Isoscalar $E2$ Strength in ^{16}O from the $(e,e'\alpha)$ Reaction

J. P. Fritsch, H. J. Emrich, A. Grasmück, R. Neuhausen, S. Schardt, and N. Zimmermann
Institut für Kernphysik, Universität Mainz, D-6500 Mainz, Federal Republic of Germany

J. R. Calarco
Department of Physics, University of New Hampshire, Durham, New Hampshire 03824

M. Potokar
Institut "Jožef Stefan," E. Kardelj University of Ljubljana, 61000 Ljubljana, Slovenia
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We have measured the first complete angular correlations of α-particle emission from the ^{16}O isoscalar giant quadrupole resonance (GQ_0R) following excitation by inelastic electron scattering. Analysis of these determines the GQ_0R strength distribution and resolves a discrepancy between previous results from photonuclear excitation and inelastic α scattering.

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From high-precision measurements of the charged particle decay of the giant resonance region in ^{16}O via the $(e,e'x)$ reaction, we have obtained the first complete angular correlations for the $(e,e'\alpha)$ channels for momentum transfers q up to 0.6 fm^{-1}. In this Letter, we present the separation of these cross sections into multipole components. We find that the dominant multipole is $E2$ and resolve a long-standing discrepancy in the amount of that strength.

Excitation of the giant quadrupole resonance (GQR) in ^{16}O has been the subject of a number of previous measurements [1-7], all of which have claimed differing amounts of strength. The inclusive electron scattering [1] and proton capture [2,3] as well as the $(e,e'p)$ [4,5] are equally sensitive to both isovector and isoscalar excitations. The isoscalar giant quadrupole resonance (GQ_0R) is most readily probed by studying its decay by α decay [6,7], because isovector strength is eliminated except for small amounts consistent with isospin mixing. In fact, a comparison of ^{12}C(α,γ_0) [6] and ^{16}O$(\alpha,\alpha'\alpha)$ [7] with the proton capture [2,3] leads to the conclusion that the GQ_0R is concentrated in the region $E_x \sim 10$–22 MeV and is dominated by α decay while the isovector GQR is located above the dipole resonance ($E_x > 23$ MeV).

However, the available data from ^{12}C(α,γ_0) and ^{16}O$(\alpha,\alpha'\alpha)$ are not fully consistent with each other. While there is some similarity in the distribution in energy of the cross sections from ^{12}C(α,γ_0) and ^{16}O$(\alpha,\alpha'\alpha_0)$ [7], in that the same major peaks are seen in both reactions, there is considerably more structure in the latter, which may indicate a contribution from higher multipoles. Furthermore, Snover has pointed out [8] that there is a large discrepancy in the integrated strength seen in the two reactions; the $(\alpha,\alpha'\alpha_0)$ strength integrated from 17.9 to 27.3 MeV is twice that seen in (α,γ_0), and 4 times as much if one excludes a large resonance at ~ 18 MeV which contains about half the (α,γ_0) strength. Since our data extend the electromagnetic excitation studies from the real photon limit up to $q=0.6$ fm^{-1}, we are much more sensitive to contributions from higher multipoles.

Using the Mainz microtron, MAMI-A, we have accumulated data on the reactions ^{16}O$(e,e'x)$, where $x=p,\alpha$. Complete descriptions of this work will appear elsewhere [5]. Here we give a brief description of the experiment. MAMI-A beams of 124.1 and 183.4 MeV were used to bombard $^{6}Li_2O$ foils of typical thicknesses of 1.5–2.0 mg/cm^2 with a cw current of 10–12 μA. Electrons were detected in a 180° double-focusing spectrometer [9], with a solid angle of 4.0 msr, at scattering angles of 22.0° to 40.0° to define transferred momenta q of 0.25, 0.35, 0.47, and 0.60 fm^{-1}. Decay charged particles were detected in an array of silicon-surface-barrier detector telescopes arranged in a plane rotated about the q axis by $\varphi=135°$ from the electron scattering plane. The array of telescopes permitted measurements of the decay correlation angle ϑ_x, in that plane, from $-10°$ (forward of q) to 180° (opposite to q) and beyond, up to $\vartheta_x=240°$ (equivalent to $\vartheta_x=120°$ at $\varphi=-45°$). Data were accumulated for excitation energy ranges of 17.5–28 MeV. Decay α's were identified and measured for $E_\alpha \geq 2.5$ MeV.

The out-of-plane geometry provides two distinct advantages. One of them is a simplification in the analysis which we will describe shortly. The other is that it allows a complete angular correlation to be measured without a gap in the angular region which is blocked in the scattering plane by the incoming beam. The necessity of measuring and analyzing a complete correlation is shown in Fig. 1 where we compare our correlations for the two largest peaks in the cross section (near $E_x=18$ and 21 MeV) with that from Dmitriev *et al.* [4], who measured $(e,e'p)$ and $(e,e'\alpha)$ in plane. The shape of the correlations in our measurements is clearly characteristic of $E2$ as indicated by the small but significant bump near 90°, which cannot be seen by in-plane measurement.

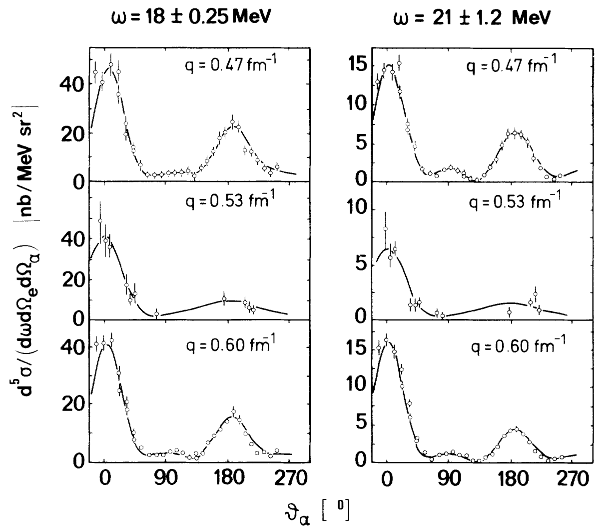

FIG. 1. Angular correlations for the two significant peaks observed in $^{16}O(e,e'\alpha_0)$ at three values of q, 0.47 and 0.60 fm^{-1} from the present work and 0.53 fm^{-1} from Novosibirsk [4]. Note the additional detail between 80° and 170° permitted by the out-of-plane apparatus. The fits to our data are described in the text.

The angular correlations have been analyzed by fitting them with a series of Legendre polynomials. In the general theory of $(e,e'x)$ reactions [10], the cross section is the Mott cross section σ_M times a sum of bilinear products of kinematic factors V_C, V_T, V_{CT}, and V_{TT} and corresponding structure functions W_C, W_T, W_{CT}, and W_{TT}. The subscripts C and T refer to the interaction of the electron with the nuclear charge density (or longitudinal current) and transverse nuclear currents, respectively. The double subscripts denote response functions which depend on the interference of these currents. If the reaction mechanism is dominated by one or two multipoles (as it is in the giant resonance region), it is useful to expand this cross section as [11]

$$\frac{d^5\sigma}{d\omega\, d\Omega_e\, d\Omega_\alpha}=\sigma_M\sum_{l=0}^{2}\sum_{k=l}^{2L}A_k^l P_k^l(\cos\vartheta_\alpha)\cos(l\varphi)\,.$$

The response functions W_C and W_T both contribute to the A_k^0 coefficients. The A_k^l coefficients constitute a multipole decomposition of the third response function, W_{CT}. Our experimental geometry was specifically chosen to set $\cos(2\varphi)=0$ and eliminate W_{TT} and its expansion in A_k^2's, since the functions P_k^2 are not independent of the P_k's. This removes any ambiguity in the analysis.

In the approximation that the reaction amplitudes are resonance dominated, the structure functions can be factored into products of excitation form factors and decay angular correlation coefficients [11-14]. Following Kleppinger and Walecka [12], we can then express the Legendre coefficients A_k^l in terms of Coulomb (or longitudinal) and transverse form factors for each multipole, C_L and T_L, respectively, and decay coefficients $a_k(L)$ which are q independent. We then fit the experimental angular correlations and directly determine C_1, T_1, $a_2(1)$, C_2, T_2, $a_2(2)$, $a_4(2)$, etc.

For example, if the reaction were dominated by a *single* $E2$ resonance (the GQR), the coefficients A_0^0, A_2^0, and A_4^0 reduced to $A_0^0=V_C|C_2|^2+V_T|T_2|^2$ [which is just the inclusive $(e,e'\alpha)$ cross section divided by $4\pi\sigma_M$],

$$A_2^0=a_2(2)[2V_C|C_2|^2+V_T|T_2|^2]\,,$$

and

$$A_4^0=a_4(2)[-1.5V_C|C_2|^2+V_T|T_2|^2]\,,$$

where $a_2(2)$ and $a_4(2)$ are the values measured at the real photon limit, $q=\omega$, i.e., the photonuclear angular correlation coefficients. Similar expressions can be written for A_2^1 and A_4^1 which depend upon the product C_2T_2 (and their relative sign) and the effect of which is to rotate the axis of symmetry away from q. In this approximation, $a_2(2)$, $a_4(2)$, C_2, and T_2 are, in general, determined by a fit to the data.

The effect of the C_2-T_2 interference in rotating the symmetry axis away from 0° is apparent by inspection of Fig. 1, where a shift of about 10° can be seen at $q=0.47$ fm^{-1} and a smaller one at 0.6 fm^{-1}. However, the size of this effect, its sign, and the fact that it decreases as q increases are all consistent with Siegert's theorem that $T_2=-\sqrt{3/2}(\omega/q)C_2$, where ω is the energy transfer. Thus, we can eliminate T_2 as a free parameter.

Furthermore, if we restrict our present discussion to the $(e,e'\alpha_0)$ channel leaving ^{12}C in its 0^+ ground state, then the photonuclear $a_k(2)$ coefficients can be simply calculated from angular momentum coupling considerations [$a_2(2)=\frac{5}{7}$ and $a_4(2)=-\frac{12}{7}$] and eliminated as free parameters. Using this, we determine C_2 from the fit as the only free $E2$ parameter.

The contribution from other multipoles can be uniquely determined in the case of $(e,e'\alpha_0)$ in a similar fashion. The effect of $E1$ and/or $E3$ is to produce an asymmetry between 0° and 180°, which is clearly seen in Fig. 1 to increase with q indicating that it is primarily due to $E3$. The $E1$ and $E3$ contributions were determined by assuming that C_1 and T_1 and C_3 and T_3 are related, respectively, by Siegert's theorem as well. There is little loss of accuracy here because it is evident from the correlations that $|C_2|^2\gg|C_1|^2,|C_3|^2$, and we expect $|C_L|^2\gg|T_L|^2$ for all the giant electric resonances in these kinematics. The C_0 contribution is uniquely determined from the isotropic component. Magnetic multipoles are forbidden, of course, by parity conservation. Typical fits to our data are also shown in Fig. 1.

The results of the fits to the $(e,e'\alpha_0)$ correlations confirm that the cross section is dominated by the decay of the GQ_0R. There are small but definite amounts of other multipoles. However, even at the largest value of q, 0.6 fm^{-1}, the $E3$ contribution is only $\leq 10\%$ of the total cross section.

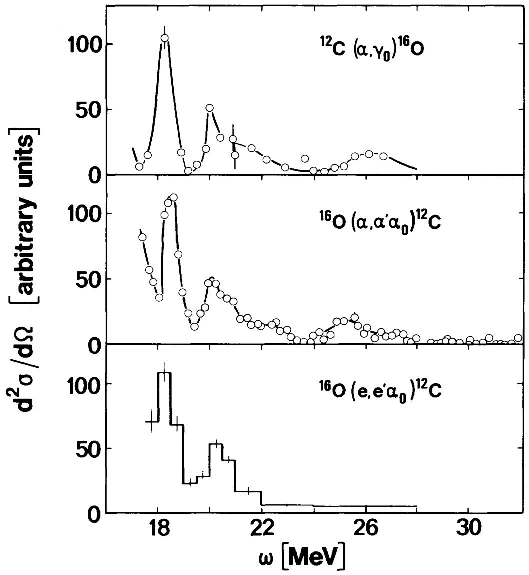

FIG. 2. The $E2$ component observed in the α_0 channel in the three reactions $^{12}C(\alpha,\gamma_0)$ (top), $^{16}O(\alpha,\alpha'\alpha_0)$ (middle), and $^{16}O(e,e'\alpha_0)$ (bottom).

The fitted $E2$ form factors $|C_2|^2$ exhibits a q dependence consistent with the Tassie model for transition radii ranging from 0.9 to 1.2 times the ground-state radius. Without data at higher q, we cannot determine the transition radius with greater accuracy.

The extracted GQ$_0$R cross section is shown in Fig. 2 in comparison with that from $^{12}C(\alpha,\gamma_0)$ [6] and $^{16}O(\alpha,\alpha'\alpha_0)$ [7]. The structure seen in $(e,e'\alpha_0)$ is very similar to both of these in this excitation energy range of $E_x = 17.5$–28.0 MeV. However, the integrated strength of $(3.6\pm0.7)\%$ of the isoscalar $E2$ energy-weighted sum rule (EWSR) [15] is somewhat lower than but within the quoted errors of $(5.0\pm1.3)\%$ from the $^{12}C(\alpha,\gamma_0)$ measurement [6], and thus in marked quantitative disagreement with the 13% from the $^{16}O(\alpha,\alpha'\alpha_0)$ experiment [7]. The errors in our integrated strength include those due to the uncertainty in transition radius. We conclude that while the dominant peaks seen in $(\alpha,\alpha'\alpha_0)$ are $E2$ due to the similarity in the structure, the reported GQ$_0$R strength from $(\alpha,\alpha'\alpha_0)$ [7] is too large by a factor of ~ 3.

We can also estimate the *total* GQ$_0$R strength in the region from 17.5 to 28 MeV under two assumptions: (1) The dominant mode of GQ$_0$R decay is via α emission as previously reported [7] and (2) the $(e,e'\alpha_1)$ reaction channel is dominated by GQ$_0$R decay to the same extent as the $(e,e'\alpha_0)$ channel. Figure 3 displays the ratio of total cross sections, integrated over the α-particle correlation angle, for $(e,e'\alpha_0)$ and $(e,e'\alpha_1)$. Under assumption (2), this is the same as the ratio of $E2$ cross sections. This assumption is supported by the fact that the ratio of total cross sections is independent of q. With this analysis, we find that $(e,e'\alpha_1)$ exhausts $(15\pm3)\%$ of the EWSR, or 4.2 ± 1.2 times that from the $(e,e'\alpha_0)$ channel. This should be compared to the fractions of the EWSR observed from the analysis of $(\alpha,\alpha'\alpha_0)$ and $(\alpha,\alpha'\alpha_1)$ [7] which are 13% and 36%, respectively. The relative distribution of $E2$ strength between the α_0 and α_1 channels is the same within the quoted uncertainties. Thus, the absolute strength seen in our total $(e,e'\alpha)$ analysis is still approximately a factor of 3 less than quoted from the $(\alpha,\alpha'\alpha)$ work [7]. Since $E2$ comprises all but about 10% of our total cross section, there is no way to reconcile these results unless either some substantial fraction of the $(\alpha,\alpha'\alpha)$ cross section is due to multipoles of order 3 or higher and/or there is some systematic effect in basing the $(\alpha,\alpha'\alpha)$ $E2$ strength [7] on that from the inclusive (α,α') cross section [16]. One should note in this context that the detailed fits to the $(\alpha,\alpha'\alpha)$ angular correlations shown in Ref. [7] do not agree with the data over the full angular range, particularly in the region of the small maximum near 90°. Thus we must conclude that the isoscalar $E2$ strength quoted from the $(\alpha,\alpha'\alpha)$ analysis is too large, that we are in agreement with the values reported from (α,γ_0) for the α_0 channel, and that we have extended these results to include the α_1 channel.

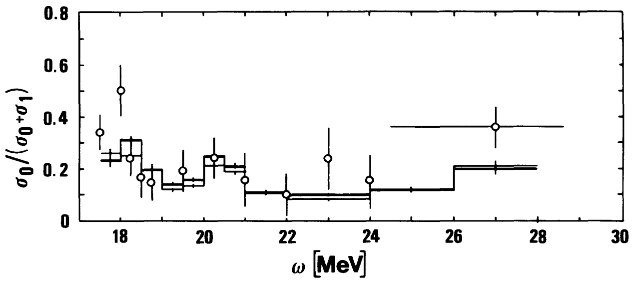

FIG. 3. The fraction of $(e,e'\alpha)$ into the $(e,e'\alpha_0)$ channel at $q = 0.47$ fm^{-1} (thin line) and 0.60 fm^{-1} (thick line) compared to that from Novosibirsk at 0.53 fm^{-1} (points).

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