Isoscalar Electric Quadrupole Strength in ^{16}O†

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(Received 11 March 1974)

A detailed study of $^{12}C(\alpha,\gamma_0)^{16}O$ from $E_x = 12$ to 28 MeV reveals a $T=0$, $E2$ strength which constitutes $\approx 17\%$ of the sum rule in the α_0 channel alone. Together with other results, $\approx 42\%$ of this sum rule is accounted for in ^{16}O. We estimate that the inclusion of other channels would raise this total strength to $\sim 70\%$ and give an $E2$ energy centroid and width both of ~ 15 MeV.

Recently a variety of inelastic scattering experiments[1] have been interpreted as yielding evidence for a concentration of isoscalar $E2$ strength in a "giant" resonance at an excitation energy of $\sim 75\%$ of the giant-dipole-resonance (GDR) energy, and with a comparable width (~ 4 MeV). Some of the best evidence from radiative capture or photonuclear studies which bears on the existence of this giant $E2$ resonance comes from (α,γ) measurements.[2] Several such measurements of α capture into $2s1d$-shell nuclei[2,3] show an appreciable amount of isoscalar $E2$ strength (~ 12–20% of the sum rule) and have been interpreted[3] as being consistent with the existence of a giant $E2$ resonance. However, these data also permit an interpretation in which the $E2$ strength is considerably more spread out in excitation energy. In this Letter we present the results of a detailed study of α-capture into ^{16}O which bears directly on this issue.

We have measured $^{12}C(\alpha,\gamma_0)^{16}O$ from $E_\alpha = 7$ to 27.5 MeV ($E_x = 12.5$ to 28 MeV) using a 0.4-mg/cm^2 carbon target enriched to 99.9% ^{12}C.[4] The α beam was produced by the University of Washington FN tandem accelerator, and the γ rays were detected in a 10-in.×10-in. NaI spectrometer.[5] The cross section measured at $\theta_\gamma = 52°$ [Fig. 1(a)] contains contributions from $E1$ to $E2$ capture ($E3$ capture being negligible) given by

$$\sigma(\theta) = |\sigma_{E1}(\theta)^{1/2} + e^{i\delta}\sigma_{E2}(\theta)^{1/2}|^2,$$

where $\sigma_{E1}(\theta) \propto \sin^2\theta$, $\sigma_{E2}(\theta) \propto \sin^2 2\theta$, and δ is the relative phase angle. Three- and four-point angular distributions taken at key energies were decomposed into the $E1$ and $E2$ contributions and the relative phase factor $\cos\delta$ [Figs. 1(b) and 1(c)]. Small effects due to finite geometry were included in this analysis. Using the measured $\sigma(52°)$, the curves labeled $\sigma_{E1}(52°)$ and $\sigma_{E2}(52°)$ were interpolated between the points determined from the angular distribution.

Most of the structure in these cross sections is apparently due to individual resonances. Strong variations in $\cos\delta$ are apparent in regions of overlapping $E1$ and $E2$ resonances. The $E2$ cross section shows resonances at $E_x \simeq 13.2$, 15.9, 16.5, 18.3, 20.0, and 26.5 MeV with level widths $\Gamma \simeq 0.23$, ~ 0.6, ≤ 0.2, 0.37, ~ 0.4, and 1.2 MeV, and strengths $\Gamma_\alpha\Gamma_\gamma/\Gamma$ of 0.71, ~ 0.4, 0.45, 0.95, ~ 0.4, and 1.2 eV, respectively. The uncertainty in these strengths ranges from 15 to 30%. In addition, there is $E2$ strength in the region $E_x = 14$ to 15.5 MeV and 20.5 to 23 MeV which is not clearly resolved into contributions from particular resonances. Since $\Gamma_\alpha/\Gamma \leq 1$, each resonance strength represents a lower limit for Γ_γ, the $E2$ radiative width. These widths can be compared directly with the $T=0$, $E2$ sum rule.[6]

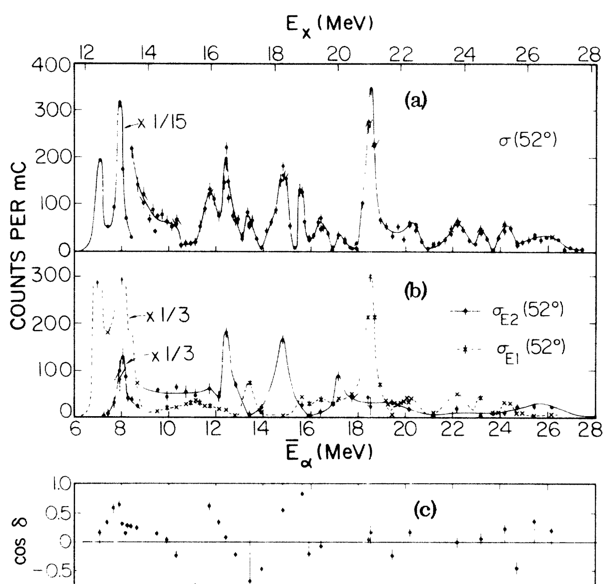

FIG. 1. (a) Measured cross section at 52° for $^{12}C(\alpha,\gamma_0)^{16}O$; (b) excitation curves for $\sigma_{E1}(52°)$, $\sigma_{E2}(52°)$; (c) $\cos\delta$. The absolute normalization (in μb/sr) is given by $\sigma(52°) = [4.10 + 0.22 E_x$ (MeV)$] \times 10^{-4} \times$ counts/mC.

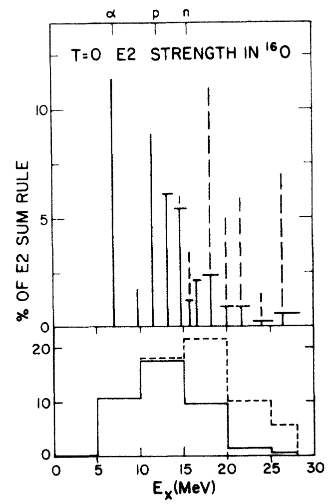

FIG. 2. Top, measured $E2$ strength (solid bars) and estimated strength (dashed bars). Bottom, measured and estimated $E2$ strength summed over 5-MeV intervals.

Alternatively, the integrated $E2$ (α,γ) cross section may be compared to the sum rule in the form[7]

$$\int[\sigma_{E2}(\gamma)/E_\gamma^2]\,dE_\gamma = 7.32\ \mu\text{b/MeV},$$

where for the total $E2$ absorption cross section $\sigma_{E2}(\gamma)$ we substitute the partial cross section, $\sigma(\gamma,\alpha) = (2.10\times10^3\ \text{MeV})\sigma(\alpha,\gamma)E_\alpha/E_\gamma^2$. The results are shown in Fig. 2 where for unbound levels the latter sum rule was used. For $E_x > 12$ MeV, the solid vertical bars represent the contribution to the $E2$ sum rule from the (α,γ) cross section in the energy range covered by the horizontal bars. The total contribution from a 15.25-MeV 2^+ state[8,9] with $\Gamma_\gamma \approx 0.8$ eV is also included. The solid bars below 12 MeV represent $E2$ strength taken from a recent compilation.[9] The total $E2$ strength from $E_x = 12$ to 28 MeV seen in (α,γ) represents about 17% of the $T=0$, $E2$ sum rule, while the additional known strength represents 25% of the sum rule, for a total of about 42%.

The resonances seen in (α,γ) above $E_x = 12$ MeV may have significant strength in other particle channels, especially above 18 MeV where many channels are open. Evidence from other reactions for $E2$ strength above $E_x = 12$ MeV and below the GDR is scant, aside from the 15.25-MeV state mentioned above, the 16.5-MeV state ($\Gamma_\gamma = 0.5 \pm 0.2$),[9] and a 2^+ state near 19.1 MeV[8,10] which is apparently $T=1$. The reaction $^{15}N(p,\gamma_0)^{16}O$ shows evidence[8] for $E2$ radiation in this energy range, but it is difficult to estimate its strength quantitatively. In the absence of detailed information about the wave functions for the (α,γ) resonances, we can only roughly estimate the strength in other channels. We assume the important channels are α_0, α_1, and proton and neutron decay to the ground $(p_{1/2}^{-1})$ and 6-MeV $(p_{3/2}^{-1})$ states of mass 15. If we take the reduced width for decay in each of these channels to be proportional to the single-particle limit $\gamma_{\text{s.p.}}^2$, with the same proportionality constant for each channel, then the factor

$$\sum_{i,l} P_{i,l}\gamma_{\text{s.p.}}^2(i)/P_{\alpha_0}\gamma_{\text{s.p.}}^2(\alpha)$$

(where $P_{i,l}$ is the Coulomb penetrability for channel i and orbital angular momentum l) corrects the measured (α,γ) strength for what is lost in other channels. We do not suggest that this factor should be quantitatively correct for each resonance, but rather that it represents a correction which should roughly account for the opening of other channels. This factor increases from near 1 at $E_\gamma = 13$ MeV to about 12 at $E_\gamma = 26.5$ MeV and, when applied to the measured (α,γ) strengths, yields the enhancements indicated by the dashed lines in Fig. 2, for a total estimated $E2$ strength of ~70% of the $T=0$ sum rule. In Fig. 2 we have not enhanced the resonance near $E_x = 16.5$ MeV, for which the measured (α,γ) strength is close to the radiative width given above; on the other hand the enhanced (α,γ) resonance strength near $E_\lambda = 15.25$ MeV is in agreement with the known radiative width for a 2^+ level at this energy.

We make the following observations of $T=0$, $E2$ strength in ^{16}O based on the measured plus estimated distribution (summed over 5-MeV intervals) shown in Fig. 2: (1) Most of the strength (~70%) allowed by the sum rule lies below 28 MeV. (2) The $E2$ energy centroid is ~15 MeV (although the discovery of higher strength could shift this upward). (3) The strength appears to be spread with a width of the order of 15 MeV. This should be contrasted with recent "screened Tamm-Dancoff- and random-phase-approximation" calculations[11] for ^{16}O which predict most of the $T=0$, $E2$ strength to be concentrated in a *narrow* energy region somewhere between $E_x = 15$ and 30 MeV (depending on the approximation).

It is interesting to compare these results with (γ,p) and (p,γ) measurements which show evidence for a "giant" $E2$ resonance[12,13] in ^{16}O in the region $E_x = 22$–30 MeV. A comparison of the magnitude and sign of the odd Legendre coefficients in the $(\gamma, p_0)^{8,12}$ and $(\gamma, n_0)^{11}$ angular distributions suggests that this $E2$ radiation is mainly isovector. Thus, there is evidence for an energy splitting between the isoscalar and isovector $E2$-strength distributions.

Of course the details of the above conclusions depend upon our estimate of the contribution to the strength from other particle channels. It will be important to have data from other reactions in order to complete the empirical determination of the $E2$-strength distribution. Further details of this work, including the $E1$ resonances and their bearing on isospin mixing and intermediate structure in the GDR, will soon be published.

The authors are pleased to acknowledge the help of S. T. Lim and K. Ebisawa during the experimental measurements.

†Work supported in part by the U. S. Atomic Energy Commission.

*Alfred P. Sloan Foundation Fellow.

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Kinematically Complete Measurement on the Reaction ^{2}H(n, np) at $\theta_n = 0°$

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(Received 9 October 1973)

The differential cross section of the reaction ^{2}H(n,np) was measured at $\theta_n = 0°$. Because of the applied special geometry the experimental data extend over a large fraction of the phase space, including several final-state interaction regions as well as regions far from the dominance of the quasi-two-body processes. This offers the possibility of extracting neutron-neutron scattering parameters and obtaining simultaneously additional information on the N-N potentials and three-body forces in the frame of an exact three-body calculation.

In order to determine the low-energy neutron-neutron scattering parameters a large number of experiments on the reaction $n + {}^2\text{H} \rightarrow n + n + p$ were performed during the last years. The method to extract these data was based on comparison of experimental results with theoretical calculations mainly in regions where the n-n final-state interaction (FSI) is dominant; consequently, efforts were made to use a geometry which allows detection of events with small relative kinetic energy of the two neutrons.

Since the numerous kinematically incomplete measurements[1] did not give unique results, mainly because of the insensitiveness of the various integrated theoretical differential cross sections to the parameters to be determined, it was nec-