changes in the value of the equivalent square well range.

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An Accurate Determination of the Threshold for the Nuclear Reaction $C^{12}(d,n)N^{13}$

T. W. Bonner, J. E. Evans,* and J. E. Hill**
The Rice Institute, Houston, Texas

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The threshold for the production of neutrons from the bombardment of C^{12} by deuterons was found to occur at a bombarding energy of 328 kev. The Q value of the reaction calculated from this threshold is -0.281 ± 0.003 Mev. From this Q value and other disintegration energies, the calculated mass difference between the neutron and proton $(n-H)$ is 0.77 Mev.

INTRODUCTION

When carbon is bombarded by deuterons, neutrons and radioactive N^{13} are formed according to the following reactions:

$$C^{12}+H^2\rightarrow N^{13}+n+Q_1, \qquad (1)$$

$$N^{13}\rightarrow C^{13}+e^++Q_2. \qquad (2)$$

The value of Q_1 has been reported by Bonner and Brubaker,[1] Cockcroft and Lewis,[2] and by Bennett and Richards.[3] The experimental values of Q_1 vary from -0.25 to -0.28 Mev. Several determinations of the maximum energy of the positrons from N^{13} have been made.[4] Probably the most accurate determinations[5] of this energy are those of Lyman who obtained an end-point energy of 1.198 ± 0.006 Mev, and Siegbahn and Slatis who found an end-point energy of 1.24 ± 0.02 Mev.

A precise determination of the value of Q_1 from the threshold energy of the reaction is important so that the mass difference between the neutron and proton $(n-H)$ may be calculated by combining the values of Q_1, Q_2, and the energy release Q_3, in the following reaction:

$$C^{12}+H^2\rightarrow C^{13}+H^1+Q_3. \qquad (3)$$

If the mass difference $(n-H)$ is accurately obtained by other methods, then the rest mass of the neutrino may be obtained from precise values of Q_1, Q_2, and Q_3. The absolute yield of neutrons near the threshold is of interest since this reaction can be used as a source of monoenergetic neutrons to supplement the reactions $Li(p,n)Be^7$ and $H^2(d,n)He^3$. To get the number of neutrons per incident deuteron, positrons from N^{13} were counted, since there are an equal number of neutrons and N^{13} atoms formed. This method of counting the neutrons indirectly has the advantage that Geiger counters have nearly 100 percent efficiencies for the positrons and also the positrons are emitted with spherical symmetry in contrast to the neutrons which are asymmetrical about the direction of the deuteron beam.

APPARATUS

The Rice Institute Van de Graaff generator was used as a source of deuterons. The slit width of the magnetic analyzer was adjusted so that deuterons with an energy spread of 1 kev could pass through the slits and strike the carbon target. This opening of the slits was three times as large as previously described;[6] this arrangement was used in order to get nearly all the deuteron beam through the slit. However, from visual observation of the fluorescence of the deuteron beam striking a Pyrex plate, it was estimated that more than 90 percent of the deuterons which hit the target were within an energy interval of 300 volts at the threshold energy.

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* Now at Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

** Clinton National Laboratory, Oak Ridge, Tennessee.

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The carbon target was made by evaporation of ceresin wax onto a silver disk, 0.0045 inch in thickness. Since the target had been used in a previous experiment, the thickness of the target was determined at the end of this experiment by comparing the relative number of gamma-rays obtained under deuteron bombardment with a newly evaporated target, which was weighed on a microbalance. The calculated weight of the ceresin target was 45 micrograms per cm^2. Its original weight at the time of evaporation about six months earlier was 56 micrograms per cm^2.

A thin-walled Geiger counter, 60 mm long and 18 mm in diameter with a wall thickness of 0.15 mm of glass, was placed as close to the carbon target as possible. The counter was mounted inside a thin copper tube which had a window covered with an aluminum foil of thickness 0.0005 inch. The positrons had to pass through a total thickness of 0.163 g/cm^2 of material to go from the carbon target into the counter. About half of the positrons were transmitted through this amount of material. Lead absorbers 4 cm thick were placed around the counter in order to reduce the background.

PROCEDURE

Bombardment of the target was carried out in the following manner. At the moment the beam was brought on the target, the electrical clock and current integrator were started. The target was bombarded for 1200 sec., that is, for two half-lives. The reading of the current integrator was taken every 100 seconds to see that the bombarding current remained reasonably constant throughout the run. After 1200 seconds, the voltage of the statitron was turned off, and the reading on the Geiger tube was recorded. A scale of 64 was used but readings were taken to the individual count by means of the interpolation lights. The number of counts over the half-life following bombardment were used to determine the relative numbers of N^{13} atoms which are formed. On some of the runs the

TABLE I. Relative yield of N^{13}.

Magnet current in amperes	Energy of deuterons in kev	Number of counts in 10 minutes	Background, including residual activity in 10 minutes	Saturation activity per 5000 integrator counts	Relative yield of N^{13} (above 370-kev cross section in barns)*
2.200	323	246 (May 31)	243	0.2	3.0×10^{-7}
2.220	329	223 (May 28) 265 (May 31)	239 243	−0.9 1.3	3.0×10^{-7}
2.230	332	292 (May 28) 339 (May 31)	239 243	2.6 5.0	6.0×10^{-6}
2.240	335	410 (May 28) 435 (May 31)	239 243	8.5 9.7	1.43×10^{-5}
2.250	338	554 (May 28) 632 (May 31)	242 243	14.3 17.9	2.53×10^{-5}
2.260	341	699 (May 28) 742 (May 31)	244 245	21.1 23.1	3.47×10^{-5}
2.300	353	1020 (May 29) 918 (May 29) 1008 (May 31)	289 247 260	63.2 67.9 60.7	9.80×10^{-5}
2.350	369	1912 (May 29) 1903 (May 31)	271 263	113 112	1.78×10^{-4}
2.380	378	2521 (May 28) 2507 (May 31) 2519 (June 1)	255 263 274	145 142 143	2.26×10^{-4}
2.410	387	3163 (June 1)	286	179	2.83×10^{-4}
2.450	399	4073 (June 1)	293	231	3.64×10^{-4}
2.500	415	6283 (June 1)	320	346	5.45×01^{-4}
2.550	432	8416 (June 1)	311	477	7.54×10^{-4}
2.800	520	36,800 (June 1)	356	2066	3.27×10^{-3}
3.100	636	46,700 (June 1)	453	6720	1.06×10^{-2}
4.280	1184	42,500 (June 1) 43,700 (June 1)	530 650	88,800 87,800	0.139

* Since the target is 42 kev thick, the cross sections are the average value over this range of bombarding energy. Below 370 kev, disintegrations are only produced in the top part of the target, and hence the values given in the table are considerably smaller than the true cross sections.

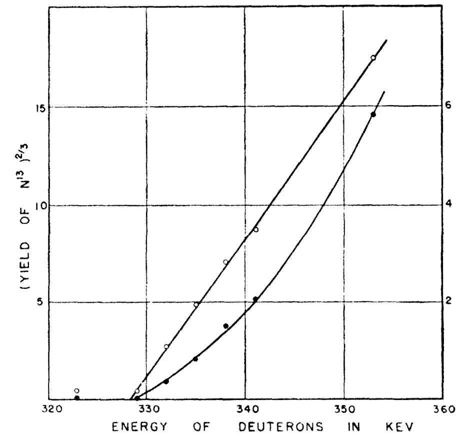

FIG. 1. Solid circles refer to yield of N^{13} *versus* the energy of the deuterons. Open circles give (yield of neutrons)$^{\frac{2}{3}}$ as a function of deuteron energy.

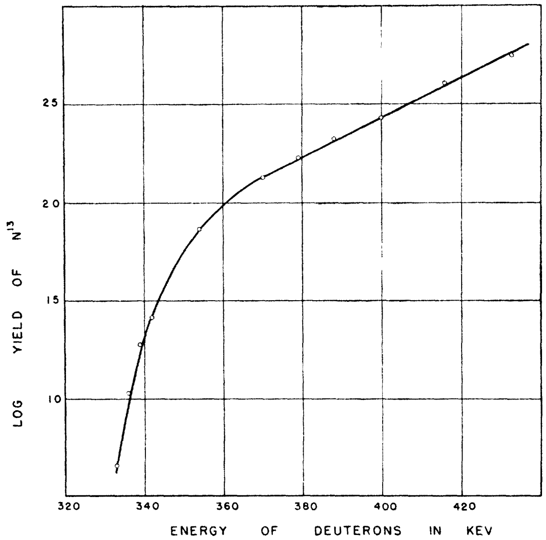

FIG. 2. Logarithm of the yield of N^{13} *versus* energy of deuterons. The linear portion of the curve above 370 kev shows exponential increase with energy for a thin target. Below 370 kev, the target is thick and the yield is not exponential.

number of counts in 100-sec. intervals were plotted to make certain that the effect being counted had a half-life of 10 minutes. Before going through the above procedure for a different current in the magnetic analyzer, the activity was allowed to decay through at least five half-lives. Allowance was made for any activity remaining.

Experiments were carried out in the region of the threshold and also at a bombarding voltage of 1188 kev. Absolute cross sections were assigned to our excitation curve by making use of the accurate determination of the cross section for this reaction at higher energies as determined by Bonner, Evans, Harris, and Phillips.[7]

Upon completion of the experiment, the magnetic analyzer was calibrated by means of the two narrow resonances at 485 kev and 873.5 kev in the reaction $F^{19}(p,\alpha)^*O^{16}$. The precise energy of the higher resonance is that recently obtained by Herb.[8] In the case of the lower resonance 1.3 percent has been added to the older result of 479 kev, in view of the more recent results of Herb. A very thin target of ZnF_2 which weighed 2 micrograms per cm^2 was used in these experiments. The peak of the lower resonance was observed at a current of 1.902 amperes in the magnetic analyzer. The maximum of the higher resonance was obtained at 2.562 amperes. The threshold for the production of N^{13} was obtained at an intermediate value of 2.223 amperes, and so the voltage scale was probably known at the threshold to an accuracy of better than one percent.

RESULTS

Table I gives the relative yield of N^{13} obtained from the individual runs. The averaged values of the number of N^{13} atoms formed as a function of bombarding energy are shown in Fig. 1. The yield of N^{13} is not a linear function of energy near the threshold. In the case of the similar reaction $C^{14}(p,n)N^{14}$, Stephens, Spruch, and Schiff find that the number of neutrons should vary as $(E_p-E_t)^{\frac{3}{2}}$ for a thick target. Consequently, in Fig. 1 we have plotted (yield of $N^{13})^{\frac{2}{3}}$ as a function of the energy of the deuterons. The result appears linear with energy near the threshold, and an accurate value of the threshold (328 kev) is obtained. The Q value of the reaction is $-6/7\cdot 0.328=-0.281$ Mev. The limit of error is estimated to be ± 3 kev, which corresponds to an uncertainty in the absolute value of the bombarding voltage of one percent. Figure 2 shows the variation of yield with deuteron energy on a logarithmic scale. Above 370 kev, the cross section increases exponentially with energy; below 370 kev, the curve is no longer exponential. At bombarding energies less than 370 kev, the target is "thick," and above this value it becomes "thin." A target thickness of $370-328=42$ kev is indicated. From the mass of the carbon target its thickness was calculated to be about 45 kev at 350-kev bombarding energy.

The difference between the mass of the neutron and proton $(n-\mathrm{H})$ neglecting the mass of the neutrino is equal to $Q_3-Q_1-Q_2$ minus the mass of two electrons. The range of the protons from Eq. (3) has been determined by Cockcroft and Lewis,[2] and a calculated value[9] of Q_3 is 2.71 ± 0.05 Mev. The computed energy difference $(n-\mathrm{H})$ is 0.773 Mev from a value of $Q_1=-0.281$ Mev, $Q_2=1.198$ Mev, and $Q_3=2.71$ Mev. If the higher value of $Q_2=1.24$ Mev is used, the $(n-\mathrm{H})$ difference is 0.73 Mev which appears to be too low a value, particularly in view of the recent accurate value of $(n-\mathrm{H})=0.804\pm 0.009$ Mev obtained by Bell and Elliott.[10] Stephens[11] has pointed out that values of Q_3 of comparable accuracy can be obtained from mass spectrographic data. The combined data of Ewald[12] and Mattauch[13] yield a value of $Q_3=2.673$ Mev. The resulting $(n-\mathrm{H})$ difference is either 0.74 or 0.69 Mev, depending on the values taken for Q_2. These mass differences seem too low. The older mass spectrographic data of Bainbridge and Jordan[9] give a value of $Q_3=2.76$ Mev; this leads to values of $(n-\mathrm{H})$ of either 0.82 or 0.78 Mev, depending on the value of Q_2 which is used.

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