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The Neutrons from the Disintegration of C^{13} by Deuterons*

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Nuclear energy levels in N^{14} are calculated from Q-values of neutron groups in the reaction $C^{13}(D,n)N^{14}$. Levels occur at 2.19±0.07, 3.47±0.07, 3.87±0.07, and 4.90±0.07 Mev. From a comparison with results of other measurements, it appears that several different nuclear reactions excite the same levels in N^{14}.

I. INTRODUCTION

THE neutrons from deuterons on carbon were investigated by Bonner and Brubaker[1] who irradiated the unseparated isotopes of carbon with deuterons of energy 0.9 Mev. The nuclear reactions are

$$C^{12}+D\rightarrow N^{13}+n^1+Q_1, \quad (1)$$

$$C^{13}+D\rightarrow N^{14}+n^1+Q_2$$
$$\rightarrow {}^*N^{14}+n^1+{}^*Q_2. \quad (2)$$

They measured the energies of the neutrons by noting the ranges of the recoil protons in a cloud chamber. These early measurements gave a value of -0.37 ± 0.05 Mev for Q_1, and 5.2 ± 0.4 Mev for Q_2. A group of neutrons was also noted at ${}^*Q_2=1.2$ Mev. Using the method of cloud-chamber recoils and a target of C^{13} having an isotopic concentration of 23 percent, an additional value of ${}^*Q_2$ was found at 0.40 Mev by the Rice group.[2]

Bennett and Richards[3] have shown that for bombarding energies of 2 Mev or less, the neutrons of reaction (1) are monochromatic. The Q-value for reaction (1) has recently been redetermined very accurately[4] at -0.281 ± 0.003 Mev. Since the neutrons of reaction (1) are endothermic in character, the exothermic neutrons of reaction (2) can be observed without ambiguity, regardless of the concentration of C^{12} in the target. Naturally occurring carbon is 99 percent C^{12}. In the present experiments, the isotopic concentration of C^{13} was 53 percent in $BaCO_3$ obtained from the Research Laboratory of the Eastman Kodak Company, Rochester, New York. Targets of $BaCO_3$, having a thickness of 100 kev at the bombarding energy employed, were obtained by preparing suspensions of $BaCO_3$ by mixing 100 mg of $BaCO_3$ with 1 cc of H_2O. A suspension of fine particles, obtained by allowing the original suspension to settle for 30 sec., was transferred with a pipette to a silver disk. The water was evaporated slowly under an infra-red heating lamp, leaving on the disk a smooth uniform film of $BaCO_3$. Occasional agitation of the evaporating suspension aided in producing a uniform deposition of the solid.

Recoil protons of the neutrons located in reactions (1) and (2) were detected in Ilford C_2 plates located at distances of 2 to 10 cm from the target and making angles of zero and 90 degrees with the bombarding beam in the laboratory system of coordinate axes. Recoils making angles within 12° of the forward direction were deemed acceptable, and the track lengths were measured in a microscope. The observed neutron energies were increased by two percent to allow for the use of the finite angle of acceptance. Suitable corrections were also made for variation with energy of the $n-p$ scattering cross section and acceptance probability.

II. THE NEUTRON SPECTRA

In the first exposure, photographic plates were located at zero degrees with the bombarding beam, the edges of the plates being a distance of 10 cm from the target. After an exposure of 7 μa-hr. at a mean bombarding energy of 1.43 Mev, the spectrum of Fig. 1 was obtained. Groups appear at neutron energies of 0.95, 1.65, 2.64, 3.04, and 6.42 Mev. The group at 0.95 Mev is assigned to $C^{12}(D,n)N^{13}$ whereas the one at 1.65 Mev arises from $C^{13}(D,n)N^{14}$ and was previously said[3] to have a Q-value of 0.40 Mev. The Q-value calculated from the present data is 0.27 ± 0.05 Mev.

In order to locate more precisely the groups of high energy, measurements were continued with the acceptance of only those tracks corresponding to energies

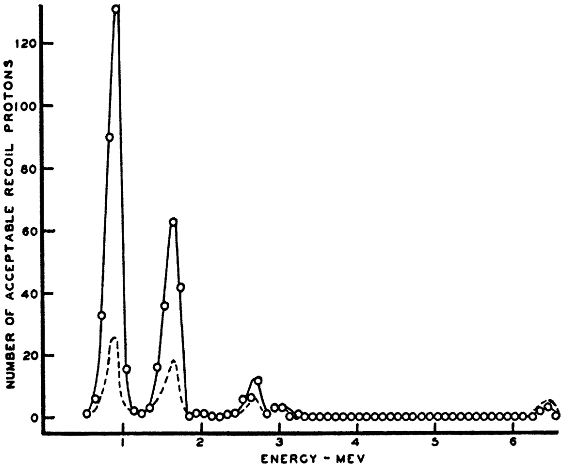

FIG. 1. Distribution in energy of the recoil protons knocked on by neutrons from $C^{13}(D,n)N^{14}$. Observations were made at an angle of zero degrees with the incident deuterons. Correction of the distribution for variation with energy of $n-p$ scattering cross section and acceptance probability is given by the broken line. The bombarding energy was 1.43 Mev.

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[3] W. E. Bennett and H. T. Richards, Phys. Rev. **71**, 565 (1947).

[4] Bonner, Evans, and Hill, Phys. Rev. **75**, 1398 (1949).

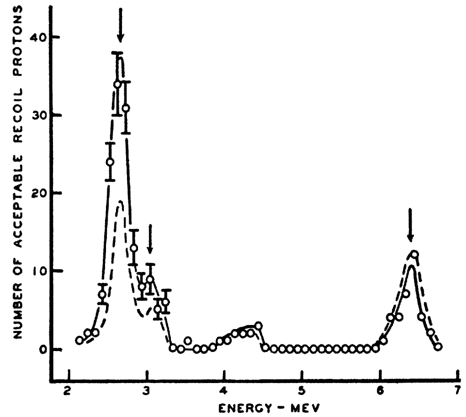

FIG. 2. High energy neutrons emitted in the forward direction from the disintegration of C^{13} by deuterons. The Q-values of the groups indicated by arrows are 1.30±0.05, 1.70±0.05, and 5.17 ±0.05 Mev. A group of low intensity also is present, though poorly defined, between neutron energies of 4 and 5 Mev.

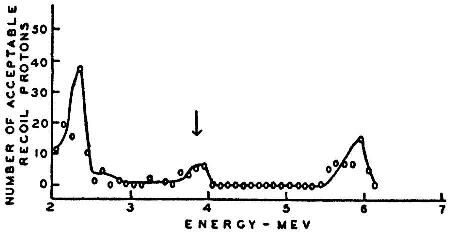

FIG. 3. Neutrons from $C^{13}(D,n)N^{14}$ emitted at 90° with the incident deuterons of energy 1.43 Mev. A neutron group at an observed energy of 3.85 Mev ($^*Q_2=2.98\pm0.05$ Mev) is clearly present.

greater than 2 Mev. When these newly observed tracks were combined with those of energy in excess of 2 Mev in Fig. 1, the energy distribution of Fig. 2 resulted. The observed energies of the neutron groups denoted by arrows are 2.68, 3.06, and 6.42 Mev, corresponding to Q-values[5] of 1.30±0.05, 1.70±0.05, and 5.17±0.05 Mev. A poorly defined group of neutrons appears to be centered at about 4.3 Mev. However, only ten tracks are included in the group, although 2.5 cm^2 of surface area of photographic plate were surveyed. The weak group also appears near the energy where any deuteron-deuterium contamination might be found.

In order to determine more precisely the nature of the group of particles, near 4 Mev, a second exposure was carried out at 1.43 Mev with photographic plates at 90° with the bombarding beam and within 2 cm of the target. At this angle, the neutrons in question appeared with considerable intensity relative to the remaining groups. Their observed position in energy, 3.85 Mev, is such as to suggest that they cannot result from deuterium contamination of the target. The position of neutrons from the deuteron-deuterium reaction would have shifted from 4.66 Mev in the forward direction to 2.83 Mev at 90° with the incident deuterons. The deuteron-deuterium reaction has never been observed to contaminate any experiment at Bartol, but the low intensity of the group made it necessary to verify the assignment to $C^{13}(D,n){}^*N^{14}$ by noting the change of energy with angle. The Q-value of this group of neutrons, calculated from its position in Fig. 3 is 2.98±0.05 Mev.

III. DISCUSSION OF RESULTS

The groups of neutrons observed in these measurements establish energy levels in N^{14} at 2.19±0.07, 3.47±0.07, 3.87±0.07, and 4.90±0.07 Mev. Thomas and Lauritsen[6] have reported gamma-rays having energies of 6.1, 5.7, 5.1, 3.9, 3.4, 2.3, 1.6, and 0.73 resulting from deuterons on C^{13}. Many of these quanta can be accounted for by transitions between the levels of N^{14} reported in this paper. However, some of the gamma-rays may be related to the reactions

$$\begin{aligned} C^{13}+D&\rightarrow C^{14}+H^1+Q_3\\ &\rightarrow {}^*C^{14}+H^1+{}^*Q_3, \end{aligned}\qquad (3)$$

$$C^{13}+D\rightarrow B^{11}+He^4+Q_4. \qquad (4)$$

For reaction (3), values of $Q_3=5.91\pm0.03$ Mev and $^*Q_3=0.32\pm0.03$ have been reported.[7] No excited states of B^{11} have as yet been observed in reaction (4). Sherr, Muether, and White[8] have reported gamma-rays of energy 2.3±0.2 Mev emitted in de-excitation of N^{14}, formed in the radioactive decay of O^{14}. This level at 2.3 Mev compares favorably with the value 2.19 Mev obtained in these neutron measurements. Fowler, Lauritsen, and Lauritsen[9] report gamma-ray energies of 8.1, 5.8, and 2.3 Mev emitted in the reaction $C^{13}(p,\gamma){}^*N^{14}$. Here again, the 2.3-Mev gamma-ray may result from de-excitation of the level observed in the present measurements.

Stuhlinger[10] has found energy levels in N^{14} at 4.0, 4.8, 5.4, 6.1, and 6.6 Mev in the reaction $B^{11}(d,N^1)N^{14}$. Alburger[11] has reported gamma-rays of energy 4.0 Mev and 2.3 Mev from the reaction $O^{16}(d,\alpha)N^{14}$.

Although uncertainties of several percent are associated with all of the quoted values, the frequent recurrence of at least some levels (e.g., the excited state at ~2.3 Mev), makes it seem reasonable to assume that the different methods of excitation do lead to the same excited levels of N^{14}.

The writers wish to express appreciation to Dr. Edward Shapiro for having prepared the thin targets of $BaCO_3$, and to acknowledge the continued interest of Dr. W. F. G. Swann, Director of Bartol.

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[5] The group at $^*Q_2=1.70$ Mev appears as a satellite relative to the more intense one at $^*Q_2=1.30$ Mev. Although its presence might be difficult to justify on considering the statistical probable errors of the points, the breadth of the two groups at the base is too great to assign to a single group. This interpretation is strengthened by the fact that the satellite is located on the high energy side of the principal group. Had it appeared on the low energy side, it might easily have been explained by scattering of the more energetic particles.

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[10] E. Stuhlinger, Zeits. f. Physik **114**, 185 (1939).

[11] D. E. Alburger, Phys. Rev. **75**, 51 (1949).