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Neutron and Gamma-Ray Yields from Deuterons on Carbon

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Observations on the yield of neutrons and gamma-rays from carbon bombarded with deuterons of discrete energies between 0.85 and 3.25 Mev are reported. The yield of neutrons per unit solid angle at 0° and 90° is given in absolute terms. Resonances for the formation of the compound nucleus N^{14} exhibit features such as: varied widths of resonances, shifts in energy between gamma-ray and neutron resonances, exclusion of neutron resonances by gamma-ray resonances and *vice versa*, and the strong forward asymmetry of the neutron yield.

1. INTRODUCTION

INVESTIGATIONS of the yields of neutrons from the reaction

$$D^2+C^{12}\rightarrow(N^{14})\rightarrow N^{13}+n^1, \qquad (1)$$

and gamma-rays from the competing reaction

$$\begin{aligned} &D^2+C^{12}\rightarrow(N^{14})\rightarrow C^{13*}+H^1 \qquad (2)\\ &C^{13*}\rightarrow C^{13}+h\nu \end{aligned}$$

have been made by the Rice Institute group[1–4] and at the University of Minnesota.[5]

These early researches established the nature of these reactions and showed a number of resonances for the production of neutrons and gamma-rays. The present paper reports an extension of these studies to higher deuteron energies and an investigation of the angular dependence of the yield of neutrons from reaction (1). In reference 1, the neutron yield in the forward direction was measured as a function of deuteron energy up to 2 Mev, whereas in reference 5 essentially the total yield, averaged over all angles, was observed up to 2.75 Mev. The partial disagreement between these two results suggested that the neutron reaction is asymmetric; therefore, it was decided to investigate the yield of neutrons in two directions, namely, 0° and 90°, in the laboratory system of coordinates.

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[1] W. E. Bennett and T. W. Bonner, Phys. Rev. **58**, 183 (1940).
[2] T. W. Bonner, E. Hudspeth, and W. E. Bennett, Phys. Rev. **58**, 185 (1940).
[3] W. E. Bennett, T. W. Bonner, E. Hudspeth, H. T. Richards, and B. E. Watt, Phys. Rev. **59**, 781 (1941).
[4] W. E. Bennett and H. T. Richards, Phys. Rev. **71**, 565 (1947).
[5] C. L. Bailey, M. Phillips, and J. H. Williams, Phys. Rev. **62**, 80 (1942).

2. APPARATUS

Deuterons whose energy was controlled to the order of 0.2 percent were furnished by the Minnesota electrostatic generator. This accelerator has been modified since it was first described[6] and a report of these improvements is forthcoming. The energy of the deuterons was controlled and measured by electrostatic analysis of the diatomic ion beam. The energy scale was normalized by assuming that the threshold of the Li(p,n) reaction is 1.86 Mev.[7,8]

Thin carbon targets were made by slowly depositing soot from a gas flame onto thin tantalum plates. With a little practice it was found possible to produce uniform deposits of any thickness desired up to 60-kev stopping power. In practice, several different targets were used with thicknesses from 20 to 60 kev to cover the range of bombarding energies. To prevent carbon from residual vapors in the accelerating tube being added to the target during ion bombardment, and also to prevent absorption of D_2, we heated these targets electrically throughout the time of the observations. Under these conditions the yield of neutrons could be duplicated from day to day to within an accuracy of a few percent.

As is common to all experiments with deuteron accelerators, a background of neutrons and gamma-rays exists as a result of deuterium absorbed on diaphragms and other surfaces. In order to measure this background, the heated

[6] J. H. Williams, L. H. Rumbaugh, and J. T. Tate, Rev. Sci. Inst. **13**, 202 (1942).
[7] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. **58**, 1035 (1940).
[8] A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1947).

tantalum backing of the carbon target was mounted on a tapered ground joint, so that it could be turned over to present a clean tantalum surface to the deuteron beam. It was found necessary to make many alternate observations of the background count to be subtracted from the total count, since the background effect varied considerably with time and other operating conditions.

The neutrons were detected by means of a "long counter" of the type described by A. O. Hanson and J. L. McKibben.[9] These authors have shown that the sensitivity of this detector is constant to within a few percent for neutrons of energies from 23 kev to 3 Mev. A further advantage of this counter is the side and back shielding, so that only those neutrons which enter its front face are detected.

The gamma-rays were detected by a thick wall Geiger counter encased in a two-inch thick lead shield which had a $\frac{1}{2}$-inch square window cut out on the side facing the carbon target. It seems reasonable to attribute the gamma-rays to reaction (2) where the energy of excitation of the intermediate C^{13} nucleus is 3.15 Mev. Even at deuteron energies of 7 Mev there seems to be[10] only one further excited state of C^{13}, at 3.95 Mev. We can therefore expect the gamma-ray energy to be approximately constant over the range of deuteron energies reported here and consequently the yield as measured by a Geiger counter will be a true representation of the relative gamma-ray yield as a function of deuteron energy.

The geometrical arrangement of the detectors with respect to the carbon target is shown in Fig. 1. The angular definition of the neutron detector is difficult to estimate. The efficiency for detecting a neutron depends on the distance between the central axis of the counter and the point of impact of the neutron on the front paraffin surface of the counter in an unknown way. A rough estimate of this efficiency gives the angular definition as $\pi/16$ steradians for the geometry employed in these experiments. The angular definition of the gamma-ray counter is of little importance since the gamma-rays are expected to be emitted in a spherically symmetrical fashion. This expectation has been checked approximately by observations at 0° and 90°.

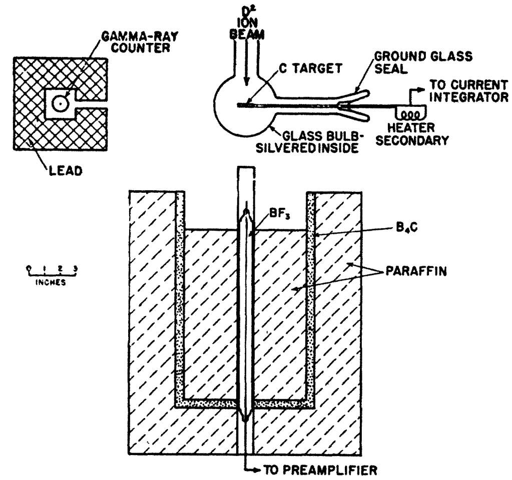

FIG. 1. Geometrical arrangement of gamma-ray detector at 90° and neutron detector at 0°.

The possibility of gamma-rays being generated by absorption of neutrons in the massive paraffin block and then being detected by the Geiger counter was eliminated by removing the paraffin during a test run. Similarily, the contribution of neutrons scattered from the lead into the neutron detector was found to be negligible.

3. PROCEDURE

With the geometry shown in Fig. 1, simultaneous readings of the neutrons detected at 0° with respect to the direction of the deuterons and of the gamma-rays at 90° were made. The number of such counts was recorded for a given total charge of deuterons striking alternately the carbon covered face of the target and the clean surface. Since the time for these observations was on the average the same, the difference between them could be attributed to the yield from the thin carbon alone. Since the neutrons and gamma-rays were observed simultaneously, there was no uncertainty in the relative voltages at which resonance maxima occurred in the respective yields from reactions (1) and (2).

When the geometry of the neutron counter was changed from 0° to 90°, the solid angle subtended at the target was kept constant and,

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[9] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

[10] K. M. Guggenheimer, H. Heitler, and C. F. Powell, Proc. Roy. Soc. **A190**, 196 (1947).

consequently, the relative neutron yield at these two laboratory angles was observed directly.

To obtain the absolute value for the efficiency of reaction (1) we measured the neutron flux by counting fissions from a thin layer of normal uranium. This thin target, surface density 0.40 mg/cm^2, was prepared by spraying uranyl nitrate on a platinum plate and reducing the compound to U_3O_8 by heating. This uranium foil was fastened to the negative high voltage electrode of a simple parallel-plate ionization chamber which was covered with cadmium, 0.020 inch thick. When the chamber was placed in the flux of 0° neutrons, tests showed that the number of background fissions in U^{235} due to the presence of thermal and epethermal neutrons was neglible. For these observations the deuteron energy was 2.8 Mev, so that the neutron energy was 2.5 Mev. In order to calculate a value for the neutron yield from the thin carbon target, we have assumed[11,12] that the fission cross section of U^{238} for 2.5-Mev neutrons is 0.5×10^{-24} cm^2, 0.5 barn, that the masses of C^{12} and U^{238} on the target and foil could be determined by weighing the tantalum and platinum disks before and after deposition of the soot and U_3O_8, respectively, and that the ion beam contained only D^+ ions with no H_2^+ contamination. This last assumption should introduce a negligbly small error, less than 1 percent, since the ion source was operated with 99 percent pure D_2O for more than 100 hours before these observations were made. The cross section for reaction (1) was thus found to be $1.4\pm0.4\times10^{-26}$ cm^2 per unit laboratory solid angle in the forward direction at a deuteron energy of 2.8 Mev. The uncertainties in the weights of the uranium foil and carbon target were the principal sources of error in this determination.

The above cross section for the $C^{12}(d,n)N^{13}$ reaction is subject to the assumption that the contribution to the neutron flux from the $C^{13}(d,n)N^{14}$ reaction can be neglected; this contribution is negligible for the present measurement, at least up to 2-Mev deuteron energy.[4]

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[11] R. Ladenburg, M. H. Kanner, H. H. Barschall, and C. C. vanVoorhis, Phys. Rev. 56, 168 (1939).

[12] N. Bohr and J. H. Wheeler, Phys. Rev. 56, 426 (1939).

4. RESULTS

The observations are shown in Fig. 2. The neutron yield curves are given to an absolute scale determined by the fission method described above. The gamma-ray yield curve is plotted to an arbitrary scale, but the earlier results of Bennett and co-workers[3] indicate that the yield of gamma-rays and neutrons at 0° is about equal for a deuteron energy of 1.6 Mev.

A comparison, with respect to the structure of the resonance peaks, of the 0° neutron curve and the gamma-ray curve with those of the Rice Institute group[1,2] shows good agreement. The present results do not confirm the existence of a resonance for reaction (1) at 1.15 Mev. A comparison with the earlier results obtained in this laboratory[5] is difficult because the early observations measured a yield averaged roughly over all angles. A common feature is the decline in the 90° neutron curve of Fig. 2, and the diminishing yield of neutrons for a bombarding deuteron energy of 2.3 Mev shown in Fig. 1 of reference 5.

5. DISCUSSION

Although a detailed interpretation of these results is not possible at the present time, it seems worth while to emphasize some features which present evidence for the complexity of these nuclear reactions, and may be common to (d,n) and (d,p) reactions in this energy region and range of atomic numbers.

The true widths of the resonances for the formation of the compound nucleus, N^{14}, are probably only slightly less than those shown in Fig. 2 with the exception of the gamma-ray resonance at 1.43 Mev. This particular resonance has been studied in some detail by Bennett and co-workers.[3] For the 11- to 14-Mev range of excitation energy of the compound nucleus, N^{14}, presented here, the widths of the resonance energies vary by at least an order of magnitude from 10 to more than 100 kev.

A more puzzling feature of these observations is disclosed by a study of the relative positions of the 1.80- and 2.96-Mev resonances for 0° neutrons and the 1.75- and 2.90-Mev resonances for gamma-rays. It seems reasonable to attribute the first pair (1.80 Mev and 1.75 Mev), of these resonances to a common excited state of the N^{14}

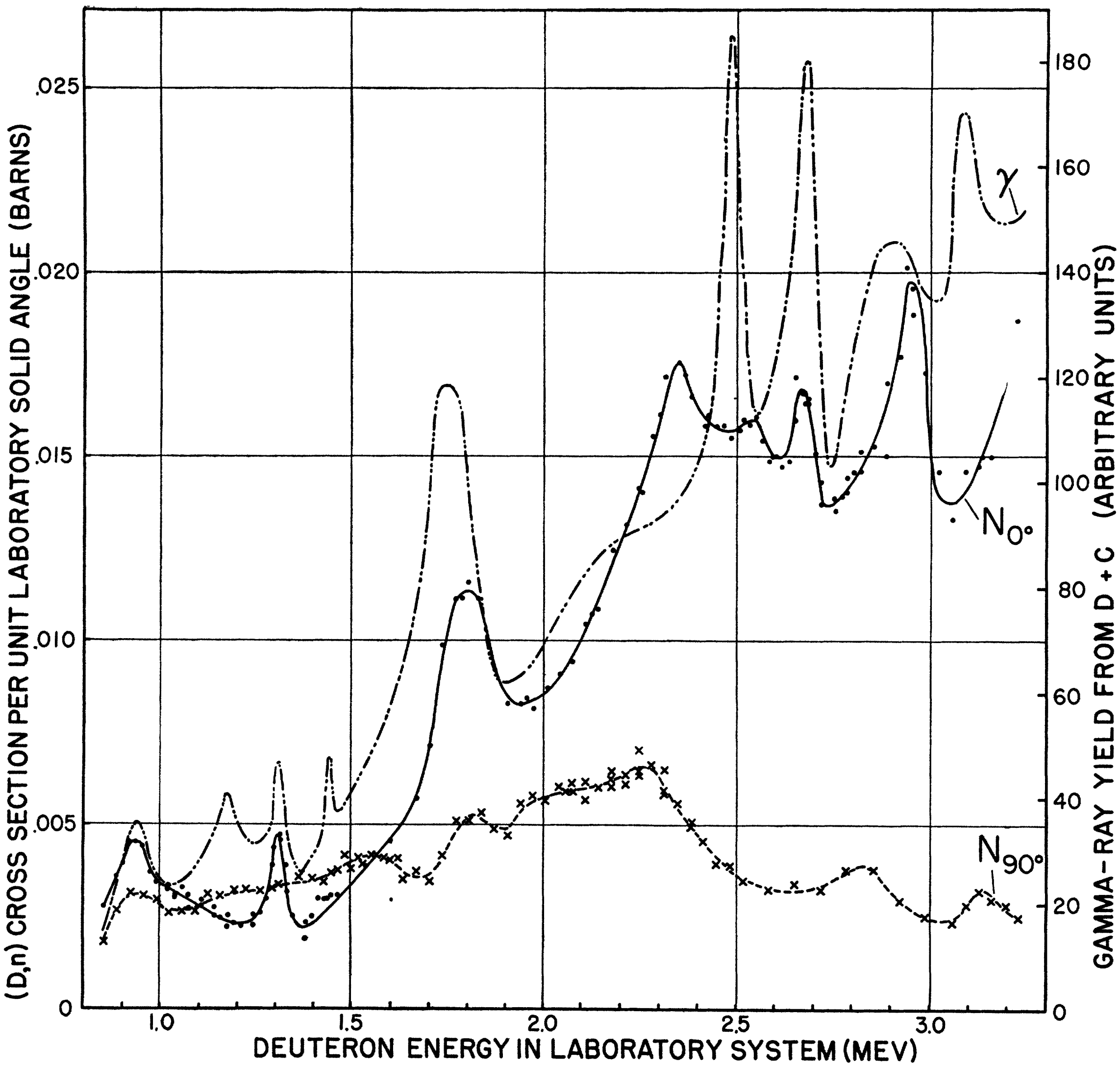

FIG. 2. Absolute yield of neutrons per unit solid angle in laboratory system of coordinates in the forward direct, $N_{0°}$, full curve, and at right angles to the deuteron beam, $N_{90°}$, dashed curve with crosses. The dot-dash curve shows the yield of gamma-rays to an arbitrary scale.

nucleus because these resonances are pronounced and broad for both modes of disintegration. It is not so obvious that the latter pair (2.96 and 2.90 Mev) is a common state of N^{14}. If this assumption is accepted, it is noticed that the gamma-ray resonance occurs for a bombarding energy of the deuteron which is considerably less, 50 kev, than for the neutron resonance. There is no experimental uncertainty as to the reality of this shift in energy since the observations are taken simultaneously.

Any expected effects of the potential barrier would result in a shift in the opposite sense since the gamma-rays are emitted after the emission of a proton. Since the observations of the yield of competitive reactions are, on the basis of theories involving the formation of a compound nucleus, a measure of the product of the probability of the formation of the compound nucleus and the probability of emission of the alternative nuclei, it is not easy to account for the differences in energy observed. For the resonances at 0.92, 1.30, 2.68 Mev, the gamma-rays and 0° neutrons are emitted at the same bombarding energies to within the accuracy of the experimental observations which can be estimated at ± 5 kev.

For deuteron energies of 2.35- and 2.55-Mev, reaction (1) emits neutrons in the forward direction with no corresponding resonance for gamma-rays. Conversely, for deuteron energies of 1.17, 1.43, 2.2, 2.49, and 3.08 Mev the observations show resonances for gamma-ray emission following reaction (2) and no corresponding resonances for neutrons. An explanation of the exclusive nature of these disintegrations from the resonance states of N^{14} must await a detailed description of the quantum states involved.

Considering the angular dependence of reaction (1) it should be noticed that the observations do not serve to measure the number of neutrons at exactly 0° or 90° for at least two reasons. First the angular aperture of the neutron detector is approximately $\pi/16$ steradians, as mentioned earlier. Second, observations of fast neutrons in a laboratory of limited dimensions are always fraught with the practical difficulty of detecting neutrons directly from a target over the atmosphere of neutrons which fills the laboratory.

An estimate of these two effects leads us to suggest that the true ratio of the yield of neutrons at 0° and 90° might be as large as twenty to one when the deuteron energy is of the order of 3 Mev. This marked asymmetry seems to be a common feature of many particle reactions in this range of energy and atomic number. Heitler, May, and Powell[13] have drawn attention to this phenomenon which occurs for the inelastic scattering of 4.2-Mev protons by neon. An analysis of the angular distribution of reactions of this type must await further detailed experimental examination of the distribution.

Only in the case of the lowest resonance energy, 0.92-Mev deuterons, is there a common character to the three curves of Fig. 2. The almost complete dissimilarity between the 0° and 90° neutron curves lacks an explanation at this time. The only common feature is in the neighborhood of 2.3 Mev. Here the decline of the continuum on which the 0° neutron resonances are superimposed and the sharper decline of the 90° neutron yield indicate that a competitive process is becoming important. The endoergic (d,α) process may be expected to play this role at approximately this energy.

6. ACKNOWLEDGMENTS

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[13] H. Heitler, A. N. May, and C. F. Powell, Proc. Roy. Soc. **A190**, 180 (1947).