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Neutrons From $C^{12}+D$*

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Recoil protons in a cloud chamber have been used to measure the energy spectrum of the neutrons from $C^{12}+H^2$. The neutrons are found to be monochromatic when produced by 2-Mev deuterons. An accurate Q value of -0.27 ± 0.02 Mev is computed from the range of the recoil protons. This Q value gives a mass of 13.00988 ± 0.00004 for N^{13}.

INTRODUCTION

THE neutrons from carbon bombarded by deuterons have been used as a monochromatic source of fast neutrons of variable energy. In the present experiment the energy spectrum of these neutrons has been measured to determine whether or not the neutrons from C^{12} are in fact monochromatic.

EXPERIMENTAL ARRANGEMENT

A thin carbon target was prepared by depositing camphor black on a silver disk. Its thickness was determined by weighing and by comparing the yield of neutrons from it with the yield from a thick graphite target, using the known excitation curve[1] for the reaction to effect the comparison. Its thickness was found to be 75 kev for deuterons of two million volts.

The target was bombarded with 2.00-Mev deuterons from The Rice Institute pressure electrostatic generator. The energy of the neutrons in the forward direction was measured by stereoscopically photographing the recoil protons in a cloud chamber filled to half an atmosphere with methane and 95 percent ethyl alcohol. The cloud chamber was 25 cm in diameter, and its near side was 12 cm from the source of neutrons. Tracks in a strip 8 cm wide from front to rear of the chamber could be measured.

RESULTS

The lengths of tracks of recoil protons in the cloud chamber were measured when the direction of the track was within 15° of the line drawn from the source of neutrons. Tracks as short as one centimeter in length could be measured reliably. The lengths were converted to lengths in standard air using (a) the pressure of gas in the cloud chamber when expanded as measured on a Bourdon gauge, (b) the vapor pressure of 95 percent alcohol and water as given in the International Critical Tables, and (c) the atomic stopping powers of the gases in the cloud chamber as given by Livingston and Bethe.[2] Account was taken of the fact that the methane is

* This work was done in June 1942 under OSRD contract.
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[1] T. W. Bonner, E. Hudspeth, and W. E. Bennett, Phys. Rev. 58, 185 (1940).
[2] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 274 (1937).

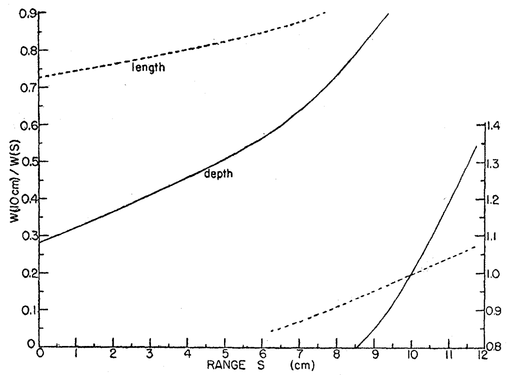

FIG. 1. Geometry corrections. The dotted curve is the correction for the finite length of the cloud chamber while the solid curve is for the finite depth of the illuminated portion of the chamber. S is the observed range in the cloud chamber.

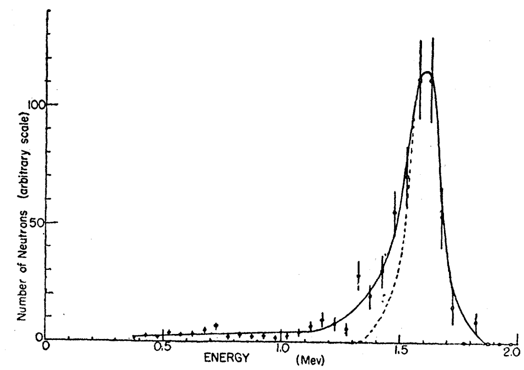

FIG. 2. The energy spectrum of neutrons from a thin target of carbon bombarded by 2.0-Mev deuterons. A methane filled cloud chamber at 0° to the deuteron beam was used for energy measurement.

actually natural gas and is 13 percent ethane. This was checked by determining the density of the gas from the methane cylinder.

Track lengths were converted to neutron energies using the Cornell range-energy curve for protons. The numbers of tracks in each energy interval of 0.05 Mev were counted. These numbers were corrected for the variation with energy of the cross section for neutron-proton scattering and also for geometrical factors which made more probable the measurement of short tracks than of long ones.

Longer recoil protons have smaller probability of being measured because they leave the chamber at the distant wall or at the top and bottom of the illuminated space. (If they left the side of the stereoscopic space they could still be measured on one of the stereoscopic photographs.) Hence, two geometrical corrections were required. The first, for the finite length of the chamber, is

$$W_L=(1/L_0)-1/(L_0+\lambda-S), \quad (1)$$

where W_L is the probability of observing a track of length S in the rectangular illuminated area of a cloud chamber of diameter λ. L_0 is the distance from the source to the chamber and S is the range in the chamber of the recoil proton. The correction for the finite depth of the chamber is of the simple form

$$W_d=1-4S\sin\theta_0/3\pi d \quad (2)$$

if the source is infinitely distant from the chamber. θ_0 is the maximum angle that the recoil proton can make with the neutron and still be acceptable for measurement; d is the depth of the illuminated portion of the chamber. However, if the neutron source is not infinitely distant, use of the above expression discriminates against the longer tracks. The correct expression for W_d when the neutron source is at a finite distance from the chamber may be obtained in a manner similar to that used in deriving the above expression;[3] however, the resulting expression is then rather involved and was actually solved numerically for only five different track lengths. A smooth curve was drawn through these five values and the resulting correction curve (normalized to one for a 10 cm track) is plotted on Fig. 1.

The final energy spectrum of neutrons from $C^{12}+D$ is shown in Fig. 2. For comparison, the dotted curve shows the width of a group of monochromatic neutrons, the straggling being caused by (a) the thickness of the target, (b) the fluctuations in voltage of the Van de Graaff machine, (c) the angular straggling of the neutrons which could reach the cloud chamber, (d) the angular straggling of the protons, which were measured out to 15°, and (e) the range straggling. The asymmetry on the low energy side of the group is probably to be attributed to small angle elastic scattering of neutrons in the wall and roof of the cloud chamber on the side toward

[3] H. T. Richards, Phys. Rev. 59, 796 (1941). The expression derived in this reference is for a different geometry than used in the present cloud-chamber measurements.

the neutron source. The wall was one-quarter inch of iron and the roof was one inch of glass.

The constant background at low energies probably represents scattering by the walls of the room rather than slow neutrons from the source. A blank run was taken with no carbon on the silver disk and the number of neutrons observed was negligible. Therefore, not more than a few percent of the neutrons observed could have been produced by the molecular beam in the analyzer.

The graph shows that the mean energy of the neutron group is 1.60 Mev. This becomes 1.65 Mev when corrected because recoil protons were measured out to 15°. The mean deuteron energy in the target was 1.96 Mev. This gives an energy evolution of $Q=-0.27\pm 0.02$ Mev in the reaction.

CONCLUSIONS

The neutrons from carbon bombarded by deuterons are monochromatic, except for the high energy neutrons from C^{13}, when produced at 2 Mev; and are therefore likely to be monochromatic when produced at lower bombarding voltages.

The Q of the reaction is -0.27 ± 0.02 Mev. This value is believed to be more accurate than previous determinations.[4] This Q value gives a mass of 13.00988 ± 0.00004 for N^{13}.

[4] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **154**, 261 (1936). $Q\geq -0.28$ Mev (from theshold of reaction).
T. W. Bonner, Phys. Rev. **53**, 496 (1938). $Q=-0.25\pm 0.05$ Mev (from recoil protons in cloud chamber).
W. E. Bennett, T. W. Bonner, E. Hudspeth, H. T. Richards, and B. E. Watt, Phys. Rev. **59**, 781 (1941). $Q=-0.19\pm 0.05$ Mev (from recoil protons in cloud chamber).

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On the Neutron-Proton Scattering Cross Section

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The sensitivity of the theoretical neutron-proton scattering cross section to possible variations in the quantities defining the potential has been investigated in the energy range from 0 to 6 Mev. It is found that in this energy range the variations in exchange or tensor character and range of the potential which are consistent with what is known about the interaction do not result in so large a modification of the predicted cross section as do variations in shape.

A well resembling a Yukawa potential ($A\exp(-\alpha r)/r$) is found to yield a cross section at 6 Mev which is 10 percent lower than that given by a square well fitted to the epithermal neutron cross section and the binding energy of the deuteron. The Yukawa well is in better agreement with experiment than is the square well. One of the constants entering into the determination of the potential is the epithermal neutron scattering cross section in hydrogen. We have determined this by extrapolating the data of Frisch with the aid of the theory, and obtained a value of 20.8×10^{-24} cm^2.

INTRODUCTION

CURRENT nuclear theories attempt to correlate all known facts about nuclear scattering and nuclear binding by means of the assumption that these phenomena are caused by a potential energy of interaction between the fundamental particles. Unfortunately, the present data are too meager and too crude to permit the determination of this potential in any but the most schematic way. As a result, it is desirable to find out how critically the predictions for experimental results depend on each of the many parameters needed to specify the potential, and thus to indicate the range and accuracy of experiments needed to determine any feature of the potential within the limits desired.

In this paper, the neutron-proton scattering cross section is investigated in the energy range

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