The Disintegration of Li^7 by Deuterons

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The yield function for the disintegration of lithium bombarded by deuterons has been measured with detectors sensitive to neutrons, gamma-rays, and beta-rays. A gamma-ray of 4.9-Mev energy was found in the course of this investigation. Resonances were found at 0.65, 1.02, and 1.35 Mev corresponding to excited states of the intermediate nucleus (Be^9) at 17.14, 17.43, and 17.69 Mev. The resonance at 1.35 Mev was found only for the formation of radioactive Li^8 accompanied by the emission of a proton. Apparently proton emission is permitted and neutron emission forbidden from the 17.69-Mev state.

THE yield of Li^8, neutrons and alpha-particles from lithium bombarded by deuterons of energies up to 1 Mev has been measured by Rumbaugh, Roberts, and Hafstad.[1] Their excitation curves showed a smooth increase in yield with energy until energies of about 700 kev were reached. From 700 to 1000 kev their yield curves continued to increase but less rapidly than at lower energies. Later experiments[2] which were carried out at Rice Institute on the excitation curves of carbon bombarded by deuterons of energies up to 2.0 Mev showed a number of resonances with half-widths of from 10 kev to 100 kev. These experiments with carbon suggest that similar resonances might be found in the disintegration of lithium by deuterons and so a similar study was undertaken for lithium bombarded by deuterons; preliminary results of these experiments were reported at a meeting of the American Physical Society.[3,4]

APPARATUS

The Rice Institute pressure Van de Graaff machine was used to produce bombarding particles of homogeneous and variable energy. Thin targets of LiCl, LiOH, and metallic lithium were used. They were produced by evaporation from a tungsten filament onto a polished disk of pure silver or copper. The LiCl targets blackened rapidly during bombardment and the yield of neutrons increased with time as a result of the deposition of carbon. These targets were made thicker (50–100 kev) than the metallic lithium targets which were used later so that the carbon would have a relatively small effect. They were also moved frequently to bombard a new spot. The thickness of the targets was estimated from the amount of material evaporated, and also, somewhat more precisely, by comparing the yield from the thin target with that of a thick target of the same material. The latter calculation was possible after the yield function for the reaction was known. It also involved suitable correction for the range-energy relationship of the bombarding particles in the thick target. The thickness of the target was expressed in kev, meaning the average energy lost by a bombarding particle in passing through it.

The yields of beta- and gamma-rays were measured with Geiger counters filled with a self-quenching mixture of argon and alcohol. A scale of eight was used in the recording circuit. Coincidence counting was sometimes used, a bias being set to cut out pulses from one counter and record only the pulses of double size produced by simultaneous discharge of the two counters. To count gamma-rays, carbon blocks were used to absorb out the beta-radiation.

THE GAMMA-RAYS FROM Li^7+H^2

Only one gamma-ray (of 450-kev energy) has been reported[5] from the deuteron bombardment

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[1] L. H. Rumbaugh, R. B. Roberts, and L. R. Hafstad, Phys. Rev. **54**, 657 (1938).
[2] W. E. Bennett, T. W. Bonner, E. Hudspeth, H. T. Richards, and B. E. Watt, Phys. Rev. **59**, 781 (1941).
[3] W. E. Bennett and B. E. Watt, Phys. Rev. **60**, 167 (1941).
[4] T. W. Bonner and H. T. Richards, Phys. Rev. **60**, 167 (1941).
[5] J. H. Williams, W. G. Shepherd, and R. O. Haxby, Phys. Rev. **52**, 390 (1937).

of lithium. In the course of these experiments, a gamma-ray of higher energy was found.[6] Its energy was determined by inserting aluminum sheets between two coincidence counters and recording the coincidence counting rate as a function of the thickness of aluminum. The curve is given in Fig. 1. The maximum range of Compton electrons as estimated from this curve is 8.7±0.4 mm of aluminum. This corresponds to an energy of 4.9±0.3 Mev. The relation between

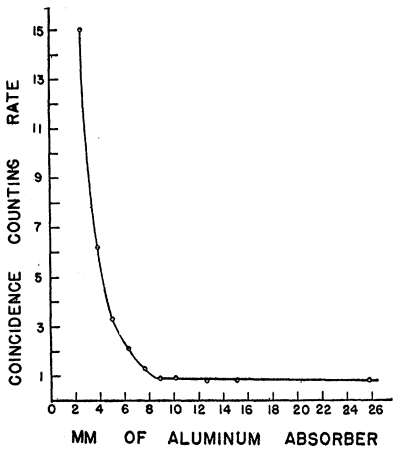

FIG. 1. The rate of coincidence counting as a function of the thickness of aluminum between counters. The end point at 8.7±0.4 mm implies an energy of 4.9±0.3 Mev for the gamma-rays from Li^7+H^2.

range and energy had previously been determined by measurements on gamma-rays of known energy with the same apparatus.[7]

It is very probable that the high energy gamma-ray is associated with a neutron group as indicated by the following equation:

$$_3Li^7+{}_1H^2\rightarrow{}^*_4Be^8+{}_0n^1+10.1 \text{ Mev},$$
$$^*_4Be^8\rightarrow{}_4Be^8+\gamma+4.9 \text{ Mev}.$$

The spectrum of neutrons from this reaction shows evidence of the associated neutron group. Both Stephens[8] and Richards[9] found a wide group of neutrons at about 10.5 Mev. This group is too wide and of too low energy to be entirely accounted for by the 2.8-Mev level in Be^8 which breaks up into two alpha-particles, but it may be regarded as consisting of two unresolved groups, one associated with the 2.8-Mev level and the other with a level at 4 or 5 Mev which emits gamma-rays because of a selection rule which forbids the break-up into alpha-particles. A similar level in Be^8 at 17.5 Mev is responsible for the high energy gamma-rays from Li^7 bombarded by protons.

To detect 4.9-Mev gamma-rays in the presence of 450-kev gamma-rays, coincidence counters were used, the wall thickness being sufficient to prevent detection of gamma-rays of less than 2-Mev energy. However, this procedure was found unnecessary and a single Geiger counter was used for the final data. The single counter was used to take a lead absorption curve under good geometrical conditions and the radiation seemed to be homogeneous. The 450-kev radiation was too feeble to give a noticeable effect under our conditions. The single Geiger counter did not respond appreciably to neutrons. A block of paraffin which reduced the neutron intensity to half, did not affect the counting rate in the Geiger counter. The neutrons produced radioactivity in the counter walls, but this was subtracted as part of the natural effect.

THE YIELD CURVE FOR GAMMA-RAYS AND NEUTRONS

The yield of gamma-rays and neutrons as a function of energy from 0.5 to 1.9 Mev is given in Fig. 2. The neutrons were observed in the forward direction. The scale of ordinates is arbitrary and different for the two curves. The absolute yield of gamma-quanta was roughly 3 percent of the yield of neutrons. This figure was arrived at by assuming that the Geiger counter was 2 percent efficient for counting gamma-rays and by using the data of Amaldi, Hafstad, and Tuve[10] for the yield of neutrons from a thick target.

The similarity of the gamma-ray and neutron curves shows that the same intermediate nucleus is involved. Since most of the neutrons are from bombardment of the Li^7 isotope, it is out of the

[6] W. E. Bennett, T. W. Bonner, H. T. Richards, and B. E. Watt, Phys. Rev. 59, 904 (1941).
[7] W. E. Bennett, T. W. Bonner, and Bob E. Watt, Phys. Rev. 59, 793 (1941).
[8] W. E. Stephens, Phys. Rev. 53, 223 (1938).
[9] H. T. Richards, Phys. Rev. 59, 796 (1941).
[10] E. Amaldi, L. R. Hafstad, and M. A. Tuve, Phys. Rev. 51, 896 (1937).

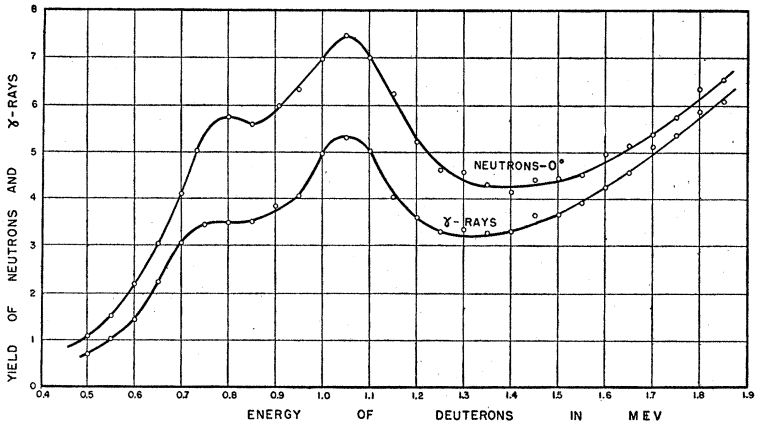

FIG. 2. Yields of neutrons and gamma-rays from "partially thin" targets of lithium bombarded by deuterons. The thickness of the targets was 55 kev for the gamma-ray curve and 90 kev for the neutron curve. The scale of ordinates is arbitrary and different for the two curves.

question that the gamma-rays might have been produced by bombardment of the Li^6 isotope.

THE YIELD CURVE FOR BETA-RAYS AND NEUTRONS

Coincidence Geiger counters were used to detect the beta-rays. The wall thickness discriminated against beta-rays of less than 2 Mev energy. The arrangement counted some gamma-rays. To see how many gamma-rays were counted, carbon absorbers were placed between the target and the counters to absorb out the beta-rays. Less than one percent of the counts remained after absorption of all the beta-rays from the target.

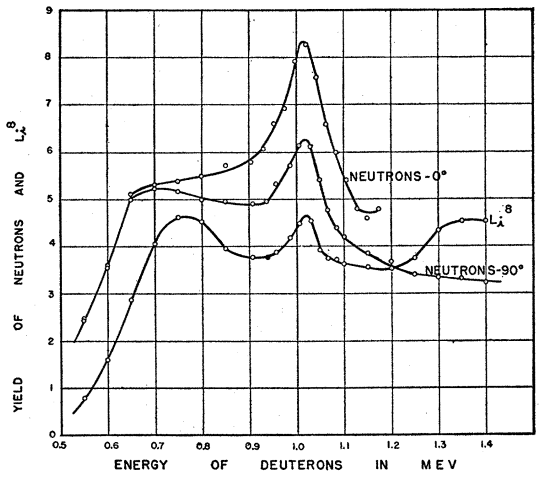

FIG. 3. Yields of neutrons and gamma-rays from "thin" lithium targets bombarded by deuterons. The yield is in arbitrary units, different for each curve. The neutron curves have been fitted at 0.55 Mev. The angular distribution of neutrons changes with bombarding energy.

The yield curves for beta-rays and neutrons were taken simultaneously. The methane-filled electroscope used to detect neutrons was placed at 90° to the bombarding beam. The beta-rays were detected in the forward direction. The target was made by evaporating lithium metal in vacuum, and its thickness was estimated from the yield to be 14 kev.

The excitation curves for beta-rays and for neutrons at 90° were run from 0.55 Mev to 1.4 Mev. They are shown in Fig. 3. Another curve was run with the neutron detector in the forward direction. This was normalized to agree with the 90° curve at 0.55 Mev and plotted in Fig. 3.

The neutron curve shows resonances at 0.65 and 1.02 Mev. The neutrons show a departure from a spherical symmetry which is different for the two resonances. If there is spherical symmetry for the first resonance, then the second resonance shows a marked maximum of neutron intensity in the forward direction. Further studies of the angular distribution of the neutrons from the reaction would be desirable.

For beta-rays, the first resonance appears to be at 0.75 Mev, about 0.1 Mev higher than the corresponding neutron resonance. It may, however, correspond to the same state of the intermediate nucleus. The beta-rays are produced in the reaction:

$$_3Li^7 + {}_1H^2 \rightarrow {}_3Li^8 + {}_1H^1 - 0.26 \text{ Mev},$$

$$_3Li^8 \rightarrow {}_4Be^8 + \beta.$$

The yield of beta-rays is equal to the yield of low energy protons. The protons must penetrate a potential barrier to escape and, therefore, the

yield of protons would be expected to differ from the yield of neutrons by a factor which increases with energy in the low energy region. This factor would shift a maximum in the yield curve toward higher energies. This shift does not occur for the second resonance at 1.02 Mev; but this second resonance is narrower and the proton is more energetic, so it is less affected by the potential barrier. This argument seems to be contradicted by the fact that the first resonance is stronger than the second for proton emission; however, other differences in the states of the intermediate nucleus may affect the strength of a resonance. A third resonance at 1.35 Mev in the beta-ray curve corresponds to a state of Be^9 for which neutron emission is forbidden or at least is much weaker than for the other resonances at 0.65 and 1.02 Mev.

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The Self-Diffusion Coefficient of Uranium Hexafluoride*

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A method is reported for measuring the self-diffusion coefficient of a vapor by observing with a mass spectrometer the rate at which material enriched in one isotope diffuses into normal material in an apparatus of known geometry. A value of ρD (where ρ is the density and D the diffusion constant) was obtained for uranium hexafluoride at 30°C. Knowledge of the viscosity together with the constants reported here allow calculation of the molecular force law.

IN the kinetic theory of transport phenomena ρD is a prominent factor whose value must be known. Heretofore its value has been determined from the coefficient of viscosity, η, on the basis of the equation $\rho D = \epsilon\eta$ where ϵ is at best an uncertain quantity. The following is a report of the measurement of ρD in which D is understood to be the diffusion coefficient for one gas diffusing into another where the only difference between the gases is their isotopic ratios.

This measurement represents an excellent approximation to the self-diffusion coefficient, which strictly speaking cannot be measured.[1] If one may speak of the self-diffusion of a gas whose molecules are composed of more than one isotope, one should probably define it as the diffusion of one gas in which the isotopes are in their normal ratio into another with normal ratio. The ideal experiment to measure this would consist of tagging one group of molecules differently from the other group in such a way that the tagging would not affect the phenomenon of diffusion. If uranium hexafluoride slightly enriched in U^{238} and uranium hexafluoride slightly enriched in U^{235} diffuse into each other exactly as normal uranium hexafluoride diffuses into normal then isotopic concentration is just such an ideal tag. As can easily be seen the measurement of the changing concentration of one isotope as the diffusion takes place gives directly the changing concentration of one group in the mixture of both groups of molecules.

I. DESCRIPTION OF APPARATUS AND PROCEDURE

The apparatus is shown schematically in Fig. 1. The diffusion bulbs F and B were two coaxial copper cylinders of volumes 925 and 259 cubic centimeters, respectively. They were connected by the copper pipes C (length 6.80 cm; area

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[1] Rigorously the self-diffusion coefficient can be defined only for a gas composed of identical molecules, e.g., all $U^{238}F_6$ or all $U^{235}F_6$.