# ANGULAR DISTRIBUTIONS IN THE GIANT RESONANCE OF $^{16}O$†

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[*Manuscript received December* 19, 1967]

*Summary*

The $^{16}O(\gamma, p_0)^{15}N$ reaction has been studied in the region of excitation in $^{16}O$ from $20 \cdot 5$ to $25 \cdot 6$ MeV. Angular distributions on the resonances observed were extracted from the spectra, which were taken at 20° intervals from 30° to 150°. The results are compared with other related work.

## I. Introduction

The giant resonance region of $^{16}O$ has been the subject of much theoretical and experimental attention over the past 10 years. The reason is that $^{16}O$ is a light, doubly-closed shell nucleus, and so is particularly suited to calculations based on the shell model; in fact it has become a yardstick against which the success of such calculations may be gauged. The stage has now been reached at which efforts are being made to account for more than just the gross overall shape of the giant resonance (Greiner 1963; Gillet, Melkanoff, and Raynal 1967) and it has become important to obtain more detailed experimental information than has so far been available, in order to test the validity of the predictions of the theories.

In particular, a knowledge of the spin and parity of all the observed states in the vicinity of the giant resonance of $^{16}O$ would be of great value. There is at present only indirect evidence for the spin and parity of the state at $21 \cdot 0$ MeV and very little is known about the smaller resonance at $23 \cdot 1$ MeV. Further, there is contradictory evidence regarding the state at $24 \cdot 3$ MeV, since Dodge and Barber (1962), using the (e, pe′) reaction, found $J^\pi = 1^-$, whereas the electron scattering measurements of Isabelle and Bishop (1963) indicated $J^\pi = 2^+$ for this resonance.

The present paper presents the results of measurements of the angular distribution of protons on the peaks in the ground state cross section from $20 \cdot 5$ to $25 \cdot 6$ MeV. Proton angular distributions from the $^{16}O(\gamma, p)$ reaction have been studied previously by Johannson and Forkman (1957), Milone *et al.* (1958), and Brix and Mascke (1959), but these works all suffered from poor resolution and so were able to give only very general information. The most detailed photoproton work is that of Dodge and Barber (1962), who established the electric dipole nature of the strong state at $22 \cdot 3$ MeV. Recently a detailed study of angular distributions in the inverse $^{15}N(p, \gamma_0)^{16}O$ reaction was published (Earle and Tanner 1967). This work covers the energy region examined in the present study, and is discussed further in Section IV.

† This work was supported by the United States Army Research Office.

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## II. Experimental Details

The first excited state of $^{15}N$ lies at 5·3 MeV, and it follows that only the highest 5·3 MeV of each proton spectrum can be assumed to contain purely ground state protons. With a bremsstrahlung end-point energy of 25·6 MeV this means that the region above 20·3 MeV excitation in $^{16}O$ can be examined. This lower limit corresponds to an emitted proton energy of 7·7 MeV.

Protons were detected in silicon surface barrier detectors 1000 $\mu$ deep (Ortec type SBEI 200–1000) that were placed in a 24 in. diameter scattering chamber, which featured a table mounted on tapered roller bearings that enabled it to be rotated under vacuum. This table had tracks cut into it radially at 20° intervals in which the detector mounts were positioned. Up to four spectra could be accumulated simultaneously. The pulses from each detector were fed via a preamplifier to a discriminator stage that biased out the low energy electrons, and then after further amplification and shaping were presented to one quadrant of a 512-channel pulse height analyser. The time duration of the $\gamma$-ray pulse was lengthened to about 150 $\mu$sec to reduce electron pile-up.

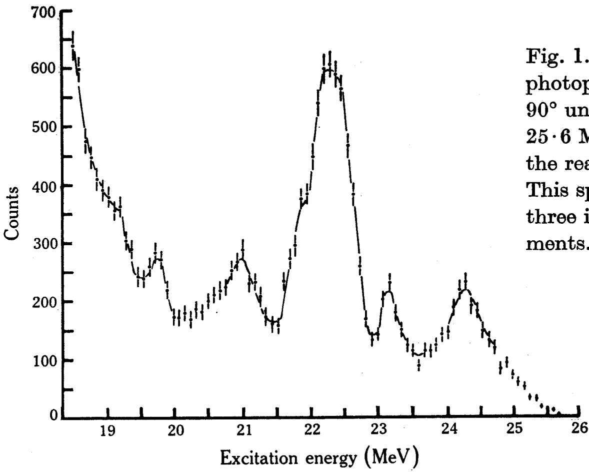


Fig. 1.—The spectrum of photoprotons from oxygen at 90° under bombardment by 25·6 MeV bremsstrahlung in the reaction $^{16}O(\gamma, p_0)^{15}N$. This spectrum is the sum of three independent measurements.

The chamber was filled with 1 atmosphere of oxygen gas and the collimated $\gamma$-ray beam passed axially through it, so that the target was that cylinder of irradiated gas seen by the detectors. The detectors were each collimated to an acceptance angle of $\pm 10°$ by two parallel, vertical, aluminium plates mounted on a base that ran in the tracks cut into the turntable. Measurements were taken at 20° intervals from 30° to 150°. The detectors were situated 16·0 cm from the chamber centre; the beam diameter was 3·4 cm and did not change significantly over the region viewed by the detectors. Corrections for geometric factors (e.g. variation of detection efficiency over the face of each detector and variation in the amount of target seen by detectors at different angles) were made using the calculations of Silverstein (1959). It was found to be unnecessary to correct for variations in cross section over the acceptance angle of a detector.

Detectors were positioned at 90° on either side of the beam line in each run, and the total counts above a particular energy in these spectra were used to normalize the runs. The two independent normalizations obtained from these data agreed to within $\pm 0\cdot5\%$.

The stability of each system was checked at two-hourly intervals using a mercury relay pulser; the energy calibration was determined using the known energies of the main resonances in $^{16}$O, since an independent calibration using $\alpha$-particle spectra from ThC+C′ showed some variation from detector to detector. The overall energy resolution was about 200 keV. The spectrum obtained by summing the three 90° runs is shown in Figure 1.

## III. Analysis of Data

Despite the high initial proton energy of interest, Figure 1 shows that electron background is still evident at energies of 6 MeV and above. However, exponential fits showed that in almost all cases it is zero for proton energies corresponding to an excitation energy above 21·5 MeV, and has very little effect on the lowest peak of interest, namely that centred at 21·0 MeV.

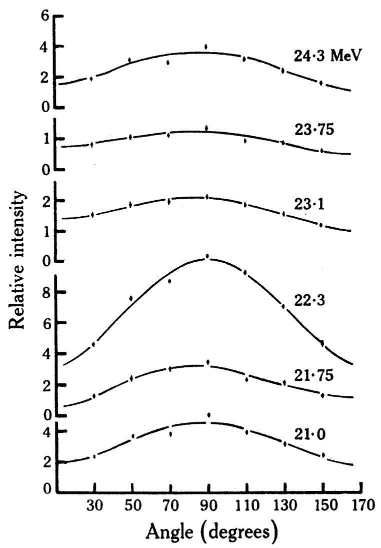


Fig. 2.—The measured photoproton angular distributions in the reaction $^{16}O(\gamma, p_0)^{15}N$ and the fits to them using the sum of Legendre polynomials with coefficients as given in Table 1. Note the changes in the vertical scale.

Angular distributions were extracted from the data both by summing total counts within particular energy bins and by fitting a series of Lorentz curves to each spectrum.

The distributions obtained were fitted by the least squares method to an equation of the form

$$W(\theta) = A\left(1+\sum_{i=1}^{n} a_i\,P_i(\cos\theta)\right),$$

where the $P_i(\cos\theta)$ are Legendre polynomials. The programme gave fits for all values of $n$ from 1 to 4. The variances given for each fit showed that in all cases except one the best fit was obtained by only retaining terms up to $P_2$. In the higher order fits the coefficients $a_3$ and $a_4$ were generally indistinguishable from zero, indicating that they were too small to be measured by this experiment. The data and Legendre fits are shown in Figure 2, and the coefficients $a_i$ are listed in Table 1.

TABLE 1

EXPERIMENTAL ANGULAR DISTRIBUTION COEFFICIENTS FOR THE REACTION $^{16}O(\gamma, p_0)^{15}N$

In the form $W(\theta) = A\left(1+\sum_{i=1}^{n} a_i P_i(\cos\theta)\right)$

| $E_\gamma$ | (MeV) | $a_1$ | $a_2$ | $a_3$ |
|---|---|---|---|---|
| 21·00 | (20·25–21·45) | 0·04 ± 0·07 | −0·53 ± 0·10 | |
| 21·75 | (21·45–22·00) | 0·06 ± 0·08 | −0·68 ± 0·10 | −0·21 ± 0·15 |
| 22·30 | (21·45–22·90) | 0·00 ± 0·02 | −0·65 ± 0·02 | |
| 23·10 | (22·95–23·65) | 0·12 ± 0·02 | −0·36 ± 0·03 | |
| 23·75 | (23·50–24·00) | 0·14 ± 0·06 | −0·43 ± 0·09 | |
| 24·30 | (23·70–25·60) | 0·10 ± 0·08 | −0·58 ± 0·10 | |

## IV. DISCUSSION

The features of the spectra that are of particular interest are the resonances centred at 21·0, 22·3, 23·1, and 24·3 MeV.

Previous evidence on the state at 21·0 MeV indicates that it has $J^\pi = 1^+$. Tanner, Thomas, and Earle (1964) concluded that $J = 1$, while the $^{16}O(\gamma, n)$ work of Caldwell *et al.* (1965) indicated that the state had positive parity. However, the present experiment gives $a_2 = -0{\cdot}53 \pm 0{\cdot}10$ for this resonance, compared with the expected value of $-0{\cdot}5$ for pure d-wave emission from a $1^-$ state. This result cannot exclude the possibility that the $a_2$ value is due to p-wave proton emission from a $1^+$ state with just the right proportion of channel spins 0 and 1 contributing, but the former explanation must be regarded as more likely. Angular distribution data on the $^{16}O(\gamma, n)^{15}O$ reaction by Verbinski and Courtney (1965) also indicate a $1^-$ state emitting d-wave neutrons, although in that experiment spectra were taken at only three angles.

Earle and Tanner (1967) give values of $a_1 = 0{\cdot}13$, $a_2 = -0{\cdot}17$, and $a_3 = -0{\cdot}10$ at 21·0 MeV. This may be interpreted as evidence for the presence of the basic shell model state composed predominantly of the $(1p_{3/2})^{-1}(2s_{1/2})$ configuration and predicted to lie at 19·6 MeV (Gillet and Vinh-Mau 1964), since a state emitting s-wave neutrons will lead to an essentially zero value for the $a_2$ coefficient. If this interpretation is correct, then the upper portion of the averaging interval used in the present work at this energy will be influenced strongly by interference between that state and the state at 22·3 MeV. Earle and Tanner (1967) do not make this interpretation, but conclude that the states seen by them at 18·97 and 19·48 MeV are probably connected with the shell model state in question.

The value of $a_2$ found for the 22·3 MeV resonance ($-0{\cdot}65 \pm 0{\cdot}02$) is in excellent agreement with the value obtained by Dodge and Barber (1962), namely $a_2 = -0{\cdot}68$.

The mean value of $a_2$ given by Earle and Tanner in this energy region is $-0\cdot6$. The simplest hypothesis is again that the resonance is formed by predominantly d-wave protons emitted from a $1^-$ state in $^{16}O$. A small s-wave component is then sufficient to give agreement with experiment. This conclusion agrees with the one-particle–one-hole shell model calculation of Gillet and Vinh-Mau (1964), which predicts a state at $22\cdot2$ MeV with 73% of the dipole strength and composed predominantly of the configurations $(1p_{3/2})^{-1}\,1d_{5/2}$ and $(1p_{1/2})^{-1}\,1d_{3/2}$.

The smaller resonance at $23\cdot1$ MeV shows forward peaking and is more isotropic than the other resonances, as reflected by the smaller $a_2$ coefficient. Dodge and Barber (1962) quote $a_2 = -0\cdot36$ at $23\cdot3$ MeV, again in excellent agreement with the present work. Earle and Tanner (1967) do not cover the resonance fully, but give values of $a_1 = 0\cdot19$ and $a_2 = -0\cdot25$ at $22\cdot9$ MeV. The $a_1$ coefficient indicates the presence of two states of opposite parity, though only a small admixture of a positive parity state underlying a predominantly $1^-$ state is required to give an $a_1$ value of the observed magnitude. The simplest explanation of the data again appears to be in terms of a $1^-$ state emitting both s- and d-wave protons, with a small underlying positive parity component causing the odd polynomial coefficient, although again other combinations cannot be excluded.

The data from the resonance at $24\cdot3$ MeV are also most simply explained as due to a $1^-$ state emitting predominantly d-wave protons, and agree very well with the work of Dodge and Barber, who quote $a_2 = -0\cdot68$. Earle and Tanner (1967) show values of $a_2$ of about $-0\cdot6$ in this energy region. It is concluded that no evidence is found for the $2^+$ state reported by Isabelle and Bishop (1963) at this energy (this would require a positive $a_2$ coefficient).

The data show little evidence for the presence of other than $1^-$ states, although the $a_1$ coefficient tends to increase towards higher energies. However, $a_2$ never becomes positive and seldom varies far from the one-particle–one-hole model prediction in this energy region of predominantly d-wave emission from a $1^-$ state. More recent calculations, which include effects of the continuum (Buck and Hill 1967; Wahsweiler, Greiner, and Danos, personal communication), still seem unable to significantly improve upon this description.

## V. Acknowledgments

The author wishes to acknowledge assistance from Miss J. M. Dixon, Mr. P. H. Cannington, and Mr. D. Holmes, and would like to thank Professor B. M. Spicer for helpful discussions. Financial assistance in the form of a CSIRO Senior Post-graduate Studentship is also acknowledged.

## VI. References

Brix, P., and Mascke, E. R. (1959).—*Z. Phys.* **155**, 109.

Buck, B., and Hill, A. D. (1967).—*Nucl. Phys.* A **95**, 271.

Caldwell, J. T., Bramblett, R. L., Berman, B. L., Harvey, R. R., and Fultz, S. C. (1965).—*Phys. Rev. Lett.* **15**, 976.

Dodge, W. R., and Barber, W. C. (1962).—*Phys. Rev.* **127**, 1746.

Earle, E. D., and Tanner, N. W. (1967).—*Nucl. Phys.* A **95**, 241.
Gillet, V., Melkanoff, M. A., and Raynal, J. (1967).—*Nucl. Phys.* A **97**, 631.
Gillet, V., and Vinh-Mau, N. (1964).—*Nucl. Phys.* **54**, 321.
Greiner, W. (1963).—*Nucl. Phys.* **49**, 522.
Isabelle, D. B., and Bishop, G. R. (1963).—*Nucl. Phys.* **45**, 209.
Johannson, S. A. E., and Forkman, B. (1957).—*Ark. Fys.* **12**, 359.
Milone, C., Milone-Tamburino, S., Rinzivillo, R., Rubbino, A., and Tribuno, C. (1958).—*Nuovo Cim.* **7**, 729.
Silverstein, E. A. (1959).—*Nucl. Instrum. Meth.* **4**, 53.
Tanner, N. W., Thomas, G. C., and Earle, E. D. (1964).—*Nucl. Phys.* **52**, 45.
Verbinski, V. V., and Courtney, J. C. (1965).—*Nucl. Phys.* **73**, 398.