Properties of the $E1$ giant resonance built on the first excited state of ^{16}O

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Radiative capture of protons leading to the first excited state of ^{16}O ($E_x = 6.05$ MeV, $J^{\pi} = 0^+$) has been measured in the energy range $E_p = 10-17$ MeV in 200 keV steps. A pronounced concentration of dipole strength is observed, which is interpreted as a giant dipole resonance built on the 0_2^+ state. The observed strength has a γ-ray energy significantly less than that for the giant dipole resonance built on the ground state. The sign and magnitude of the shift is what would be expected if the giant dipole resonance observed is the lower energy component of a resonance split because of interaction with the quadrupole deformation of the 0_2^+ state, although this conclusion is model dependent. The strength of the excited state giant dipole resonance is somewhat larger than would be predicted by simple models in which the strength scales with the proton spectroscopic factor of the final state.

I. INTRODUCTION

The isovector giant $E1$ resonance is among the most studied phenomena in nuclear physics.[1] Early work focused on photoabsorption by the nuclear ground state. This work, which demonstrated the universality of the giant resonance phenomenon, was interpreted in terms of a macroscopic out-of-phase collective oscillation of the neutrons against the protons.[2,3] Later, more microscopic explanations were attempted, in which the role of the particle-hole interaction in shifting the $E1$ strength upwards in energy from the unperturbed value of 1 $\hbar\omega$ was explored, particularly in light nuclei.[4]

More recently, experimental and theoretical attention has shifted to giant dipole excitations built on nuclear excited states. Such excitations were predicted[5] by Brink and Axel, who also noted that the absorption of dipole photons should be approximately independent of the structure of the initial state. Giant resonances built on excited states cannot be observed in photoabsorption, but can be studied using the time-reversed process of radiative capture in which the residual nucleus is left in an excited state after emission of the $E1$ photon. A recent review of work in this field has been given by Snover.[6]

There is considerable evidence which has suggested that the basic idea embodied in the Brink-Axel hypothesis is correct. The first suggestion that giant resonances built on excited states might have been observed experimentally appears to be the work of Kovash *et al.*[7] who discussed the possibility that they had observed 2 $\hbar\omega \rightarrow 1$ $\hbar\omega$ radiative transitions in ^{12}C. (They considered proton capture to a state which emitted an $E1$ γ ray leading to stretched 1 $\hbar\omega$ excitations at an excitation energy of about 19 MeV.) However, a more complete subsequent study[8] of this reaction by a group including some of the same authors concluded that it was uncertain whether such a giant resonance had in fact been observed. Somewhat more convincing evidence for such states comes from recent experiments[6,9,10] which have shown that in several light nuclei the integrated (γ, p_0) strengths (obtained from the measured radiative capture yields by detailed balance) are proportional to the spectroscopic factors for proton transfer reactions on the same targets used in the radiative capture reactions leading to the same final states. This proportionality, which in some cases[10] was found to hold for spectroscopic factors as small as a few percent, was interpreted as indicating the dominance of direct and semidirect capture, and suggests that the probability of absorbing a dipole photon is independent of the initial state. The same experiments[9] also showed that the giant dipole resonances (GDR's) built on excited states in ^{28}Si were characterized by a nearly constant gamma-ray energy. Both of these observations are consistent with the simple picture implied by the Brink-Axel hypothesis. The idea of a GDR of constant energy and strength being built on every state of a nucleus has also been used recently with considerable success to describe the decay of statistically equilibrated compound nuclei following the fusion of two heavy ions. Calculations (see Ref. 6) based on these assumptions give a reasonable account of singles spectra of high energy γ rays observed following such reactions and have formed the basis for studies of the properties of giant dipole resonances built on highly excited states which cannot easily be studied otherwise.

In both the direct and semidirect mechanisms of radiative capture the integrated yield $\int \sigma(\gamma, p) dE$ is proportional to the proton spectroscopic factor S_p because the dipole photon removes a single proton from the final state in a capture reaction, either directly or through the intermediate formation of the GDR.[11] Such a mechanism should be important mainly for states with significant parentage involving a proton coupled to the target ground state. When the spectroscopic factor (and hence direct-semidirect capture) is small, other capture mechanisms must in general be taken into account. Possibilities previously considered in this regard included multistep processes of various types (e.g., inelastic excitation[12] of the target followed by capture) and, in heavier nuclei, formation of a statistically equilibrated compound nucleus in which γ decay competes with all other allowed decay modes.

It is important to note that there exists considerable experimental data which is not consistent with the simple picture described above. For example, the idea that the energy of the GDR is approximately independent of the structure of the initial state has been questioned by a recent series of detailed photoabsorption measurements, which have demonstrated a pronounced configuration dependence. These experiments, described in a recent detailed review[13] by Eramzhayan *et al.*, consist of (γ,p_j) studies in which j labels different final states in the residual nucleus. Such measurements of course can study only photoabsorption by the nuclear ground state, but can in principle give information about the shell model orbitals involved in the electromagnetic transition. For example, in *sd*-shell nuclei absorption of an $E1$ photon can either lift an *sd*-shell nucleon to the $1f$-$2p$ shell or promote a $1p$-shell nucleon to the $2s$-$1d$ shell. The final state reached in a (γ,p) reaction depends on which of these possibilities actually occurred. For example, Fig. (3.5) of Ref. 13 shows that for $(2s\text{-}1d)\rightarrow(1f\text{-}2p)$ transitions the GDR resonance energy is approximately 20 MeV, in agreement with the value found in Ref. 9, whereas for $(1p)\rightarrow(2s\text{-}1d)$ transitions $E_\gamma^{\mathrm{GDR}} \approx 23$ MeV. Similar results are found for other transitions. Exceptions to the proportionality of integrated strengths to proton spectroscopic factors also have been observed at the factor of two level, for example capture leading to the first excited state of ^{28}Si (see Ref. 9).

The present work was undertaken to study the properties of a GDR built on a state with a small value of S_p but whose structure is reasonably well understood. Specifically, we have studied radiative proton capture leading to the low lying (0_2^+) state of ^{16}O. This state is widely believed[14] to be dominated by 4p-4h excitations based on a closed $1p$-shell, but 2p-2h configurations are probably also present. The presence of these 2p-2h components provides an interesting example of a mechanism whereby the proportionality between the spectroscopic factor and the integrated capture strength can be destroyed. Specifically, if particle-hole excitations are already present in the initial state in a (γ,p) reaction, absorption of a dipole photon can return an *sd*-shell proton to the $1p$-shell; some other proton is then emitted into the continuum when the GDR decays. The usual description of semidirect capture would appear not to include this case. As an example, consider the two diagrams shown in Fig. 1. [We refer to the (γ,p) process here.] The first (a) is the standard picture of semidirect capture. It is assumed that the initial state is a closed $1p$-shell, and that the final state is a continuum proton plus the (1-hole) ground state of ^{15}N. An example of what can happen if 2p-2h configurations are present in the initial state of ^{16}O has been discussed by Brown[15] and is shown in Fig. 1(b). In this diagram both the electromagnetic field and the residual nucleon-nucleon interaction act once, and the final state is once again a proton plus the ground state of ^{15}N. Note, however, that the initial 2p-2h state cannot be reached by adding a single proton to the ground state of ^{15}N; the corresponding spectroscopic factor is identically zero. Diagrams of the type shown in Fig. 1(b) will in general be

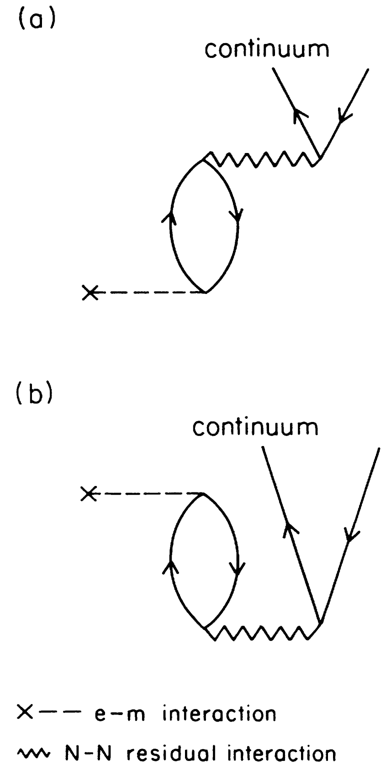

FIG. 1. (a) Standard semidirect process. Incoming photon creates p-h pair, particle emitted to continuum; (b) photoabsorption on 2p-2h pair in g.s.; photon annihilates one p-h pair, one particle emitted to continuum leaving one hole.

expected to contribute less than those in Fig. 1(a) because the $E1$ transition is less collective, but in cases where most of the dipole strength leads to configurations which cannot decay into the ground state proton channel (e.g., the 3p-3h, 4p-4h, and 5p-5h states reached by dipole absorption by the dominant 4p-4h piece of the initial state in ^{16}O) they should almost certainly be considered. In any event, one should exercise caution regarding expectations concerning the proportionality of $\int \sigma(\gamma,p)dE$ to S_p in such cases.

An additional motivation for the experiments undertaken here is to study the usefulness of the concept of macroscopic deformation in describing the interaction of the dipole degree of freedom with low-lying collective modes in light nuclei. In heavy nuclei, recent work (mostly involving the statistical decay of the ensemble of all possible giant dipole states in a nucleus as populated in heavy-ion radiative capture experiments) has shown that GDR's built on very highly excited states in nuclei with well-established ground-state deformation also show the characteristic splitting with deformation known from studies of the ground state GDR.[16] In contrast, the extensive set of (γ,p) experiments in light and medium-A nuclei discussed above (Ref. 13) concluded that macroscopic deformation was *not* an important determinant of the structure of the GDR. Since the first excited state of ^{16}O has been described in terms of simple collective models, this would appear to be a favorable case to test the applicability of these concepts to the structure of the GDR in light nuclei.

The remainder of this paper is organized as follows. Section II gives an account of the experimental procedure, followed by a presentation of the results and discussion in Sec. III. Our conclusions are given in Sec. IV.

II. EXPERIMENTAL PROCEDURE

Experiments to study the ^{15}N(p,γ)^{16}O(0_2^+) reaction are difficult for two reasons. First, a giant $E1$ resonance built on the predominantly np-nh excited 0^+ state ($E_x = 6.05$ MeV) will have a small overlap with the predominantly 1p-1h states formed by proton capture on the ground state of ^{15}N; direct and semidirect capture will consequently be quite weak. Second, any such experiment must be able to distinguish the process of interest from capture leading to the nearby second excited state (E_x = 6.13 MeV, $J^\pi = 3^-$). Previous studies[17] of ^{15}N(p,γ)^{16}O* have not resolved the γ decays leading to the first two excited states, and arguments similar to those given above have been used to attribute essentially all of the capture strength seen to the (p,γ_2) reaction. At some bombarding energies the observed capture strength has been experimentally proven to lead to the second excited state by coincident observation of the 6.13 MeV γ rays from its decay.

A related coincidence technique can be used to observe the decays to the first excited state. Since the first excited state of ^{16}O decays almost exclusively by internal pair emission, coincident observation of a fast electron or positron provides a characteristic signature for formation of states decaying to ^{16}O(0_2^+). Because of the very small cross section expected and because of the background from ^{16}O(3_1^-) decays, a high geometric efficiency for electrons or positrons and a low sensitivity to γ rays are needed. To achieve this we have used a thin (0.4 mm) anthracene scintillator of diameter 6.5 cm located approximately 1.65 cm above the target.[18] The efficiency of this device for detecting an electron or positron from the decay of ^{16}O(0_2^+) has been measured directly using coincidences between protons from the ^{16}O(p,p$'$)^{16}O(0_2^+) reaction and the deexcitation electrons or positrons. In these measurements the first two excited states of ^{16}O were resolved in the proton energy spectrum. An efficiency of 38 ± 2 % was measured for detecting e^+ or e^- or both, i.e., for recording any coincident pulse in the thin scintillator. The measured efficiency for recording a count in coincidence with protons leading to ^{16}O(3_1^-) was found to be a factor of 90 ± 15 smaller. This level of background rejection is adequate for the present study, as will be demonstrated below. It is possible to reduce the sensitivity to photons by approximately another order of magnitude by requiring a coincidence between the electron and positron from the internal pair decay, but at a cost of reduced efficiency. This was demonstrated[19] in 1962 when an e^+-e^--γ triple coincidence technique was used to measure the very weak γ branch connecting ^{16}O(2_1^+) and ^{16}O(0_2^+). The coincidence efficiency of the pair detector was approximately 1.7%. Recent measurements in this laboratory using two electron detectors of the type described above (in a less efficient geometry) also show that the γ-ray rejection can be improved in this way. Preliminary results[20] suggest that the observed e^+-e^- coincidence rate can be accounted for by the internal pair decays of the second, third, and fourth excited states of ^{16}O, which are known[21] to occur at the level of a few tenths of a percent.

In the present experiment capture γ rays were observed in coincidence with single electrons or positrons from the $0_2^+ \rightarrow 0_1^+$ internal pair decay. Proton beams with energies between 10 and 17 MeV in the laboratory system from the University of Pennsylvania tandem Van de Graaff accelerator were used to bombard a target of melamine ($C_3H_6N_6$) with the nitrogen enriched to 99% in ^{15}N. The target used was measured to have a total thickness of 2.3 ± 0.1 mg/cm^2 based on the energy loss of 5.47 MeV α particles from an ^{241}Am source. This corresponded to proton energy losses of 60 to 92 keV in the laboratory system. The laboratory beam energy was incremented in 200 keV steps.

Gamma rays were detected in two cylindrical NaI(Tl) scintillation detectors of dimensions 11.43 cm diameter by 15.24 cm long and 11.43 cm diameter by 12.70 cm long. Each was collimated to a diameter of 7.62 cm with 2.5 cm of Pb. One detector was kept fixed at a scattering angle of 90°. The second was placed at scattering angles of 56° or 131°. Some cosmic ray rejection was achieved by operating the NaI crystals in anticoincidence with 30.5 cm by 45.7 cm by 0.64 cm thick plastic scintillators, located just above the crystals. In practice the cosmic ray rejection had little effect in the (p,γ_1) measurements since the coincidence requirement with electrons or positrons already largely eliminates cosmic ray background. For the (p,γ_0) yield, measured for normalization purposes, the relatively large capture cross section dominates the small cosmic ray yield so the cosmic ray background could easily be subtracted.

During the experiment coincidence losses, due for example to pileup, were monitored with two pulsers operated in coincidence. One pulser was used to fire an LED optically coupled to the NaI phototube, while the other simulated a pulse from the thin scintillator and was added into the same electronics as the actual signals. A correction for the losses measured in this way was applied to the data; the size of the correction ranged from roughly 1% to 4%. The LED pulser and the strong 15.11 MeV peak from the ^{15}N(p,$\alpha\gamma$)^{12}C reaction served to monitor gain shifts in the electronics. The data were recorded in event mode on magnetic tape and analyzed off-line.

Typical γ-ray singles and coincidence spectra are shown in Fig. 2. (For the coincidences several spectra measured independently have been added together to improve the statistical accuracy.) The coincidence spectrum is extremely clean in the energy range of interest, and contains essentially only contributions from the (p,γ_1) reaction of interest. Accidental coincidences have been subtracted.

Determination of the γ-ray intensity as a function of

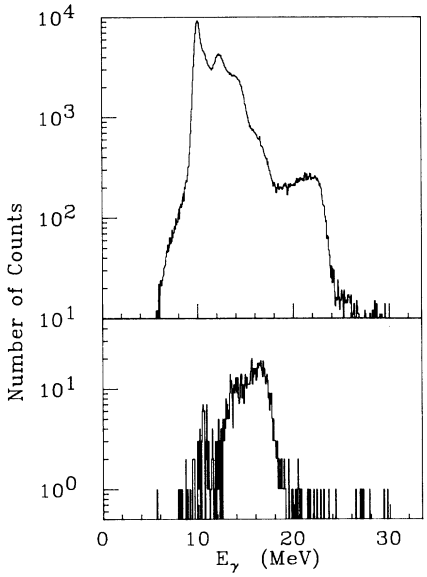

FIG. 2. Top, singles γ spectrum observed at $E_p = 12.4$ MeV, $\theta_\gamma = 90$ °; bottom, γ spectrum at the same bombarding energy in coincidence with an electron or positron in thin anthracene scintillator above the target.

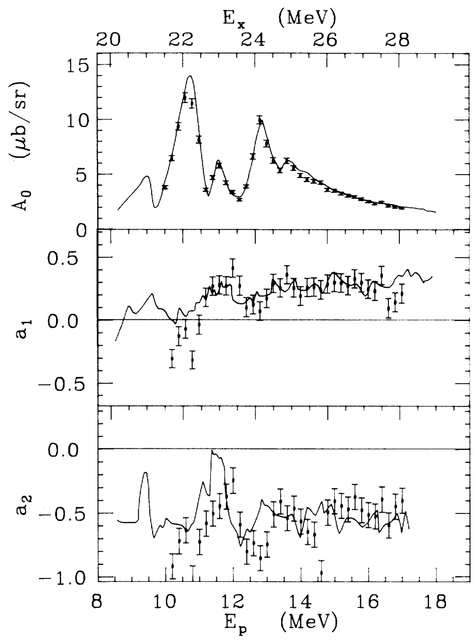

FIG. 3. Comparison of Legendre polynomial coefficients for ^{15}N (p, γ_0) as measured in the present work (data points) with the previously measured values reported in Ref. 23 (solid line).

energy and angle requires knowledge of the response of the NaI detectors as a function of γ ray energy. Some rough guidance in this regard was obtained from a Monte Carlo program[22] designed primarily for somewhat lower energy γ rays. The calculated line shapes did not agree in detail with those observed, however. Accordingly, it was decided, somewhat arbitrarily, to integrate the number of counts in a region above 82% of the nominal energy of the γ ray (as determined from a linear energy calibration based on low-energy γ rays for which a full energy peak is clearly visible.) The lower cutoff was fixed by the requirement that it must be above the strong line at $E_\gamma = 15.11$ MeV at bombarding energies where that contaminant line is prominent. The uncertainty associated with each data point was estimated by combining the statistical error associated with the number of counts with a (somewhat arbitrarily chosen) 6% constant error designed to represent a combination of uncertainties associated with the fitting procedure and the reproducibility of the data points, many of which were measured more than once. As will be seen below, for the newly measured (p,γ_1) data the statistical error dominates. The resulting integrals were fitted at each energy to the standard expansion

$$\frac{d\sigma}{d\Omega} = A_0 + A_1 Q_1 P_1(\cos\theta) + A_2 Q_2 P_2(\cos\theta). \quad (1)$$

The Q_k are the standard finite geometry attenuation coefficients. These have a negligible effect on the angular distribution in the present geometry. They were, however, included using estimates provided by the Monte Carlo program (Ref. 22). Terms with $L > 2$ were assumed to be negligible; these terms are known to be small for the GDR built on the ground state.[23] In the following the normalized coefficients $a_k = A_k / A_0$ will be used to characterize the angular distribution; the total cross section is equal to $4\pi A_0$.

In order to test whether the overall data reduction procedure gives the cross section as a function of energy and angle with sufficient accuracy for the present purpose, we compared the energy dependence in the (p,γ_0) yield observed in the present work to the results of previous experimental work.[23] That comparison, shown in Fig. 3, suggests that the energy dependence is reasonably well measured, particularly for the total cross section. Since in the present work the principal physics conclusions emerge from the *relative* cross sections in the capture channels leading to the 0_1^+ and 0_2^+ states, no effort was made to measure an absolute cross section; one overall energy-independent normalization constant has accordingly been obtained by comparing the present (p,γ_0) yield with the results of Ref. 23. This constant was obtained from the excitation curve measured at 90°, since those data were measured more accurately than at the other angles as a result of repeated measurements.

III. RESULTS AND DISCUSSION

The (p,γ_1) excitation curve measured at $\theta_\gamma = 90°$ is shown in Fig. 4. Note that the γ_1 capture yield is much less than the γ_0 yield, as expected. Also, the (p,γ_1) cross section shows a significant concentration of strength with a centroid at $E_\gamma = 24.6$ MeV. This concentration of strength bears a qualitative resemblance to the well-known GDR built on the ground state (i.e., a broad peak with superimposed intermediate structure) although the overall capture strength is much smaller. Also shown in Fig. 4 is the result of a previous measure-

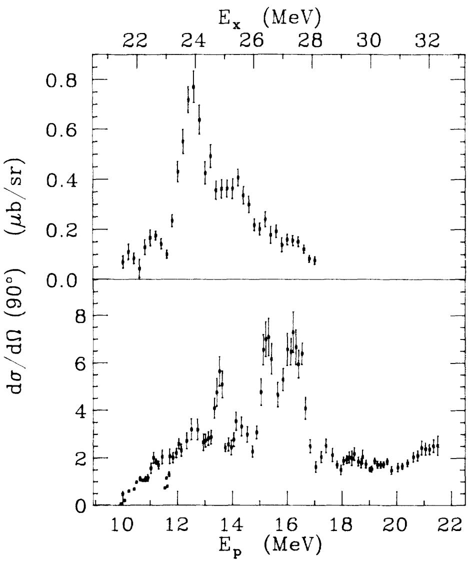

FIG. 4. Top, excitation curve in the $^{15}N(p,\gamma_1)^{16}O$ channel observed by requiring γ-e$^{\pm}$ coincidences; bottom, unresolved sum of $^{15}N(p,\gamma_{1+2})^{16}O$ (Ref.17).

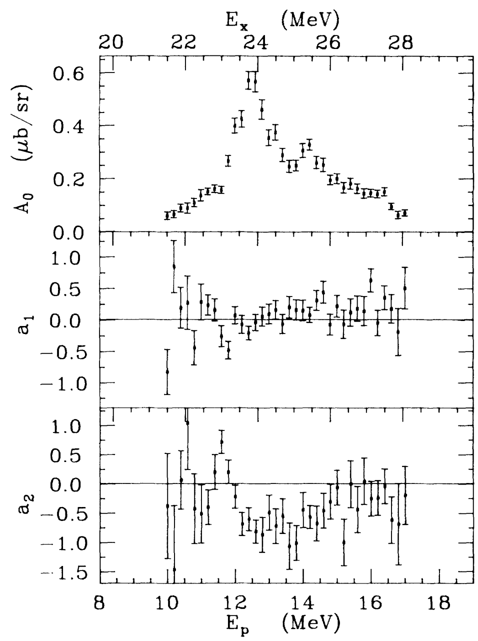

FIG. 5. Legendre polynomial coefficients for the (p,γ_1) channel, as measured in the present work.

ment[17] of the combined capture yield to the first two excited states of ^{16}O. Note that in the first paper cited as Ref. 17 the overall normalization differs from that obtained in the second paper by about 30%. We have adopted the normalization of the first paper, which also agrees with that obtained in Ref. 23. A comparison with the present (p,γ_1) data demonstrates that good experimental separation of the two channels has been achieved. The strong intermediate structure peaks at $E_x = 26.4$ and 27.3 MeV are confirmed to originate in the γ_2 channel, as reported by Chew *et al.* In contrast, the weak intermediate structure peak observed in the γ_{1+2} data at $E_x = 23.8$ MeV arises almost entirely from the γ_1 channel. Note that the much larger cross section in the (p,γ_2) channel implies that some background is present in the present (p,γ_1) data at the few percent level from events in which a 6 MeV photon interacts in the electron detector. This background has been neglected.

The similarity between the γ_1 and γ_0 capture processes extends to the angular distributions as well. These are measured rather poorly in the present work, but the trends (shown in Fig. 5) resemble the known behavior in the (p,γ_0) channel in the sense that the Legendre polynomial coefficient a_2 is negative and a_1 is weakly positive throughout most of the region of enhanced capture strength. The negative a_2 is expected for a dipole transition, and results from the tendency for capture with nonzero orbital angular momentum to align the angular momentum of the capture state perpendicular to the beam direction. The sign of a_1 is more difficult to interpret, since a nonzero a_1 must result from dipole-quadrupole interference. We note that there is some hint of a narrow structure in the a_2 and possibly the a_1 coefficient near $E_p = 11.6$ MeV, but the present three point angular distributions are not able to characterize it in a definitive way.

The centroid of the capture strength observed in the γ_1 channel occurs at $E_x = 24.6$ MeV. This corresponds to an average γ-ray energy of 18.5 MeV, considerably lower than the corresponding value for the GDR built on the ground state, which has $\langle E_\gamma \rangle = 23.4$ MeV. The origin of this energy shift is of some interest since the usual behavior[10] observed with giant resonances built on a wide range of excited states is that the γ-ray energy remains remarkably constant while the width increases with excitation energy. Note that the sign of the observed shift is consistent with the configuration dependence noted in the photoabsorption studies of Ref. 13, in the sense that configurations with one particle excited to the $1f$-$2p$ shell contribute to the GDR built on the 0_2^+ state but not to the principal components of the GDR built on the ground state. As noted above, transitions to such configurations were found to involve a lower gamma ray energy than the standard transitions from the $1p$ to the $2s$-$1d$ shell. Unfortunately, it is difficult to go much beyond such qualitative comparisons. It would obviously be desirable to investigate whether, say, a shell-model calculation including up to 5 $\hbar\omega$ excitations from a filled $1p$-shell core could explain the observed shift. Such calculations have not been performed.

Some additional insight into the nature of the GDR built on the 0_2^+ state may be gained by comparing the results of the present study with previous work involving the GDR built on the ground state of ^{20}Ne. In the simplest weak coupling picture,[24] the four nucleons in the sd-shell in $^{16}O(0_2^+)$ occupy the same configurations as the sd-shell nucleons in the ^{20}Ne ground state. In fact, the GDR in ^{20}Ne, as observed in the $^{19}F(p,\gamma_0)$ reaction,[25] bears a strong resemblance to the present (p,γ_1)

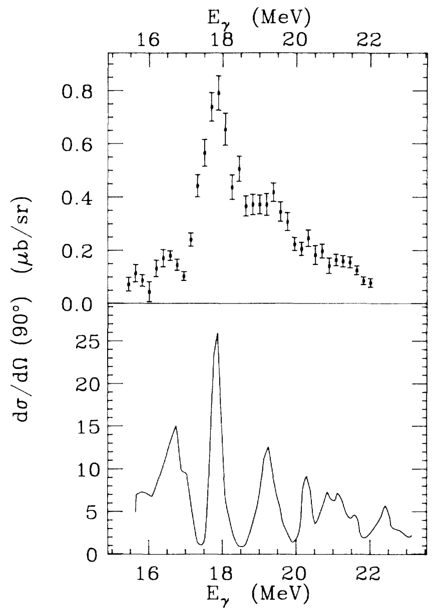

FIG. 6. Comparison of present $^{15}N(p,\gamma_1)^{16}O$ 90° excitation curve (top) with the $^{19}F(p,\gamma_0)^{20}Ne$ channel (bottom, Ref. 25) plotted as a function of γ ray energy.

data when plotted as a function of E_γ (see Fig. 6). The centroid is nearly the same in both cases, and there appears to be some correlation between the intermediate width structure as well. This comparison suggests the speculation that the doorway states which are responsible for the intermediate structure are not affected very much by removing four nucleons from the $1p$ shell. It would certainly be interesting to see whether a calculation could reproduce this unexpected behavior.

In order to study the strength of the GDR observed in the γ_1 channel, the observed (p,γ_1) cross sections have been converted to integrated (γ,p) yields using detailed balance,

$$\sigma_{\gamma p} = 2m_p c^2 \frac{E_p^{c.m.}}{E_\gamma^2} \frac{(2i+1)(2I+1)}{2(2I_F+1)} \sigma_{p\gamma} \tag{2}$$

where i, I, and I_F are, respectively, the spins of the projectile, target, and final state for the (p,γ) reaction. The results are given in Table I, where the corresponding information for the GDR built on the ground state has been taken from previous work. Also given are the corresponding spectroscopic factors[26] for single proton stripping reactions leading to the first two 0^+ states in ^{16}O. As expected from the complicated nature of the excited state, both the integrated (γ,p) yield and the spectroscopic factor are much smaller than the corresponding quantities for the ground state. Note, however, that the ratio of integrated (γ,p) strength for the 0_2^+ state to that of the 0_1^+ state is approximately 1.7 times larger than the corresponding ratio of spectroscopic factors. This discrepancy is probably attributable at least in part to the process of absorption by 2p-2h states shown in Fig. 1(b). It may be noteworthy that the same comparison for the two lowest 0^+ states in ^{12}C shows a similar discrepancy.[27]

TABLE I. Comparison of integrated (γ,p_0) strengths with proton spectroscopic factors for 0^+ states in ^{16}O.

E_x	$\int \sigma(\gamma,p_0)dE$ (MeV mb)	S_p[b]
0	37[a]	3.52
6.05	2.8	0.16
Ratio 6.05/0	0.076	0.045

[a]Reference 23.
[b]Reference 26.

Because the spectroscopic factor is small, and because of the possible contribution at a low level of other more complicated reaction mechanisms, including for example statistical capture, the present data cannot be interpreted as *requiring* the process shown in Fig. 1(b), which is offered merely as an example of one possible mechanism in which the integrated capture strength to a given final state might not be proportional to S_p. The present results do however suggest the possible presence of 2p-2h components in the 0_2^+ state of ^{16}O in another way. Specifically, if 2p-2h components are negligible, then the lowest 0^+ states in ^{16}O can be described in the two-state mixing approximation,

$$\begin{aligned} |0_1^+\rangle &= \cos\theta\,|0p\text{-}0h\rangle + \sin\theta\,|4p\text{-}4h\rangle , \\ |0_2^+\rangle &= -\sin\theta\,|0p\text{-}0h\rangle + \cos\theta\,|4p\text{-}4h\rangle . \end{aligned} \tag{3}$$

The predominantly 1p-1h GDR built on $|0p\text{-}0h\rangle$ and populated strongly in the (p,γ_0) reaction would in this case be expected to decay to the excited 0^+ state in direct proportion to the mixing amplitude. We assume here that the 1p-1h GDR does not mix with more complicated 1^- states, e.g., 3p-3h and that the ^{15}N ground state is a pure 1p-shell hole. The ratio of the $E1$ widths connecting the GDR built on the (0p-0h) state to the upper and lower 0^+ states is then given by $(E_{\gamma_1}/E_{\gamma_0})^3\sin^2\theta/\cos^2\theta$. The precise value of θ depends on the details of the two-state model. However, even the smallest values found in the literature[28] ($\theta \approx 18°$) lead to the prediction that the intermediate structure at $E_p = 10.8$ MeV should appear in the (p,γ_1) channel with an average cross section A_0 of about 0.5 μb/sr. Experimentally no structure is observed; an upper limit of approximately 100 nb/sr can be obtained from the data shown in Fig. 5. The absence of this structure in the γ_1 channel could then result from destructive interference between 0p-0h and 2p-2h configurations in the first excited state of ^{16}O, i.e., the assumptions of the two state model are incorrect.

An alternative way of attempting to interpret the present data is in terms of macroscopic deformation. In this specific variant of the two state model, the np-nh components of the 0_2^+ state constitute a deformed intrinsic state which is the bandhead of a rotational band. Other members of the band include the 2^+, 4^+, and 6^+ levels located at E_x = 6.92, 10.36, and 16.2 MeV, respectively. In this view[28] the energy of the deformed 0^+ state can be calculated from the positions of the 2^+ and

4^+ states using the known relationship between the energy levels of a rotational band. We assume axial symmetry for simplicity. Some previous treatments[29] have suggested that the intrinsic state of this band is triaxial with $\gamma \approx 25°$, but later more complete studies of electron scattering[30] have not been so interpreted. The properties of the lowest $K=0$ band should not be terribly sensitive to the details of the shape parametrization; in any case the approximations involved in the extreme two-state model may prevent detailed arguments concerning the shape from being terribly informative. Once the energy of the rotational 0^+ state is fixed, the energies of the physical 0^+ states determine the value of θ in Eq. (3). The mixing angle θ can be independently determined from the $B(E2)$'s connecting the 2^+ state at $E_x = 6.92$ MeV with the two 0^+ states by assuming that the $E2$ decays connect only the deformed components of the wave functions. The admixture obtained in this way agrees very well with that determined by the energy levels, as was originally pointed out in Ref. 28. (It is interesting that if the energy levels of a triaxial rotor[31] are used, the agreement is considerably worse for an asymmetry parameter $\gamma = 25°$.) The quadrupole deformation of the intrinsic state can now be obtained either from the $B(E2)$'s or from the known electric monopole matrix element connecting the two 0^+ states and the measured charge radius of the ground state.[21] In the latter case it is assumed that no one-body operator connects the spherical and deformed states. This procedure also yields the rms radii in the spherical and deformed states. The quadrupole deformation of the intrinsic state obtained in this way is quite large (see below for a specific estimate). Consequently, some care must be exercised in using standard formulae based on series expansions in powers of the (assumed small) deformation.

In heavy nuclei it is well known that the GDR built on an axially symmetric deformed nucleus is split into two components. The splitting results from the fact that the nuclear radius is different along and perpendicular to the symmetry axis in the body-fixed coordinate system. If the dipole resonance frequency is assumed to be inversely proportional to the radius, as is the case in the Steinwedel-Jensen[3] (SJ) version of the hydrodynamic model, the splitting can be simply calculated from the measured quadrupole deformation of the low-lying states. In heavy nuclei reasonably good agreement has been claimed between the quadrupole moments obtained from these two methods.[32] Some caution is required in interpreting this comparison, which is clearly model dependent. Consistent values of the nuclear radius must be used throughout, and higher order deformations (e.g., hexadecapole) must be taken into account if appropriate. The summary of this issue in Ref. 1, for example, leaves open the question of whether systematic discrepancies exist or not between the two methods of determining the quadrupole deformation.

Any attempt to predict the splitting of a GDR resulting from macroscopic deformation in ^{16}O is particularly vulnerable to the model dependence noted above. It is known that in light systems the A-dependence of the energy of the GDR is $\approx A^{-1/6}$, as in the original Goldhaber-Teller (GT) model. In fact, it has been suggested[33] that the physical GDR corresponds to a linear superposition of the SJ and GT modes, with comparable amplitudes in the heaviest nuclei and with the GT mode dominant in the lightest nuclei. In the GT model the dipole resonance frequency is inversely proportional to the square root of the nuclear radius, and the splitting in lowest order is one-half the value found in the SJ case.[34] For definiteness we assume a pure Goldhaber-Teller vibration here. For a prolate spheroidal nucleus with semimajor and semiminor axes a,b we have

$$\frac{E_2 - E_1}{\frac{1}{3}(E_1 + 2E_2)} = \frac{\sqrt{\eta} - 1}{\frac{1}{3}(1 + 2\sqrt{\eta})} \tag{4}$$

where E_2 and E_1 are, respectively, the energies of the upper and lower components of the split GDR and $\eta = a/b$. We can estimate η from the intrinsic quadrupole moment of the rotational band. Averaging the values for the $4_1^+ \rightarrow 2_1^+$ and $2_1^+ \rightarrow 0_{def}^+$ transitions gives $Q_0 = 68 \pm 10$ fm^2, where the quoted uncertainty reflects both the experimental errors in the lifetimes and the fact that the two transitions do not give results completely consistent with the rotational model. The ratio of the semimajor to the semiminor axis is then determined from

$$Q_0 = \tfrac{2}{5} Z (a^2 - b^2) = \tfrac{2}{5} Z R^2 \frac{\eta^2 - 1}{\eta^{2/3}} . \tag{5}$$

Here R is the radius of the sphere of equivalent volume, and is taken from $R^2 = \frac{5}{3} \langle r_s^2 \rangle$, where r_s is the rms radius of the spherical component of the ground state wave function. Diffusivity corrections have been neglected. Using $r_s = 2.68$ fm, $\eta = 1.94$. (r_s has been determined from the measured $E0$ matrix element and charge radius of the ground state, as noted above.) If we assume that the centroid of the dipole strength is the same as that of the GDR built on the ground state, $\langle E_\gamma \rangle = 23.4$ MeV, the two components of the split resonance have energies of 18.5 and 25.8 MeV. The lower component is in good agreement with the concentration of dipole strength observed in the present work, although this agreement should not be taken very seriously without having observed the upper component, which is predicted to occur beyond the range of the present data. Note also that if this interpretation were shown to be correct, the discrepancy between the integrated (γ,p) strength and the proton spectroscopic factor noted above would become 3 times worse than it is now.

It would be premature to conclude on the basis of these results that the present data are explained by macroscopic deformation; at a minimum data at higher energies would be required to confirm the presence of the predicted higher energy component of the split resonance. We are planning such measurements for the future. It should also be noted that in $^{20}Ne(\gamma,n)$ measurements[35] covering the range $18 < E_\gamma < 30$ MeV do not show the expected upper component of a resonance split by the amount one would predict based on the known deformation of the ground state. This would be in line with the conclusions of Ref. 13 that in *sd*-shell nuclei macroscopic deformation is less important than configurational splittings in explaining the structure of the GDR as observed in (γ,p) reactions. It may well be that in such a light system there are simply not enough particles to develop the coherence required for a macroscopic explanation to make sense. Since the influence of individual particle-hole states in different configurations is still clearly important, as evidenced by the observed intermediate structure, it is clear that any complete explanation of these phenomena will most probably involve a microscopic description of the individual nucleons participating.

IV. SUMMARY AND CONCLUSIONS

A pronounced concentration of dipole strength has been observed in the (p,γ_1) channel, and has been interpreted as a giant dipole resonance built on the first excited state of ^{16}O. The γ-ray energy of the resonance is about 4.9 MeV lower than that of the well-known GDR built on the ground state. The γ-ray energy and intermediate structure of the resonance agree reasonably well with the GDR built on the ^{20}Ne ground state, consistent with the idea that the 0_2^+ of ^{16}O involves the weak coupling of four particles in the *sd*-shell to four holes in the $1p$ shell. The energy shift between the dipole strengths in the 0_2^+ and 0_1^+ channels in ^{16}O is consistent with a picture in which the dipole frequency is inversely proportional to the square root of the nuclear radius and in which the shape of the deformed excited state is fixed from the electromagnetic properties of the rotational band built upon it. This picture would predict an additional concentration of strength beyond the energy range of the present experiment. The sign of the energy shift is also consistent with the fact that the GDR built on the 0_2^+ state can involve $2s$-$1d \rightarrow 1f$-$2p$ transitions, which show different GDR energies, as noted in Ref. 13.

The yield in the (p,γ_1) channel is found to be small, as expected from the complicated many-particle many-hole nature of the 0_2^+ state; the coincidence technique employed permits a clean measurement of the capture cross section at the 1 μb/sr level. Comparison of the integrated (γ,p) strengths with the corresponding proton spectroscopic factors shows that they are not simply proportional. This may be explained by the presence of dipole absorption by 2p-2h configurations in the initial state, a process normally neglected in direct-semidirect calculations. Alternatively, more complex reaction mechanisms may be involved; a small contribution from statistical capture cannot be excluded. In any case, all such processes can be important when studying capture to states with small overlap with the p_0 entrance channel.

Finally, it would clearly be very interesting to compare the results of the present study with a fully microscopic calculation of the 16-particle system. Such a calculation should be possible with modern shell model codes, and would hopefully illuminate some of the questions raised by the present work. Quantitative predictions concerning the relative role of 2p-2h states and the relationship between the capture cross section and the proton spectroscopic factors emerging from such a calculation could then be directly compared with experiment. In addition, of course, the energy of the deformed GDR would be predicted as well. We offer the present data in the hope that it may stimulate answers to these questions.

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