Angular Correlation in the $B^{11}(d,n\gamma_{15.11\text{ MeV}})C^{12}$ Reaction*

H. J. KIM† AND E. F. SHRADER
Case Institute of Technology, Cleveland, Ohio
(Received 21 January 1963; revised manuscript received 27 May 1963)

Distorted-wave effects in stripping reactions may be more apparent in the analysis of nucleon-γ-ray angular correlation than in the angular distribution of the stripped nucleon. The reaction $B^{11}(d,n\gamma_{15.11\text{ MeV}})C^{12}$ has been used to study the distortion effect, since the angular distribution of neutrons feeding 15.11-MeV 1(+) state shows remarkably good agreement with the Butler stripping pattern. The angular distribution of other neutron groups of the reaction $B^{11}(d,n)C^{12*}$ cannot be fitted satisfactorily by Butler approximation. The neutrons feeding the 1(+) 15.11-MeV state of C^{12} as determined by a time-of-flight technique were detected in coincidence with the 15.11-MeV de-excitation γ ray emitted in direction of 10° and 90° relative to the incident deuterons at deuteron energies of 2.59 and 2.29 MeV. The result of the n-γ correlation shows marked departure from the plane-wave, Butler theory.

I. INTRODUCTION

THE angular distribution of the stripped nucleon from the deuteron stripping reaction has been a subject of considerable investigation, experimentally as well as theoretically. In particular, the deuteron stripping reactions on very light nuclei have been analyzed by numerous investigators in terms of ordinary stripping (both with plane waves and distorted waves) and plane-wave heavy particle stripping. Thus far, the various interaction modes have been applied mainly to the analysis of the angular distributions of the stripped nucleon, with sporadic success.

A consistent study of the angular correlation of the stripped nucleon and decay gamma ray and the nucleon polarization along with the angular distribution for a given reaction is a powerful means of studying the mode of stripping as has been discussed by Satchler and Tobocman.[1]

As a demonstrative case of testing the various modes of stripping mechanism involved, the reaction $B^{11}(d,n)C^{12*}$, $C^{12*}(15.11\text{ MeV})\rightarrow C^{12}+\gamma_{15.11\text{ MeV}}$ is experimentally convenient and a very interesting one to analyze. The heavy stripping mode of Owen and Madansky[2] was devised in order to explain the (d,n) reaction on B^{11}, and the $B^{11}(d,n)C^{12*}(15.11\text{ MeV})$ reaction is the very reaction Warburton and Chase[3] considered to be a case where the stripping would mainly proceed by plane-wave approximation of Butler since the Q value is low. The dispersion relation applied to the stripping[4] reaction implies that for $E_d\cong 2|Q|$ and $Q\cong -1$ MeV the predominant contribution to the angular distribution is from the stripping pole implying that the Butler stripping theory would be well applied to the $B^{11}(d,n)C^{12*}(15.11\text{ MeV})$ at $E_d\cong 2.5$ MeV, since the Q value of the above reaction is -1.38 MeV.

The neutron angular distribution of the above reaction has been studied in detail for the incident energies ranging from the threshold to 2.7 MeV, and it was shown that the Butler stripping theory indeed does predict the shape of the neutron angular distribution very accurately for the whole incident energy range considered. However, the neutron groups feeding the ground, 4.43-MeV, and 12.73-MeV states of C^{12} do not show such simple angular distributions.[5] Despite the success with which the Butler theory predicts the shape of the above angular distribution, the absolute cross section is off by an order of magnitude. In view of the above observation and consideration, it was felt that a more sensitive test of the stripping mechanism than the mere angular distribution was necessary in order to examine the validity of the dominance of stripping pole under the conditions $E_d\cong 2|Q|$ and $Q\cong -1$ MeV and to see the distorted-wave effects. The n-γ angular correlation of this reaction is a very suitable and convenient one experimentally, for the 15.11-MeV (1^+) state of C^{12} mainly decays to the (0^+) ground state through pure dipole radiation,[6] making its detection quite easy even against copious γ-ray background from other reactions as well as the neutron background.

II. THEORY

In the reaction $B^{11}(d,n)C^{12*}(15.11\text{ MeV})$ the stripped nucleon carries one unit of orbital angular momentum, i.e., $l=1$. If, in addition, the j value of the nucleon is $\frac{3}{2}$ or a mixture of $\frac{3}{2}$ and $\frac{1}{2}$, a nonisotropic n-γ correlation is possible. In this case the correlation function, in the notation of Ref. 1, may be written

$$W(\theta,\phi)=1+A_2^0P_2(\cos\phi)+A_2^2P_2^2(\cos\phi)\cos(\theta-\theta_0),\quad(1)$$

where θ and ϕ are the angles relative to the z axis perpendicular to the reaction plane, i.e., along $\mathbf{n}=\mathbf{k}_d\times\mathbf{k}_n$.

When the γ ray is observed in the reaction plane, i.e., $\phi=\frac{1}{2}\pi$, the expression reduces to

$$W(\theta,\tfrac{1}{2}\pi)=[2/(2+\alpha)][1+\alpha\cos^2(\theta-\theta_0)],\quad(2)$$

* Supported in part by the U. S. Atomic Energy Commission.
† Present address: ORNL, Oak Ridge, Tennessee.
[1] G. R. Satchler and W. Tobocman, Phys. Rev. **118**, 1566 (1960).
[2] G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).
[3] E. K. Warburton and L. F. Chase, Phys. Rev. **120**, 1095 (1960).
[4] R. D. Amato, Phys. Rev. Letters **2**, 399 (1959).
[5] H. J. Kim and E. F. Shrader, Phys. Rev. **129**, 1275 (1963).
[6] R. W. Kavanagh and C. A. Barnes, Phys. Rev. **112**, 503 (1958).

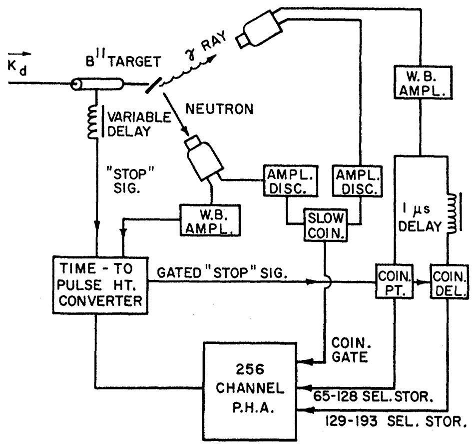

FIG. 1. Block diagram of the instrumentation.

where

$$\alpha=\frac{-6\lambda A_2{}^0}{2-(1-3\lambda)A_2{}^0}\quad\text{and}\quad\lambda=2\left(\frac{-A_2{}^2}{A_2{}^0}\right).$$

The distorted-wave theory restricts $1\leq\lambda\leq 0$ and $\lambda=\lambda(\theta_n)$, while λ is independent of neutron emission angle θ_n and $\lambda=1$ in the plane-wave approximation. Also, the plane-wave theory requires γ-ray symmetry angle θ_0 to coincide with recoil angle. The existence of a symmetry axis is predicted by the distorted-wave theory, however, the symmetry angle need not coincide with the recoil angle. The constant $A_2{}^0$ contains information pertinent to the nuclear coupling scheme.

An efficient way to obtain the effects of distortion by observing the n-γ angular correlation for an $l=1$ stripping reaction would be to observe the neutron angular distribution in coincidence with the de-excitation γ ray for the fixed γ-ray angle θ_γ in the scattering plane. In the scattering plane, the correlation function (2) becomes

$$W(\theta_n,\theta_\gamma)=[2/(2+\alpha)][1+\alpha(\theta_n)\cos^2(\theta_{n\gamma}-\theta_0)],\quad(3)$$

where $\theta_{n\gamma}$ is the angle between the neutron and γ ray and $\theta_0=\theta_0(\theta_n)$. In the plane-wave approximation θ_0 is the recoil angle and α is independent of θ_n, therefore, experimental determination of Eq. (3) is a very efficient method of examining the validity of the plane-wave approximation. Furthermore, $W(\theta_n,\theta_\gamma)+W(\theta_n,\theta_\gamma+90°)=1$, independent of the details of mechanism. This fact is the unique property of $l=1$ stripping.

III. EXPERIMENTAL DETAILS

An elemental B^{11} target, isotopically enriched to 98.6% and evaporated on a Ta sheet, was used for the investigation. The neutrons were detected by a 2-in.-diam×2-in.-long plastic scintillator detector, their energy being determined by the time-of-flight method utilizing the Case pulsed 3-MeV Van de Graaff accelerator. A 3-in.-diam×3-in.-long NaI(Tl) crystal was used for the γ-ray detector. A block diagram of the electronic instrumentation is shown in Fig. 1. The time-of-flight spectrum of neutrons from the (d,n) reaction on B^{11} in coincidence with the 15.11-MeV de-excitation γ ray $(1^+\rightarrow 0^+)$ was observed by demanding a prompt coincidence between a stop pulse gated on by a detected neutron and a pulse from the NaI crystal corresponding to the detection of a 15.11-MeV γ ray. The prompt coincidence generated a routing pulse which stored the time-of-flight spectrum in the second quadrant of a 256-channel pulse-height analyzer. Not all such coincidences of this kind arise from associated production (i.e., from the same nuclear event).

The time-of-flight spectrum resulting from n-γ coincidences of the nonassociated variety was obtained as follows. The γ-ray pulse was delayed 1 μsec in a second coincidence channel and a routing pulse was generated whenever this delayed γ pulse and neutron-gated stop signal were in coincidence. Since the interval between pulses from the Van de Graaff is 1 μsec such coincidences arise from γ rays and neutrons from adjacent beam pulses and hence are nonassociated. The nonassociated (or accidental) time-of-flight spectrum is stored in the third quadrant of the pulse-height analyzer by a suitable routing pulse. A slow side channel coincidence circuit was used to set the neutron detector efficiency and to select only the 15.11-MeV γ rays.

A typical performance of the instrumentation is illustrated in Fig. 2 which shows the time-of-flight spectrum in the neutron energy region of interest. The difference in counts between the accidental plus real coincidences and the accidental coincidences determines the unambiguous true coincidences between the neutron and the associated de-excitation γ ray. The data shown in Fig. 2 were the result of 1 hour run with a time average deuteron current of 2 μA with detector distances of 18 cm for

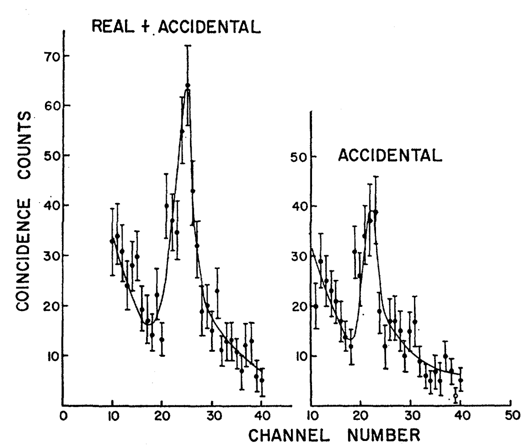

FIG. 2. A typical time-of-flight neutron spectrum in coincidence with 15.11-MeV de-excitation γ ray. Neutron flight time increases from left to right. The real plus accidental coincidences and the accidental coincidences are recorded simultaneously by routing pulses as described in the text.

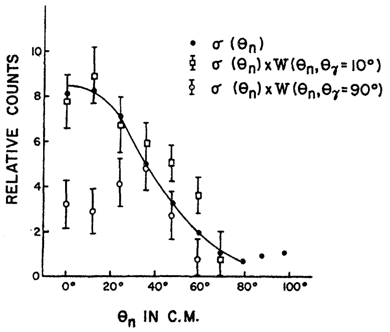

FIG. 3. Coincident neutron counts for $E_d=2.59$ MeV and fixed $\theta_\gamma=10°$ and 90°. The solid circles represent uncorrelation neutron angular distribution and the smooth curve is a Butler fit with l captured proton $=1$, $R=5.6$ F, and $E_d=2.6$ MeV.

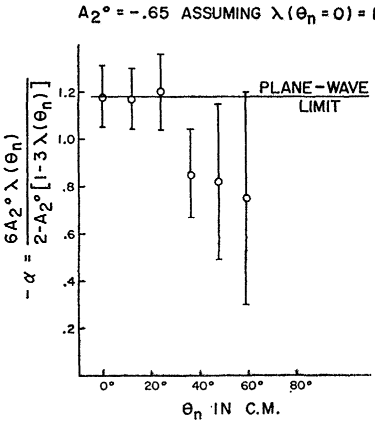

FIG. 5. Distortion parameter $\alpha(\theta_n)$ for $E_d=2.59$ MeV. See Ref. 1 for the notations used.

the γ-ray detector and 85 cm for the neutron detector. On the average 3 hour runs were made per correlation datum.

IV. RESULTS

The results of n-γ coincidences for $\theta_\gamma=90°$ and $\theta_\gamma=10°$ along with the uncorrelated neutron angular distribution for $E_d(\text{lab})=2.59$ MeV are shown in Fig. 3 along with the arbitrarily normalized result of plane-wave deuteron stripping approximation. Since the neutron angular distribution obtained in coincidence with the γ ray is proportional to the product of $W(\theta_n,\theta_\gamma)$ and the uncorrelated angular distribution, the correlation functions as defined in Eq. (3) were obtained by dividing the coincidence counts by the experimental angular distributions, and they are shown in Fig. 4. The uncertainties shown in the figures are standard deviations due to counting statistics only.

A correlation function for $\theta_\gamma=0°$ was physically unattainable, therefore a correlation function for $\theta_\gamma=10°$ was taken instead. The relation $W(\theta_n,\theta_\gamma)+W(\theta_n,\ \theta_\gamma+90°)=1$ is seen in Fig. 4. Attempts to fit the correlation functions with the plane-wave approximations ($\lambda=1$, θ_0 is the recoil angle) for many arbitrary values of $A_2{}^0$ failed to produce the experimental results. However, the experimental results can be fitted by varying λ and θ_0. The distorted-wave theory, unlike the plane-wave theory, requires θ_n dependence of λ and existence of θ_0 which is not necessarily the recoil angle. The best fitting parameters α and θ_0 are shown in Figs. 5 and 6 along with the plane-wave limits.

An attempt to obtain usable data for incident deuteron energy $E_d=2.88$ MeV was rather fruitless due to the poor counting rate, and the scanty data taken at that energy were discarded from the discussion.

V. CONCLUSION

Despite the poor statistics shown, it is very evident that the plane-wave approximation is not adequate to explain the results of n-γ angular correlation of the reaction $B^{11}(d,n\gamma_{15.11\text{ MeV}})C^{12}$. In the spirit of the plane-wave approximation, it is very surprising that the theory is adequate to predict the shape of the neutron angular distribution for a wide range of incident energy, but fails entirely to predict the proper correlation. In view of the present result, one needs to examine the validity of the plane-wave stripping approximation for low Q-value deuteron stripping reactions.

It is not anticipated that a realistic distorted-wave calculation can be made for the present investigation since the analysis of elastic scattering at these energies

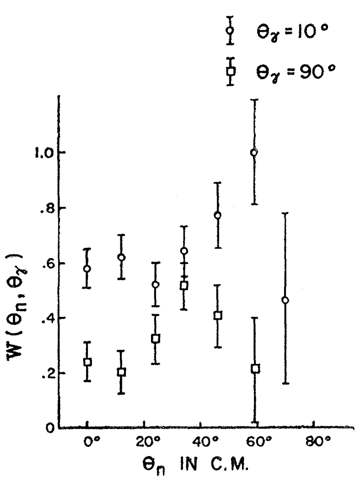

FIG. 4. Normalized correlation functions $W(\theta_n,\theta_\gamma)$ for $E_d=2.59$ MeV and $\theta_\gamma=10°$ and 90°.

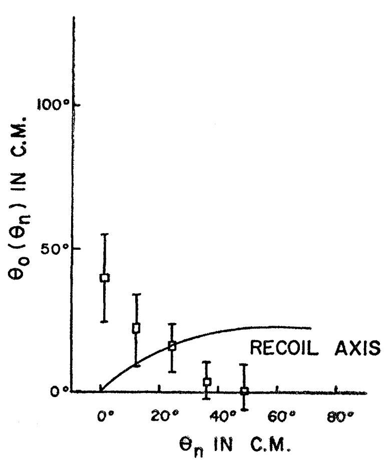

FIG. 6. γ-ray symmetry angle θ_0 as a function of neutron direction. The average values of θ_0 determined from the correlation functions $W(\theta_n,\ \theta_\gamma=10°)$ and $W(\theta_n,\ \theta_\gamma=90°)$ are shown. The smooth curve is the plane-wave limit.

from B^{11} as well as C^{12} in terms of the optical model presents difficulties. The present investigation, however, is a definite demonstration of the value and sensitivity with which the mechanism of stripping reaction may be tested by means of n-γ angular correlation.

It seems that the dominant mechanism of observed stripping reaction can be analyzed in detail by observing stripped nucleon angular distribution along with n-γ angular correlation and/or stripped nucleon polarization.

The present investigation also casts some light on the observed difficulty of explaining the neutron angular distributions feeding ground, 4.43-MeV, and 12.73-MeV states of C^{12} by the (d,n) reaction on B^{11}. The fact that these neutron groups deviate radically from the plane-wave approximation, while the neutrons feeding the 15.11-MeV state show remarkable "good stripping" pattern, need not be puzzling, if one considers the significant distortion effects demonstrated by the present investigation.

ACKNOWLEDGMENTS

We would like to express our appreciation to B. M. Shoffner for his interest and help with the instrumentation, and to L. L. Hinkley for looking after the accelerator at difficult times. Discussions with W. Tobocman, G. R. Satchler, and M. A. Nagarajan are very much appreciated. One of the authors (H.J.K.) is very grateful to the Oak Ridge National Laboratory for making the completion of this investigation possible.

PHYSICAL REVIEW VOLUME 131, NUMBER 6 15 SEPTEMBER 1963

Decay of Pt^{197}†

R. G. HELMER
National Reactor Testing Station, Phillips Petroleum Company, Idaho Falls, Idaho
(Received 13 May 1963)

The decay of $_{78}Pt^{197}$ (20 h) to $_{79}Au^{197}$ was studied by means of gamma-ray scintillation spectrometry. Three gamma-ray transitions of 77, 191, and 269 keV exist. The energy of the third transition was found to be (269.2 ± 0.5) keV, instead of the previously reported value of 279 keV. A new decay scheme is proposed with only two excited states, at 77 and 269 keV. The possible effects of these results on the interpretation of measurements of the Coulomb excitation of Au^{197} and of the decay of Hg^{197} are discussed.

I. INTRODUCTION

THE primary purpose of this study was to remeasure the energy and relative intensity of the highest energy gamma ray in the decay of Pt^{197} (20 h).[1] Previously, this energy had been reported to be 279 keV.[2,3] This value is inconsistent with the interpretation of this transition as the cross over from the 269-keV level which is depopulated by a cascade made up of transitions of 191 and 77 keV. The level scheme proposed in Ref. 2 is shown in Fig. 1.

The low-energy levels of Au^{197} are also populated by the decay of Hg^{197m} (24 h), Hg^{197} (65 h), and the Coulomb excitation of Au^{197}. Also shown in Fig. 1 are the decay schemes[1,4–7] associated with these processes. These results establish the existence of levels in Au^{197} at about 269 and 279 keV. (Conversion-electron measurements[4,6] definitely show that these are distinct levels.)

The samples used in this study consisted of platinum metal enriched in Pt^{196} (2% Pt^{198}, 66% Pt^{196}, 26% Pt^{195}, 6% Pt^{194}). The samples were irradiated in the Materials Testing Reactor in a flux of 2×10^{14} neutrons-sec^{-1}-cm^{-2} for about 12 h. After the Pt^{199} (30 min) activity had decayed several half-lives, the daughter activity Au^{199} was observable. The gold was then removed by solvent extraction of the chloride in ethyl acetate. The platinum was further purified by precipitation as ammonium chloroplatinate.[8] Gamma-ray spectra taken subsequently did not reveal the presence of any residual gold in the platinum.

Gamma-ray spectra are measured with a scintillation spectrometer consisting of a 3-in.×3-in. cylindrical NaI(Tl) crystal, DuMont 6363 photomultiplier, preamplifier, A-8 amplifier, and a 512-channel pulse-height analyzer. The crystal is mounted near the center of a

---

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC 5-1-17 to 5-1-19, and 5-1-21 to 5-1-28. See data on Au^{197}, Pt^{197}, and Hg^{197}.

[2] V. R. Potnis, C. E. Mandeville, and J. S. Burlew, Phys. Rev. **101**, 753 (1956).

[3] M. C. Joshi and B. V. Thosar, in *Proceedings of the International Conference on Nuclear Structure, Kingston, Canada*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 623.

[4] J. W. Mihelich and A. de-Shalit, Phys. Rev. **91**, 78 (1953).

[5] See references in Table IV.2 of K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956).

[6] D. H. Rester, M. S. Moore, F. E. Durham, and C. M. Class, Nucl. Phys. **22**, 104 (1961).

[7] P. H. Stelson and F. K. McGowan, Phys. Rev. **99**, 112 (1955).

[8] The author wishes to express his appreciation to L. D. McIsaac for carrying out the chemical separations.