NEUTRONS EMITTED IN THE DEUTERON BOMBARDMENT OF CARBON*

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Energy levels in ^{14}N have been observed at 2·31, 3·95, 4·91, and 5·10 MeV in the study of the inelastic scattering of protons and deuterons by nitrogen (Bockelman *et al.* 1953), and these levels may be used to explain all the low energy γ-rays associated with the ^{14}N nucleus except for a 0·725 MeV γ-ray (Woodbury, Day, and Tollestrup 1953; Ajzenberg and Lauritsen 1955). Experiments on the reaction $^{13}C(d,n)^{14}N$ give evidence for the same levels with additional ones suggested at 3·47 MeV (Mandeville and Swann 1950) and 3·8 MeV (Benenson 1953) although the energy values obtained do not agree very well with those of Bockelman *et al.* It may be noted that the measurements of Benenson give better agreement if, in the calculation of the level energies, his measured ground state Q-value is used rather than the value given by the atomic masses.

A further study of the reaction $^{13}C(d,n)^{14}N$ has been made by bombarding a thick target of natural carbon with 0·92 MeV deuterons for an integrated target exposure of 100,000 μC. Although the more abundant isotope of carbon does not interfere with the study of energy levels in ^{14}N below 5 MeV the low yield of neutrons from the required reaction necessitates precautions to reduce the number of neutrons from contaminant reactions. For this reason the copper diaphragm used to limit the size of the deuteron beam and the copper target backing were kept at several hundred degrees C during the exposure.

The camera was constructed from 0·030 in. brass and the supports for the target mounting and the electrical leads were mounted in a side tube at a considerable distance from the target in order to reduce the effects of neutron scattering. A paraffin wax stack was mounted between the camera and the electrostatic generator to cut down the number of neutrons from deuterium

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contamination of the accelerating tube and the back scattering of neutrons by the analysing magnet.

Pieces, 1 by 3 in., of 400μ Ilford C2 plates were held by wire frames at angles of 0, 30, 90, and 150° to the direction of the incident deuteron beam. The plane of the surface of each emulsion lay in the direction of the neutron flux and the front edges of the plates were at a distance of 3 cm from the target. The plate chamber was isolated from the target chamber and filled with air which was kept dry with phosphorus pentoxide. The plates were vacuum dried for 24 hr before loading in the camera, and measurements of the emulsion density for plates which were treated in a similar way gave the value 4·00 g/cm^3. The plates were processed by the " temperature " method in order to ensure uniform development throughout the depth of the emulsion.

Measurements were made on each plate over areas subtending an angle of $\pm 2°$ at the target, and tracks were accepted which had an angle of dip in the unprocessed emulsion not greater than $\pm 5°$ and an angle in the plane of the emulsion not greater than $\pm 10°$. These angles together with the distance between the first and last grains were tabulated for each acceptable track which did not cross either surface of the emulsion. The measured range of each recoil proton was corrected according to the angle of recoil and then converted to neutron energy using the microscope calibration and a range-energy relation based on the results of Rotblat (1951). The energy distributions plotted in 100 keV intervals are shown in Figure 1, after correction for the variation of the neutron-proton scattering cross section with neutron energy. No additional correction has been made for the loss of tracks from the emulsion since this would change the correction factor by less than 2 per cent. A total of about 3000 tracks was measured and the ordinates in Figure 1 represent the true variation of neutron intensity with energy and angle of emission.

Energy Levels

The peak energies obtained from Figure 1 have been corrected to give the corresponding thin target energies, making allowance for the possible effects of resonances in the yield of neutrons as observed in the reaction $^{13}C(d,n)^{14}N$ by Richardson (1950). The dotted peaks in Figure 1 are attributed to the D–D reaction, and give a weighted mean Q-value for this reaction of $3·24 \pm 0·05$ MeV, which is in satisfactory agreement with the value calculated from the atomic masses. The low energy group in the 0° spectrum is attributed to the reaction $^{12}C(d,n)^{13}N$. The number of tracks is very much underestimated in Figure 1, since they were only measured over a small portion of the area scanned. The high intensity and the estimated Q-value ($-0·33 \pm 0·06$ MeV) are consistent with the allocation of this group to the ^{12}C reaction.

The peaks numbered 1–4 arise from the ^{13}C reaction and give weighted mean Q-values of $5·325 \pm 0·04$, $3·02 \pm 0·05$, $1·37 \pm 0·03$, $0·37 \pm 0·02$ MeV, which define levels in ^{14}N at 2·30, 3·95, and 4·95 MeV. The probable errors represent the observed fluctuations in individual Q-values together with the uncertainties in the range-energy relation and bombarding energy. Peak 4 is about 100 keV wider than would be expected from the width of the higher energy peaks, and this can be explained by the assumption of a pair of levels at 5 MeV excitation. The 30 and 90° peaks are wider than the 0° peak which may support the suggestion by Benenson (1953) that the angular distributions of the two groups are different.

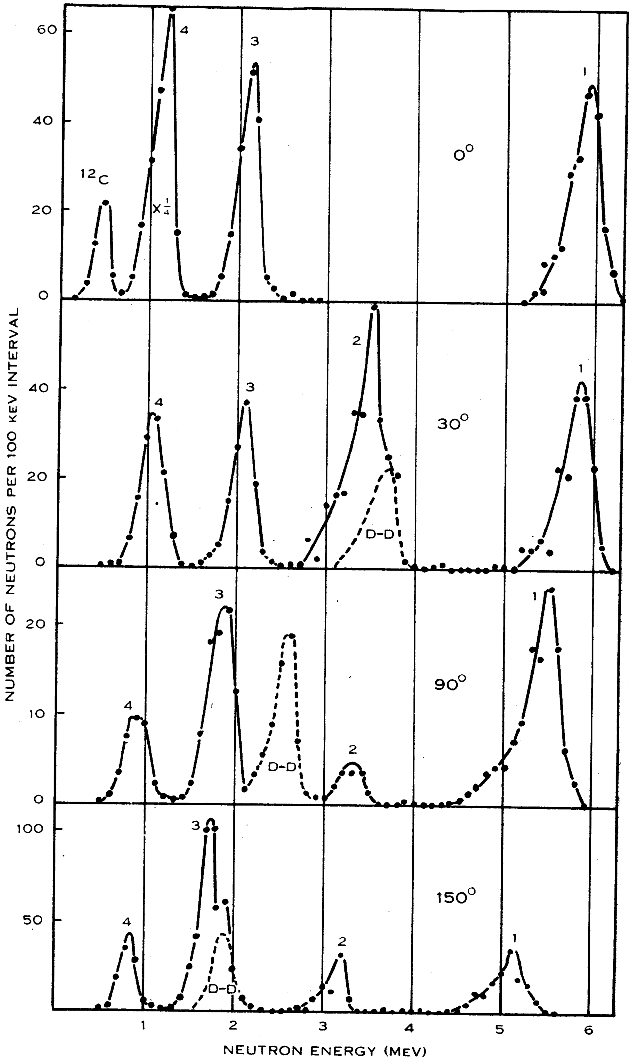

Fig. 1.—Neutron spectra from the reaction $^{13}C(d,n)^{14}N$.

These results are in satisfactory agreement with those obtained from other reactions leading to the same final nucleus. No evidence is obtained for the existence of a level at 3·47 MeV as reported by Mandeville and Swann (1950), and an upper limit of 5 per cent. of the ground state intensity can be placed on the possible intensity of a neutron group corresponding to such a level. Similarly no indication is obtained of a doublet at 4 MeV excitation as suggested by

Benenson. The lack of intermediate low-lying levels requires the allocation of the $0 \cdot 725$ MeV γ-ray to a cascade involving a level above 5 MeV excitation as suggested by Woodbury, Day, and Tollestrup (1953).

Angular Distributions

The contribution to the yield of deuteron induced reactions by the process of deuteron stripping is dependent on the deuteron energy and therefore cannot be readily calculated for a thick target. However, the forward peaks which are characteristic of the stripping process will still be observed and may give qualitative information about the transfer of angular momentum to the final nucleus. The variation with angle in the laboratory system of coordinates, of

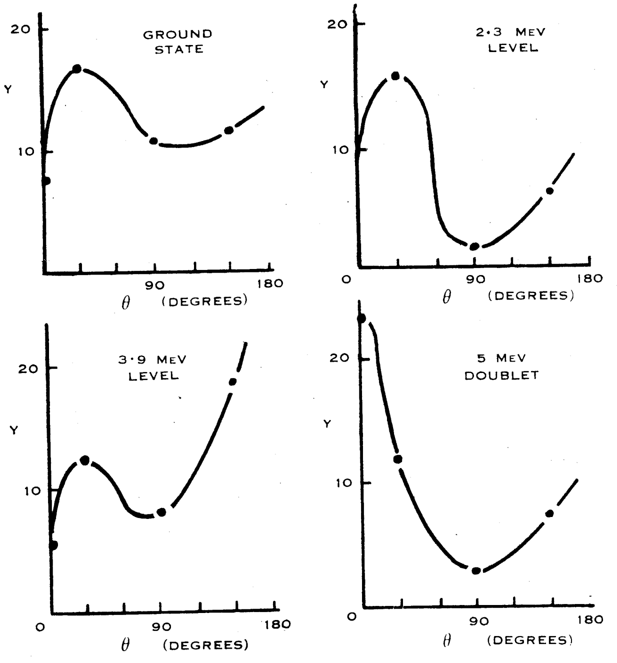

Fig. 2.—Variation with angle of observation of the thick target yield of neutrons from natural carbon. Y, number of neutrons per unit solid angle per 10^{10} deuterons ; θ, angle in laboratory system of coordinates.

the thick target yield of the neutron groups corresponding to each state of ^{14}N, is shown in Figure 2. Each curve has a pronounced forward peak which suggests that stripping makes an appreciable contribution to the yield of neutrons for deuteron energies below $0 \cdot 92$ MeV.

The angular distributions observed for the excited states are similar to those given by Benenson (1953) and would therefore lead to the same conclusions as to the spin and parity of these states. However, the distribution for the ground state has a peak at an angle greater than 0° and agrees with the results of Bromley and Goldman (1952) rather than those of Benenson. This implies even parity for the ground state of ^{14}N which is therefore different from the ground state of ^{14}C and leaves unexplained the forbidden nature of the β-decay of ^{14}C.

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