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Ground-state photoneutron reactions in ^{18}O

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Differential cross sections have been measured for the reaction $^{18}O(\gamma,n_0)^{17}O$ over the region of excitation energy from 14 to 26 MeV. The angle-integrated cross section for the ground-state transition reveals that this channel accounts for less than 20% of the total photoneutron cross section in the structured pygmy resonance region (near 14 MeV) and is a small fraction (10–15 %) of the cross section in the region of the giant resonance (near 25 MeV). The values of angular distribution coefficients fitted to the data are consistent with a description of this reaction in which electric dipole excitations dominate the cross section in the pygmy resonance. Narrow regions exist near 15.0, 16.0, and 20.0 MeV where nonzero a_1 coefficients are observed indicating the absorption of non-$E1$ radiation. The measured cross section and a_2 coefficients are compared to a direct-semidirect calculation which gives reasonable agreement and suggests that f-wave neutron emission dominates the ground-state channel and that there is little justification for the introduction of $E2$ amplitudes other than a pure direct $E2$ term.

I. INTRODUCTION

Well-defined pygmy resonances have been observed in a number of light nuclei such as ^{13}C (Ref. 1), ^{15}N (Ref. 2), and ^{17}O (Ref. 3), which are often described in the framework of the weak coupling model in which a weakly bound valence nucleon (or hole) is associated with a nuclear core. Usually, these resonances are found several MeV below the giant dipole resonance (GDR), and are usually made up of many narrow resonances believed to arise from single-particle transitions involving the valence particles.

The ^{18}O nucleus, with two extra-core neutrons in the *s-d* shell, might be an excellent example of this phenomenon. Measurements of the total photoneutron cross section at Livermore[4] and at Giessen[5] have shown a large and highly structured pygmy resonance in the excitation region from 10 to 18 MeV (the GDR is centered near 25 MeV). We have set out to investigate the upper part of this region by choosing the ground-state neutron decay channel for angular distribution measurements with moderately high energy resolution. This technique can often permit the assignment of the multipolarity of the transitions involved and, in certain cases, it can be employed to assess the applicability of collective or single-particle models describing the reaction.

This is useful in the case of ^{18}O where, because of the isospin $T=1$ character of the ground state, the photoabsorption cross section will be split into two isospin components ($T_< = 1$ and $T_> = 2$). Angular distribution information on the ground state channel (involving uniquely $T_<$ intermediate states) can aid in the differentiation between a classical single-particle pygmy resonance from the collective $T_<$ component of the GDR.

A recent shell model calculation of Assafiri and Morrison[6] has predicted the distribution of the two isospin components of the cross section. The present results can serve to test these predictions as well as to enhance the understanding of coupling between the ^{16}O core and the two valence neutrons.

II. EXPERIMENTAL DETAILS

Neutron energy spectra were measured as a function of laboratory angle using the photoneutron angular distribution facility at the electron linear accelerator laboratory of the National Research Council of Canada. This facility had been described in detail previously,[7,8] and consequently a very brief description is presented here.

Neutron time-of-flight techniques were used with 10 m flight paths to measure simultaneously eight photoneutron spectra for angles from 48° to 139° in 13° steps. Since the first excited state in the ^{17}O daughter nucleus lies at 0.87 MeV, the portion of each spectrum uniquely corresponding to ground-state transition was kinematically separated by choosing the 0.87 MeV wide region of the highest neutron energies. Such regions were combined to yield differential cross sections from a series of runs using end-point energies of the incident photon distributions ranging from 14.7 to 26.2 MeV in 0.5 MeV steps.

The ^{18}O sample was in the form of 60 g of $H_2\,^{18}O$ (99.5% purity) contained in a thin-walled right circular glass cylinder. Samples of $H_2\,^{nat}O$ and D_2O and an empty container were used in an identical geometry and were cycled into the photon beam at one minute intervals to provide nearly simultaneous measurements of the background and photon flux (via the D_2O-H_2O difference).

The neutron time-of-flight spectra were converted to center-of-mass energy spectra with relativistically exact kinematic relations and were fitted in this frame by a series of Legendre polynomials to extract the normalized angular distribution coefficients a_i $(i = 0,1,2)$ as functions of excitation energy. Fits to higher orders were not statistically justified.

The cross section scale of the total angle-integrated cross section, $\sigma(E_\gamma)$, was determined from the deuterium data (measured at the same time as the ^{18}O) by use of calculations by Arenhövel *et al.*[9] and Partovi.[10]

III. RESULTS AND DISCUSSION

The total angle-integrated ground-state cross section for ^{18}O obtained from the present work is shown in Fig. 1(a). Shown in Figs. 1(b) and 1(c) are the normalized Legendre coefficients a_1 and a_2, respectively. Error bars indicate statistical errors only. In the regions between

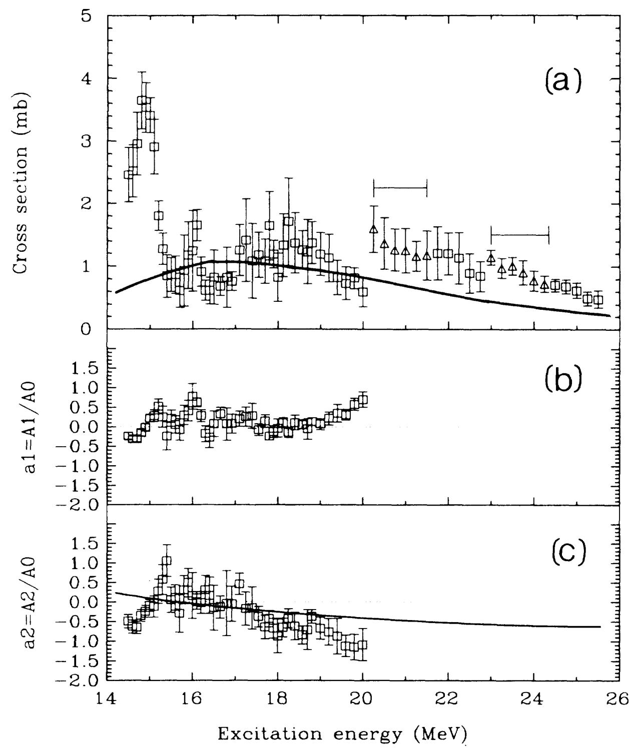

FIG. 1. Results for the $^{18}O(\gamma,n_0)$ reaction. (a) The total angle-integrated cross section, $4\pi A_0$. The solid line is a result of a DSD calculation which considered direct reactions only. (b) and (c) The normalized angular distribution coefficients a_1 and a_2, respectively. The horizontal bars indicate regions where non-ground-state cross sections (open triangles) are included. The solid curve in part (c) is the result of a DSD calculation including both direct and semidirect terms as described in the text.

20 and 21.5 MeV and between 23 and 24.3 MeV (indicated by the horizontal bars) the data represent the sum of the ground-state and first excited-state cross sections because of limited accelerator time to perform end-point measurements at 20.6 and 23.6 MeV.

A. Ground-state cross section

The angle-integrated ground-state cross section shows significant peaks in the pygmy resonance region ($E_\gamma < 23$ MeV) at 14.8 and 16.1 MeV. A broad structure is seen between 17 and 19 MeV. Because the ground state isospin of ^{18}O is $T_0 = 1$, the splitting of the GDR into its $T_<$ and $T_>$ components is expected; this structure around 18 MeV is possibly part of the $T_<$ GDR.

The peaks at 14.8 and 16.1 MeV are also seen in the $^{18}O(\gamma,1n)$ and $(\gamma,2n)$ cross sections of Woodworth *et al.*[4] The 14.8 MeV resonance was also observed in the 98° differential (γ,n_0) and (γ,n_1) cross sections of Allan *et al.*,[11] but the 16.1 MeV peak was observed only in the (γ,n_0) channel by Allan *et al.* There are indications that the structure seen at 18.2 MeV in the (γ,n_0) channel is also present in the $(\gamma,1n)$ and the $(\gamma,2n)$ cross sections of Woodworth *et al.* Shown in Fig. 2 is the

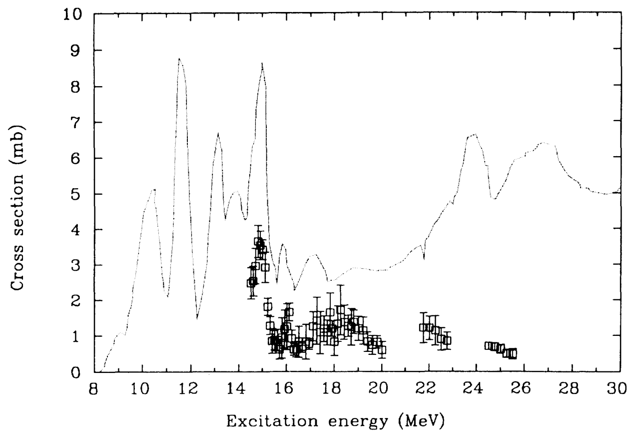

FIG. 2. A comparison of the present ^{18}O ground-state measurement with the $^{18}O(\gamma,1n)$ cross section of Woodworth *et al.* (Ref. 4) (dotted line).

present ground-state cross section and the $(\gamma,1n)$ data of Ref. 4.

Contrary to the observation[4,5] of structure in the $^{18}O(\gamma,n_{tot})$ cross section in the region of the GDR between 17 and 29 MeV, no prominent GDR type of structure is seen in the present ground-state work except for a broad resonance centered around 18.2 MeV. This is not surprising when the spins and parities of the states involved are taken into consideration. Although the isospin Clebsch-Gordan coupling coefficients suggest, for $E1$ transitions, a higher probability of the ^{18}O $T_<$ states decaying to $T=\frac{1}{2}$ states than to $T=\frac{3}{2}$ states in ^{17}O (the ground state of ^{17}O has spin, parity, and isospin of $J^\pi;T=\frac{5}{2}^+;\frac{1}{2}$), the angular momentum coupling coefficients suggest that the ground state has a low probability of being populated from $J^\pi=1^-$ excited states in ^{18}O. The same argument applies to magnetic dipole ($M1$) excitations. In comparison to states arising from dipole transitions, the $J^\pi=2^+$ excited states resulting from electric quadrupole ($E2$) excitations can more readily decay to the $J^\pi=\frac{5}{2}^+$ ground state of ^{17}O.

The lack of a prominent GDR structure in the ground state neutron channel is consistent with the average (single) neutron energy measured by Woodworth *et al.*[4] These authors found that between 14.5 and 26 MeV the average neutron energy is far less than what would be obtained from ground state transitions. This indicates that population of excited states in ^{17}O is preferred over the ground state.

Also, other particle decay channels have opened up starting at 12.2 MeV: the $(\gamma,2n)$ threshold is 12.19 MeV, the $(\gamma,\alpha n)$ threshold is 14.40 MeV, and the (γ,p) threshold is 15.94 MeV. The opening of these channels can compete with the (γ,n_0) channel, thus reducing its decay strength.

There is no evidence for a peak in the region from 22 to 26 MeV, described in Ref. 4 as the center of the GDR. At these energies significant $T_<$ strength was observed in the $^{18}O(\gamma,n_{tot})$ work[4,5] and has been predicted in a recent particle-hole shell model calculation.[6] From isospin selection rules and in the absence of isospin mixing, only the $T_<$ component of the GDR in ^{18}O can decay to the ground state of ^{17}O.

A $T_<$ collective GDR at these energies can decay to many states in ^{17}O including, but not preferentially, the ground state. However, if the nature of the GDR here were to be dominantly $T_>$, we would then expect essentially zero strength in the ground state channel. In fact, this channel represents about 10–15 % of the neutron strength at these energies. This is in accordance with the reported $T_<$ nature of the GDR at these energies.

The integrated ground-state cross section between 14.5 and 20.0 MeV is 12 $\pm$1 MeV mb, corresponding to about 4.5$\pm$0.4 % of the semiclassical Thomas-Reiche-Kuhn (TRK) dipole sum rule value of 267 MeV mb for ^{18}O. The measured strength in the region represents less than 20% of the total photoabsorption integrated cross section measured in Ref. 4.

B. Angular distribution coefficients

The measured angular distribution a_1 coefficients show nonzero values in the energy regions of 14.5–16.5 MeV and 19–20 MeV, indicating the presence of either $M1$ or $E2$ absorption strength (or both) interfering with the dominant $E1$ character of the pygmy resonance.

The a_1 coefficient is observed to change sign, from -0.25 to about $+0.5$, across the 14.8 MeV peak. The zero-crossing of the a_1 value occurs at about 14.8 MeV, the energy center of the resonance. Also, the a_1 coefficient is seen to go from zero to about $+0.7$ near 16.1 MeV, where a peak is observed in the cross section, and it then returns to zero. This behavior of the a_1 coefficient suggests that both of these resonances are subject to interference with higher order multipolarities. It should be noted that a very small non-$E1$ cross section (in the order of a few percent or less of the $E1$ magnitude) can sometimes bring about large values of the a_1 coefficient.

The a_2 coefficient is seen to undertake a significant excursion from about -0.5 to $+1.0$ and back to 0 near 15.2 MeV. This type of behavior has been noted in other light nuclei such as ^{13}C (Ref. 12) and ^{16}O (Ref. 13), where it has been interpreted to be evidence for secondary doorway state effects. Possibly that is the case here, but additional data, including polarized neutron capture measurements on ^{17}O, are required to support this conjecture. It is of relevance to note that at an excitation energy of 18.2 MeV, Bangert *et al.*[14] have observed a resonance in the $^{18}O(\gamma,\alpha_0)$ reaction. It is at about this energy where the a_2 results of the present experiment deviate towards zero, suggesting the possible presence of a multiparticle-multihole secondary doorway state.

With the exception of the resonance structure near 14.8 MeV and the deviation near 18.2 MeV discussed above, the general trend of the a_2 coefficients is to decrease monotonically from values of about 0.3 (near 15 MeV) to values of about -1.0 (near 20 MeV). It should be noted that at the higher energies of the GDR regions of both ^{12}C and ^{16}O, the a_2 coefficient undergoes a similar behavior, starting slightly positive or near zero and

TABLE I. Calculated (based on a direct-semidirect model calculation—see the text) values of a_2 coefficients and the contribution of various single-particle transitions to the cross section.

Excitation energy (MeV)	a_2 (calculated)	a_2 (experimental)	Photoneutron single-particle transition as a percent of total angle integrated cross section $p_{3/2}$	$f_{5/2}$	$f_{7/2}$
13.7	0.27		26.5	1.8	71.7
15.2	0.03	$+0.16\pm0.2$	15.1	1.9	83.0
16.6	-0.16	-0.13 ± 0.3	10.7	2.3	87.0
18.0	-0.30	-0.61 ± 0.2	9.8	3.1	87.1
19.4	-0.40	-0.80 ± 0.3	10.3	4.4	85.3
22.2	-0.53		12.5	7.8	79.7

decreasing (with variations) to values near -0.5 in the center of the GDR. In these nuclei, which are devoid of pygmy resonances, collective excitations are believed to dominate the GDR and yield these values of the a_2 coefficient.

In order to attempt to account for the observed behavior of the cross section and the a_2 coefficients in the pygmy resonance region of ^{18}O in terms of single-particle transitions ($d_{5/2}\rightarrow p_{3/2}$, $d_{5/2}\rightarrow f_{5/2}$, and $d_{5/2}\rightarrow f_{7/2}$), we have carried out a direct-semidirect (DSD) model calculation.

In this model, the semidirect term represents collective excitation of the core which can lead to enhanced single particle emission. The a_2 coefficients are not changed when this semidirect term is added to the direct term. However, the absolute cross section is sensitive to the amount of semidirect component in the reaction mechanism. Direct capture alone gives an angle-integrated cross section which accounts for much of the measured strength (see below).

The calculation, performed at the Triangle Universities Nuclear Laboratory (TUNL), used a simple form of the DSD model[15] to compute values of the cross section and the a_2 coefficients and the relative contributions of the transitions cited above to the cross section.

Both $E1$ and $E2$ amplitudes were included in the calculation which predicted the a_1 values to be essentially zero. These a_1 values arise from the DSD $E1$ strength interfering with the direct $E2$ strength. The $E2$ effective charge ($0.025e$) greatly suppresses the $E2$ strength.

For the $E1$ case, the *relative* amplitudes and phases of the contributing transition matrix elements are the same for a pure direct calculation as for the DSD model with a form factor proportional to r. To obtain the relative amplitudes and phases, it was necessary to evaluate the radial matrix element

$$\langle \Psi_{l'j'}(r) \mid r \mid \Phi_{nlj}(r) \rangle \ , \tag{1}$$

where $\Psi_{l'j'}(r)$ is the continuum neutron wave function and $\Phi_{nlj}(r)$ is the wave function of the valence neutron bound in the initial state. The continuum wave function was calculated using the optical model potential for 14.1 MeV neutrons incident on ^{16}O (Ref. 16). The bound state wave function of a $1d_{5/2}$ single particle (around a ^{17}O core) was found by adjusting the Woods-Saxon potential, including a spin-orbit term, to bind the state at 8.174 MeV. The results of the DSD calculation are shown in Fig. 1. Figure 1(a) shows the angle-integrated cross section obtained by detailed balance from the results of a DSD calculation performed with the semidirect term set to zero and a spectroscopic factor of $C^2S=1.0$ for the $d_{5/2}$ single particle state of ^{18}O. There is generally good agreement with the measured cross section, except in the region of the pronounced resonances at 14.8 and 16.1 MeV. Figure 1(c) shows the values of a_2 coefficients calculated with the direct-semidirect model. In the present case, however, these results are the same as those for a pure direct model calculation (see above). These calculated values are also given in Table I, where they are compared with the results obtained in the present experiment. Also tabulated are the relative contributions of the different single-particle transitions to the angle-integrated cross section. There is reasonable agreement between the calculated and measured values for the a_2 coefficient, particularly in the trend from positive to negative values with increasing energy (see Fig. 1). Resonance effects have not been taken into account in the DSD calculation but the general agreement with experiment suggests that the single-particle transitions of the type $d_{5/2}\rightarrow f_{7/2}$ could describe the reaction mechanism at these energies. This is what would be expected on the basis of the shell model where $1d_{5/2}\rightarrow 1f_{7/2}$ transitions are favored on the basis of energy considerations and the overlap of the single-particle wave functions involved.

On the other hand, any $J^\pi=1^-$ configuration, no matter how complicated, which decays to the ground state must couple to a $d_{5/2}$ hole in the final state. In this case $f_{7/2}d_{5/2}^{-1}$ and $p_{3/2}d_{5/2}^{-1}$ (and other) configurations are possible. If the former were dominant, an angular distribution similar to that calculated here would arise. Thus, agreement with the calculation is interesting and suggestive of a dominant $f_{7/2}d_{5/2}^{-1}$ single particle transition, but does not make a conclusive case for the single particle reaction mechanism implied by application of the weak coupling model.

An investigation of the ground state reaction providing polarization information [such as a study of the inverse ^{17}O($\vec{n},\gamma_0$)^{18}O reaction with polarized neutrons] would provide values of the amplitudes and phases of the contributing transition matrix elements. This information should provide a more critical test of reaction

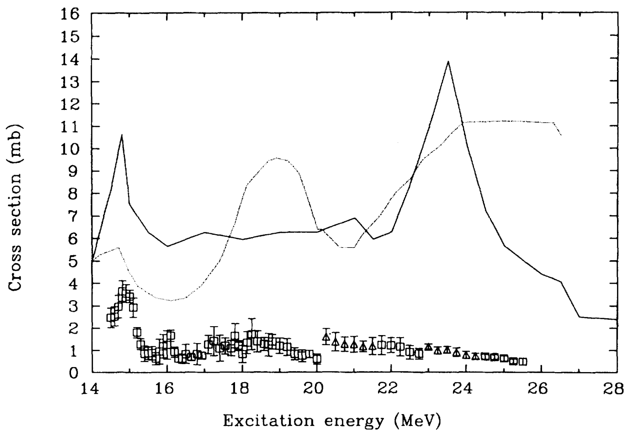

FIG. 3. Our results show that the $T_<$ ground-state channel (open squares and triangles) contributes only about 10% of the total $T_<$ transition strength (Ref. 4) (solid line). The particle-hole shell model calculation of Assafiri and Morrison (dotted line) for the ^{18}O total $T_<$ cross section shows fair agreement in shape with the present measured ($T_<$) cross section but does not reproduce the structures observed in the total $T_<$ data of Ref. 4.

model calculations such as the DSD calculation described above.

C. Comparison with other calculations

Shown in Fig. 3 is a comparison of the recent particle-hole shell model calculation of Assafiri and Morrison[6] for the total $T_<$ cross section with the present ($T_<$) cross section. The calculation was carried out under a dipole approximation using the residual nucleon-nucleon interaction of Cooper and Eisenberg[17] using a well depth of 60 MeV.

Some agreement in the structure is observed between the shell model calculation and the present experimental data. In the energy region of overlap, it is seen that the predicted cross section is many times higher than that measured here. This is to be expected because the ground-state transitions do not necessarily exhaust all the $T_<$ strength except at low energies; $T_<$ components of the ^{18}O GDR can decay to the ground state as well as to the (isospin-allowed) excited states in ^{17}O. The calculated cross section is in general agreement with the $T_<$ cross section extracted by Woodworth *et al.*[4] (see Fig. 3), but fails to reproduce the structure seen in Ref. 4 below 16 MeV.

IV. SUMMARY

Measurement of the ground-state photoneutron cross section in the vicinity of the pygmy resonance of ^{18}O (between 14.5 and 20 MeV excitation energy) has revealed that this channel accounts for less than 20% of the decays from states in this region. This is unlike the case in the ^{17}O nucleus[18] where this channel exhausts nearly 100% of the decays. Clearly, the configurations of the ground and pygmy resonance states in ^{18}O are much more complex than those for the corresponding states in ^{17}O. It is reasonable to assume that the weak coupling model is less likely to describe adequately the case of ^{18}O. Possibly the polarization of the ^{18}O core by the two valence neutrons gives rise to this partial failure in the model.

However, there is reasonable agreement of the present measured values of the a_2 coefficients and those values predicted by a DSD calculation. The application of this model predicts that most of the ground state cross section strength in the low energy region (below 20 MeV) arises from transitions involving the weakly coupled valence $d_{5/2}$ neutrons. This arises both from direct single particle transitions and from semidirect collective excitation of the core which provides for enhanced absorption. Direct transitions alone can account for most of the measured cross section in regions not associated with the resonances at 14.8 and 16.1 MeV.

The measurement has also suggested several regions where the dominant $E1$ photoabsorption process is accompanied by $M1$ or $E2$ transitions. This effect has been observed in ^{16}O (Ref. 19) as well as in ^{17}O (Ref. 20), for states at about the same energies. Thus, the presence of non-$E1$ transitions also seems to be little affected by the valence neutrons.

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