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Publication Date

1951-03-28

UCRL- 1204

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Contract No. W-7405-eng-48

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March 28, 1951

Berkeley, California

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I. Introduction

Recent determinations(2,3,4,5,6) of the spatial distribution of fast neutrons produced by the bombardment of various targets by deuterons of energy less than 20 Mev indicate that there is a group of neutrons emitted in a forward direction in addition to a roughly isotropic background. Serber's theory of stripping(7) has satisfactorily explained the high energy (190 Mev) results of Helmholz, McMillan, and Sewell,(8) but the application to the low energy results is not so satisfactory.(5,6) The present work establishes information about the neutron distributions from deuterons of maximum energy 20 Mev, which show that several different processes operate in the production of these neutrons, and that the neutron energies are characteristic of the processes producing them.

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(1) Reported at the Los Angeles meeting of the American Physical Society, December 28-30, 1950.

(2) R. B. Roberts and P. H. Abelson, Phys. Rev. 72, 76 (1947)

(3) C. E. Falk, E. Creutz, and F. Seitz, Phys. Rev. 74, 1226 (1948)

(4) C. E. Falk, E. Creutz, and F. Seitz, Phys. Rev. 76, 322 (1949)

(5) P. Ammiraju, Phys. Rev. 76, 1421 (1949)

(6) C. E. Falk, Carnegie Institute of Technology Report No. 5, July 1, 1950

(7) R. Serber, Phys. Rev. 72, 1008 (1947)

(8) A. C. Helmholz, E. M. McMillan, and D. C. Sewell, Phys. Rev. 72, 1003 (1947)

II. Experimental Details

This set of measurements was carried out using the 60-inch cyclotron of the Crocker Laboratory, which produces an external deuteron beam of energy about 20 Mev. This has the advantage that no corrections need be made for the scattering of the neutrons before their detection. The target. bombarded include Be, Al, Cu, Sn, Pb, and U, and were of sufficient thickness to stop all the deuterons. Thick targets were necessary in order to minimize the effect of neutrons due to deuterons bombarding parts of the cyclotron tank and dee system other than the external target. The bombarding currents were all of the order of 15 microamperes.

The neutrons were detected by the beta-activities, induced by exposure, in arrays of C, Cu, and Al foils. The foils, 1 in. x 1-1/8 in. x maximum beta-range, were enclosed in 1/32 in. Cd and placed in a circular arc of 10-1/2 in. radius, with the target as center. This arc covered an angular range from -16 degrees to + 66 degrees, relative to the incident deuteron beam direction, and was limited by the cyclotron tank wall on one side, and the target cooling lines on the other. This method was chosen for the following reasons: (1) all foils receive exactly the same exposure, so that no monitor is necessary; (2) by choosing foil materials with suitable activation thresholds, a selection of energy ranges can be made, and, in addition, neutrons which have lost a certain amount of energy by inelastic scattering from nearby matter are not detected; (3) Falk has shown(6) that this simple scheme gives substantially the same results as those from detection by a proportional counter telescope.

The activities induced in every foil were each measured two or three times in a standard Geiger tube and lead chamber arrangement, and then extrapolated back to some convenient time so that they could be compared. The activities consisted of the 20.5 minute activity of C^{11}, the 10.5 minute activity of Cu^{62}, the

10.2 minute activity of Mg^{27}, and the 14.8 hour activity of Na^{24}. The reactions and their thresholds are shown in Fig. 1. Independent determinations were made of the half-life of each activity in order to positively identify the activity for accurate extrapolation purposes, and also to define the time interval in which the desired activity could be counted before other activities became important. The high bombarding currents resulted in large activity yields, so that the counting error (in the forward direction) was less than 1 percent for points determined by the Cu^{62} and Mg^{27} activities, and less than 5 percent for points determined by the C^{11} and Na^{24} activities.

III. Results and Discussion

The characteristics of the neutron distributions are conveniently described in terms of the forward-to-isotropic yield ratio, the width at half-maximum, and the angular position of the maximum with respect to the incident beam direction. A typical set of distributions is shown in Fig. 1. In each case there is a maximum in the forward direction superimposed on what appears to be an isotropic background. This was measured only out to about 65 degrees and has been assumed constant beyond that. The ratio of the number of neutrons emitted in the forward peak to the number emitted isotropically is shown in Table. I. While the numbers are rough because of the uncertainty in the isotropic component, they indicate a relative increase in this component as the atomic number of the target increases. The isotropic background is presumably due in part to the formation of a compound nucleus by the addition of a deuteron with the subsequent boiling off of a neutron. In addition, there is an irregularity at Sn, which also appears in the discussion of the half-widths below.

Table II, which lists the half-width of the forward peaks for the elements investigated, shows a non-regular variation in the shapes of the distributions. However, there is a tendency for higher energy neutrons to be concentrated in the forward direction, as evidenced by narrowing of the forward peak as the detector threshold increases, particularly for the data on Al and Pb. Prof. V. P. Weisskopf has pointed out(5) that for heavy elements the deuteron loses so much energy in climbing the potential barrier that the neutron can obtain sufficient momentum to cause, say, the Cu(n,2n) reaction only by adding its internal momentum in the deuteron parallel to the center of mass momentum. This will cause a sharpening of the peak for essentially energetic reasons, the neutrons at wide angles being of lower energy. It is to be noted that in the case of Sn, the distribution is somewhat wider than all the others for neutrons above 11 Mev.

Table II also shows that in the cases of Be and Cu, neutrons are emitted, which, above 20 Mev, have their spatial maximum displaced from the direction of the incident deuteron beam. Similar results have been reported by Falk.(6) At lower energies, this apparent "double peak" is washed out, indicating that the distributions result from several different nuclear processes of comparable magnitude. This feature is clearly shown in Fig. 1 for the case of Be, and is to be compared to the distributions found(8) for high energy deuteron impacts. The latter show "single peaks" exclusively, whose half-widths increase in a regular way with atomic number, and which agree quantitatively with the Serber process of stripping.(7) Electric separation(9) of the deuteron, to be sure, does predict a double peaked distribution of neutrons from the action of the Coulomb field of the target nucleus upon the proton in the deuteron. However, field separation of a deuteron of 20 Mev can produce a neutron of maximum energy only 18 Mev, which is insufficient to cause the C(n,2n) reaction. The further observation that double peaked distributions result from Be and Cu targets only

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(9) S. M. Dancoff, Phys. Rev. <u>72</u>, 1017 (1947)

would seem to rule out these usual theories as the sole mechanisms involved. The same reasons rule out the possibility that the double peaks may be due simply to the Coulomb field action on the deuteron before stripping or electric separation occurs.

The collision times for deuterons of less than 20 Mev are, of course, longer than those for the high energy case. This suggests a mechanism by which some neutrons can gain energy in sufficient amount for them to be detected in the carbon foils. The mechanism consists in keeping the deuteron together long enough so that the binding energy given up when the proton sticks, forming a compound nucleus, can be wholly or partly communicated to the neutron.

Since the present data were collected, a quantitative examination of this process has been made by S. T. Butler.(10) The model used by him has been applied to the small-angle structure observed in (d,p) angular distributions(11,12) with considerable success, and the calculations reveal significant information concerning the parities and possible spin states of the nuclei formed in this way. It seemed worthwhile, therefore, to apply the theoretical considerations to the information collected here. The theoretical curves of Butler depend on (1) the radius of the target nucleus; (2) the incident deuteron energy; (3) the outgoing neutron energy; (4) the angular momentum carried by the proton, which sticks. These have been suitably modified to fit the conditions of the experiment. The circumstance that the 60-inch cyclotron produces 20 Mev deuterons, while the threshold for the carbon reaction is 20.25 Mev, results in the fact that neutron distributions from collisions of the type described above can be examined

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(10) S. T. Butler, Phys. Rev. 80, 1095 (1950)

(11) H. B. Burrows, W. M. Gibson, and J. Rotblat, Phys. Rev. 80, 1095 (1950)

(12) J. R. Holt and C. T. Young, Proc. Phys. Soc. London 78, 833 (1950)

separately, without having superimposed upon them neutrons due solely to the other processes of stripping, electric disintegration, and compound nucleus formation.

However, the use of threshold detectors does not allow the outgoing neutron energy, and consequently the states of excitation of the final nucleus, to be determined. In fact, the observed distributions from carbon detectors are themselves the superposition of contributions from the various final nuclear states, so that with this method, unambiguous spin and parity values cannot be assigned in general.

But in the cases of Be^9, Al^{27}, and Cu^{63} targets, the distribution structure is definite enough so that it can be safely assumed that probably only one of the final states enters in determining the angular distribution. By comparing the theoretical and experimentally observed angular distributions, an example of which is shown in Fig. 2, it has been possible to find agreement good enough to assign parity and possible spin values to either the initial or final state, the other being assumed known. The results are given in Table III.

For the Be^9 reaction, it has been assumed that only the ground state of B^{10} has been produced. Taking the spin value 3 and the shell model prediction of even parity for this state, the necessary spin assignments for Be^9 include the known value of 3/2, while the parity must be different from that of B^{10}. For the Al^{27} reaction, the initial state has been assumed to be 5/2, even, and the resulting Si^{28} state must be assigned a rather large spin and like parity. Since the ground state of Si^{28} is expected to have spin zero, it is thus shown that the capture of a proton by Al^{27} to form the ground state of Si^{28} is forbidden; rather, an excited state is formed which has the properties listed above. This is in agreement with other measurements,(13) which show a low

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(13) R. A. Peck, Jr., Phys. Rev. 76, 1279 (1949)

probability for the production of the ground state, compared to excited states. For the Cu^{63} reaction, transition to the ground state of Zn^{64} is assumed, which leads to possible spins for Cu^{63} which include the value 3/2. However, in this case, the ground state of the Cu^{63} must be of even parity, which is in disagreement with the prediction from the shell model of Mayer.

IV. Acknowledgments

An expression of appreciation is due to Professor A. C. Helmholz for his continued interest, advice, and encouragement during the course of this work. The criticisms and discussions of Professor R. Serber and Mr. Warren Heckrotte were of great value. Mr. Heckrotte also aided in making the necessary calculations. The author is greatly indebted to Dr. S. T. Butler for making his analysis available before publication. Finally, thanks are due to Mr. Thomas M. Putnam and the crews of the 60-inch cyclotron for their aid in making the bombardments.

This work was performed under the auspices of the Atomic Energy Commission.

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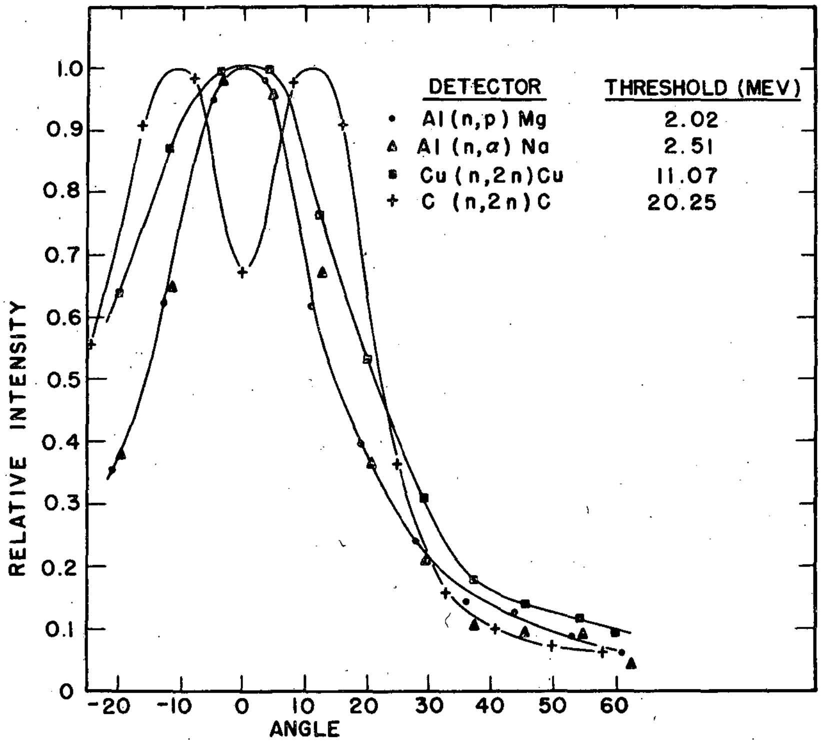

FIG. I

ANGULAR DISTRIBUTION OF NEUTRONS FROM DEUTERONS ON BERYLLIUM

MU 1611

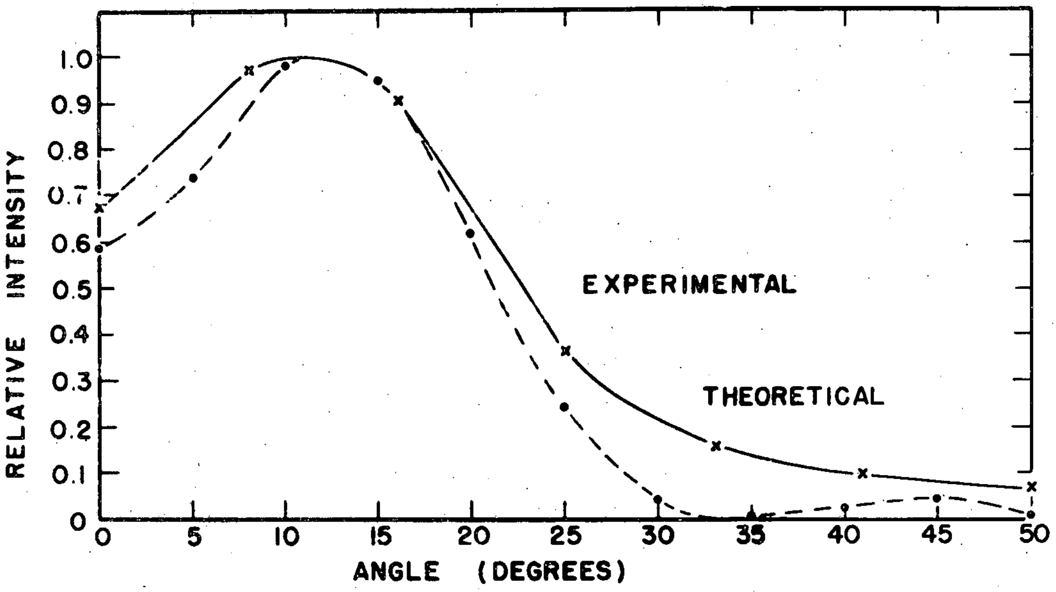

FIG. 2

ANGULAR DISTRIBUTION OF NEUTRONS (FROM DEUTERONS ON BERYLLIUM) DETECTED BY THE CARBON FOILS.

MU 16 12

	DETECTOR			
TARGET	$Al^{27}(n,p)Mg^{27}$	$Al^{27}(n,\alpha)Na^{24}$	$Cu^{63}(n,2n)Cu^{63}$	$C^{12}(n,2n)C^{11}$
Be	2.4	4.8	1.8	2.4
Al	2.0	3.7	2.0	1.5
Cu	1.4	1.8	0.48	0.61
Sn	1.6	2.3	0.52	2.1
Pb	2.5	1.1	0.38	0.33
U	0.47	0.66	0.14	0.34

TABLE I

RATIO OF FORWARD-TO-ISOTROPIC NEUTRONS IN THE OBSERVED ANGULAR DISTRIBUTIONS.

MU 1608

	DETECTOR			
TARGET	$Al^{27}(n,p)Mg^{27}$	$Al^{27}(n,\alpha)Na^{24}$	$Cu^{63}(n,2n)Cu^{62}$	$C^{12}(n,2n)C^{11}$
Be	34	34	42	DOUBLE ± 11 32% DIP
Al	30	28	28	22
Cu	44	40	36	DOUBLE ± 7 13% DIP
Sn	44	38	48	30
Pb	40	34	36	24
U	38	38	40	30

TABLE II

FULL WIDTH AT HALF-MAXIMUM, IN DEGREES, OF THE OBSERVED ANGULAR DISTRIBUTIONS.

MU 1609

REACTION	GROUND STATE OF INITIAL NUCLEUS		ℓ_p	STATE OF FINAL NUCLEUS	
$Be^9(d,n)B^{10}$	$\frac{3}{2}, \frac{5}{2}, \frac{7}{2}, \frac{9}{2}$	$-$	1	3	$+$
$Al^{27}(d,n)Si^{28}$	$\frac{5}{2}$	$+$	0	2,3	$+$
$Cu^{63}(d,n)Zn^{64}$	$\frac{3}{2}, \frac{5}{2}$	$+$	2	0	$+$

TABLE III

RESULTS OF ANALYSIS. ℓ_p IS THE ANGULAR MOMENTUM TRANSFERRED TO THE TARGET NUCLEUS.

MU 1610