PHYSICAL REVIEW C VOLUME 9, NUMBER 6 JUNE 1974

Angular distribution and polarization of $^{16}O(\gamma, n_0)^{15}O$†

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(Received 16 November 1973)

We report a detailed calculation of the angular distribution and polarization of the photoneutrons from ^{16}O in the giant dipole region. The electric dipole ($E1$) amplitudes are obtained from a continuum shell-model calculation which reproduces the intermediate structure in the total cross section. A consistent interpretation of the angular distribution and polarization may be obtained either by (i) assuming a phenomenological *giant* quadrupole ($E2$) resonance, or (ii) by modifying the phase difference between the $E1$ amplitudes. In case (ii), we do not require any $E2$ resonance to fit the data, or, alternatively, the magnitudes of the $E2$ amplitudes used can be taken to be in reasonable agreement with those extracted from the polarized-proton capture experiment. As we show in case (i), there is a theoretical possibility for an $E2$ resonance. On the other hand, the present experimental results indicate the absence of such a resonance in the dipole region; this possibility is studied in case (ii).

[NUCLEAR REACTIONS $^{16}O(\gamma, n_0)$; giant dipole resonance; angular distribution and polarization of photoneutrons. Giant $E2$ resonance in ^{16}O.]

I. INTRODUCTION

We have previously studied the nuclear compound states responsible for generating the intermediate structure in the photonuclear cross section of ^{16}O.[1] We have shown, in a doorway-state formalism, that the intermediate resonances in the giant dipole region could be due to coupling of three-particle–three-hole (secondary doorway) states to the one-particle–one-hole giant dipole (doorway) states. Such configuration mixing redistributes the strength of the dipole transition and thus modifies the energy variation of the photodisintegration amplitudes. For detailed theoretical formalism and comparison to the experimental data, we refer to Ref. 1. However, this calculation investigated only the energy dependence of the *magnitudes* of the scattering amplitudes. In this work, we shall extend the investigation to the interference of these amplitudes.

The interference appears in angular correlation measurements: angular distribution and polarization of the photoneutrons. In a preliminary letter,[2] we reported such a calculation and concluded with evidence for a giant quadrupole resonance in the dipole region. Here we would like to give the detailed results and show some alternative interpretations of the data.

We would first like to mention that there are coupled-channel formulations by Weiss,[3] Buck and Hill,[4] and Sarius and Marangoni.[5] These authors, however, were only interested in the gross structure of the angular correlations.

Experimentally, the differential (γ, n_0) cross section was obtained by Jury, Hewitt, and McNeill[6] and recently by Syme and Crawford.[7] The (γ, n_0) polarization was first measured by Hanser[8] and then, with better resolution, by Cole, Firk, and Phillips,[9] and by Nath *et al.*[10] We shall try mainly to interpret these data.

There are several other closely related experiments. The $^{16}O(\gamma, p_0)^{15}N$ angular distribution measurements were performed by Baglin and Thompson,[11] and Stewart, Morrison, and Frederick.[12] The inverse processes (proton capture and polarized proton capture) have been reported by Earle and Tanner,[13] and Hanna *et al.*[14] In Refs. 11, 12, and 14, an attempt has been made to extract the quadrupole amplitudes in the dipole region. We shall return to the question of whether there is a giant quadrupole resonance later in our discussion.

In Sec. II, we review the general formulation of the angular distribution and polarization. It is then simplified for our application to include the electric dipole ($E1$) and electric quadrupole ($E2$) amplitudes. A possible quadrupole resonance is parametrized in Sec. III. The effects of the $E2$ amplitudes are studied in Sec. IV, where numerical results are presented. Our conclusions are presented in Sec. V.

II. BASIC FORMULATION

In the giant dipole region, the most important photodisintegration amplitudes are the $E1$ amplitudes. For ^{16}O, these amplitudes have been calculated in Ref. 1; they contain rather complicated energy dependence, which may be represented by the following T matrix (see Ref. 1)

$$T = \langle \psi_0^{(-)} | H_\gamma | 0 \rangle + \sum_d \frac{\langle \psi_0^{(-)} | H_{pd} | \phi_d \rangle \langle \phi_d | H_\gamma | 0 \rangle}{E - E_d - \Delta_d - \Delta_x + (i/2)(\Gamma_d + \Gamma_x)}, \quad (1)$$

where $|0\rangle$ is the ^{16}O ground state, and H_γ the photonuclear interaction. The doorways $|\phi_d\rangle$ are the usual 1p-1h (Tamm-Dancoff) dipole states at $E_d = 22.3$ and 24.3 MeV. The mixing of 3p-3h secondary-doorway states (with the dipole states) causes the shift and width, Δ_d and Γ_d, to have rapid energy dependence which gives rise to intermediate resonances in the T matrix. The shift Δ_x and width Γ_x are parameters whose physical significance is discussed in Ref. 1. The channel wave functions $|\psi_0^{(-)}\rangle$ included $s_{1/2}$ and $d_{3/2}$ continuum neutrons coupled to a $p_{1/2}$ hole state in the case of the ground-state cross section $^{16}O(\gamma, n_0)^{15}O$.

If we neglect continuum-continuum coupling, we may write the T matrix for each partial wave (denoted by l, j) as

$$T_{lj}(E) = e^{i\delta_{lj}(E)}[D_{lj}(E) + R_{lj}(E)], \quad (2)$$

where the potential scattering phase shift $\delta_{lj}(E)$ is due to the real optical potential for the continuum waves. We have denoted the *direct* and the *resonant* amplitudes by $D_{lj}(E)$ and $R_{lj}(E)$, respectively. We may further write Eq. (2) as

$$T_{lj}(E) = C_{lj}(E) e^{i\Phi_{lj}(E)}, \quad (3)$$

where $C_{lj}(E)$ is real and positive and $\Phi_{lj}(E)$ is the total phase of the amplitude T_{lj}. The total phase is the sum of two phases:

$$\Phi_{lj}(E) = \delta_{lj}(E) + \Theta_{lj}(E), \quad (4)$$

where the resonant phase $\Theta_{lj}(E)$ is defined by

$$\Theta_{lj}(E) = \tan^{-1}\left\{\frac{\mathrm{Im}[D_{lj}(E) + R_{lj}(E)]}{\mathrm{Re}[D_{lj}(E) + R_{lj}(E)]}\right\}. \quad (5)$$

From Eqs. (4) and (5), we expect the total phase to vary on approximately the same energy scale as the intermediate structure, due to the rapid energy variation of $\Theta_{lj}(E)$.

The total (γ, n_0) cross section is given by

$$\sigma_t(E) = \frac{4\pi^2}{k_\gamma} \sum_{lj} |C_{lj}(E)|^2, \quad (6)$$

where k_γ is the incident photon wave number. This expression contains only the squared amplitudes and thus does not depend on the relative phases of various terms. To study the interference effects, we turn to the angular distribution and the polarization. We usually expand these quantities in terms of angular functions (for details, see Firk,[15] for example). The angular distribution is

$$\frac{d\sigma}{d\Omega} = \left(\frac{1}{8k_\gamma}\right) \sum_n A_n P_n(\cos\theta), \quad (7)$$

where P_n are the Legendre polynomials. Also the differential polarization is

$$\frac{dP}{d\Omega} = \left(\frac{1}{8k_\gamma}\right) \sum_n B_n \bar{P}_n^1(\cos\theta), \quad (8)$$

where $\bar{P}_n^1$ are the associated Legendre polynomials. The polarization direction is perpendicular to the scattering plane. The general expressions for A_n and B_n may be found, for example, in Ref. 15. We shall restrict ourselves to the neutron channels with channel spin 1 for a target with zero spin, $I = 0$. Such channels include $E1$ and $E2$ transitions to a final nuclear state with $I = \frac{1}{2}^-$. The unitary transformation of the formulas from the channel-spin formalism to the jj coupling used in our calculation may be easily carried out. We have found that the transformation in the $E1$ channels of our interest does not change the expressions. We have, for electric multipole transitions, the angular coefficients

$$A_n = (2n+1) \sum C_{lj}^J C_{l'j'}^{J'} \cos\Delta_{l'l} [J][J']([l][l'])^{1/2} \times \begin{pmatrix} l & l' & n \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} J & J' & n \\ -1 & 1 & 0 \end{pmatrix} \begin{Bmatrix} l & J & 1 \\ J' & l' & n \end{Bmatrix}, \quad (9)$$

where $[J] \equiv 2J + 1$ etc., the round brackets are the Wigner 3-j symbols and the curly bracket the usual 6-j symbol.[16] The amplitudes C_{lj}^J are now in the jj representation. The summations are over l, l', J, and J'. The superscripts (J or J') indicate the multipolarity of the transitions. The amplitudes may be indicated only by the orbital angular momentum l of the emitted particle, since, in our case, there is always only one unique value of j associated with each l. The phase difference $\Delta_{ll'}$ is defined as

$$\Delta_{l'l} \equiv \Phi_{l'j'} - \Phi_{lj}. \quad (10)$$

Similarly we have the polarization coefficients B_n,

$$B_n = \sqrt{3}\,(2n+1)\sum C^J_{lj}\, C^{J'}_{l'j'}\, \sin\Delta_{l'l}(-1)^{J'+n+l} \times [J][J']([l][l])^{1/2}\begin{pmatrix} l & l & n \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} J & J' & n \\ -1 & 1 & 0 \end{pmatrix} \times \begin{Bmatrix} J & l & 1 \\ J' & l' & 1 \\ n & n & 1 \end{Bmatrix}, \qquad (11)$$

where the large curly bracket indicates a 9-j symbol.[16] For our reference, the values of l and l' may be 0, 1, 2, or 3 for s, p, d, f waves and J and J' may be 1 or 2 for $E1$ or $E2$ transitions. We note that $n \leqslant (2J,\ 2l,\ 2l')$, i.e., $n \leqq 4$ in our applications.

The above expressions may be further simplified for specific cases. In the $E1$ approximation, the differential cross section is[15]

$$\frac{d\sigma}{d\Omega} = [\tfrac{3}{16}k_\gamma^{-2}]\{2(a_s^2 + a_d^2) + [2\sqrt{2}\,a_s a_d \cos\Delta_{ds} - a_d^2]P_2(\cos\theta)\}, \qquad (12)$$

and the differential polarization

$$\frac{d\vec{P}}{d\Omega} = \left[\frac{0.207}{k_\gamma^2}\right] a_s a_d \sin\Delta_{ds}\,\overline{P}{}_2^1(\cos\theta), \qquad (13)$$

where s and d stand for $s_{1/2}$ and $d_{3/2}$ partial waves, respectively. The amplitudes a's are related to the C's of Eq. (3), by a simple factor:

$$a_{lj}(E) = \left[\frac{8\pi k_\gamma}{(2J+1)}\right]^{1/2} C_{lj}(E); \quad J = 1. \qquad (14)$$

Equations (12) and (13), together with the measurements of $(d\sigma/d\Omega)$ and $(d\vec{P}/d\Omega)$, may be used to obtain the relative amplitudes (a_s/a_d) and the phase difference Δ_{ds}. Such extraction from experimental data is, however, only valid for dipole transitions.

The angular distribution measurements have indicated admixture of other multipoles in the giant dipole region of ^{16}O. They could be $E2$ or $M1$, or both. To simplify our discussion, we shall consider only the $E2$ amplitudes. In the case of ^{16}O, the $M1$ amplitudes are probably small since the $M1$ excitations involve spin-flips which are forbidden for closed-shell nuclei, without ground-state correlations. In the following discussion, we should, however, bear in mind that no $M1$ amplitudes are considered. In this case, our channel wave function $|\psi_0^{(-)}\rangle$ in Eq. (1) also includes the $p_{3/2}$ and $f_{5/2}$ continuum waves. In case of a quadrupole resonance, the "$E2$ doorway states" may be included as $|\phi_d\rangle$ in Eq. (1). The $E2$ amplitudes are then also denoted in the form of Eq. (3).

The effects of the $E2$ amplitudes on the angular distribution and the polarization are generally quite complicated. It is therefore useful to have a systematic way to ameliorate the situation. To begin our discussion, we assume that the $E1$ amplitudes are completely determined from our previous study. We then have four parameters (two $E2$ amplitudes a_f and a_p and their phases ϕ_f and ϕ_p, respectively) to be determined from the data.

We shall begin with the following two quantities from the angular distribution:

$$\frac{A_2}{A_0} = \frac{\{[-0.5 + 1.41\tilde{a}_s\cos(ds)] + 0.733\tilde{a}_p^2 + 0.953\tilde{a}_f^2 - 0.58\tilde{a}_f\tilde{a}_p\cos(fp)\}}{\{[1+\tilde{a}_s^2] + 1.667(\tilde{a}_p^2 + a_f^2)\}} \qquad (15)$$

and

$$\frac{A_4}{A_0} = \frac{4.67\tilde{a}_p\tilde{a}_f\cos(fp) - 0.952\tilde{a}_f^2}{1+\tilde{a}_s^2 + 1.667(\tilde{a}_p^2+\tilde{a}_f^2)}, \qquad (16)$$

where we have defined $\tilde{a}_s = a_s/a_d$ and $\cos(ds) = \cos(\Delta_{ds})$ etc. The quantities shown within the square brackets are the known $E1$ contributions. It is experimentally observed that A_4/A_0 is very small in the energy region of our interest. From Eq. (16), $A_4 = 0$, if

$$\cos(\Delta_{fp}) = \left[\frac{1}{4.9}\frac{a_f}{a_p}\right]. \qquad (17)$$

Equation (17) gives a restriction on our parameters. A more important consequence of Eq. (17) is the simplification in our search procedure. If we substitute Eq. (17) for $\cos(fp)$ in Eq. (15), we immediately find that the A_2/A_0 ratio does not depend on the $E2$ *phases*; moreover, it depends nearly only on the total sum of the squared $E2$ amplitudes $(a_f^2 + a_p^2)$. This observation isolates the effects of the total $E2$ strength on a single experimental quantity. That is, we may determine the total $E2$ strength from the A_2/A_0 ratio, regardless of their phases. (Note that this is so only in the absence of $M1$ amplitudes.)

Effectively, we have now reduced the number of undefined parameters to two; we have to determine (1) the $E2$ relative amplitude a_f/a_p or their phase difference Δ_{fp} and (2) any $E1$-$E2$ phase difference such as Δ_{fd}. For this purpose, we may choose the remaining two experimental constraints: the A_1 and A_3 coefficients. We note that these two quantities contain only $E1$-$E2$ interferences and therefore serve as a very sensitive criterion for the $E2$ amplitudes and phases. We remark at this point that the $E2$ amplitudes could be determined by the angular distribution alone.

For a further test of such amplitudes, we may turn to the polarization calculation. We are particularly interested in the polarizations at 45 and 90°, where there are data available. The 45° polarization could be dominated by $E1$ contributions, while the 90° polarization contains only $E1$-$E2$ interference. Experimentally the 90° polarization is very small; this could be due to either small $E2$ amplitudes or cancellation of the $E1$-$E2$ interference.

In the following we shall speculate on the possibility of the presence of a quadrupole resonance, since there is such evidence in our calculation if we assume our $E1$ amplitudes are correctly reproduced. We shall discuss the details in the next section.

The existence of giant-quadrupole resonance in nuclei seems to be observed in proton inelastic scattering[17] and in electron scattering.[18] For the nucleus in question here, there has been evidence for a goint-quadrupole ($E2$) resonance in the angular distribution measurement of $^{16}O(\gamma, p_0)^{15}N$, as first analyzed by Stewart, Morrison, and Frederick.[12] The data of $^{16}O(\gamma, n_0)^{15}O$ of Jury, Hewitt, and McNeill[6] and Syme and Crawford[7] also show evidence for strong $E2$ interference in the giant-dipole region. However, the extraction of the $E2$ amplitudes directly from the experimental data is quite uncertain without *a priori* knowledge of the dominant $E1$ components. Since we have a complete theoretical prediction of the $E1$ amplitudes, it becomes much easier to determine the $E2$ amplitudes.

The choice of $E2$ amplitudes will strongly affect the values of A_1, A_3, and A_4, which contain purely $E1$-$E2$ interferences. Their effects on polarization are more complicated. Lacking a more complete theory for the $E2$ amplitudes, we shall be content with a simple qualitative parametrization of these quantities, as discussed in the following section.

III. QUADRUPOLE RESONANCE

We may parameterize the $E2$ T matrix as, for each $E2$ partial wave (lj),

$$T_{lj}(E2) = D_{lj} + \left(\frac{5}{4\pi k_\gamma}\right)^{1/2} \frac{\sqrt{\Gamma_{lj}}\,\sqrt{\Gamma_\gamma(E2)}}{E - E_q + i\Gamma_{q/2}}, \qquad (18)$$

where D_{lj} is the direct amplitude. The $E2$ resonance is assumed to be at energy E_q and have a total width Γ_q. $\Gamma_\gamma(E2)$ is the total ground-state photoabsorption width. For simplicity we take E_q and Γ_q to be constants. The total width of the $E2$ resonance may be separated into $\Gamma_q = \sum_{lj}\Gamma_{lj} + \tilde{\Gamma}_q$ where Γ_{lj} is the continuum width for neutron escape from the $E2$ state. The compound width $\tilde{\Gamma}_q$ generally contains all the coupling to more complicated states and continuum channels other than the neutron channels. The normalization factor $(5/4\pi k_\gamma)^{1/2}$ in Eq. (15) is so chosen that the following relation between the total absorption cross section $\sigma_a(E2)$ and the ground-state radiation width $\Gamma_\gamma(E2)$ holds approximately[19]:

$$\int \sigma_a(E2)dE = \frac{5\pi^2}{k_\gamma^2}\Gamma_\gamma(E2). \qquad (19)$$

The magnitudes of $E2$ amplitudes, for a chosen E_q and Γ_q, would depend only on the product $(\Gamma_{lj}\Gamma_\gamma)$. In order to estimate the neutron width, we have to determine the value of Γ_γ from an independent consideration, such as the $E2$ sum rule.

The energy-weighted sum rule for $E2$ $(\Delta T = 0)$ multipole is given as, assuming a simple $E2$ state $|n\rangle$,[19]

$$S_{EW} = \hbar\omega \left| \left\langle n \left| \sum_i r_i^2 Y_{2M}(\hat{r}_i) \right| 0 \right\rangle \right|^2 = \frac{5\hbar^2 A}{4\pi M}\langle r^2\rangle, \qquad (20)$$

where A is the mass number of the nucleus and M the nucleon mass. The γ absorption width from the ground state $|0\rangle$ to the state $|n\rangle$ is given as

$$\Gamma_\gamma = 4e^2 k_\gamma^5 \left| \left\langle n \left| \sum_i r_i^2 Y_{2M}(\hat{r}_i) \right| 0 \right\rangle \right|^2. \qquad (21)$$

If we choose our $E2$ state to exhaust the sum rule, we obtain

$$\Gamma_\gamma = \left[\frac{2.37A}{\hbar\omega}\right] k^5 R^2 \qquad (22)$$

by assuming a uniform nucleus $\langle r^2\rangle = 3R^2/5$. In our calculation we use $R = 1.14A^{1/3}$.

The above consideration determines the neutron decay widths and the *magnitudes* of our $E2$ amplitudes. The resonant phases Θ_{lj} can be calculated directly from Eq. (15). However, the calculation of A_1, A_3 and polarization is *very* sensitive to these phases. The $E2$ phases directly determined from Eq. (18) are found to be inadequate. We therefore treat the $E2$ phases as parameters, to be determined by fitting the data. The resultant phases should, of course, retain their resonant behavior (i.e., changing by π through the resonance region).

IV. NUMERICAL RESULTS

In this section we first present the results of our calculation with the $E1$ amplitudes obtained in Ref. 1. In order to interpret the experimental data, we need to introduce an $E2$ resonance in the dipole region. The $E2$ amplitudes found are much larger than those found in polarized-proton capture of Hanna *et al.*[14] We shall finally show that our $E2$ amplitudes could be a factor of 5 smaller if our $E1$ *phases* are modified. The evidence for an $E2$ resonance is, however, still indicative, although not conclusive; the fact is that any *large* $E2$ amplitudes must have their phases change by π in the dipole region.

We shall call the first part of our study as case I, where we assume that the $E1$ quantities as calculated in Ref. 1 are accurate representations of the ^{16}O photodisintegration and we shall use them without any modification.

The complete $E1$ T matrices for $s_{1/2}$ and $d_{3/2}$ partial waves are shown in Fig. 1, where we can clearly see the resonance behavior of each partial wave as represented by the rapidly varying amplitudes along the circular trajectories in the complex plane as the energy increases through the resonance energies. The phase difference Δ_{ds} is approximately constant and equal to about $-150°$. The $E1$ total phases, as defined in Eq. (4), are shown in Fig. 2, which exhibits rather strong energy dependence due to the intermediate resonances. For zero-energy neutrons, the potential phase shifts are π and 2π for $d_{3/2}$ and $s_{1/2}$ waves. The value of π for the $d_{3/2}$ wave is due to the projection procedure discussed in detail in Refs. 1 and 20. The $d_{3/2}$ total phase has been slightly adjusted to give a positive polarization at 45°, as to be discussed later.

We may now calculate $P(\theta=45°)$ and A_2/A_0 in the $E1$ approximation. The results are shown as the dashed lines in Figs. 3 and 4. The pure $E1$ A_2/A_0 ratio shows a large discrepancy when compared with the experimental data of Syme and Crawford,[7] and also that of Jury, Hewitt, and McNeill.[6] The magnitude and the shape of the polarization at 45° are, however, reasonably reproduced. We recall that the phase difference Δ_{ds} is close to the value π and that the sign of the polarization at 45° therefore critically depends on Δ_{ds} being greater or less than π. The phase difference Δ_{ds} obtained in our calculation (from the dashed lines in Fig. 1) gives *negative* polarization near 24 MeV. We have to modify our phase difference Δ_{ds} by changing $\Phi_{d_{3/2}}$ as shown in the figure. It is, of course, also possible to modify further the $d_{3/2}$ phase shift or Δ_{ds} at lower energy (20–23 MeV) to *increase* the polarization there; this will be shown later. It is worthwhile to point out that the "intermediate structure" in $P(45°)$ could be due to the energy dependence in the $E1$ amplitudes, with a smooth phase difference. The coupled-channel calculation of Buck and Hill[4] gives a larger polarization; our gross structure calculation (by neglecting the 3p-3h secondary doorways) would yield a curve similar to the dashed line in Fig. 4, without its intermediate-structure oscillations. It is interesting that our polarization is quite similar to the square-well calculation of Weiss.[3]

We infer from the above comparisons that the interference of non-$E1$ states in the dipole region may be quite important. This is particularly evident in the A_2/A_0 ratio, which is also quite insensitive to small changes in the phase difference Δ_{ds}. It is clear, from Eqs. (15) and (17), that $E2$ amplitudes always tend to reduce the discrepancy shown in Fig. 3. It is worthwhile to point out that one may fit the data with no $E2$ amplitudes; such a fit would require an a_s/a_d ratio very much smaller than that obtained from our theory and a strongly energy-dependent value of Δ_{ds}.[9]

The $E2$ amplitudes are parameterized in Eq. (18), where we take $E_q=23$ MeV, $\Gamma_q=4$ MeV, and $\sum\Gamma_{lj}$ (at 23 MeV) = 1.4 MeV. The energy dependence in the numerator of Eq. (18) is taken to be $[1.0+0.1(E_\gamma-23)]^2$. This slight energy dependence is obtained by a qualitative fit to the A_2/A_0 ratio, which is shown as the solid line in Fig. 3. The relative magnitudes of the $E2$ amplitudes are shown in Fig. 5. We note that the $E2$ amplitudes are particularly large off the resonances; this is partly due to the fact that our $E1$ amplitudes, there, are slightly underestimated as compared to the total cross section as shown in Ref. 1.

It is also interesting to see that the giant-quadrupole resonance as specified by Eq. (18) is in reasonable agreement with theoretical predictions. For ^{16}O, a simple harmonic oscillator model due to Bohr and Mottelson[21] predicts $E_q=24$ MeV, and the sum rule consideration of Satchler[17] gives $E_q=27.5$ MeV. The analysis of proton inelastic scattering from ^{16}O by Geramb, Sprickman, and Strobel[17] also shows a $E2$ resonance state near 25 MeV. Our calculation is not sensitive to the position of the resonance, but, from the phases shown in Fig. 7, the resonance is within the giant dipole region.

We next have to determine the relative amplitudes a_f/a_p and the $E2$ phases, using A_1 and A_3 coefficients as constraints (experimental data are shown in Fig. 6). The result is not quite sensitive to the *relative* amplitude. The value of a_f/a_p may be chosen as constant between about 0.5 to about

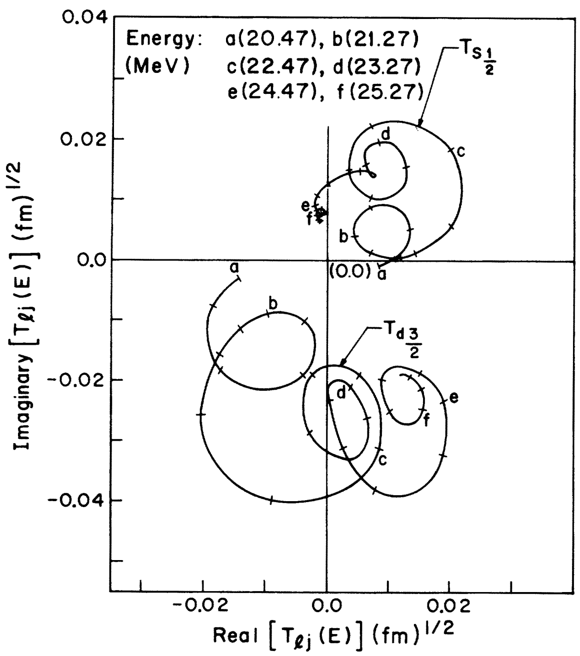

FIG. 1. The total T matrix as function of energy, showing the resonance behavior.

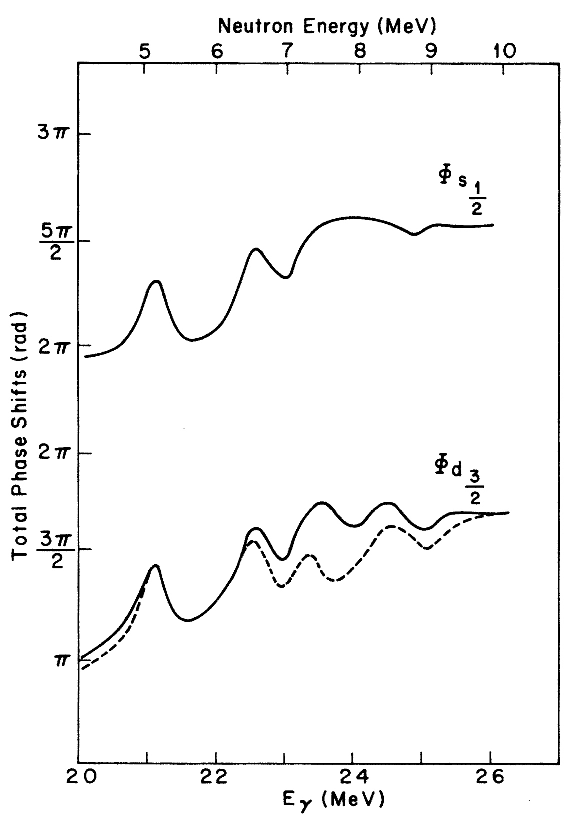

FIG. 2. Total phases Φ_{lj} of $E1$ amplitudes. The d-wave phase (the dashed line) is modified to the solid line which is used in our calculation as explained in the text.

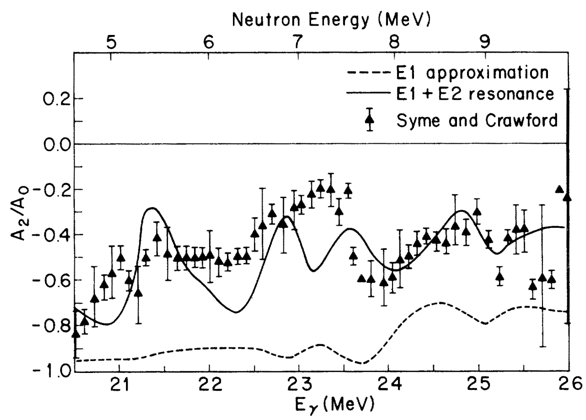

FIG. 3. Angular distribution coefficient A_2/A_0. The dashed line is the $E1$ approximation. The solid line is obtained by including a giant $E2$ resonance. The experimental data are from Syme and Crawford (Ref. 7).

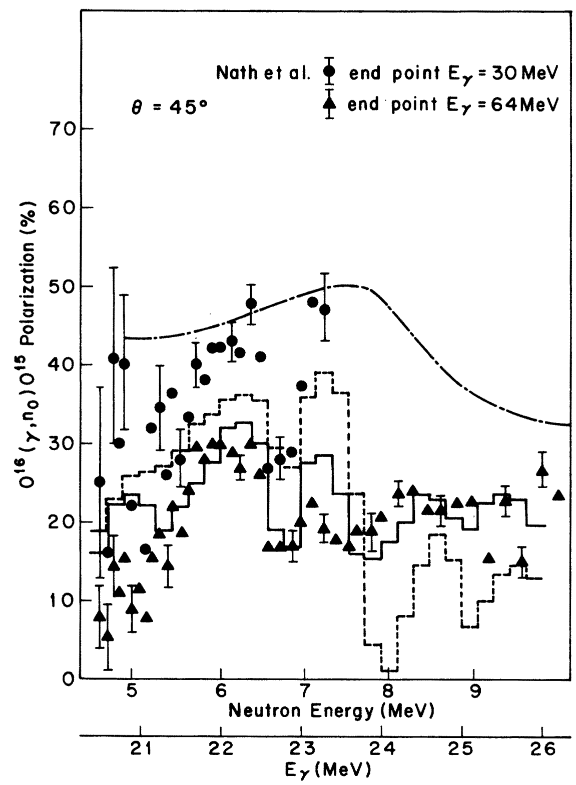

FIG. 4. Polarization at $\theta = 45°$. The dashed line is the result of the $E1$ approximation; the solid line shows the effect of including the $E2$ resonance. The dash-dot line is the result of a coupled-channel calculation of Buck and Hill (Ref. 4). The data are from Nath *et al.* (Ref. 10). The calculation is carried out at 0.2 MeV intervals.

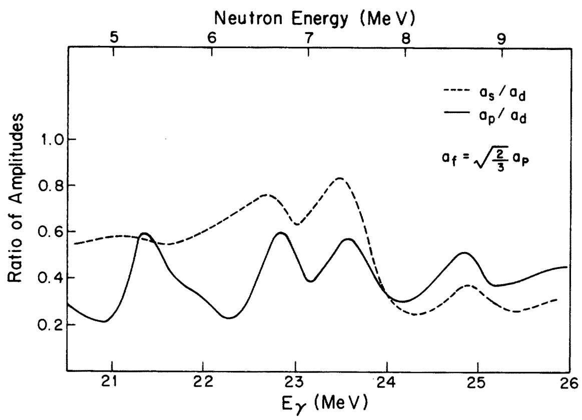

FIG. 5. The relative amplitudes (with respect to the dominant d-wave amplitude). The dashed line is a_s/a_d and the solid line is a_p/a_d. The f-wave amplitude is chosen to be $a_f = \sqrt{\frac{2}{3}}\,a_p$.

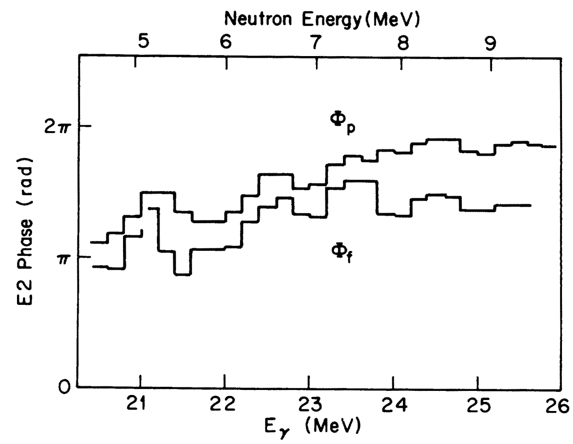

FIG. 7. The extracted $E2$ phases. The p-wave phase shows a clear resonance behavior through the dipole region. In the calculation, we find at least one of the $E2$ amplitudes has to show a resonance behavior, the other one is less certain.

1. We would like to point out that the assumption $a_f = 0$ (or $a_p = 0$) could not give a consistent result for A_1, A_3 and the polarization at 90°; these quantities are very sensitive to the cancellation of the $E1$-$E2$ interferences. We choose $a_f/a_p = \sqrt{\frac{2}{3}}$ and the $E2$ phases shown in Fig. 7. The fit to the experimental A_1 and A_3 coefficients is shown in Fig. 6. These coefficients are small, in this case, only due to cancellation of $E1$-$E2$ interferences. We note again that the $E2$ phases change by π through the resonance region, as is assumed in Eq. (18). It is, however, important to note that the $P(90°)$ can be made arbitrarily small due to the cancellation of two $E1$-$E2$ interference terms. The strong oscillations in Fig. 7 should not be taken seriously.

Here we conclude the first phase of our investigation. We have assumed that our $E1$ amplitudes are accurately reproduced in the calculation of Ref. 1. We, however, immediately notice the large discrepancy of our $E2$ amplitudes as compared to those extracted from polarized-proton capture of Hanna *et al.*[14] This leads to the following alternative interpretation of the data. We shall call the following investigation as our case II study.

To allow modifications, we first notice that the $E1$ phase differences may not be accurately reproduced in our calculation. The phase *difference* requires great accuracy in our $E1$ phases. Therefore we assume that it is not unreasonable to modi-

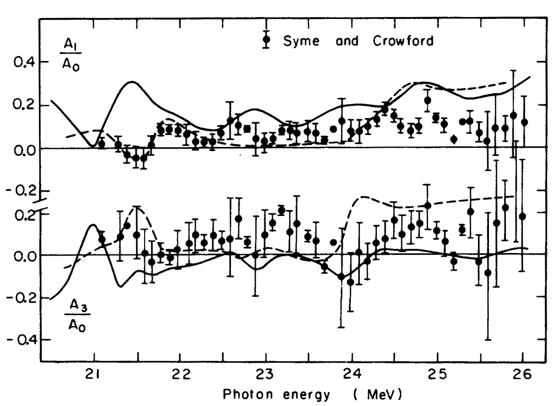

FIG. 6. Angular distribution coefficients A_1/A_0 and A_3/A_0. The data are from Syme and Crawford (Ref. 7). The dashed line is obtained in case I where our $E1$ phase difference Δ_{ds} is not modified. The solid line shows the result in case II, where Δ_{ds} is modified, as discussed in the text. (See Fig. 8.)

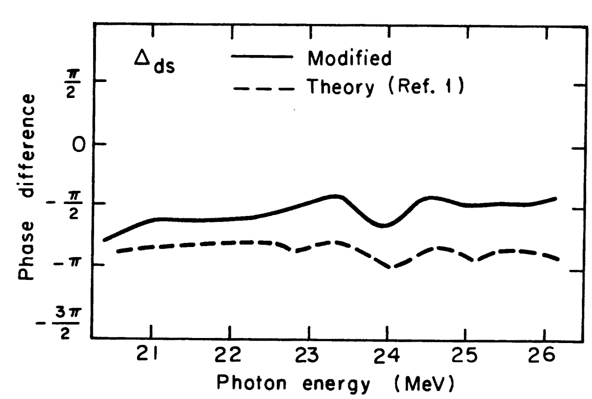

FIG. 8. The $E1$ phase difference Δ_{ds}. The dashed line is the result from Ref. 1, with phases shown in Fig. 2. The solid line is extracted from a fit to the A_2/A_0 ratio allowing for small $E2$ amplitudes.

fy the calculated quantities somewhat. There are many ways to choose the modified phase difference.

We begin with the observation that the polarization at 45° will be enhanced by reducing the magnitude of Δ_{ds}, and the A_2/A_0 ratio will also be reduced in magnitude. In order to fit the $P(45°)$ as measured by photon end-point energy $E_\gamma = 30$ MeV, we find a simple choice of $\Delta_{ds} = -130°$ to be sufficient. The A_2/A_0 ratio, however, is not properly reproduced; we note that this ratio A_2/A_0 has been quite well determined. If we next try to remedy the discrepancy in A_2/A_0 ratio by adding the $E2$ amplitudes as shown in Eq. (15), the $E2$ strength will be about three times or more larger than allowed from the analysis of polarized-proton capture.[14]

For a more probable choice of the phase difference Δ_{ds}, we shall restrict ourselves to the observation of Hanna *et al.*[14] that the $E2$ amplitudes are small; i.e., $A_f/A_d \leq 0.15$ and $A_p/A_d \leq 0.08$ at 21.7 MeV. Such $E2$ amplitudes could correspond to our choice of our $T(E2)$, as specified by Eq. (18), reduced by a factor of 5. The width and the position of the resonance are kept the same. If we assume this new "resonance" also exhausts the sum rule, then the total neutron width would be about 0.67 MeV. We would like to point out that this interpretation also depends on the choice of the width and energy of the resonance. We have apparently assumed a *broad* $E2$ state, with its strength determined at only one energy. However, with this choice of the $E2$ amplitude, we proceed to modify our phase difference Δ_{ds}. For a criterion, we choose the A_2/A_0 ratio, which has been quite consistently measured.[6,7] (On the contrary, the polarization at 45° is more complicated for analysis and the experimental result is not yet very definite.)

If we modify our Δ_{ds} as shown in Fig. 8, the fit to the A_2/A_0 ratio, shown in Fig. 9, is excellent, even without any $E2$ amplitude. It is interesting that the change in Δ_{ds} is simply a uniform shift; the wiggles still remain. This energy-independent modification may be simply due to an error in the determination of the potential phases. We then follow the procedure described earlier to search for the $E2$ phases. The fit to A_1 and A_3 is shown as the solid lines in Fig. 6, where we find the magnitude is well reproduced; the discrepancy off the resonance peaks is probably more due to our underestimated $E1$ strength than to the overestimate of the $E2$ strength. The polarization at 45 and 90° are in reasonable agreement with the experiments, as shown in Figs. 10 and 11.

It is appropriate to make some comment on the "quadrupole resonance" postulated here. The magnitudes of the $E2$ amplitudes have been greatly reduced in our case II. We, therefore, gain more

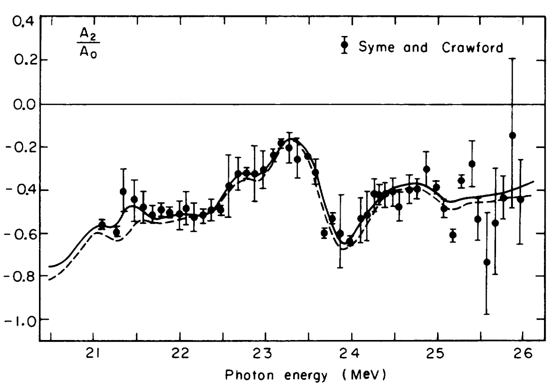

FIG. 9. The A_2/A_0 ratio. The dashed line is obtained by assuming no $E2$ contribution, but with a modification of the $E1$ phase difference Δ_{ds} as shown in Fig. 8. The solid line shows the contribution of adding some small $E2$ amplitudes, consistent with polarized-proton capture measurements of Hanna *et al.* (Ref. 14). The data are the same as in Fig. 3.

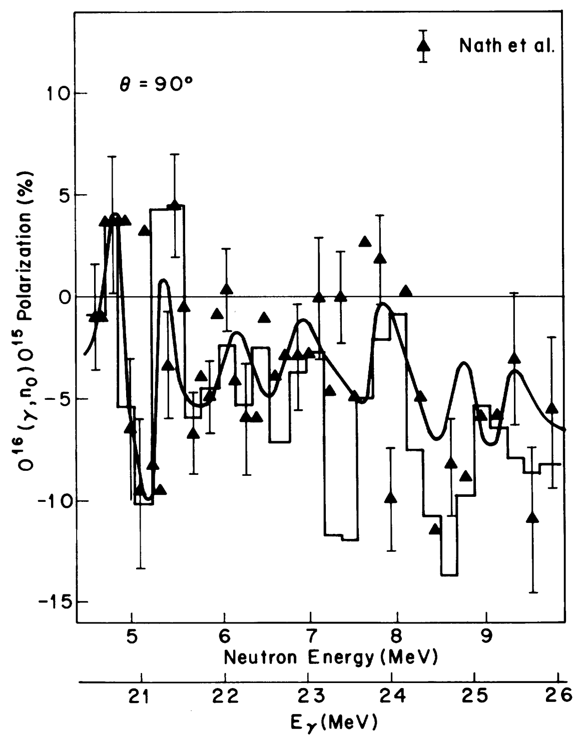

FIG. 10. Polarization at $\theta = 90°$. The data are from Nath *et al.* (Ref. 10). The thin solid line is the result using the search procedure described in the text, assuming that our $E1$ quantities are accurately reproduced from Ref. 1; the heavy solid line is that obtained by modifying the phase difference Δ_{ds} as shown in Fig. 9 (see the text). The difference between these two results are not significant, it is sensitive to the particular set of the $E2$ phases.

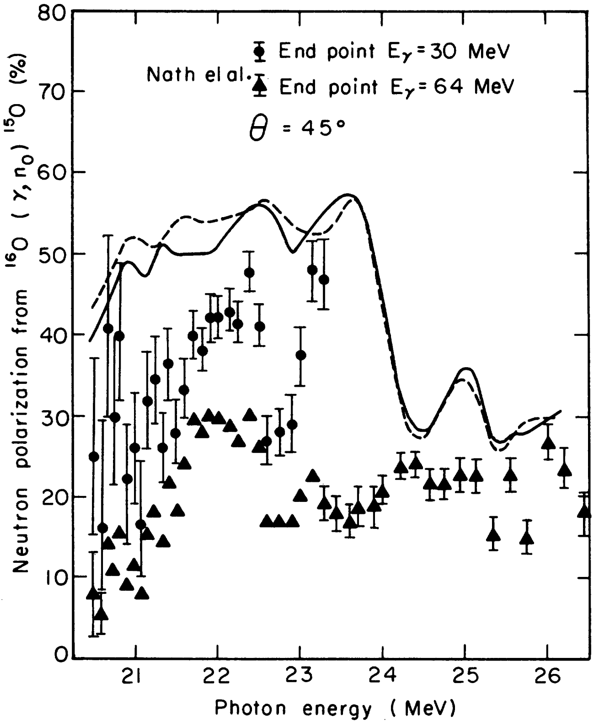

FIG. 11. The polarization at 45°. The dashed line is obtained by modifying the $E1$ phase difference Δ_{ds} as shown in Fig. 8, assuming no $E2$ amplitudes. The solid line shows the effect of $E2$ amplitudes in the same calculation with modified Δ_{ds}.

freedom in searching for appropriate $E2$ phases to fit the A_1, A_3, and $P(90°)$ data. We have found that, for $E2$ amplitudes as large as in case II, we need to require the $E2$ phases to follow quite closely the resonance pattern as shown in Fig. 7. This signature of a resonance remains rather clear. It is, however, also obvious that in case II, we do not need any appreciable $E2$ amplitude to improve the agreement with the experimental data.

We would therefore maintain that the $E1$ amplitudes, *without* $E2$ amplitudes and *with* the phase modification as described, have reproduced the angular distribution rather well and predicted larger polarizations at $\theta = 45°$ (compared to the data of Nath *et al.*[10]) below 24 MeV. Our prediction of $P(45°)$ is in good agreement with the earlier data of Hanser.[8] The $E1$-$E2$ interferences shown in coefficients A_1, A_3, and A_4 may be reasonably reproduced by considering only the direct amplitudes, with smooth $E2$ phases.[22] [We note, however, that these coefficients for (γ, p) measurements are much larger.[11, 13]]

V. CONCLUSION

We have shown that the $E1$ photodisintegration amplitudes obtained in the doorway-state formalism are adequate to interpret the experimental data, provided that we modify our $E1$ phase differences. Such *smooth* modification on the phase differences may be simply due to the inaccuracy in the potential scattering phase shifts. Further investigation of the various approximations in the reaction formalism should be useful. The conjecture of an $E2$ resonance in the dipole region remains as a possibility, but not with very strong evidence; a more definite answer would require more experimental and theoretical investigations.

ACKNOWLEDGMENTS

We would like to thank Professor H. F. Glavish and Professor S. S. Hanna for their discussions which initiate our case II investigation. We are also grateful to Dr. R. Nath and Dr. D. B. C. B. Syme for discussions and for kind supply of their data prior to publication.

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†Work performed under the auspices of the U.S. Atomic Energy Commission and the U.S. National Science Foundation.

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