per half-volt interval of pulse height as a function of pulse height for observations at 16° with respect to the direction of the 40-Mev protons bombarding deuterium.

[16] L. H. Johnston and D. A. Swenson (private communication).

TABLE I. The differential cross section (in millibarns per steradian) for elastic scattering as a function of the angle of the scattered proton, in the laboratory system. For angles greater than 90° the figures given are calculated from observations on the recoil deuterons.

θ_{lab}	$(d\sigma/d\Omega)_{lab}$	θ_{lab}	$(d\sigma/d\Omega)_{lab}$
4°	325 ±4	50°	16.2 ±0.4
5°	135 ±2	55°	13.3 ±0.4
6°	96 ±2	60°	9.0 ±0.3
7°	92 ±2	65°	7.1 ±0.2
8°	93 ±2	70°	5.4 ±0.2
9°	100 ±2	75°	4.5 ±0.2
10°	104 ±2	80°	3.8 ±0.3
11°	109 ±2	90°	1.9 ±0.7
12°	109 ±1	117°44′	1.42±0.07
13°	108 ±2	120°28′	1.68±0.06
14°	108 ±2	123°18′	1.96±0.04
15°	106 ±1	126°12′	2.11±0.05
16°	102 ±1	129°12′	2.42±0.07
17°	102.5±2	132°18′	2.55±0.07
18°	98 ±2	135°29′	2.87±0.05
20°	93 ±3	138°45′	3.50±0.07
25°	74 ±2	142°6′	4.07±0.08
27½°	65 ±2	145°35′	4.24±0.08
30°	56 ±1	149°8′	4.62±0.08
35°	45 ±1	152°7′	4.62±0.09
40°	32 ±1	156°30′	5.23±0.10
45°	23.9±0.7	160°18′	5.18±0.10
		164°10′	5.47±0.11

of elastically scattered protons and recoil deuterons is illustrated in Fig. 1. The dashed curve represents the background that was subtracted from the total number of events recorded. A single curve of the nature shown in Fig. 1 is not very convincing as to the correctness of this procedure but the nature of the background curve is made more reasonable by an examination of the many such curves recorded at many other angles of observation where the energy and relative magnitude of the deuteron recoil peak changes with angle in a monotonic fashion. In any case the contribution of errors by this procedure is essentially negligible for the elastically-scattered proton peak and cannot exceed more than approximately five percent for the most ambiguous deuteron recoil peak.

The elastically scattered proton peak could be identified and its magnitude determined with accuracy over the range of angles from 4° to 90°. At larger angles the cross section for scattering is small and the energy of the scattered protons reaching our detectors was reduced to less than 10 Mev. These two factors make it difficult to distinguish the peak over the background of piled-up pulses of lesser magnitude and render it difficult to extend observations into the backward hemisphere.

However, our ability to observe the recoil deuterons at the laboratory angles of from 4° to 18° served to provide the desired information since these deuterons correspond to protons scattered through the laboratory angle range from 164° to 118°. The intermediate angular region, 90° to 118°, has not been explored by these experiments.

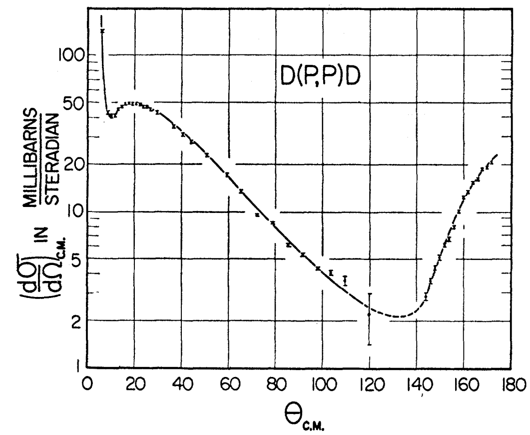

FIG. 2. Differential elastic scattering cross sections of 40-Mev protons by deuterons as a function of angle in the center-of-mass system. Dotted section of curve from 100° to 140° is uncertain.

IV. RESULTS

The results of our observations are listed in Table I. The probable errors shown include estimates of the ambiguity in background subtraction discussed above as well as the statistical uncertainty arising from the limited number of particles observed. The absolute value for the cross sections is estimated to be uncertain by not more than three percent as a consequence of errors in measuring geometric factors, number of target nuclei, contamination, and incident proton current. No corrections have been made for second-order geometry effects which should be negligible.

The data, after conversion to the center-of-mass system, are presented in Fig. 2. The probable errors shown are those converted from the errors given in Table I. The dotted line between 100° and 140° is simply a guess as to the variation of cross section in this angular range.

The variation of cross section in the center-of-mass angular range $7\frac{1}{2}°$ to 60° is also presented in Fig. 3 to illustrate more clearly the sharp minimum which occurs in the neighborhood of 11°.

V. DISCUSSION

The present data are typical of those observed by scattering protons from other very light nuclei in that the cross section exhibits a minimum in the neighborhood of angles slightly in excess of 90° and increases at backward angles. A detailed theory of this general behavior is not presently available.

The other feature of a sharp minimum at a small angle is also common to observations on the elastic scattering of protons by He^4.[15] It undoubtedly arises from the destructive interference between the repulsive Coulomb potential and an attractive nuclear potential. Detailed analysis of this phenomenon is under consideration in this laboratory.

Comparison of these observations with those in other laboratories, over the angular range which shows both of the above features, can only be made with the 20.6-Mev experiments of Caldwell and Richardson,[13] where the same general features were exhibited by their results. The measurements of Ashby[14] at 32 Mev covered the limited center-of-mass angular range of 22° to 150° and demonstrated a broad minimum at approximately 125°.

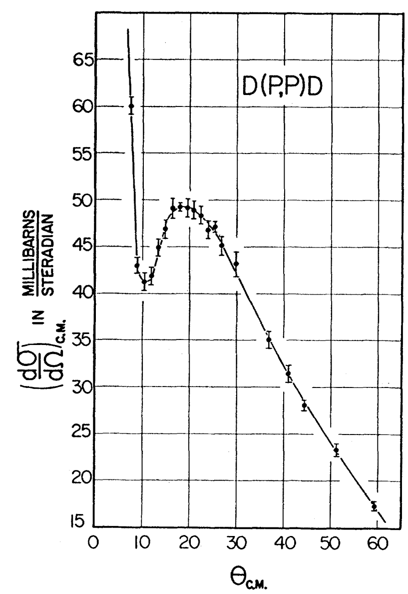

FIG. 3. Differential elastic scattering cross sections of 40-Mev protons by deuterons over a range of small angles in the center-of-mass system.

VI. ACKNOWLEDGMENTS

We are indebted to Professor L. H. Johnston and Mr. D. A. Swenson for the use of their small-angle scattering chamber and wish also to express our thanks to the crew of the linear accelerator, under the direction of Mr. R. P. Featherstone, for their aid.