PHYSICAL REVIEW VOLUME 121, NUMBER 3 FEBRUARY 1, 1961

Angular Distributions for $C^{13}(d,n)N^{14}$†

RICHARD ZDANIS,* GEORGE E. OWEN, AND L. MADANSKY
Department of Physics, The Johns Hopkins University, Baltimore, Maryland

(Received September 2, 1960)

Angular distributions of neutrons corresponding to transitions to the first (2.31 Mev) and second (3.95 Mev) excited states in the reaction $C^{13}(d,n)N^{14}$ have been measured at an incident deuteron energy of 1.3 Mev. A time-of-flight technique utilizing the associated gamma ray as a trigger was employed to separate the various neutron groups. Because the data, particularly for the first excited state transition, exhibited a relatively large intensity in the backward direction, a simple deuteron-stripping process is not sufficient to account for the results. An analysis which included the heavy-particle stripping mode was consistent with the data.

INTRODUCTION

THE reaction $C^{13}(d,n)N^{14}$ has been studied previously[1]; however, many of the investigations have concentrated upon the determination of the energy levels of N^{14}. Some attempt has been made[2] to make Butler[3] fits to the angular distributions.

The angular distributions of the neutrons corresponding to transitions to the first and second excited states exhibit a relatively high intensity at the backward angles. As a result a detailed investigation of the angular distributions has been made at a deuteron bombarding energy of 1.3 Mev.

The nucleus C^{13} should not undergo a heavy-particle stripping[4] of the outer $p_{\frac{1}{2}}$ neutron because of parity conservation. Therefore, if the large intensity at backward angles is to be interpreted as a process in which some of the emitted neutrons originate in the C^{13} nucleus, one must consider contributions from the $p_{\frac{3}{2}}$ shell.

A time-of-flight spectrometer based upon the design of Neilson and Sample[5] was constructed to study these angular distributions.

Since the gamma ray which is used to initiate the timing circuits arises from transitions between a $0(+)$ and a $1(+)$ state, the gamma neutron correlation for a fixed neutron angle is isotropic. Therefore this time-of-flight technique utilizing a fixed gamma-ray counter at 90° to the reaction plane enables one to measure a true neutron angular distribution.

† Supported by the U. S. Atomic Energy Commission.
* Now at the Department of Physics, Princeton University, Princeton, New Jersey.

[1] D. A. Bromley, Phys. Rev. **88**, 565 (1952); R. J. Mackin *et al.*, Phys. Rev. **98**, 43 (1955); R. D. Bent *et al.*, Phys. Rev. **98**, 1237 (1955); J. B. Marion *et al.*, Phys. Rev. **100**, 847 (1955).

[2] D. A. Bromley and L. M. Goldman, Phys. Rev. **86**, 790 (1952); R. E. Benenson, Phys. Rev. **90**, 420 (1953).

[3] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951); A. B. Bhatia *et al.* Phil. Mag. **32**, 485 (1952).

[4] L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955); G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957); T. Fulton and G. E. Owen, Phys. Rev. **108**, 787 (1957).

[5] G. C. Neilson, J. T. Sample, and J. B. Warren [Interscience Publishers, New York, (to be published)]; G. C. Neilson and D. B. James, Rev. Sci. Instr. **26**, 1018 (1955).

EXPERIMENTAL ARRANGEMENT

The time-of-flight spectrometer was set up to utilize the gamma ray associated with the 2.312-Mev state as a trigger. Since this gamma ray represents the decay from a spin-zero state, the $n-\gamma$ correlation is isotropic; and therefore an angular distribution taken in coincidence with this gamma ray represents a true angular distribution.

The gamma detector consisted of a $1\frac{1}{2}$-inch diameter, 1-inch thick NaI(Tl) crystal mounted upon an RCA-6342 phototube. This detector was located 12 cm above the target at 90° to the reaction plane. Although the NaI(Tl) does not provide maximum time resolution for the spectrometer, it does provide the energy resolution needed for gamma-ray selection. A side gating channel was used to select the 2.31-Mev photopeak from the NaI(Tl).

Because the neutron counter must be a large distance from the target in order to obtain sufficient time resolution, a large 2-in.×5-in.×24-in. Pilot *B* plastic scintillator was employed as a neutron detector. This scintillator was oriented with the long dimension perpendicular to the plane of the reaction and with the scintillator face bisected by the reaction plane. The scintillator was viewed through one end by an RCA-7046 photomultiplier which was coupled to the scintillator by means of a tapered light pipe 4 inches in length.

The neutron flight path was 1 meter in length and the neutron detector was tilted[5] 7° with respect to the perpendicular to compensate for the time of transit of light emitted at the far end of the scintillator.

Further side gating of the proton recoil pulses from 1.4 to 3.6 Mev kept the accidental background within workable limits.

The C^{13} targets were made by cracking C^{13}-enriched methyl iodide on a nickel backing. The targets used in these experiments were kindly made available to us by the U. S. Naval Research Laboratory.

In Fig. 1 a typical time-converter spectrum is shown. The nonlinearity in the time scale for short delays is caused by the unequal sensitivity of the two control grids of the 6BN6 converter tube.[5]

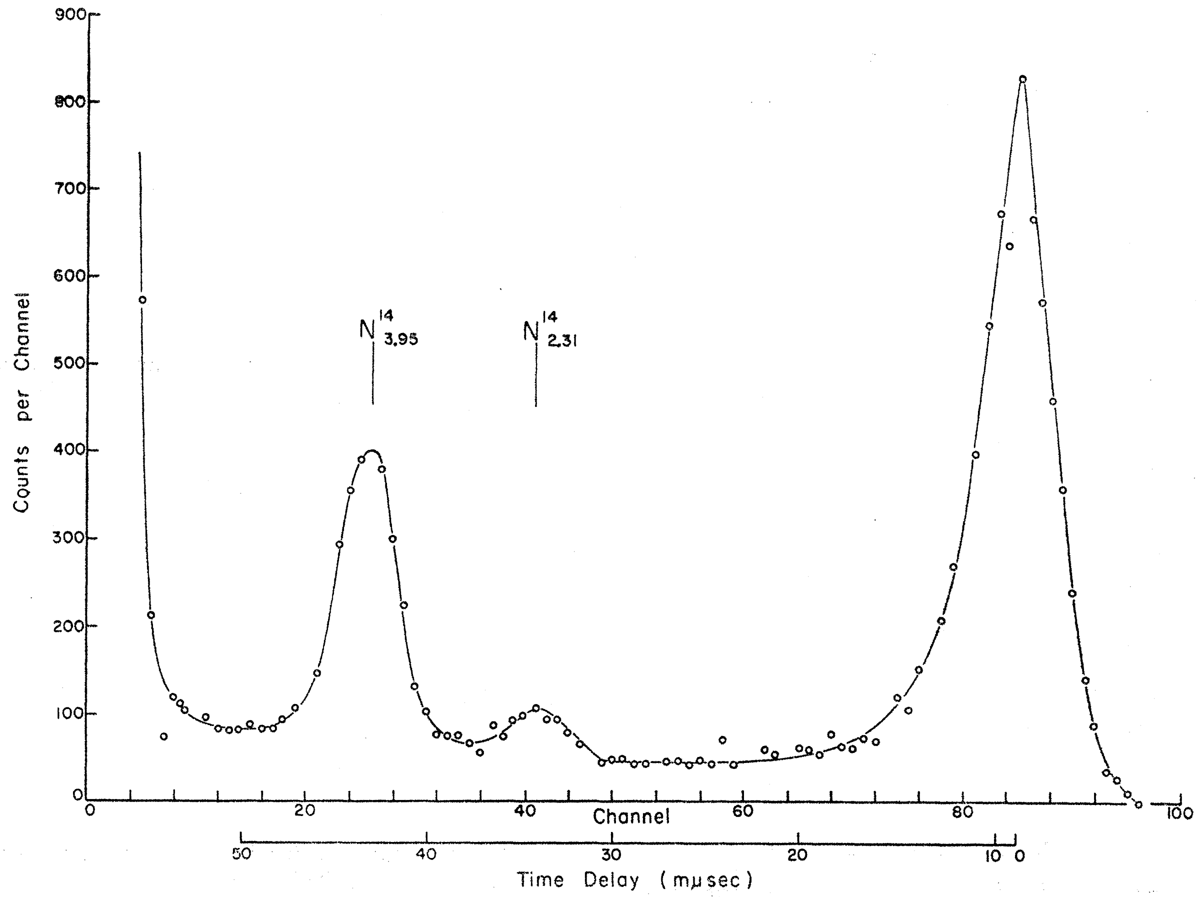

FIG. 1. Typical time-converter spectrum for $C^{13}(d,n)N^{14}$.

ANALYSIS OF THE DATA

Since the settings for the neutron side gate remained fixed for all runs, the efficiency of the side gating system varied as a function of observation angle. The number of counts in the peak of a time spectrum is proportional to the integral of the recoil proton spectrum between the limits set by the side-gating system. If the scintillation crystal is large enough so that end effects may be neglected, the integrated spectrum is a linear function of proton recoil energy.[6] This linear relationship may be expressed by

$$N=-(N_0/E_0)E+N_0,$$

where N = the number of recoil protons with energy above E, E_0 = the incident neutron energy, and N_0 = the total number of recoil protons. If kB and dE/dx are known for the scintillating material, then Birk's formula may be used to express N_0 in terms of N and pulse height. dE/dx was calculated using the method of Hirschfelder and Magee,[7] in which the formula $(C_{10}H_{11})_n$ was used for Pilot B.

[6] C. D. Swartz, G. E. Owen, and O. Ames, U. S. Atomic Energy Commission Report NYO-2053, 1957 (unpublished).

[7] J. E. Hirschfelder and J. L. Magee, Phys. Rev. **73**, 207 (1948).

With no upper limit used on the neutron side gate the number of counts in a time-spectrum peak is taken as a function of the setting of the lower limit for several incident neutron energies. These curves were extrapolated to zero counts for each incident energy. The experimental points so obtained were used to establish a kB value of 0.012 mg/kev-cm^2 for Pilot B.

The correction factor to the data is

$$(N_0/N)=P_0/(P_{\max}-P_{\min}),$$

where

$$P_0=\int_0^{E_0}\frac{dE}{1+kBdE/dx};$$

$P_{\max}$ is the smaller of the two quantities, (1) P_0 and (2) the maximum pulse height allowed by the side gate; $P_{\min}$ is the minimum pulse height allowed by the side gate.

The data were also corrected for the center-of-mass transformation and for the variation in detector efficiency due to a variation in $n-p$ cross section.

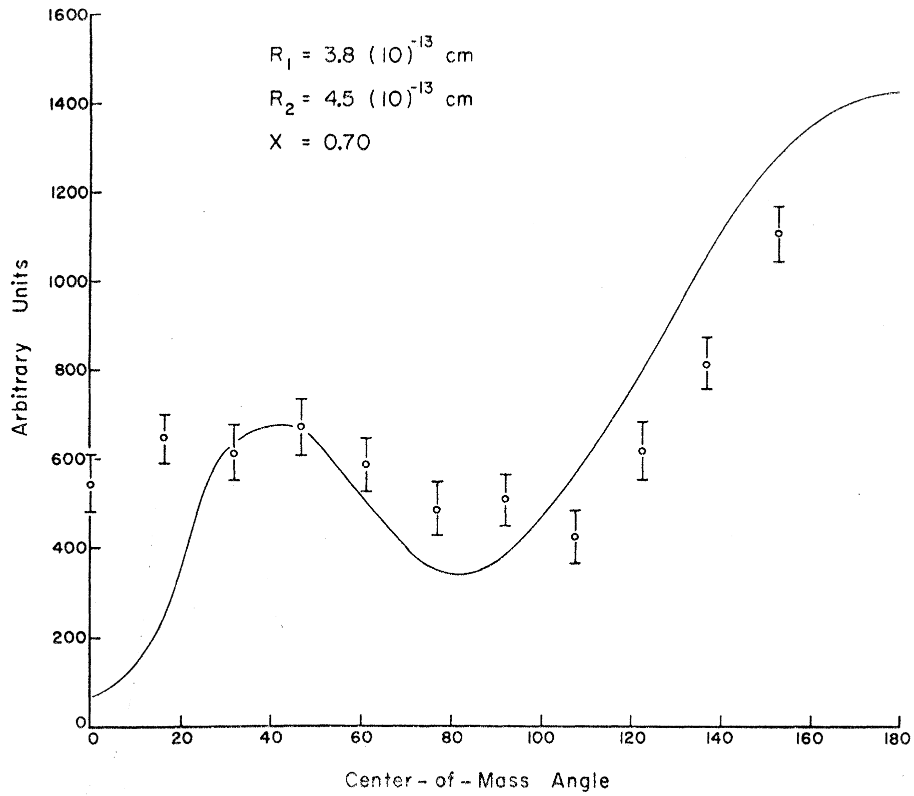

FIG. 2. Angular distribution for $C^{13}(d,n)N^{14}(2.31$ Mev).

RESULTS AND DISCUSSION

Angular distributions for the first and second excited state neutrons, at a bombarding energy of 1.3 Mev, are shown in Figs. 2 and 3, respectively.

The data were analyzed using the dual-mode stripping theory as given by Edwards.[8] For the heavy-particle stripping mode of the theory the "last" neutron is separated from the target nucleus and the residual core is captured by the deuteron to form the final excited state. It shall be shown that if a shell-model configuration (neglecting the closed s shell) of $p_{\frac{1}{2}}(p_{\frac{3}{2}})^8$ is used for the C^{13} ground state and $(p_{\frac{3}{2}})^{-1}(p_{\frac{1}{2}})^{-1}$ is used for the second excited state of N^{14},[9] then with $J-J$ coupling the $p_{\frac{1}{2}}$ neutron of C^{13} cannot be used as the "last" neutron.

TABLE I. Parameters used in obtaining the fits shown in Figs. 2 and 3.

	N^{14} excited state 1st	2nd
R_1	3.8×10^{-13} cm	3.8×10^{-13} cm
R_2	4.5×10^{-13} cm	4.5×10^{-13} cm
x	0.70	1.00
l_p	1	1
l_c	0	0

[8] S. Edwards, Phys. Rev. **113**, 1277 (1959).
[9] E. Warburton and W. Pinkston, Phys. Rev. **118**, 733 (1960).

Consider the (d,n) reaction from the ground state of $C^{13}(\frac{1}{2}-)$ to the first excited state of $N^{14}(0^+)$. If the $p_{\frac{1}{2}}$ neutron were removed from the C^{13}, the core would have spin zero and even parity. Conservation of parity would require the coupling of deuteron and core with even angular momentum. However, it is impossible to couple the spin of the deuteron with any even angular momentum and obtain a resultant of zero.

For reactions which leave the N^{14} nucleus in the second excited state, a spin flip would have to accompany the stripping process if the $p_{\frac{1}{2}}$ neutron were removed. It will be possible to fit the data without assuming a spin flip.

The calculated distributions used to fit the data were

$$[d\sigma(\theta)/d\Omega]_{1st} \propto G_d^2 f_d^2(k_1R_1) + 28.4x^2 G_H^2 f_H^2(k_2R_2) - 10.1x G_d f_d(k_1R_1) G_H f_H(k_2R_2)\cos\beta,$$

$$[d\sigma(\theta)/d\Omega]_{2nd} \propto G_d^2 f_d^2(k_1R_1) + 28.4x^2 G_H^2 f_H^2(k_2R_2) - 4.1x G_d f_d(k_1R_1) G_H f_H(k_2R_2)\cos\beta,$$

where the notation is that of reference 6. A delta-function approximation to the interaction potential was not used to generate the f's but rather the method of the kinematic factor[4] was used. The fits obtained are shown by the solid curves in Figs. 2 and 3, where the values of the adjustable parameters are shown in Table I.

An analysis such as the one presented is naturally subject to the qualification that various distortion

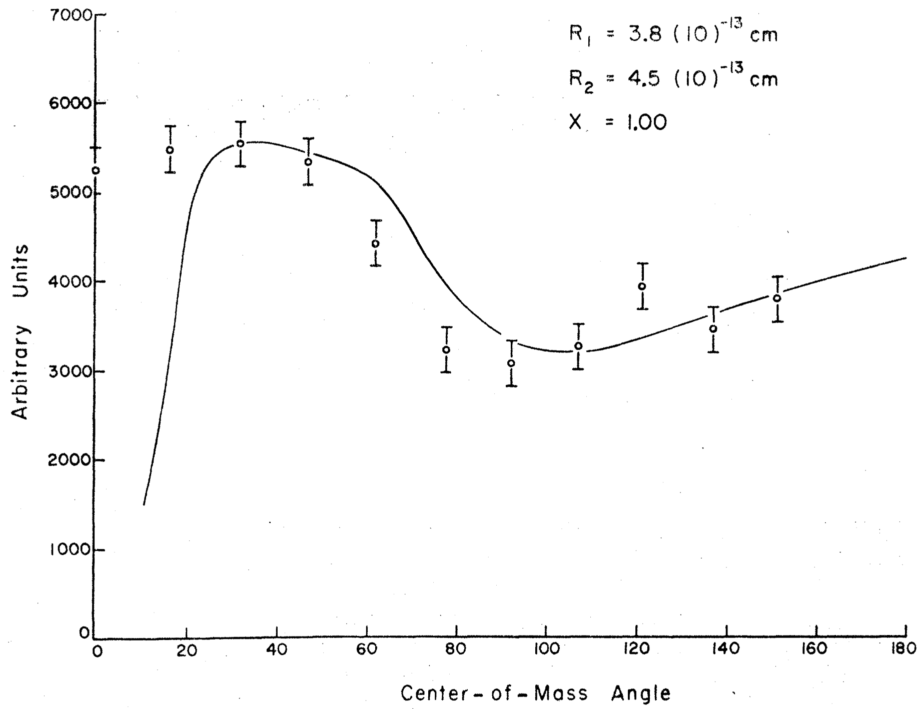

FIG. 3. Angular distribution for $C^{13}(d,n)N^{14}$(3.95 Mev).

effects have been neglected. Indeed it has been demonstrated[10] that the distortions can produce a measurable modification of the angular distributions. The results thus give a qualitative agreement only with the possible presence of "heavy-particle stripping."

It should be kept in mind, however, that the simple "forward" stripping analysis was found to hold qualitatively for many years before a distorted-wave calculation was attempted. In the same manner the "heavy-particle" stripping amplitude represents a primary process while the distorted-wave analysis is only a modification of the fundamental mode of the reaction. Because in many instances there is good reason to believe that the heavy-particle-stripping cross sections are large, it is essential that the analysis in terms of distorted waves include this amplitude. Otherwise, the resulting computation cannot be considered to provide a realistic result.

[10] L. C. Biedenharn *et al.*, Phys. Rev. **104**, 383 (1956); W. Tobocman, Phys. Rev. **115**, 98 (1959).

ACKNOWLEDGMENTS

We wish to express our gratitude to Dr. Steve Edwards for his guidance during this work. In particular we would like to express our thanks to Dr. E. A. Wolicki and Dr. H. Holmgren of the U. S. Naval Research Laboratory for making the C^{13} targets available to us.