$N^{15}(p,n)O^{15}$ Ground-State Reactions and the Quasielastic Model of (p,n) Reactions*

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The $N^{15}(p,n)O^{15}$ reaction has been studied from 3.95 to 9.0 MeV using a "long counter." Absolute cross sections and angular distributions have been measured from 0° to 170° in 10° steps. The analysis of the angular distributions has been done using the optical-model potential suggested by Lane which is a function of the isotopic spins of the incident proton and target nucleus. The calculations were made using a distorted-wave Born approximation and also, for the higher energies, optical-model analysis. The results of these two methods are compared. The excitation function shows broad resonances at 4.30, 5.50, 6.50, 7.65, and 8.99 MeV. With the exception of the resonance at 4.30 MeV, all the others can be interpreted as due to single-particle resonances. A tentative assignment of l and J values is given.

INTRODUCTION

IT has been pointed out by Lane[1] that the optical-model potential for nucleons contains a dependence on the scalar product of the isobaric spins t and T of the incident nucleon and target nucleus. This results from calculating the potential as the sum of two-body Heisenberg forces plus the exchange effects of other forces averaged over a Fermi gas. The optical potential is given by $U=U_0+(U_1/A)(\mathbf{t}\cdot\mathbf{T})$, where U_0 is the standard optical potential, and U_1 is energy-dependent and, for simplicity, is assumed to be real with the same radial dependence as the real part of U_0.

Among the effects of this isobaric-spin term in the potential are the splitting of the proton-particle levels, the proton potential anomaly pointed out earlier by Green,[2] and the so-called quasielastic (p,n) reactions observed by Anderson *et al.*[3,4]

In these (p,n) reactions the final nuclear state is the isobaric counterpart of the target state. The effect of the $(\mathbf{t}\cdot\mathbf{T})$ term has been to charge exchange the incident proton into the outgoing neutron.

On the other hand, Bloom *et al.*[5] have pointed out that the ground-state (p,n) reactions on mirror nuclei singles out the isotopic-spin exchange part of the proton-neutron interaction inside the nucleus. They suggested looking for these (p,n) reactions in light nuclei[6–8] such as Be^9, B^{11}, C^{13}, N^{15}, Al^{27}, and Si^{29}.

In the $N^{15}(p,n)O^{15}$ ground-state reaction N^{15} and O^{15} are mirror nuclei such that the ground state of O^{15} is the isobaric counterpart of the target nucleus. For this reason it was thought that it would be of interest to use the optical-model potential proposed by Lane[1] in the analysis of the angular distributions of the ground-state neutrons from this reaction.

The $N^{15}(p,n)O^{15}{}_{GS}$ reaction has been previously measured by Jones *et al.*[9] from threshold up to 6.4-MeV incident proton energy with a "long counter" and by Wong *et al.*[7] from 5.5 to 13.6 MeV using time of flight. In the present work the (p,n) reaction was measured using a long counter from threshold up to 9 MeV, which is just below the first excited state of N^{15} at 9.34 MeV.

The absolute angular distributions measured from 0° to 170° in 10° steps were analyzed using the Lane potential[1] in a distorted-wave Born approximation (DWBA) calculation.[10] Optical-model calculations were also done for the higher energies.

Furthermore, the $N^{15}(p,n)O^{15}$ reaction cross section as a function of the incident proton energy showed broad resonances at 5.5, 6.50, 7.65, and 8.99 MeV. The width of these resonances (~1-MeV total width) as well as the characteristics of the angular distributions suggest that they can be single-particle resonances due to energy levels in O^{16}. A tentative identification of these resonances with single-particle levels calculated in terms of the particle-hole interaction in O^{16} by Gillet *et al.*,[11] Brown *et al.*,[12] Elliott and Flowers,[13] and Lane[14] has been made. Although the agreement between the experimental position of these levels and the calculated one is quite good, the assignment made is only a tentative one. No calculations were performed to check them except for a Legendre-polynomial fit of the angular distributions. This procedure provided some information on the possible values of the angular momentum involved.

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[1] A. M. Lane, Nucl. Phys. **35**, 676 (1962).
[2] A. E. S. Green, Phys. Rev. **111**, 1147 (1958).
[3] J. D. Anderson and C. Wong, Phys. Rev. Letters **7**, 250 (1961).
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[5] S. D. Bloom, N. K. Glendenning, and S. Moszkowski, Phys. Rev. Letters **3**, 98 (1959).
[6] R. D. Albert, S. D. Bloom, and N. K. Glendenning, Phys. Rev. **122**, 862 (1961).
[7] C. Wong, J. D. Anderson, S. D. Bloom, J. W. McClure, and B. D. Walker, Phys. Rev. **123**, 598 (1961).
[8] S. D. Bloom, N. K. Glendenning, L. F. Hansen, and H. F. Lutz (to be published).
[9] K. W. Jones, L. J. Lidofsky, and J. L. Weil, Phys. Rev. **112**, 1252 (1958).
[10] R. Satchler (private communication).
[11] V. Gillet and N. Vihn Mau, Phys. Letters **1**, 25 (1962).
[12] G. E. Brown, L. Castillejo, and J. A. Evans, Nucl. Phys. **21**, 1 (1961).
[13] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A242**, 57 (1957).
[14] A. M. Lane, Rev. Mod. Phys. **32**, 519 (1960).

EXPERIMENTAL METHOD

Protons from the 90-in. variable-energy cyclotron were used to produce the (p,n) reactions in N^{15} and the outgoing neutrons were detected with a long counter.

The N^{15} target was a cylindrical cell $\frac{3}{4}$ in. in diameter by 2-in. long with 0.035-in. wall thickness. The entrance window was a 0.00025-in. Ta foil. The inside of the target was lined with 0.010-in. gold foil to reduce the neutron background. The background due to the target, an increasing function of incident proton energy, was around 5% below 5-MeV protons, about 50% for 7 MeV, and as much as 80% for 9-MeV protons.

To have good information on the background, two identical gas cells were mounted in a flip-flop type system, one filled with N^{15} gas to a pressure of 14.7 psi and the other at vacuum; and alternate measurements of the target neutrons and background were made at each angle. Furthermore, to minimize the general background, U^{238} collimators were used in the collimation of the proton beam, surrounded by borate-paraffin shielding.

The purity of the N^{15} gas was between 90 and 95% for the different runs and it was checked by a mass-spectrographic analysis before and after each run.

The long counter was mounted on a remote control angle changer and the face of the BF_3 counter subtended an angle of 7.52° at the center of the target. The angular distributions were measured each 10° and the reproducibility of the angles was better than 1°. The statistical error in the counting rate at each angle was 3% or less.

The experimental data presented in this paper were obtained from four independent runs at the cyclotron. The reproducibility of the data was better than 5% on the average.

The calibration of the long counter has been described elsewhere.[15] The absolute cross sections were obtained by measuring the neutron flux from a Po-Be source (calibrated by the National Bureau of Standards) set at the center of the N^{15} gas cell.

EXPERIMENTAL RESULTS

The $N^{15}(p,n)$ cross section was measured from 3.95 to 8.99 MeV. In this energy region, measurements have been made by Jones *et al.*[9] from 3.78 to 6.40 MeV and by Wong *et al.*[7] from 5.5 to 13.6 MeV.

Figure 1 shows the absolute differential cross sections for the ground-state neutrons in the center-of-mass system, as a function of the proton energy. The errors indicated are absolute errors in the differential cross section and are of the order of 10%. The errors indicated in the proton energy are the result of the energy spread of the proton beam due to target thickness.

This spread in the proton energy from around 200 keV for the lower energies to about 130 keV for the higher

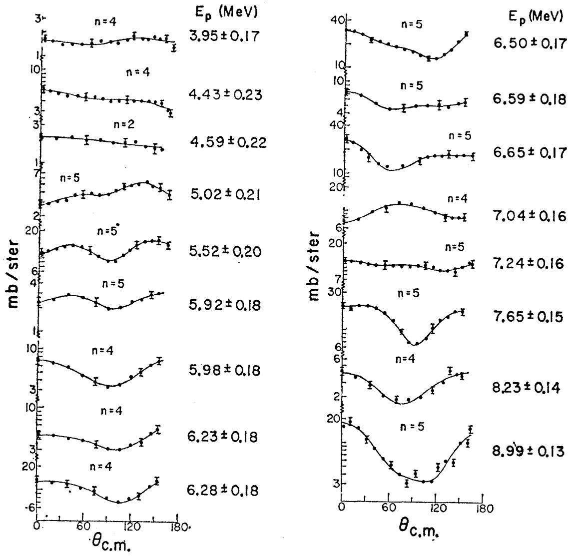

FIG. 1. Absolute angular distributions in the center-of-mass system for the ground-state neutrons from the reaction $N^{15}(p,n)O^{15}$ as a function of the proton energy in the laboratory system.

energies is wider than the level spacing in O^{16} at excitation energies above 15.66 MeV, which is the corresponding energy for the threshold of the (p,n) reaction in N^{15}.

In the present experiment, it is not possible to observe resonances due to single levels in the compound nucleus O^{16}, which have a half-width of around 40 keV as measured by Jones *et al.*[9] However, this experimental energy spread is small enough to allow observation of the gross structure consistent with the single-particle states of the shell model. As will be discussed later, these size resonances appeared in the excitation function of the $N^{15}(p,n)O^{15}$ reaction.

The main characteristic of the observed angular distributions is the slow variation of their features as a function of the increasing proton energy, which corroborates the results of Wong *et al.*[7] Figures 2, 3, and 4 show the agreement in the shape of the angular distributions, as well as the absolute values of the differential cross sections among the results of this work and those of Jones *et al.*[9] and Wong *et al.*[7] for some equivalent proton

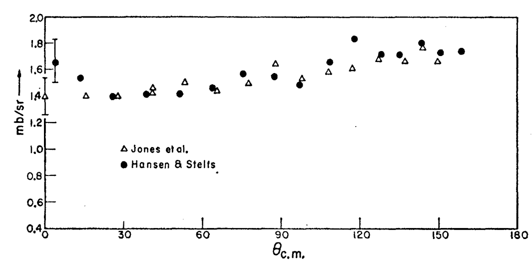

FIG. 2. Comparison of the angular distributions for the neutrons from $N^{15}(p,n)O^{15}{}_{GS}$ at 3.95 MeV (lab system) obtained by Jones *et al.* (Ref. 9) (△) and this work (●).

[15] L. F. Hansen and R. D. Albert, Phys. Rev. **128**, 291 (1962).

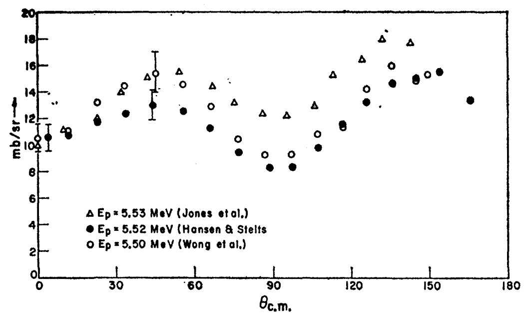

FIG. 3. Angular distributions for the neutrons from $N^{15}(p,n)$-$O^{15}{}_{GS}$ obtained by Jones *et al.* (Ref. 9) (△) at 5.53 MeV, Hansen and Stelts (●) at 5.52 MeV, and Wong *et al.* (Ref. 7) (○) at 5.50 MeV.

energies. The absolute differential cross sections from Jones' work at 3.98- and 5.53-MeV proton energy were obtained by normalizing their angular distributions to the absolute value of the cross section measured at 0°.

Table I shows the absolute measured cross sections

TABLE I. Absolute measured cross sections at 0°.

E_p (MeV)	$\sigma(p,n)_{0°\ \mathrm{lab}}$ (mb/sr)	$\sigma(p,n)_{0°\ \mathrm{lab}}$ (Jones *et al.*) (mb/sr)
3.95	3.0 ±0.30	5.3±2.65
4.43	8.15±0.85	10.3±5.15
5.52	12.6 ±1.26	8 ±4.0
6.23	5.8 ±0.58	6 ±3.0

at 0° in the laboratory system obtained by Jones *et al.*[9] and this work.

Figure 5 shows the total (p,n) cross section as a function of the incident proton energy. Combining the results of Wong *et al.*[7] with the present work, one can outline three pronounced wide resonances with a half-width of around 1 MeV at 5.5, 6.5, and 7.65 MeV. There are two other smaller resonances, one at 4.43 MeV, which has a half-width of around 0.5 MeV, and the other at 9 MeV.

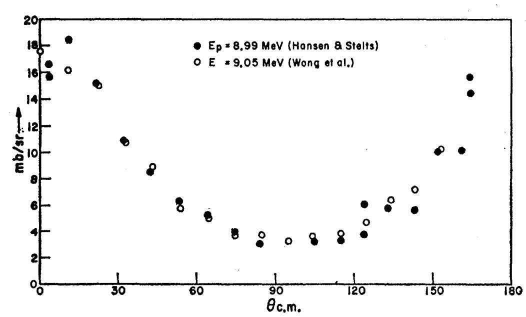

FIG. 4. Comparison of the angular distributions in the CMS for the neutrons from $N^{15}(p,n)O^{15}{}_{GS}$ obtained by Wong *et al.* (Ref. 7) (○) at 9.05 MeV and Hansen and Stelts (●) at 8.99 MeV (lab system).

This gross structure observed in the total cross section appears also in the differential cross section. Figure 6 shows the absolute differential cross section as a function of incident proton energy at 0° and 180°. The general features of these wide resonances seem to be independent of angle, and only a function of the incident energy.

DISCUSSION OF THE RESULTS

The angular distributions have been analyzed using the optical potential suggested by Lane:

$$U=U_0+(U_1/A)(\mathbf{t}\cdot\mathbf{T}), \quad (1)$$

where U_0 is the standard optical potential given by

$$U_0=V_C(r_C)-Vf(r)+iW'g(r)+\lambda_\pi V_{S0}\frac{df(r)}{dr}(\mathbf{l}\cdot\boldsymbol{\sigma}). \quad (2)$$

U_1 is assumed to be real and to have the same radial dependence as U_0, $U_1=V_1f(r)$.

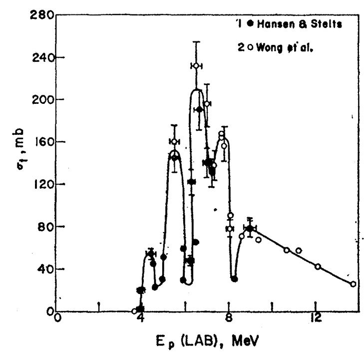

FIG. 5. Absolute excitation function for the $N^{15}(p,n)O^{15}{}_{GS}$ reaction from 3.95- to 13.6-MeV proton energy.

The symbols used in Eq. (2) have the conventional meaning in optical-model calculations.

The scalar product $\mathbf{t}\cdot\mathbf{T}$ has two eigenvalues: $\frac{1}{2}T$ and $-\frac{1}{2}(T+1)$, which correspond to the two values of the total isotopic spin of the system: $T\pm\frac{1}{2}$, where $\frac{1}{2}$ is the isobaric spin t of the proton and T the spin of N^{15}. Lane and Soper[16] have shown that the target nucleus is predominantly in the state of minimum isotopic spin T_0

$$T_{N^{15}}=T_0=\tfrac{1}{2}(N-Z)=\tfrac{1}{2}. \quad (3)$$

The angular distributions for the outgoing neutrons were calculated[10] using the distorted-wave Born approximation. The specific optical potential used was the one obtained by Perey *et al.*[17] to fit the elastic-scattering data for middle nuclei and used by Drisko *et al.*[18] to fit the quasielastic (p,n) reactions[3,4] in V^{51} and Co^{59}. The optical parameters used in these calculations were: $r_0=1.25$F, $a=0.65$F, $a'=0.47$F, and

[16] A. M. Lane and J. M. Soper, Nucl. Phys. **37**, 506 (1962).
[17] F. Perey and B. Buck, Nucl. Phys. **32**, 353 (1962).
[18] R. M. Drisko, R. H. Bassel, and G. R. Satchler, Phys. Letters **2**, 318 (1962).

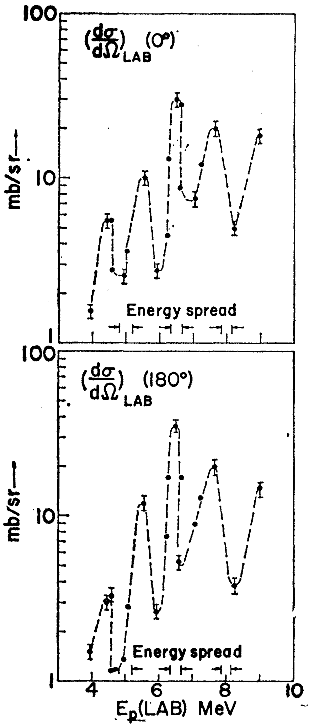

FIG. 6. Absolute differential cross sections as a function of incident proton energy for the $N^{15}(p,n)O^{15}{}_{GS}$ reaction at 0° and 180°.

$V=46$ MeV for neutrons and 51 MeV for protons. $W'=8$ MeV and $V_{S0}=6$ MeV. Since the differential cross section $d\sigma/d\Omega$ is proportional to $V_1{}^2$ in DWBA, the parameter V_1 was left as a variable to fit the angular distributions.

Figures 7, 8, 9, 10, and 11 show some of the results obtained by Satchler[10] at 5.5-, 6.5-, 7.65-, 7.80-, and 9-MeV incident proton energy. The shape of the theoretical angular distributions closely follow the experimental ones at these energies, although the magnitude of the differential cross section is not as good for all the angles.

The main characteristics of the angular distributions

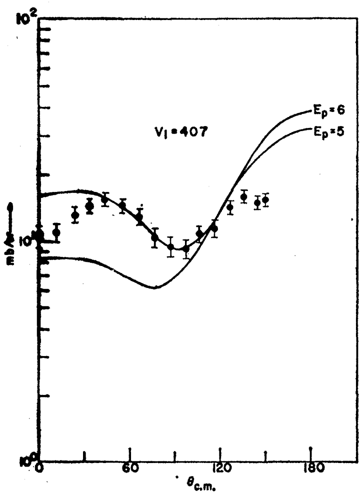

FIG. 7. Theoretical fitting using DWBA and Lane's potential for the ground-state neutrons from $N^{15}(p,n)O^{15}$ at 5.5-MeV proton energy.

obtained with the Lane potential[1] is the slow variation of the features as a function of proton energy. The value of the parameter V_1 at these energies seems to be between 300 and 400 MeV. This value is rather large compared to the 65(±50) MeV obtained from nuclear-symmetry energy and the value of around 110±20 MeV obtained from neutron and proton scattering data.

Above 10 MeV the agreement is poor, as can be seen in Figs. 12 and 13. It is interesting to notice that the value of the parameter V_1 decreases as the energy of the proton increases; this can be an indication of the velocity dependence of the potential U_1.[17]

At this stage it was thought that it would be of some interest to see how an optical-model analysis would fit the angular distributions of the neutrons and it it would be an improvement over the DWBA fitting.

The optical potential used was the one given by Eq. (1) with a Gaussian for $g(r)$ and the differential cross section given by[1,19]

$$\frac{d\sigma_{p,n}(\theta)}{d\Omega}=\frac{2T_0}{(2T_0+1)^2}|f(\theta)_{T_0+\frac{1}{2}}-f(\theta)_{T_0-\frac{1}{2}}|^2, \qquad (4)$$

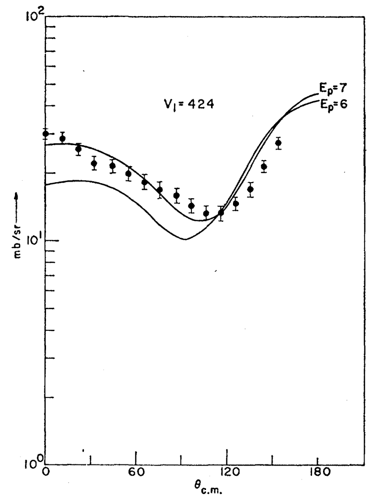

FIG. 8. Theoretical fittings with DWBA calculation and Lane's potential for the differential cross section of the ground-state neutrons from $N^{15}(p,n)O^{15}$ reaction at 6.50 MeV.

where the $f(\theta)$'s are the scattering amplitudes corresponding to the two values of the total isobaric spin.

Although Lane[1] has indicated that the expression (4) is valid for incident energies high enough to make Coulomb effects small, Hodgson[19] showed that optical model and DWBA analyses gave approximately the same results for 14-MeV protons on nitrogen.

Since no information on (p,p) scattering on N^{15} is available at the energies of this experiment for all angles,[20] the comparisons were made using the same optical parameters used in the DWBA fitting. Another set of optical parameters tried were the ones obtained

[19] P. E. Hodgson and J. R. Rook, Nucl. Phys. **37**, 632 (1962).
[20] G. Dearnaley, D. S. Gemmell, B. W. Hooton, and G. A Jones, Phys. Letters **1**, 269 (1962).

from[21] (p,p) and[22] (n,n) in O^{16} and[22] (n,n) in N^{14}. The results obtained with these different sets of parameters were not strikingly different.

The comparison with the angular distributions made with the optical model are shown in Figs. 11, 12, and 13. They represent the best fits obtained. At 9 and 11.4 MeV the optical parameters used are those of Satchler.[10] At 13.6 MeV the best fit was obtained with the parameters from $N^{14}(n,n)N^{14}$.[22] From 0° to 120° the results obtained with the two methods are indeed quite similar for 9 and 11.4 MeV. At 13.6 MeV the optical model reproduces quite well the forward features of the angular distribution.

It is felt that if corrections for Coulomb effects are taken into account in the calculation of the scattering amplitudes and if a proper set of optical parameters is used (such as the one obtained from proton elastic scattering in N^{15}), the optical-model analysis of this (p,n) angular distribution can substantially reproduce the experimental results.

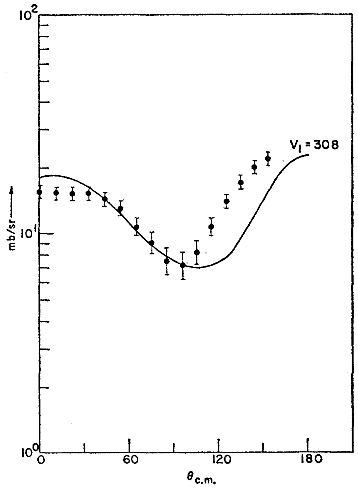

FIG. 10. As in Fig. 8 for 7.80-MeV proton energy.

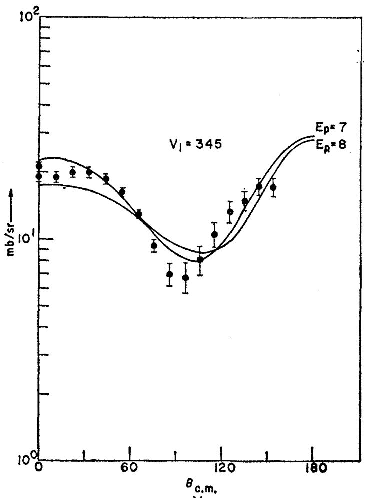

FIG. 9. As in Fig. 8 for 7.65-MeV proton energy.

$N^{15}(p,n)O^{15}$ EXCITATION FUNCTION

The gross structure observed in the excitation function for the ground-state neutrons from the $N^{15}(p,n)O^{15}$ reaction (Figs. 5 and 6) suggests the giant resonant effect seen in neutron cross sections[23] and in[24] (d,p) reactions.

As pointed out earlier, the poor resolution in the incident proton energy, with a spread of around 200 keV, does not allow separation of the compound nucleus resonances which have been observed by Jones *et al.*[9]

Feshbach *et al.*[25] and Lane *et al.*[26] have interpreted these giant or size resonances as the result of single-particle states of the incident particle in the potential of the ground state of the target nucleus. Due to interactions with nucleons in the target nucleus, the eigenstates of the single particle are spread out among levels of the compound nucleus. The sum of the reduced width of all these levels is equal to the single-particle reduced width. Furthermore, Lane *et al.*[26] have pointed out that the energy at the peak of these size resonances corresponds to the single-particle level position.

In the reaction $N^{15}(p,n)O^{15}$ the compound system is O^{16}. Lane[14] has calculated the single-particle levels in O^{16} corresponding to non-normal parity states (states whose parity is opposite to the parity of the ground state of the nucleus: $O^{16}{}_{GS}=0^+$). This model predicts

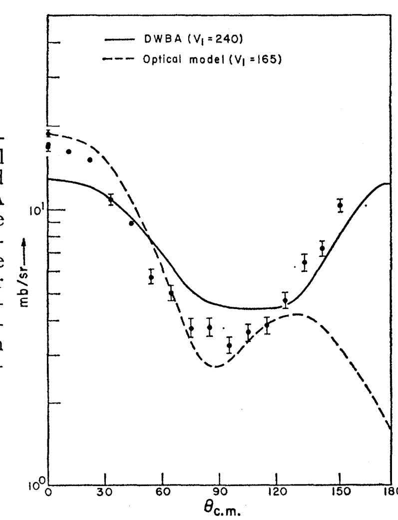

FIG. 11. Comparison of the theoretical fittings obtained with the DWBA calculation and the optical-model analysis, both using the Lane potential, for differential cross sections for the ground-state neutrons from the $N^{15}(p,n)O^{15}$ reaction at 9 MeV.

[21] C. B. Duke, Phys. Rev. **129**, 681 (1963).
[22] H. F. Lutz, J. B. Mason, and M. D. Karvelis, Nucl. Phys. (to be published).
[23] H. H. Barschall, Phys. Rev. **86**, 431 (1952).
[24] J. P. Schiffer, L. L. Lee, Jr., and B. Zeidman, Phys. Rev. **115**, 427 (1959).
[25] H. Feshbach, C. E. Porter, and V. F. Weisskopf, Phys. Rev. **96**, 448 (1954).
[26] A. M. Lane, R. G. Thomas, and E. P. Wigner, Phys. Rev. **98**, 693 (1955).

TABLE II. Single-particle levels in O^{16}.

Experimental E_{exc} in O^{16} [MeV]	Hole →	$T=0$ $p_{1/2}$	$T=0$ $p_{3/2}$	$T=1$ $p_{1/2}$	$T=1$ $p_{3/2}$
16.27±0.23	Particle	$d_{3/2}(1^-$:16.6 MeV)	$d_{5/2}(2^-$:16.6 MeV)		
17.29±0.20			$2s(2^-$:17.3 MeV)	$d_{3/2}(2^-$:17.6 MeV) $d_{3/2}(1^-$:17.6,17.3,17.5 MeV)[a]	
18.21±0.17				$d_{3/2}(1^-$:18.1 MeV)	$d_{5/2}(3^-$:18.5 MeV)
19.29±0.15					$d_{5/2}(2^-$:19.1 MeV) $2S(1^-$:19.6 MeV)
20.54±0.13			$d_{3/2}(3^-$:20.3)		$2S(2^-$:20.1 MeV) $2S(1^-$:20.0,20.4,20.0 MeV)

[a] The values calculated for the levels are in alphabetic order of the authors: Brown *et al.*; Elliott and Flowers; Lane. All the other values are taken from Gillet's calculations.

that the first states of non-normal parity of a mass A nucleus in the $1p$ shell (O^{16}) result from a $2s$ or a $1d$ particle coupled onto the ground state of the mass $(A-1)$ nucleus (N^{15}). The occurrence of these states will give origin to strong effects in the cross sections. Resonances will appear when these single-particle levels are above the nucleon threshold but below the barriers (Coulomb or angular momentum) in the nucleon channels.

Other calculations on the odd-parity states spectrum of O^{16} have been made by Elliott and Flowers,[13] by Brown *et al.*,[12] and more recently by Gillet *et al.*[11] This last calculation is the most complete, based on the unified description of nuclear excitations as a function of the particle-hole interaction. The odd-parity states in O^{16} are obtained for $T=1$ and $T=0$.

Table II shows the odd-parity levels in O^{16} calculated by the different authors. Also indicated in the table are the positions of the observed resonances in Fig. 5 as a function of the excitation energy in O^{16}.

To determine if the observed resonances corresponded to the calculated single-particle level in O^{16}, information on the angular momentum of the resonances was required. This was done by making a least-squares fit of a Legendre polynomial expansion of the form

$$P_0+\sum_{i=1}^{n}\frac{a_i}{a_0}P_i(\theta)$$

to the angular distributions. The fits are shown in Fig. 1. They are the continuous curves through the experimental points. The number of terms in the expansion is indicated by the number n over each curve.

The criterion used to determine the maximum order $(n-1)$ of the polynomial to fit the angular distributions was based first, on the shape of the experimental distribution, and second, on the maximum orbital-angular momentum allowed from energy considerations. The errors in the coefficients were calculated according to the method given by Rose.[27] They are a function of the experimental errors in the absolute value of the differential cross sections. No corrections were made for the attenuation of the coefficients due to the finite solid angle subtended by the counter.

Table III gives the values of the coefficients of the Legendre polynomial as a function of proton energy.

A tentative assignment of the angular momentum

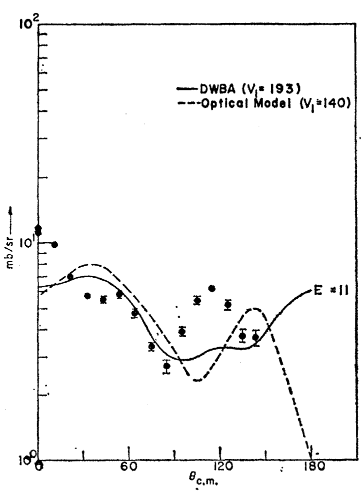

FIG. 12. As in Fig. 11 for 11.4-MeV proton energy.

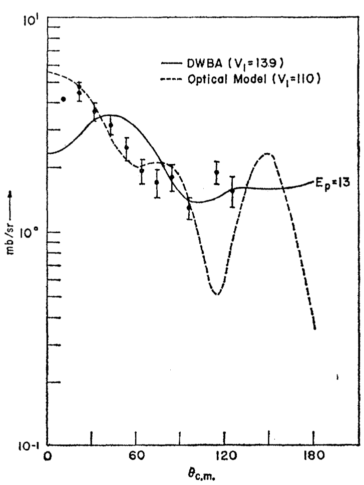

FIG. 13. As in Fig. 11 for 13.6-MeV proton energy.

[27] M. E. Rose, Phys. Rev. 91, 610 (1953).

TABLE III. Coefficients for least-squares Legendre-polynomial fits to the angular distributions.

E_p (MeV)	a_0	a_1	a_2	a_3	a_4
3.95	1.5702±0.0092	−0.1790±0.0184	−0.0063±0.0276	0.1912±0.0370	
4.43	4.3320±0.0236	0.6005±0.0464	0.0611±0.0678	0.5153±0.0917	
4.59	1.8295±0.0164	0.2646±0.0348			
5.02	4.1980±0.0230	−0.9557±0.0451	−0.2186±0.0644	0.4866±0.0847	−0.7746±0.1036
5.52	11.486 ±0.0673	−1.0928±0.1529	3.7737±0.2124	−0.5511±0.2851	−3.4788±0.3490
5.92	2.5096±0.0228	−0.0376±0.0523	0.6804±0.0770	−0.4293±0.1042	−0.4004±0.1247
5.98	4.8477±0.453	−0.2404±0.1199	2.8087±0.1804	−0.4642±0.2470	
6.23	3.8162±0.0355	−0.0740±0.0870	1.5251±0.1362	−0.7158±0.1873	
6.28	9.7637±0.0900	1.1086±0.2242	4.0972±0.3585	−1.9285±0.4840	
6.50	18.631 ±0.0801	1.1292±0.1945	9.6578±0.3054	−4.7844±0.4047	4.7186±0.4837
6.59	5.2066±0.0491	−0.0434±0.1152	0.9372±0.1921	0.5637±0.2682	0.7741±0.3295
6.65	15.0540±0.1089	−1.2844±0.2271	3.6956±0.3817	5.4766±0.5142	2.8786±0.6409
7.04	10.4120±0.0782	1.1405±0.1497	−2.6446±0.2460	−1.7190±0.3403	
7.24	10.3625±0.0585	0.6226±0.1206	0.3291±0.1845	−0.5158±0.2490	1.3114±0.3163
7.65	13.0173±0.0604	1.9504±0.1484	9.3161±0.2217	−0.6725±0.2810	4.2569±0.3500
8.23	2.6087±0.0226	−0.6346±0.0590	1.5949±0.0936	0.1921±0.1310	
8.99	6.1937±0.0368	1.7048±0.1042	7.3100±0.1692	0.0140±0.2114	2.7156±0.2994

and l values of the resonances observed in the excitation function can be done from these coefficients. Since the ground states of N^{15} and O^{15} have the same angular momentum and parity $I=\frac{1}{2}^-$, and the proton and neutron have the same spin and parity $i=\frac{1}{2}^+$, the channel spin $\bar{I}+\bar{\imath}$ can be 1^- or 0^-; the only orbital angular momentum allowed will be $\Delta l=0$ or 2. ($\Delta l=2$ is very improbable.)

(4.43±0.23) MeV [$O^{16*}=16.27$ MeV]

The small values of a_2 exclude the possibility that this resonance is due to protons with $l=2$. Furthermore, the small value of all the coefficients point out to $J=0$. Therefore, this resonance does not correspond to the single-particle level shown in Table II at 16.6 MeV.

(5.52±0.20) MeV [$O^{16*}=17.29$ MeV]

The lack of peaks in a_1 and a_3 eliminate $l=1$ or 3 values. The peak in a_2 suggests $l=2$. The value of J can be 1, 2, or 3. This last value can be excluded due to the small value of a_4. So one can have an overlapping of two resonances with $l=2$ and $J=1$ and 2. This is in very good agreement with the single-particle level $(1p_{1/2})^{-1}(1d_{3/2})$ around 17.5 indicated in Table II.

(6.50±0.17) MeV [$O^{16*}=18.21$ MeV]

The large peak observed for a_2 indicates that the main contribution is from $l=2$. The small peak at a_1 will indicate contributions of odd values of l, $l=1$, or 3. However, the lack of peak at a_3 eliminates $l=3$. Also the peak at a_4 indicates some contribution from $l=4$ and from $J=3^-$. This again can be considered a case of overlapping resonances consistent with the assignments of Table II at 18.1 and 18.5 MeV.

(7.65±0.15) MeV [$O^{16*}=19.29$ MeV]

The behavior of the coefficients at this resonance follow the same pattern as the previous resonance, where the main contribution is from $l=2$. This points to a single-particle resonance $(1p_{3/2})^{-1}(1d_{5/2})$.

(8.99±0.13) MeV [$O^{16*}=20.54$ MeV]

The very large value of a_2 again points to a resonance whose main contribution is $l=2$ (small contributions from $l=1$ from the value of a_1). This favors the assignment $(1p_{3/2})^{-1}(1d_{3/2})$ for the single-particle level.

A more detailed analysis of this assignment is quite difficult, since there is interference between odd and even l values plus two possible channel spins for each one of the incoming and outgoing orbital angular momentum.

CONCLUSIONS

The Lane model for the quasielastic (p,n) reactions explains the general features of the differential cross sections for the ground-state neutrons from the reaction $N^{15}(p,n)O^{15}$. To find out if this agreement is meaningful, it would be of interest to see how the model works for other ground-state (p,n) reactions in mirror nuclei.

A better knowledge of the optical parameters from proton elastic scattering for the respective nuclei will allow narrowing of the variation interval of V_1. It is possible, however, that the large variations in V_1 are not due mainly to the lack of a "good set of optical parameters" but to the strong resonances present in the region of analysis.

A more detailed study of U_1 is indicated, as it has been pointed out by Drisko *et al.*[18] that U_1 may not be a scalar with targets of nonzero spin I and may include higher even multipole moments. For example, in the case of the $N^{15}(p,n)O^{15}$ reaction, from shell-model considerations, the proton can charge exchange into the neutron in the $p_{3/2}$ orbit. This will allow the $l=0$ and $l=2$ multipoles to occur in U_1.

Using Lane's potential with a DWBA or an optical-model calculation, the main characteristic of the calculated differential cross sections is the slow variation with proton energy of the features of the angular distributions.

Results obtained for DWBA and optical-model calculations for the higher energies, with the same set of optical parameters, are quite similar although the value of the parameter V_1 seems to be consistently lower in the optical-model analysis.

Finally, the wide resonances observed at 5.5, 6.50, 7.65, and 9.00 MeV have been interpreted as due to single-particle levels in O^{16}. This does not contradict the experimental evidence[9] that compound-nucleus levels are also present; they will have been detected with high resolution in the proton energy. One can visualize the size resonance, whose peak is at the position of the single-particle level, as the envelope of all the narrow compound-nucleus resonances that occur in the energy interval corresponding to the width of the size resonance.

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β-γ Circular-Polarization Correlation Study of Sc^{46}

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A series of β circularly polarized γ angular-correlation measurements on Sc^{46} in seven different chemical and physical forms has been conducted at this laboratory to investigate a possible chemical effect reported by Boehm and Rogers. According to their findings, this effect attenuates the observed angular correlation. We have found no indication of such an effect. The average of all the present measurements ($A=+0.097 \pm 0.012$) is in excellent agreement with our earlier result as well as with many other independent measurements. Our conclusion is that there is no evidence for a chemical attenuation effect.

I. INTRODUCTION

SINCE the work of Boehm and Wapstra[1] on the circular polarization of the γ rays following β decay in Sc^{46}, which apparently demonstrated a large Fermi component in the β decay, many similar measurements have been performed at several laboratories. The early reports[2–4] agreed reasonably well with the original findings, but all subsequent measurements until very recently have shown only a very small Fermi component.[5–9] However, within the last year Boehm and Rogers[10] have reported new results which confirm their original findings, and they suggest that a strong attenuation of the angular correlation in certain chemical states is responsible for the small polarizations. The existence of such an attenuation is especially surprising in view of the short half-life of the intermediate state at 2.01 MeV in Ti^{46}, which in a recent measurement[11] was found to be less than 5×10^{-12} sec. Also the sum total of recent experimental findings on other nuclei[5] suggests a significantly smaller degree of breakdown of isotopic-spin conservation, in general, than this result implies (see below). For these reasons we have performed an extensive reinvestigation of Sc^{46}. The data do not confirm the results of Boehm and Rogers.

The statistical validity of all the results obtained in this investigation was determined by application of Pearson's χ^2 test, as described by Evans.[12] The test shows all the results to be fully self-consistent without regard to chemical form or time history of the source. In addition, the final value for the asymmetry parameter, $A=0.097\pm0.012$, agrees with our original result[5] and with the other independent measurements.[6–9]

II. SOURCES

The first group of measurements in this present work was made with sources prepared in a manner identical to that of Boehm and Rogers.[10] They very kindly

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