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The Angular Distribution of 1 to 3.5 Mev Deuterons Scattered by Deuterons

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The differential cross section for the elastic scattering of deuterons by deuterons has been obtained in the energy range from 1 to 3.5 Mev. The observed yields were corrected for the counted particles produced in the D – D reactions and for those scattered by contaminants by using the results of other experiments. The resultant elastic cross sections are probably accurate to about 2.5 percent.

SCATTERING experiments have been a remarkably fruitful source of information about nuclear forces; and, in general, one might say that the importance of the information and the ease with which it can be obtained decreases as the complexity of the particles involved increases. From this point of view the deuteron-deuteron combination is the most promising one not previously investigated in the energy range available to the Minnesota Van de Graaff generator, since careful work has been done on proton-proton[1,2] and proton-deuteron[3] scattering. We have measured, as described in this paper, the deuteron-deuteron elastic scattering cross section as a function of angle and energy from 10° to 45° (in the laboratory system) and from 1 Mev to 3.5 Mev.

EXPERIMENTAL METHOD

These data on the scattering of deuterons by deuterons were obtained with the same apparatus and by the same method as the data on the scattering of protons by protons presented in a recent paper.[2] A well-collimated beam of deuterons, accelerated by the Minnesota electrostatic generator, was passed through a chamber containing deuterium gas at a pressure of about one centimeter of mercury. The intensity of this beam was measured by allowing it to pass from the gas through a 0.0002-inch Nylon window into an insulated cup in an evacuated region. A fraction of the deuterons scattered from a small, well-defined volume in the center of the chamber passed through a slit system and through a Nylon window into a proportional counter. The factors for obtaining the scattering

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[1] R. G. Herb, D. W. Kerst, D. B. Parkinson, and G. J. Plain, Phys. Rev. **55**, 998 (1939).

[2] J. M. Blair, G. Freier, E. E. Lampi, W. Sleator, J. H. Williams, Phys. Rev. **74**, 553 (1948).

[3] R. Sherr, J. M. Blair, H. R. Kratz, C. L. Bailey, R. F. Taschek, Phys. Rev. **72**, 662 (1947).

cross section from the number of deuterons counted per microcoulomb of beam passing through the chamber were the same as those used in the previous work.

However, in order to determine the deuteron-deuteron scattering cross section, the data so obtained must be corrected for the particles which originate in the deuteron-deuteron disintegrations, and for the proton-deuteron scattering caused by a small molecular hydrogen contamination in the deuteron beam and by a hydrogen contamination in the deuterium in the scattering chamber. The disintegration products could be distinguished from the elastically scattered deuterons by differences in range and differences in the size of the pulses produced in the proportional counter. From the known energy release in the $H^2+H^2\rightarrow He^3+n+3.24$ Mev and $H^2+H^2\rightarrow H^1+H^3+3.98$ Mev reactions and the use of a McKibben diagram,[4] one can obtain the energy, and hence the range and rate of energy loss by ionization, of the He^3, H^1, and H^3 for each angle and each deuteron energy at which data are to be taken. From this information one can establish which particle is responsible for each step in the bias curve which is obtained from the amplified pulses from the proportional counter. A typical example of such a counting rate *vs.* bias curve is shown in Fig. 1.

The bias curves obtained at some angles and energies were slightly different from the one shown in Fig. 1 due to the variations in the relative ranges and ionizing abilities of the various particles, but it was always possible to determine which portion of the counts was due to the scattered deuterons. In the curve shown the pulses counted at the highest discriminator bias (a) are those due to the He^3. The second rise in the curve (b) is due to deuterons scattered by protons which enter the chamber as HH+ ions, and to deuterons from the beam which have made small angle collisions with hydrogen atoms in the scattering chamber. The protons in the beam have energies equal to half the generator voltage and, also because of the greater mass of the deuteron, result in scattered deuterons which are of lower energy than those scattered by other deuterons at that angle. Since, in general, the

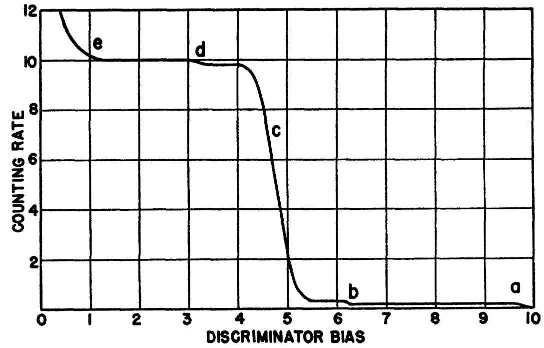

FIG. 1. Typical curve of the counting rate as a function of the discriminator bias showing the relative size of the pulses due to the various types of particles which entered the proportional counter.

particles entering the proportional counter did not stop in the counter gas; the lower energy deuterons from proton collisions produced more ionization in the counter than the elastically scattered deuterons. The deuterons colliding with hydrogen atoms also lose such a fraction of their energy as to result in increased pulse size. The third and largest rise in the counting rate (c) is due to the deuterons scattered by other deuterons. The fourth jump (d) is due to the H^3 from the disintegrations and to protons which enter the counter after hitting deuterons or being hit by deuterons. Due to the energy released in the disintegrations, the velocity of an H^3 is larger than the velocity of an H^2 elastically scattered at the same angle. This results in the H^3 producing a smaller pulse in the counter than the deuterons. In most cases the pulses responsible for steps (c) and (d) were too nearly the same size to reliably separated, so both sets of particles were counted and a correction made later. The pulses due to the H^1 from the disintegration were too small (e) to be confused with the others in this experiment. As in the proton-proton scattering experiment, two scale-of-64 circuits were used simultaneously as a continuous check on the flatness of the plateau in the bias curve and the general performance of the counter.

While taking the scattering data a third scale-of-64 circuit was commonly used with its bias set high enough to count only the He^3 pulses. However, the corrections to the cross section finally applied were obtained from a separate experiment made expressly for the purpose of

[4] J. L. McKibben, Phys. Rev. **70**, 101 (1946).

TABLE I. Deuteron-deuteron scattering cross section per unit solid angle in the center-of-mass coordinate system as a function of deuteron energy in Mev and scattering angle. Cross sections are in barns (10^{-24} cm^2). Deuteron energies are in Mev.

$\phi \backslash E_d$	0.96	1.49	2.01	2.51	3.02	3.50
20°	11.08	4.18	2.62	1.78	1.45	1.21
30°	2.57	1.28	0.877	0.712	0.634	0.578
40°	1.19	0.654	0.529	0.455	0.415	0.386
50°	0.703	0.455	0.381	0.350	0.328	0.298
60°	0.517	0.346	0.303	0.283	0.261	0.256
70°	0.430	0.317	0.264	0.235	—	0.217
80°	—	0.281	0.246	0.222	0.207	0.191
90°	—	0.265	0.234	0.215	—	—
100°	—	—	—	0.227	0.206	0.187

getting the cross sections of the deuteron-deuteron disintegrations.[5]

As in the proton-proton scattering experiment, checks were made on the effect of the accumulation of gases other than deuterium in the scattering chamber during the course of a run by closing the chamber without admitting any deuterium and measuring the rise in the counting rate at various angles over a period of time. This effect was small, usually one percent or less, and the data were corrected accordingly.

The intensity of the molecular portion of the beam from the electrostatic generator was of interest as the percentage of hydrogen molecules in the mass-2 beam affected both the current measurement and the correction for the deuterons scattered by protons. To obtain the hydrogen contamination in the deuteron beam we measured the current of both atomic and molecular beams from the generator and then assumed that the ion source had the same efficiency for producing hydrogen molecular ions as it did for producing deuterium molecular ions. The deuterium gas which was used, both in the ion source and in the scattering chamber, was analyzed mass spectrographically by Dr. A. O. Nier of this laboratory and found to contain 1.1 percent hydrogen. Our measurements of the beam currents showed that the molecular beam was about 25 percent as great as the atomic beam. Therefore, we believe that the beam of ions entering the scattering chamber contained about 0.3 percent hydrogen molecules. The measured beam currents were corrected for this impurity in the beam.

[5] See the following paper by the same authors.

While working with deuterons it was not feasible to check the voltage calibration of the electrostatic generator frequently, as was the case in the proton-proton scattering experiment, but our experience during that work showed that the calibration was very reproducible, so that we feel that the voltages given are correct to ±20 kv on the basis of 1.883 Mev for the $Li^7(p, n)Be^7$ threshold.[6] A correction has been made for the energy lost by the beam in passing through the entrance window and through the deuterium to the center of the scattering chamber.

CORRECTIONS

As mentioned above, the observed counting rate had to be corrected for the number of He^3 and H^3 which entered the counter along with the scattered deuterons. In separate experiments[5] the cross sections for the production of He^3 and

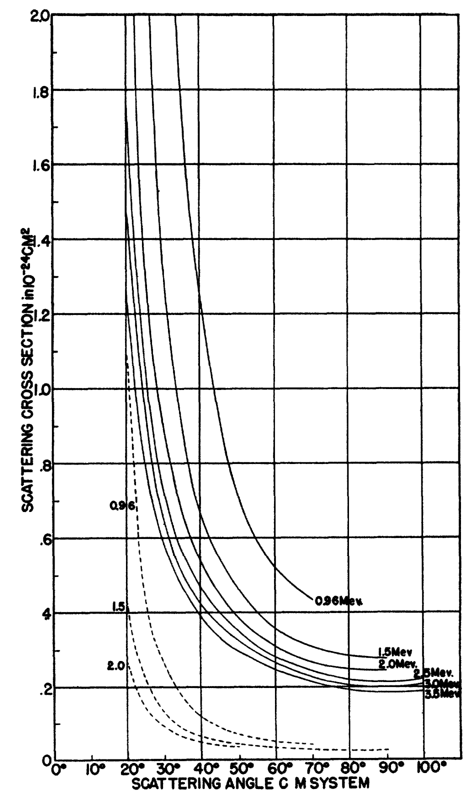

FIG. 2. Deuteron-deuteron scattering cross sections per unit solid angle in the center of mass coordinate system for various deuteron energies. The dotted curves are the same data reduced by a factor of ten.

[6] R. G. Herb, Phys. Rev. (to be published).

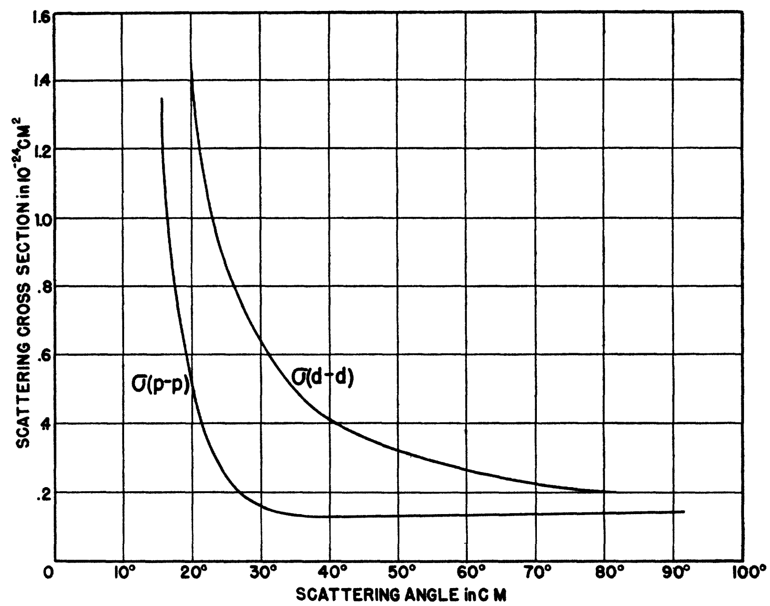

FIG. 3. Comparison of D−D and P−P scattering cross section in center of mass system for 3 Mev deuterons and protons.

H^1 in the two disintegration reactions were measured. The He^3 cross section for the corresponding angle and energy could be subtracted directly from the original scattering cross section. The number of H^3 counts to be subtracted was obtained from the number of H^1 counts observed by converting the H^1 data[5] to the center of mass coordinate system and then interpolating for the value at the proper angle and finally converting back into the laboratory system. These conversions do not cancel because of the difference in the masses of the two particles. Each of these corrections amounted to one or two percent of the scattering cross section so that the probable errors in the experiments on the disintegration cross sections did not contribute appreciably to the probable errors in the D−D scattering cross sections.

The corrections to the scattering cross sections due to the proton-deuteron scattering from the hydrogen contaminations in the ion beam and in the scattering chamber gas were obtained from the proton-deuteron scattering data obtained at Los Alamos.[3] It was necessary to make this correction in four steps, since there were four groups of particles which could enter the counter and be recorded. The protons resulting from the hydrogen molecules entering the scattering chamber with the deuterons could reach the counter after making a collision with the deuteron, and the recoil deuterons from such collisions could be counted also. Similarly, deuterons from the beam could hit a hydrogen atom and then enter the counter, and the recoil proton from such a collision could also be counted. For each case the quantities to be subtracted from the observed data were obtained from the curves presented in reference 3, converted from center-of-mass to laboratory coordinates (this is different in each case), and then multiplied by an intensity factor determined by the percentage of contamination mentioned above. The sum of these corrections varied from one to four percent of the deuter-on-deuteron scattering cross section, being, in general, more at higher energies and angles.

The presence of the 1.1 percent of hydrogen in the scattering chamber necessitated a corresponding correction to the gas pressure as read on the manometer.

The corrections to our data due to the finite size of the beam of deuterons passing through the scattering chamber and to the finite angular aperture of the slits in front of the proportional counter ("second-order geometry" corrections) were computed in the same manner as for the proton-proton scattering data previously reported.[2] These corrections are negligible for the higher angle data but rise to $\frac{1}{2}$ percent for measurements at 15°. For observations at 10° a smaller hole could be used as a counter window due to the high counting rates, so the correction was smaller.

RESULTS

The deuteron-deuteron scattering cross sections per unit solid angle in the center of mass coordinate system after the application of all the above mentioned corrections, are presented in Table I and Fig. 2. At each point enough counts were recorded to make the statistical probable error one percent or less, except at 80°, 90°, and 100° where this error at some points may be one-and-a-half percent. The probable errors due to gas pressure measurement, current measurement, measurement of geometrical factors, etc., amount to about one-and-a-half percent. However, these items should affect the internal consistency of the data somewhat less than that amount.

The 1-Mev data do not extend beyond 70° (in the center of mass system) because the scattered deuterons did not have enough energy at larger angles to enter the counter. At other energies the data do not extend beyond 90° or 100° because of the expected symmetry of the cross sections about 90° and the time consumed in counting the relatively few deuterons which are scattered to higher angles.

Figure 3 shows both the deuteron-deuteron and the proton-proton elastic scattering cross sections at 3 Mev plotted to the same scale. Although the Coulomb cross sections are not directly comparable because the deuteron-deuteron interaction has a greater ratio of symmetric to anti-symmetric spin states and the deuteron obey Bose rather than Fermi statistics, some qualitative differences in the nuclear interactions are apparent. The rapid decrease of $\sigma(d-d)$ with increasing angle between 40° and 80° where $\sigma(p-p)$ is increasing slightly, suggests the presence of scattered waves of angular momentum greater than zero. A phase shift analysis of the data presented here is being undertaken by Professor C. L. Critchfield and Mr. Donald Dodder, and will appear in a later publication.

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