Deuteron-Deuteron, Proton-Helium, and Deuteron-Helium Scattering

N. P. HEYDENBURG AND R. B. ROBERTS
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.
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Measurements have been made on deuteron-deuteron scattering at angles between 20° and 45° for incident deuteron energies of 832, 720, and 614 kv. In this range of angles and energies the ratio of the observed scattering to that predicted by classical theory, as modified according to Mott to take account of the identity of the particles, is always greater than unity. At 832 kv the ratio increases from 1.28 at 15° to 3.98 at 45°. This anomaly is of the type to be expected if there is present a short range repulsive force between the particles in addition to the Coulomb force. The scattering of protons in helium was in agreement with the Rutherford-Darwin scattering formula for 994-kv protons in the angular range from 20° to 45°. The scattering of deuterons in helium showed an anomaly which increased from about unity at 20° to 4.4 at 75°. This anomaly also indicates an additional repulsive nuclear force between the deuteron and helium particles.

INTRODUCTION AND TECHNIQUE

WHILE making the proton-proton scattering measurements described in the preceding paper, we also made some observations on the scattering of deuterons on deuterons and of protons and deuterons in helium. These measurements were confined to the region 600 to 1000 kv for the energy of the incident particles. The apparatus and technique were the same as used for the proton-proton scattering, and has already been discussed in detail in the preceding paper. The gold-foil scattering technique was used as the current monitor and integrator for the incident beam. The ratio of the number of scattered particles, N_H, from the gas to the number, N_G, from the gold foil was recorded, and the number of scattered particles, N_S, from the gas per minute per microampere of beam-current was then given by $N_S=N_Hn/N_G$, where n is the number of counts from the gold foil per minute per microampere. The value of N_S was then compared to the predicted classical scattering as calculated from the constants of the apparatus, the pressure of the gas target, and the energy of the initial particles.

Deuterium of purity better than 99 percent, obtained from the Stuart Oxygen Company, was used throughout the experiments on deuteron-deuteron scattering both in the ion-source and for the scattering gas. The deuterium was introduced into the scattering chamber through a palladium tube. It was found that very careful outgassing of the palladium tube, which had previously been used for ordinary hydrogen, was necessary to eliminate hydrogen contamination of the deuterium. The palladium tube was heated to a dull red heat in a vacuum for some time, then deuterium was passed through it for several hours. After this treatment the hydrogen contamination was negligible. For the deuteron-deuteron scattering the presence of ordinary hydrogen in the scattering volume was readily detectable from the scattering results. In the scattering of deuterons in light hydrogen (protium) the classical Rutherford-Darwin theory predicts that there will be no scattered deuterons beyond a 30° angle. This results from the fact that in the general formula for the scattering cross section

$$q=Qnt\omega\left(\frac{ZeE}{Mv^2}\right)^2 \csc^3\theta \times\frac{\{\cot\theta\pm[\csc^2\theta-(M/m)^2]^{\frac{1}{2}}\}^2}{[\csc^2\theta-(M/m)^2]^{\frac{1}{2}}},$$

the radical in the denominator becomes negative for $\theta>30°$. The presence of ordinary hydrogen can be recognized by a sharp increase in the number of scattered deuterons at 30° in going from larger to smaller angles. Preliminary observations made before the palladium tube was well outgassed showed this effect very clearly; after careful outgassing it disappeared. Any hydrogen contamination in the magnetically analyzed deuteron-beam would be in the form of diatomic hydrogen ions, each proton having only half the energy of the deuterons, and therefore would not be recorded by our ionization-chambers. We used a deuterium pressure of 12 mm of mercury in the scattering chamber for these experiments.

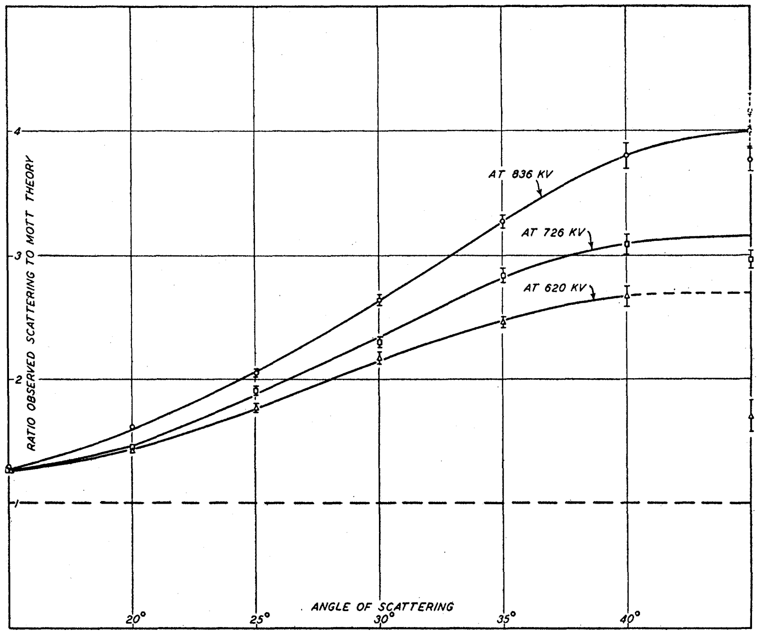

FIG. 1. Scattering of deuterons in deuterium.

For the scattering in helium we used 10-mm mercury pressure of commercial helium (98 percent), which was purified somewhat by passing through a liquid-air-cooled charcoal trap.

For proton-helium and deuteron-helium scattering there will be two groups of particles at a given angle, the scattered incident particle and the recoil helium or alpha-particle. It can easily be shown by calculating the range of the recoil alpha-particle that the recoils will not have sufficient energy to be counted in the case of the proton-helium scattering. For the deuteron-helium scattering the recoil alpha-particles entering the detector at an angle of 35° or less might perhaps have sufficient energy to be counted. The recoils at 35° are the result of collisions in which the deuteron is scattered at about 80°. The deuterons scattered at 80° and hence the recoil alphas at 35° would amount to only 2.5 percent of the number of deuterons scattered at 35° on the basis of the Rutherford-Darwin theory, and to about five times this or ten percent if one takes into account the observed scattering anomaly. Hence the effect of the recoil alpha-particles on the scattering curves would be small even if they were counted. The observed curves in Fig. 2 give no indication of their presence.

TABLE I. *Results on proton-helium, deuteron-helium scattering.*

θ	Ratio D to Au (corrected)	N observed (corrected)	N Mott	Ratio N observed to N Mott	Total count	Probable error (statistical)
			$V=832$ kv			
15°	1776.3	176,919	138,052	1.28	29,750	. .
20	564.20	56,194	34,996	1.61	12,930	0.01
25	257.39	25,636	12,651	2.02	4,410	0.03
30	153.70	15,309	5,844.7	2.62	7,270	0.04
35	106.77	10,634	3,281.2	3.24	2,170	0.07
40	82.52	8,219.0	2,182.5	3.77	2,080	0.09
45	63.73	6,347.5	1,698.2	3.74	1,930	0.09
(45)	(67.83)	6,755.9		(3.98)		
			$V=720$ kv			
15	1703.2	232,487	184,340	1.26	16,804	0.01
20	489.74	66,850	46,730	1.43	5,860	0.02
25	233.05	31,811	16,892	1.88	7,940	0.03
30	129.56	17,685	7,804.4	2.27	3,341	0.04
35	89.72	12,247	4,381.3	2.80	3,011	0.05
40	64.95	8,865.7	2,914.3	3.04	2,925	0.06
45	48.47	6,616.2	2,267.6	2.92	1,037	0.09
			$V=614$ kv			
15	1684.1	321,663	253,484	1.27	16,794	0.01
20	470.57	89,879	64,257.4	1.40	8,392	0.02
25	211.30	40,358	23,227.7	1.74	4,579	0.03
30	119.71	22,865	10,731.7	2.13	2,115	0.05
35	75.98	14,512	6,024.6	2.41	2,098	0.05
40	55.01	10,507	4,007.4	2.62	1,727	0.06
45	27.37	5,227.7	3,118.2	1.68	910	0.06

RESULTS AND DISCUSSION

In the deuteron-deuteron scattering we are concerned with identical particles, so instead of comparing our results with the Rutherford-Darwin scattering law we have used the following

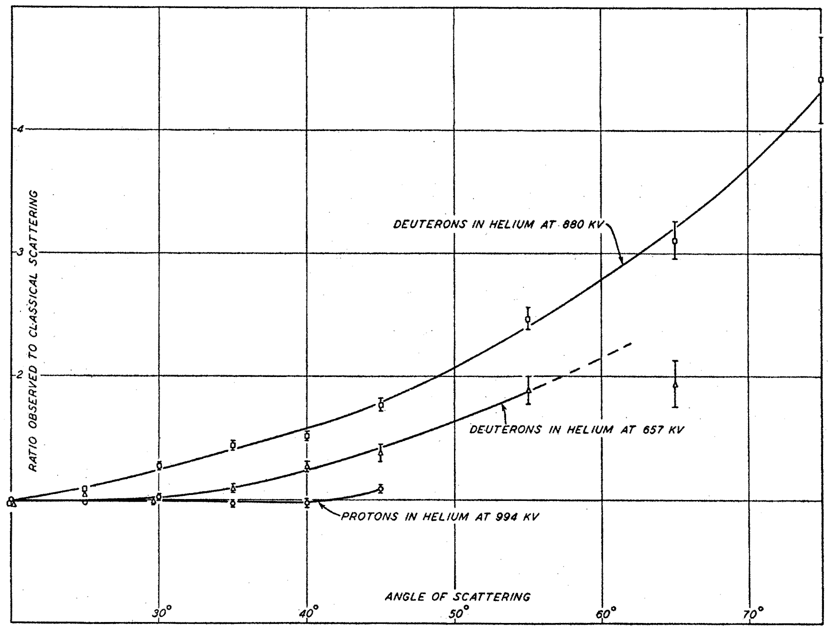

FIG. 2. Scattering of deuterons and protons in helium.

scattering cross section for Coulomb interaction, which takes into account the interference effect for identical particles:

$$q=(e^4/m^2v^4)(\csc^4\theta+\sec^4\theta+\tfrac{2}{3}\Phi\csc^2\theta\sec^2\theta)\times 4\cos\theta, \quad (1)$$

where $\Phi=\cos[(2\pi e^2/hv)\log\tan^2\theta]$. This equation includes both scattered and recoil deuterons since they are indistinguishable and was obtained directly from the equations and discussions given, by Mott and Massey.[1]

Our results are given in Table I for deuteron energies 832, 720, and 614 kv, for scattering angles between 15° and 45°. The number of scattered deuterons observed per minute per microampere of the incident beam has been compared to the number to be expected according to Eq. (1) for our apparatus constants, the number and energy of the incident deuterons, and the pressure of the scattering gas; this number we have called the Mott value. The ratio of the observed scattering to the Mott value has been plotted in Fig. 1. There is a definite disagreement with the scattering cross section calculated from the above equation. The anomaly thus indicated is of the same order as that which has been found for proton-proton scattering although it differs in its dependence on the energy of the incident deuterons and also in the dependence on angle. The deuteron-deuteron ratio remains above unity even down to an angle of 15° while the ratio for proton-proton scattering was 30 percent below

[1] N. E. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Cornell University Press, 1933), pp. 73–77.

TABLE II. *Results on deuteron-deuteron scattering.*

θ	Ratio $\times 10^3$ He to Au scatterer, He pressure $=10$ mm	N_S corrected for zero angle	$N_S(R-D)$	Ratio	Total count	Probable error (statistical)
	H–He, *994 kv, 978 kv at* Au *foil* (*gold counts 696*)					
20°	568.8	3792.2	3766.4	1.01	18,100	0.01
25	183.4	1239.3	1263.4	0.98	1,900	0.016
30	77.65	537.60	521.97	1.03	1,000	0.021
35	36.78	251.04	249.38	1.01	800	0.024
40	20.15	137.64	132.93	1.04	500	0.03
45	13.47	92.24	77.057	1.20	425	0.03
	D–He, *880 kv, 850 kv at* Au *foil* (*gold counts 904*)					
20	528.5	4569.0	4821.5	0.95	13,177	0.006
25	197.8	1741.9	1616.3	1.08	2,101	0.02
30	94.30	835.0	667.2	1.25	2,184	0.03
35	50.86	453.0	318.3	1.42	1,002	0.03
40	28.23	252.0	169.1	1.49	746	0.04
45	19.20	171.7	97.96	1.75	577	0.05
55	10.67	96.02	39.32	2.44	324	0.09
65	6.50	58.57	19.05	3.07	191	0.15
75	5.11	46.05	10.54	4.37	73	0.35
	D–He, *657 kv, 623 kv at* Au *foil* (*gold counts 1676*)					
20	510.0	8173.0	8680.8	0.94	7,986	0.01
25	182.4	2975.0	2910.1	1.02	2,774	0.01
30	71.2	1166.0	1201.2	0.97	1,440	0.02
35	37.49	617.1	573.1	1.08	804	0.03
40	22.97	380.6	304.5	1.25	515	0.04
45	14.40	239.4	176.4	1.36	200	0.07
55	7.89	131.6	70.78	1.86	116	0.11
65	3.93	65.5	34.31	1.91	57	0.19

unity at 20°. This anomaly for deuteron-deuteron scattering is of the type to be expected if there is present, in addition to the Coulomb interaction, a short range repulsive force between the deuterons. An additional repulsive force would give an increase in scattering even at small angles (15° to 30°), while an attractive force would give a reduction in scattering at small anlges due to a cancellation-effect between the Coulomb repulsive force and the assumed attractive force.

The results for the scattering of protons and deuterons in helium are summarized in Table II. We have given the number of scattered particles to be expected from the Rutherford-Darwin scattering formula; the ratio of the observed scattering to this calculated number has been plotted as a function of angle in Fig. 2. At 700 kv the proton scattering in helium from 20° to 45° was in agreement with the inverse-square law of scattering (curve and data not given). However, there appears to be a slight excess of scattering at 45° for 994-kv protons. This is probably a real effect.

The scattering of deuterons in helium was investigated at two energies, 657 and 880 kv, and for scattering angles up to 75°. Beyond this angle at 880 kv the range of the scattered deuterons is too small to count reliably in our detector; for 657 kv some of the scattered deuterons were missed at 65°. At 880 kv the scattering at 75° is 4.4 times the expected value from the inverse-square scattering law. The slope of these curves against angle is similar to those for deuteron-deuteron scattering, indicating that one also has an additional repulsive force entering here between the two particles.

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Nuclear Isomerism in Zinc

J. W. Kennedy, G. T. Seaborg and E. Segrè
Radiation Laboratory, Department of Physics, and Department of Chemistry, University of California, Berkeley, California
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Zn^{69} has two isomeric states differing by 0.47 Mev in energy. The upper state decays into the lower with a half-life of 13.8 hours, emitting a gamma-ray which has an internal conversion coefficient less than 0.1. The lower isomeric state decays to Ga^{69} with a half-life of 57 minutes. The most probable value for the spin difference between the isomeric states is five.

In a systematic study of the radioactive zinc isotopes, Livingood and Seaborg[1] found two beta-emitters, with half-lives of 13.8 hours and 57 minutes, respectively, both of which were assigned to Zn^{69}. These isomers were found to have very similar beta-spectra, but the 13.8-hour period was accompanied by gamma-radiation whereas no gamma-rays were associated with the 57-minute period. These results suggest at once that the 13.8-hour activity decays to Ga^{69} passing through the isomeric state of 57 minutes half-life. Since this case is fairly simple and experimentally accessible, we have investigated the situation in more detail.

The radioactivities were produced by the reaction Zn^{68} (d, p) Zn^{69} as the result of bombardment of zinc with about 50 microampere-hours of 8-Mev deuterons in the Berkeley cyclotron. The measurements were made upon chemically separated samples. The gallium and copper, primary transmutation products, were removed by ether extraction and with hydrogen sulfide in acid solution, respectively.[2] Zinc was precipitated last by the addition of sodium carbonate.

The measurements were made with an aluminum ionization chamber connected to a vacuum tube electrometer system. The chamber and its calibration have already been described.[3]

If the upper isomeric state decays by means of a gamma-ray with a life of 13.8 hours to a

[1] J. J. Livingood and G. T. Seaborg, Phys. Rev. **55**, 457 (1939).

[2] A. A. Noyes and W. C. Bray, *Qualitative Analysis for the Rare Elements* (Macmillan Company, 1927).

[3] W. Gentner and E. Segrè, Phys. Rev. **55**, 814 (1939); G. T. Seaborg and E. Segrè, Phys. Rev. **55**, 808 (1939).