Evidence for a Giant Quadrupole Resonance in Oxygen-16†

W. L. Wang
Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

and

C. M. Shakin
Department of Physics, Case-Western Reserve University, Cleveland, Ohio 44106
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We calculate the angular distribution and polarization of the photoneutrons from O^{16} in the giant-dipole region. We have to supplement our $E1$ amplitudes, which were obtained previously, with large phenomenological $E2$ amplitudes; we interpret this as evidence for a giant quadrupole resonance. We show that the importance of $E2$ amplitudes makes the current data analysis in $E1$ approximation very doubtful. The assumed $E2$ resonance is also shown to be easily detected experimentally.

We have recently reported a continuum shell-model calculation of the intermediate structure in the photonuclear cross sections of O^{16}.[1] We were able to show that the structure could be due to mixing of 3p-3h (three particle, three hole) configurations with the 1p-1h giant dipole states. For a more rigorous test of our reaction formalism, we now calculate the angular distribution and polarization in the (γ, n_0) reaction. Experimentally, the differential (γ, n_0) cross section was obtained by Jury, Hewitt, and McNeil.[2] The (γ, n_0) polarization was recently measured, with good resolution, by Cole, Firk, and Phillips[3] and Nath *et al.*[4] We shall compare the results of our calculation with these experiments.

We begin with the following T matrix (in the doorway-state approximation)[1]:

$$T = \langle \psi_0^{(-)} | H_\gamma | 0 \rangle + \sum_d \frac{\langle \gamma_0^{(-)} | H_{pd} | \varphi_d \rangle \langle \varphi_d | H_\gamma | 0 \rangle}{E - E_d - \Delta_d - \Delta_x + \frac{1}{2} i (\Gamma_d + \Gamma_x)}, \tag{1}$$

where $|0\rangle$ is the O^{16} ground state, and H_γ the photonuclear interaction. The doorways $|\varphi_d\rangle$ are the usual 1p-1h 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, respectively—to have rapid energy dependence. The shift Δ_x and width Γ_x are parameters whose physical significance is discussed in Ref. 1. The channel wave functions $|\psi_0^{(-)}\rangle$ include $s_{1/2}$ and $d_{3/2}$ continuum neutrons coupled to a $p_{1/2}$ hole state in the case of the ground-state cross section, $O^{16}(\gamma, n_0)O^{15}$. In this work we shall try to predict the $E2$ amplitudes and therefore include in $|\psi_0^{(-)}\rangle$ the $p_{3/2}$ and $f_{5/2}$ continuum waves. Some estimates of the $E2$ amplitudes have been made by Stewart, Morrison, and Federick[5] and Jury, Hewitt, and McNeil,[2] but no consistent calculation has been reported.

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

$$T_{lj}(E) = A_{lj}(E) \exp[i \Phi_{lj}(E)], \tag{2}$$

where $A_{lj}(E)$ is real and positive, and $\Phi_{lj}(E)$ is the total phase of the amplitude T_{lj}. The total phase is the sum of the potential phase shift δ_{lj} and the (real) resonant phase θ due to the resonant term in Eq. (1): $\Phi = \delta + \theta$. In our calculation, the $E1$ amplitudes are to be obtained from our calculation in Ref. 1; the $E2$ amplitudes will, however, be treated as parameters in our theory, to be determined by comparisons with experimental data. We shall give a detailed discussion of the $E2$ amplitudes later.

The expressions for photoneutron angular distribution and polarization are given in, for example, the review article by Firk.[6] Following Firk, we may write the differential cross section in terms of the coefficients A_n: $d\sigma/d\Omega = 0.125(\lambda/2\pi)^2 \sum_n A_n P_n(\cos\theta)$, where the P_n are the Legendre polynomials and λ is the photon wavelength. The energy-dependent coefficients A_n may then be related to the $E1$ and $E2$ amplitudes A_{lj} and their phase differences Δ, which are defined as $\Delta_{lj,l'j'} \equiv \Phi_{lj} - \Phi_{l'j'}$. The polarization is also given in terms of A_{lj} and Δ. A complete calculation will be presented elsewhere. In this Letter, we shall restrict ourselves to the following quantities: the A_2/A_0 ratio, and the relative polarizations $\vec{P}$ at 45° and 90°. The experimental data are shown in Figs. 1 and 2. [The $\vec{P}$(45°) datum

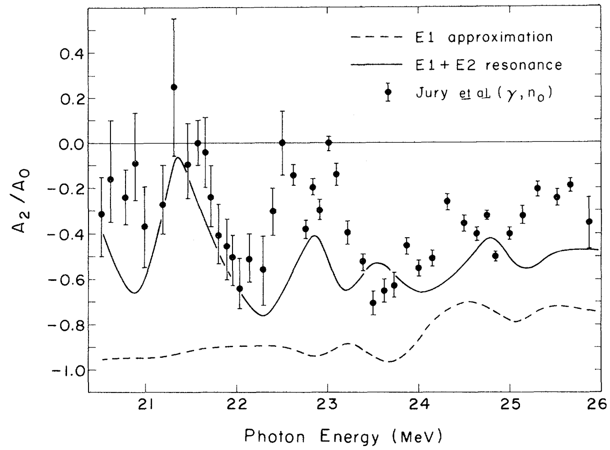

FIG. 1. Neutron angular-distribution coefficients A_2/A_0. Dashed line, obtained by using only the $E1$ amplitudes; solid line, obtained by including the effects of a giant $E2$ resonance in the region.

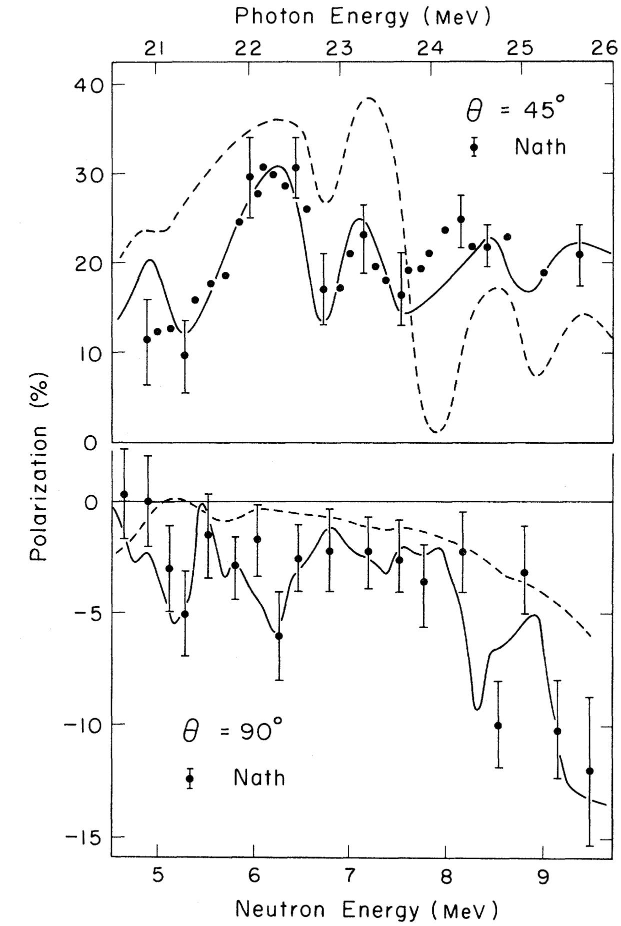

FIG. 2. Polarization of neutrons from O^{16}. For $\theta = 45°$, dashed line, result obtained by using only $E1$ amplitudes; for $\theta = 90°$, dashed line, result obtained by using only *direct* $E2$ amplitudes. Solid lines, results obtained by including the giant $E2$ resonance.

points are shifted upwards in energy by 0.5 MeV. This will be discussed later.]

Beginning with the $E1$ approximation, we obtain the d- and s-wave amplitudes and phases from our previous formulation[1]; they are shown as A_s/A_d and Δ_{ds} in Fig. 3. (Note that, for A's, we have used letter subscripts s, d, etc. for partial-wave amplitudes, and integer subscripts for expansion coefficients A_n.) The results for the A_2/A_0 ratio and the polarization at 45° are shown as dashed lines in Figs. 1 and 2. [$\vec{P}(90°) = 0$, in this case.] We note that the A_2/A_0 ratio cannot be reproduced by the $E1$ approximation, although the magnitude of $\vec{P}(45°)$ is well reproduced. It is clear that it is necessary to consider other amplitudes, such as $E2$ amplitudes.

We first calculate, in our previous formulation, the $E2$ *direct* amplitudes, which are, however, found to be too small to improve the agreement between the theory and experiment of the A_2/A_0 and the $\vec{P}(45°)$ values. We note that they *seem* to reproduce the polarization at 90°, as shown in Fig. 2 (the dashed line). A simple enhancement of the direct amplitudes is inadequate, and we have to conjecture a more complicated process for the $E2$ channels. Pending a more complete calculation, we shall be content with a qualitative parametrization of these $E2$ amplitudes. If we assume a broad $E2$ *resonance* in the giant-dipole region, the $E2$ amplitudes may be described in a Breit-Wigner form as

$$T_{lj}(E2) = T_{lj}^{\text{dir}} + \exp(i\delta_{lj})\left(\frac{5\lambda}{8\pi^2}\right)^{1/2} \frac{(\Gamma_{lj})^{1/2}[\Gamma_\gamma(E2)]^{1/2}}{E - E_q + i\Gamma_q/2}, \tag{3}$$

where T_{lj}^{dir} is the direct amplitude. The quadrupole resonance at E_q has a neutron emission width Γ_{lj} and the ground-state γ-absorption width $\Gamma_\gamma(E2)$. The total width Γ_q also contains widths for decay to other open channels and compound states, $\Gamma_q \gg \Gamma_{lj}$. The ratio Γ_{lj}/Γ_q may be determined by choosing $\Gamma_\gamma(E2)$ to exhaust the $E2$ sum rule.[7] In our calculation, we assume $E_q = 22.5$ MeV and $\Gamma_q = 10$ MeV, and obtain $\Gamma_\gamma(E2) = 0.33$ keV (≈ 30 Weisskopf units). We assume a linear neutron-energy dependence in Γ_{lj}. With the procedure described later we obtain $\sum_{lj}\Gamma_{lj} = 3$ MeV. It is also possible to fit the data with a smaller value of Γ_q. For example, the widths of such states reported by Lewis and Bertrand[8] are about 5 MeV; in this case $\sum\Gamma_{lj}$ will be smaller (≈ 0.75 MeV). We next have to determine the phases of these $E2$ amplitudes. The angular correlations are rather sensitive to the relative phases; we shall therefore take the phases to be free parameters in order to fit the experimental data.

We may now describe the procedure to determine the $E2$ amplitudes. We first note that we need four conditions to determine the two amplitudes and two phases (of the $p_{3/2}$ and $f_{5/2}$ waves). The available data include A_n ($n=0,1,2,3,4$), $\vec{P}(45°)$, and $\vec{P}(90°)$; we therefore have sufficient information to determine accurately our parameters. From the experimental data,[2] we first find that the A_4 coefficient is very small in the energy region in question. By taking $A_4=0$, we immediately obtain a simple relation between the $E2$ amplitudes:

$$A_f/A_p = 4.902\cos(\Delta_{fp}) \tag{4}$$

(see Ref. 6). Here we allow Δ_{fp} to change with energy; therefore Eq. (4) is more general than the assumption of $A_f=0$[2] or $\cos(\Delta_{fp})=1$.[5] The total *strength* of the $E2$ amplitudes may therefore be estimated from the A_2/A_0 ratio. We have

$$\frac{A_2}{A_0} = \frac{-0.5+1.414a_s\cos(ds)+0.733a_p^2+0.953a_f^2-0.58a_fa_p\cos(fp)}{1+a_s^2+1.667(a_p^2+a_f^2)}, \tag{5}$$

where we have defined $a_s \equiv A_s/A_d$ and $\cos(ds) \equiv \cos(\Delta_{ds})$, etc. Using Eq. (4) for $\cos(fp)$ in Eq. (5), we find that only the *magnitudes* of the $E2$ amplitudes (or approximately the sum of the squared amplitudes) appear in the ratio A_2/A_0. This enables us to determine the total $E2$ strength by fitting the experimental data of the ratio A_2/A_0 *alone*; with this total strength, we next have to determine the $E2$ relative amplitudes A_f/A_p (thus the Δ_{fp}) and one of the $E1$-$E2$ phase differences, for example Δ_{fd}. We shall require the $E2$ amplitudes to generate correct interference behavior when mixed with the theoretical $E1$ amplitudes; for a good criterion we choose the A_1 and A_3 coefficients which contain only $E1$-$E2$ interferences. We have, therefore, searched for our parameters, Δ_{fp} and Δ_{fd}, to reproduce the general behavior of A_1 and A_3; the resultant $E2$ amplitudes and phases are shown in Fig. 3. The ratio A_2/A_0 and the polarizations are then calculated with such amplitudes and are shown to be in excellent agreement with experimental data in Figs. 1 and 2 (the solid lines).

Several comments are in order. The $E2$ amplitudes are relatively large near the energy of the minor resonances at about 21.5, 23, and 25 MeV; this may explain some of the general difficulties in assigning spin and parity for these states. The smoothness of the $E1$-$E2$ phase differences show that the $E2$ amplitudes evidently go through a resonance (with resonant phase $\theta=\frac{1}{2}\pi$) in the energy region where we have the dipole resonance. The general behavior of $E2$ phases is therefore consistent with the form of Eq. (4) with energy-dependent parameters. We note again that the data

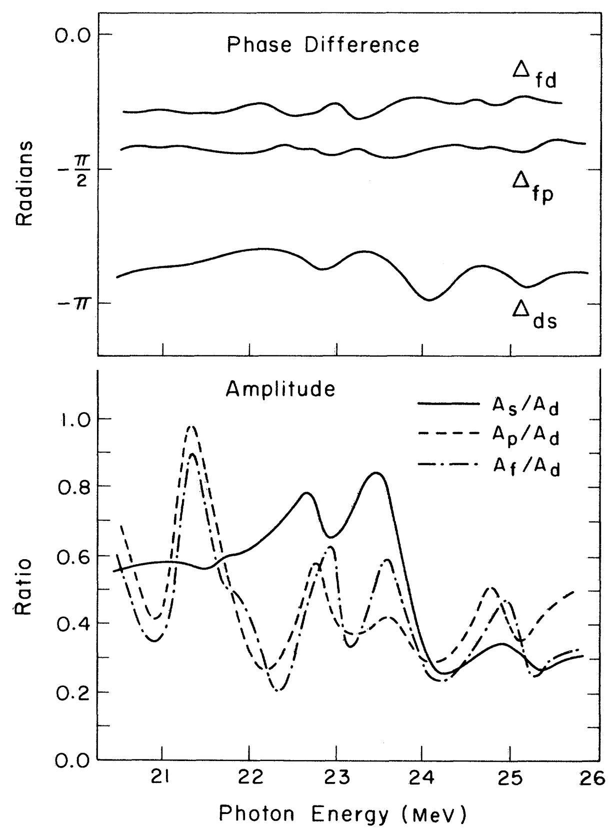

FIG. 3. Giant $E2$ amplitudes as compared to the $E1$ amplitudes. The phase differences are also shown. The $E2$ quantities are obtained by a rough fit to the angular-distribution data. The $E1$ amplitudes were obtained in Ref. 1. The $E2$ amplitudes (A_f and A_p) are *smooth functions of energy.* The $E1$ amplitudes (A_s and A_d) have strong energy dependence, which causes the strong oscillations shown.

of $\vec{P}(45°)$ have been shifted upward in energy. This uncertainty is due to the fact that we have chosen as our reference the energy scale of Caldwell *et al.*,[9] which is about 0.5 MeV higher than Nath's. It is important to see that the peaks in the 45° polarization in our calculation occur at the resonance energies; this is consistent with the observation of both Cole, Firk, and Phillips[3] and Nath *et al.*[4,10]

We have shown that all the available angular-correlation data in the giant-dipole region could be reproduced by the $E1$ amplitudes obtained in Ref. 1, together with a giant-quadrupole resonance in this region. We have also predicted the amplitudes and the phases of the $E2$ amplitudes. The *large* $E2$ amplitudes do not change the main *dipole* nature of the intermediate structure ($\sigma_{E2}^{tot} \lesssim 1$ mb). In a forthcoming report, we shall show that it is possible to detect the presence of such a quadrupole resonance, for example, in the polarization at 60°, or in the angular-distribution measurements at minima in the cross section. The effects of the quadrupole resonance on inelastic proton scattering have been recently discussed by Lewis and Bertrand,[8] and by Satchler.[11]

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