Formation of an Excited He^3 in the Disintegration of Deuterium by Deuterons

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The energy distribution of the neutrons from the reaction $H^2+H^2\rightarrow He^3+n^1+Q_1$ has been studied. Two homogeneous neutron groups with energies of 1.08 and 2.50 Mev have been observed at 90° to the 0.11 Mev deuterons. The emission of 1.08 Mev neutrons has been found to be approximately 1/10 as likely as the emission of 2.50 Mev neutrons. The corresponding values of Q_1 are $Q_1{}^0=3.29\pm0.08$ Mev and $Q_1{}^1=1.40\pm0.11$ Mev. The low energy group results when the He^3 is left excited to a level of 1.89 ± 0.11 Mev. The mass of He^3 has been calculated from the value of $Q_1{}^0$ and the mass-spectrographic value of $H^2=2.01473$. The result is He^3 3.01700. This result indicates that H^3 may spontaneously disintegrate into He^3 with the emission of an electron.

THE neutrons produced in the disintegration of deuterium by deuterons were at first thought to be monoenergetic. This was concluded on the basis of the experiments of Dee[1] and those of Bonner and Brubaker.[2] These experiments indicated that at least most of the neutrons had an energy of about 2.5 Mev. Later experiments by the writer,[3] undertaken primarily to study neutron-proton scattering, gave a first indication that there probably was a second lower energy group with considerably less intensity than the high energy group. The purpose of the present experiments was to investigate carefully the neutrons from the reaction:

$$H^2+H^2\rightarrow He^3+n^1+Q_1. \tag{1}$$

A search was made for low energy neutrons and particular care was taken to determine Q_1 as accurately as possible. A precise value of Q_1 is important because it is from this reaction that the mass of He^3 is best determined. The exact masses of He^3 and H^3 are particularly important as they each are made up of three fundamental particles (neutrons and protons). From their masses the relative magnitude of neutron-neutron forces and proton-proton forces may be deduced.

Experimental Procedure

The accelerating tube and d.c. source of potential were the same as that previously described.[3] The neutron energies were determined from the ranges of the recoil protons which were observed in a cloud chamber. The cloud chamber was 17 cm in diameter and 4.8 cm deep. It was constructed from as small an amount of material as possible in order to reduce neutron scattering to a minimum. The chamber was of the rubber diaphragm type, thus eliminating the material otherwise used in a piston. The chamber proper was made of a Pyrex glass ring which was 3 mm thick. The plate glass top had a thickness of 3 mm and the brass bottom plate a thickness of 1 mm. The cloud chamber was connected to the operating mechanism, an electromagnetic air valve, by a brass tube which was 2.5 cm in diameter and 90 cm long. With this arrangement only about 5 percent of the neutrons which pass through the cloud chamber make collisions before entering the chamber. This reduction in the number of scattered neutrons reduces the low energy tail or background which is ordinarily found on neutron energy distribution curves.[2] Consequently the experimental arrangement described above is well adapted for observing neutron groups of low intensity which are present along with higher energy neutrons.

The nearest edge of the cloud chamber was placed at a distance of 13 cm from the ion spot on the target. The neutrons which entered the cloud chamber made an angle of $90\pm11°$ to the direction of the deuterons on the target. The target was a 1 mm layer of D_3PO_4 at the bottom of a thin walled brass cup. Under these experimental conditions very few neutrons were scattered by the target or target holder.

The cloud chamber was filled with a mixture of 85 percent CH_4 and 15 percent C_2H_6 with

[1] P. I. Dee, Proc. Roy. Soc. **A148**, 623 (1935).
[2] Bonner and Brubaker, Phys. Rev. **49**, 19 (1936).
[3] T. W. Bonner, Phys. Rev. **52**, 685 (1937).

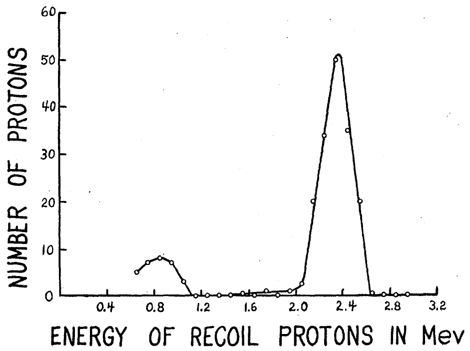

FIG. 1. The differential energy distribution curve of the recoil protons in the forward direction.

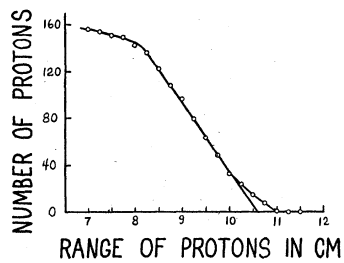

FIG. 2. The integral range number curve for long range recoil protons in the forward direction.

alcohol vapor. The expanded pressure in the chamber was slightly larger than atmospheric. The stopping power of the gas was found by measuring the mean length of polonium alpha-particles in the chamber. The stopping power for alpha-particles of range 3.805 cm was 1.07. This gas mixture has an appreciably different stopping power for polonium alpha-particles than for the highest energy protons which were observed. The stopping power for 10 cm protons was calculated from the data of Livingston and Bethe[4] and is 1.03.

Experimental Results

Sixty-eight hundred pairs of stereoscopic pictures were taken of the cloud chamber when the deuterium target was bombarded with 0.11 Mev deuterons. On these photographs roughly 4000 recoil protons were observed and 205 of these were projected within the angular cone of 0–10° to the neutron's direction. The track lengths of these 205 acceptable tracks were measured and their ranges computed from the calculated stopping power of the gas in the chamber. Their energies were then computed from the range energy curve of Bethe and Livingston.[5] Fig. 1 shows the energy distribution of the recoil protons. There appear to be two definite proton groups with energies of about 1.1 and 2.6 Mev. These correspond to two neutron groups of very nearly the proton energies. The lower energy group has roughly 1/10 the intensity of the higher energy group. This ratio is complicated by the differing probability of observing tracks of different lengths in the cloud chamber and the varying cross section for neutron-proton collisions.

A more accurate maximum energy of the neutrons was obtained from the integral range number curve of Fig. 2. The extrapolated range was 10.60 ± 0.30 cm. The calculation of the neutron disintegration energies was carried out by the method of Livingston and Bethe.[4] The experimental conditions correspond to their case of "good geometry." In their symbols, the range straggling s for 10.5 cm protons is 2.2 percent. The angular straggling γ/R was 4.55 percent and the total straggling s'' was 5.09 percent. For the thick target correction, β was calculated to be 11.9 and hence $x_{\mathrm{ex\,tr}}=0.95$. Consequently the difference between extrapolated and mean range is $0.95\cdot 5.09\cdot 10.60/100=0.51$ cm. It follows that the mean range is 10.09 cm. This corresponds to a proton energy of 2.46 Mev. The correction for using recoils which made angles of 0–10° to the direction of the neutron is $\frac{1}{2}E_2\chi_0^2=2.5/2\cdot 0.00306=0.04$ Mev. Therefore the energy of the neutrons coming from the top layer of the target at 90° is 2.50 ± 0.05 Mev. The disintegration energy is then calculated from the relation $Q_1=(4/3)En-(1/3)E_H$. The value of Q_1^0 is 3.29 ± 0.08 Mev. The corresponding value of Q_1^1, calculated from the low energy proton group, is 1.40 ± 0.11 Mev.

Discussion of Results

The low energy neutron group corresponds to an excitation level in He^3 at 1.89 ± 0.11 Mev above the ground level. One should expect to find a gamma-ray with this energy with an intensity of about 1/10 that of the neutrons. In the experiments described above some high energy electron tracks were observed in the cloud chamber which probably were produced

[4] Livingston and Bethe, Rev. Mod. Phys. 9, 275 (1937).
[5] Bethe and Livingston, private communication.

by these gamma-rays. However their quantum energy must be determined before the correlation is made certain.

In view of the excitation level in He^3 at 1.89 Mev it seems reasonable to expect a similar level in H^3 of approximately the same energy of excitation. This follows since the level in He^3 should differ from that in H^3 only by the perturbation caused by the Coulomb field of the extra proton. This level in H^3 should be observed as a second lower energy group of protons from the reaction

$$H^2+H^2\rightarrow H^3+H^1+Q_2. \quad (2)$$

One should expect a second proton group with a range of perhaps 5 cm. A careful search for such a group is planned, particularly since the results of Oliphant, Harteck and Rutherford[6] give some indication of such low energy protons.

The mass of He^3 can be most accurately found from the disintegration energy $Q_1{}^0$ together with Bainbridge and Jordan's spectrographic mass of $H^2=2.01473$ and a neutron mass[7] of 1.00893. The calculated mass of He^3 is 3.01700 ± 0.00010. Since the mass of H^3 is 3.01705, this indicates that H^3 may be unstable, disintegrating with a long half-life according to the reaction:

$$H^3\rightarrow He^3+e^-. \quad (3)$$

This predicted instability of H^3 is consistent with the failure of recent attempts to concentrate H^3 from large samples of heavy water.[8]

The value of $Q_2{}^0-Q_1{}^0$ is just the difference between the binding energies of He^3 and H^3. For the value of $Q_1{}^0$ found above, this difference becomes $3.98-3.29=0.69$ Mev. Since the calculated value[9] of the Coulomb repulsion between the two protons in He^3 is very nearly equal to the experimental difference of 0.69 Mev, this shows that neutron-neutron forces must be very nearly equal to proton-proton forces.

[6] Oliphant, Harteck and Rutherford, Proc. Roy. Soc. **A144** 695 (1934).

[7] H. A. Bethe, Phys. Rev. **53**, 313 (1938).

[8] Lord Rutherford, Nature **140**, 303 (1937).

[9] Bethe and Bacher, Rev. Mod. Phys. **8**, 82 (1936); Share, Phys. Rev. **50**, 488 (1936); Rarita and Present, Phys. Rev. **51**, 788 (1937).

MAY 1, 1938 PHYSICAL REVIEW VOLUME 53

The Energy-Range Relations for Deuterons, Protons and Alpha-Particles

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The complete deuteron, proton and α-particle energy-range relations as given by Livingston and Bethe and as subsequently revised by Bethe to include the latest data, are presented as a set of eleven equations. Given the range of a known particle, the corresponding kinetic energy of the particle can be computed easily and quickly from these equations.

In 1937 Livingston and Bethe[1] published a very extensive set of kinetic energy *vs.* range relations for deuterons, protons and α-particles. These relations were in the form of graphs, in which the particle energies were plotted as functions of particle ranges. Later in 1937 these graphical energy-range relations were revised[2] to include the recent data of Parkinson, Herb, Bellamy and Hudson[3] on proton ranges and of Blewett and Blewett[2] on α-particle ranges. Now, to provide these latest revised energy-range relations in a complete and compact form suitable for the easy and rapid computation of energies, we present the following.

Let r be the mean range in cm of a particle in air at a temperature of 15°C and at a pressure of 760 mm Hg; let V be the corresponding energy of the particle expressed in millions of electron volts. Let the subscripts D, P, and α refer the symbols to which they are affixed to deuterons, protons and α-particles respectively. Then, given a value of r_D, r_P, or r_α (by observa-

[1] Livingston and Bethe, Rev. Mod. Phys. **9**, 266–269 (1937).

[2] See Bethe, Phys. Rev. **53**, 313 (1938).

[3] Parkinson, Herb, Bellamy and Hudson, Phys. Rev. **52**, 75 (1937).