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Neutrons from the Disintegration of Nitrogen by Deuterons

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The energy distribution of the neutrons resulting from the disintegration of nitrogen by 0.93 MV deuterons has been investigated in a high pressure cloud chamber. Three groups of recoil protons were found with maximum enegies of 5.7 MV, 2.7 MV and 1.9 MV and with relative intensities of 2 : 1 : 3. The 2.7 MV group is attributed to deuterium contamination on the target. The other two groups are from the reaction

$$_7N^{14}+_1H^2={}_8O^{15}+_0n^1+Q_1$$

where $Q_{10}=5.1\pm0.2$ MV and $Q_{11}=1.1\pm0.2$ MV.

INTRODUCTION

WHEN nitrogen is bombarded with deuterons, three reactions are known to take place

$$_7N^{14}+_1H^2={}_8O^{15}+_0n^1+Q_1, \qquad (1)$$
$$_8O^{15}={}_7N^{15}+_+e+Q_e,$$

$$_7N^{14}+_1H^2={}_7N^{15}+_1H^1+Q_2, \qquad (2)$$

$$_7N^{14}+_1H^2={}_6C^{12}+_2He^4+Q_3. \qquad (3)$$

The neutron reaction was first detected by the radioactivity of O^{15} [1] which has a half-life of 126 seconds[2] and a maximum positron energy of 1.7 MV.[3] The neutrons have been observed,[2,4] but have not been measured heretofore. The protons and alpha-particles have been observed[5] and accurately measured,[6] giving values of

$$Q_{20}=8.53\pm0.1 \text{ MV}, \quad Q_{21}=3.25\pm0.07 \text{ MV},$$
$$Q_{30}=13.22\pm0.1 \text{ MV}, \quad Q_{31}=8.93\pm0.03 \text{ MV}.$$

Gamma-rays have been found to accompany these reactions.[7] At 0.5 MV energy of the deuterons, these reactions have about the same yields,[6] while at 1.4 MV, the alpha-particles are thirty times as numerous as the protons.[5]

It was the purpose of this experiment to investigate the energy distribution of the neutrons from reaction (1).

EXPERIMENTAL PROCEDURE

The high pressure cloud chamber used has been described by Brubaker and Bonner.[8] The

[1] Henderson, Livingston and Lawrence, Phys. Rev. **45**, 428 (1934).
[2] Livingston and McMillan, Phys. Rev. **46**, 437 (1934).
[3] Fowler, Delsasso and Lauritsen, Phys. Rev. **49**, 561 (1936).
[4] Cockcroft, Gilbert and Walton, Proc. Roy. Soc. **A148**, 225 (1935).
[5] Lawrence, McMillan and Henderson, Phys. Rev. **47**, 273 (1935).
[6] Cockcroft and Lewis, Proc. Roy. Soc. **A154**, 261 (1935).
[7] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **48**, 100 (1935).
[8] Brubaker and Bonner, Rev. Sci. Inst. **6**, 143 (1935).

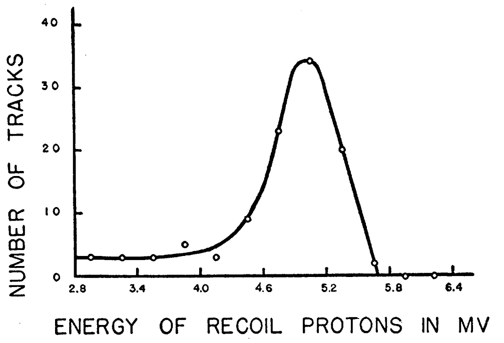

FIG. 1. The energy distribution of the high energy recoil protons observed when nitrogen was bombarded with deuterons.

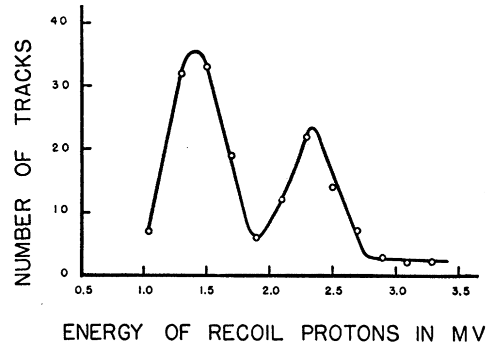

FIG. 2. The energy distribution of the low energy recoil protons observed when nitrogen was bombarded with deuterons.

method of determining neutron energies by measuring the ranges of recoil protons in the cloud chamber has also been discussed.[9–12]

Targets of $NaNO_2$ melted onto copper were bombarded with 0.93 MV deuterons from a short ion path a.c. tube built by one of us (W.E.S.). The target was bombarded only for the 1/10 of a second that the chamber was sensitive and was changed after about 2000 expansions to avoid carbon and deuterium contamination. The current was of the order of 100 to 200 microamperes of unresolved ions. According to a magnetic analysis made on a similar ion source, the ratio of deuterium ions to molecules may be 1 to 10.[13] The gas used in the ion source was 95 percent deuterium, 4.5 percent hydrogen, and 0.5 percent nitrogen which can now be bought in tanks.[14]

To investigate the high energy neutrons, the chamber was filled with illuminating gas to 10.2 atmospheres. The initial composition of the gas was known from the gas company's analysis. We assumed that the composition was not altered by putting it in the chamber except for the methane-ethane ratio. This should change due to the different solubilities of methane and ethane in the 500 cc of ethyl alcohol in the chamber. To determine this ratio, a sample was drawn from the chamber after the run and its specific gravity measured. The percentage of methane had changed from 82 to 89 percent. The stopping power was then calculated using Mano's values.[15] This calculated stopping power of 0.93 per atmosphere was then checked by determining the mean range of polonium alpha-particles in the chamber at one atmosphere pressure of the same gas. To resolve the low energy neutron groups, another run was made with 11.4 atmospheres of hydrogen in the chamber. Here the stopping power was determined directly by measuring polonium alpha-particle tracks in the chamber at the same time as the recoil proton tracks.

RESULTS

9500 stereoscopic pictures were taken with methane in the cloud chamber and the tracks within 8° of the forward direction were measured. The energy number curve for these is shown in Fig. 1. 5500 of these pictures were measured carefully enough to resolve the low energy groups and to the tracks from them were added the tracks from 7500 pictures taken with hydrogen in the chamber. The energy number curve for these low energy tracks is shown in Fig. 2. (The ordinates of the two curves are not directly comparable.) It is apparent from these curves that there are three distinct groups of neutrons with maximum energies of 5.7 MV, 2.7 MV and 1.9 MV.

Since the 2.7 MV group has the same energy as would be expected from deuterons on deuterium,[11] it was suspected of being due to

[9] Bonner and Brubaker, Phys. Rev. **47**, 910 (1935).
[10] Bonner and Brubaker, Phys. Rev. **48**, 742 (1935).
[11] Bonner and Brubaker, Phys. Rev. **49**, 19 (1936).
[12] Bonner and Brubaker, Phys. Rev. **50**, 308 (1936).
[13] R. B. Roberts, Phys. Rev. **51**, 810 (1937).
[14] Stuart Oxygen Company, 211 Bay Street, San Francisco.
[15] G. Mano, J. de phys. et rad. **5**, 628 (1934).

deuterium contamination on the target. To check this, 2500 pictures were taken with methane in the chamber and everything the same as in the first run except that the bombarding energy was 0.72 MV instead of 0.93 MV. The yield from deuterium (D_3PO_4), as determined under similar conditions, decreases only 20 percent[11] in reducing the voltage from 0.9 MV to 0.7 MV, while the yield from nitrogen would be expected to decrease faster even than from beryllium (which decreases 70 percent[11]). Hence the relative intensity of the 2.7 MV group to the 5.7 MV group would be expected to increase by a factor greater than 2.5 if the 2.7 MV group were from deuterium. If they were both from nitrogen, the relative intensity should not be greatly altered. Actually the ratio increased by a factor of 10. Further confirmation of the presence of deuterium contamination is gotten from previous work on carbon[12] where deuterium neutrons were present in similar numbers under similar conditions. Also in a run with a target of NaOH to check the background, only deuterium neutrons were observed. Hence there is little doubt that this group is from deuterons on deuterium. Since the number of deuterium neutrons does not seem to increase appreciably with time of bombardment, it may be that most of the deuterium in this case is not driven into the target from the beam, but is adsorbed on the surface of the target from the deuterium in the tube. The energy Q_D calculated from this peak is $Q_D=3.2$ MV, slightly less than the more accurate value $Q_D=3.35$ MV recently found.[16] The difference is probably due to the fact that with an a.c. tube and with such a slowly rising excitation function, the effective bombarding energy is slightly smaller than the peak energy (by about 0.2 MV).

The 5.7 MV and 1.9 MV groups have approximately the same energies as the neutrons attributed to the reaction ${}_6C^{13}+{}_1H^2={}_7N^{14}+{}_0n^1$.[12] If these neutrons were due to carbon contamination on the target, then the C^{12} neutrons (energy 0.35 MV[12] or 0.46 MV[17]) would be 100 times as numerous. A run with one atmosphere of methane in the chamber showed no C^{12} neutrons. Furthermore, the number of neutrons from $NaNO_2$ was greater than the number of C^{13} neutrons produced under similar conditions by bombarding a pure carbon target.[12]

The Q's for the nitrogen reaction come out $Q_{10}=5.1$ MV and $Q_{11}=1.1$ MV with the errors of ± 0.2 MV due to uncertainty in the stopping power and uncertainty in interpretation of the end points. The observed end-points of the proton groups were corrected by subtracting the probable error in measuring the track length. The maximum mean range was then gotten by subtracting the calculated straggling. This range was converted to energy using the energy-range curve of Mano's.[15] The disintegration energies were calculated in the usual manner, assuming that the maximum energy neutrons came off at an angle of 80° to the direction of the deuteron (since the neutrons were observed at $90°\pm 10°$ to the direction of the incident deuterons).

The relative intensity of the 5.7 MV group to the 1.9 MV group is 2 : 3. The relative intensity of the 5.7 MV group to the deuterium group is 2 : 1 at 0.9 MV and 1 : 5 at 0.7 MV. These relative intensities were corrected for the area in which a track could start and still not hit the wall, and for the collision cross section.[10]

A very few recoil protons with energies greater than 7 MV were observed. These may have been from N^{15} or from Na^{23}.[18]

$$ {}_7N^{15}+{}_1H^2={}_8O^{16}+{}_0n^1+9.9 \text{ MV}, $$
$$ {}_{11}Na^{23}+{}_1H^2={}_{12}Mg^{24}+{}_0n^1+8.3 \text{ MV}. $$

Discussion

These two groups of neutrons imply an excited level in O^{15} at 4.0 ± 0.3 MV. The normal level in O^{15} is supposed to be a ${}^{12}P$,[19] and since 4 MV seems large for doublet separation, this excited level may be a D state. If we suppose the excited level in N^{15} at 5.28 MV[6] is a similar level, then the energies of these two states should differ only by the perturbation caused by the Coulomb field of the extra proton in O^{15}. It is somewhat surprising that this difference is so great when

[16] T. W. Bonner, Phys. Rev. **52**, 685 (1937).
[17] Lewis and Burcham; unpublished (see Cockcroft, Proc. Roy. Soc. **A161**, 450 (1937)).
[18] E. O. Lawrence, Phys. Rev. **47**, 17 (1935).
[19] Feenberg and Wigner, Phys. Rev. **51**, 95 (1937).

in the similar case of C^{11} and B^{11} the difference is[12, 20]

$$2.2\pm 0.2-2.1\pm 0.1=0.1\pm 0.3 \text{ MV}.$$

The gamma-rays observed[7] are at least consistent with a gamma-ray of 4 MV, but the spectrum is very complex and assignments are impractical.

According to Bohr's idea of the nucleus,[21] low energy neutrons should have much more probability of escape than higher energy neutrons. That this is not so in this case implies some compensating probability in favor of the higher energy neutrons. If the high energy neutrons came out with no angular momentum and the low energy ones had an angular momentum of one, the increased probability of escape with zero angular momentum would balance the increased probability of escape with low energies.

If we subtract Eq. (2) from Eq. (1) we get

$$Q_e=Q_2-Q_1-({}_0n^1-{}_1H^1)-2e.$$

Using the values $Q_1=5.1\pm 0.2$ MV, $Q_2=8.53 \pm 0.1$ MV[6] and $({}_0n^1-{}_1H^1)=0.85$ MV[12] we can calculate Q_e, the maximum energy of the O^{15} positrons. This comes out $Q_e=1.56\pm 0.2$ MV, which agrees within the errors with the observed end point 1.7 ± 0.2 MV.[3] This is in accord with the cases of N^{13}, C^{11}, F^{17} and P^{30} where also the calculated value is slightly lower but in agreement within the experimental errors with the observed end point rather than the Konopinski-Uhlenbeck extrapolated end point.[22]

If we use the mass-spectroscopic value for the doublet $(N^{14}H^1-N^{15})$,[23] and the photodisintegration value for the binding energy of the deuteron[24] and substitute in Eq. (1),

$$(N^{14}H^1-N^{15})-\text{binding of deuteron}-2e=Q_1+Q_e,$$

where

$$(N^{14}H^1-N^{15})=10.0\pm 0.2 \text{ MV},$$
$$\text{binding of deuteron}=2.22 \text{ MV},$$
$$2e=1.02 \text{ MV},$$
$$Q_1=5.1\pm 0.2 \text{ MV};$$

then
$$Q_1+Q_e=6.76\pm 0.2 \text{ MV}$$
or
$$Q_e=1.66\pm 0.3 \text{ MV}.$$

This also is in much better agreement with the observed end point of 1.7 MV, than with the Konopinski-Uhlenbeck extrapolated end-point of 2.0 MV.

Livingston and Bethe[25] ascribe the 4/35 MV neutron group obtained by bombarding boron with deuterium to C^{12} instead of to C^{11}, thus not leaving any evidence for a 2 MV excited level in C^{11}. If this is so, there is no experimental reason to expect similar levels in nuclei differing by interchange of a neutron and proton to have closely the same energy.

We wish to thank Dr. C. C. Lauritsen for continued encouragement, Dr. Walter Elsasser for a discussion of the theoretical aspects, and the Seeley W. Mudd Fund for financial support.

[20] Cockcroft and Lewis, Proc. Roy. Soc. **A154**, 246 (1936). *Note added in proof:* It should be pointed out that it is not certain that the 4.35 MV neutron group appearing when boron is bombarded with deuterons is to be associated with C^{11} rather than C^{12}. So the existence of a 2.2 MV level in C^{11} is not definitely established.

[21] N. Bohr, Nature **137**, 344 (1936).

[22] J. D. Cockcroft, Proc. Roy. Soc. **A161**, 450 (1937).

[23] Jordan and Bainbridge, Phys. Rev. **50**, 98 (1936).

[24] Feather, Nature **136**, 467 (1935); Bethe and Bacher, Rev. Mod. Phys. **8**, 123 (1936).

[25] Livingston and Bethe, Rev. Mod. Phys. **9**, 333 (1937).