Isoscalar $E2$ Strength in ^{12}C from the $(e,e'\alpha)$ Reaction

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(Received 8 February 1993)

We have measured the first complete angular correlations of α-particle emission from the ^{12}C isoscalar giant quadrupole resonance (GQ_0R) following excitation by inelastic electron scattering, for momentum transfers from 0.24 to 0.61 fm^{-1}. Analysis of these uniquely determines the GQ_0R strength distribution for the α_0 channel and sets limits on that for α_1.

PACS numbers: 25.30.Fj, 24.30.Cz, 25.30.Dh, 27.20.+n

Although the systematic characteristics of the giant quadrupole resonance (GQR) are well established in medium to heavy nuclei, the data for the light nuclei, which are more amenable to microscopic calculations, are incomplete and inconsistent. In particular, excitation of the GQR in ^{12}C has been the subject of several previous measurements using various reactions [1-9], which have claimed differing amounts of strength. Electromagnetic probes [1-4] are equally sensitive to both isovector and isoscalar excitations. On the other hand, hadron scattering is more strongly selective for isoscalar excitations because of the relative weakness of the $\mathbf{t}\cdot\boldsymbol{\tau}$ component of the hadron-nucleus interaction, as evidenced by previous studies using (^3He,$^3He'$) scattering [5] and (p,p') reactions [6]. Inelastic (α,α') scattering [7] is even more selective due to the $S=0$, $T=0$ nature of the probe.

The best way to isolate and identify the ^{12}C isoscalar GQ_0R from isovector modes is by studying its *decay* by α emission, because (1) isovector strength is eliminated, except for small amounts consistent with isospin mixing, (2) the angular correlation is characteristic of the multipolarity, and (3) theoretical studies have shown that, for nuclei with $1p$ and $2s$-$1d$ valence orbitals, α emission is expected to account for most of the GQ_0R decay [10]. However, in spite of the selectivity of hadron scattering coupled with α emission, the observed isoscalar $E2$ strength reported in $(\alpha,\alpha'\alpha)$ [8] is only half or less than that seen in the $(p,p'\alpha)$ [9] reaction.

In the present experiment, we address this discrepancy by exciting ^{12}C via electron scattering and use α decay to select isoscalar excitations. The well-known electromagnetic interaction then allows us to make unambiguous determinations of the multipole strengths from the dependence on correlation angle and transferred momentum of the measured cross sections.

We have measured the first complete angular correlations for the $^{12}C(e,e'\alpha)$ reaction, for momentum transfers q up to 0.61 fm^{-1}. We separate these cross sections into multipole components and extract the form factors for those multipoles. The dominant multipole is $E2$, and we make the first determination of its strength for this particular reaction. However, the contribution of other multipoles, particularly $E0$ and $E3$, cannot be neglected.

Using the Mainz microtron, MAMI-A, we have accumulated data on the reactions $^{12}C(e,e'x)$, where $x=p,\alpha$. A detailed description of the apparatus will appear in a discussion of the $(e,e'p)$ reaction [3]. MAMI-A electron beams of 124.1 and 183.4 MeV were used to bombard naturally abundant ^{12}C foils of thicknesses of 2.4 and 3.6 mg/cm^2 with a cw current of 8–15 μA. Scattered electrons were detected in a 180° double-focusing spectrometer [11], with a solid angle of 4.0 msr, at scattering angles of 22.0° to 40.0° to define transferred momenta, q, of 0.24, 0.35, 0.41, and 0.61 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 the azimuthal angle $\varphi=135°$ from the electron scattering plane (in a spherical coordinate system with the $\hat{\mathbf{z}}$ axis along $\mathbf{q}$ and $\hat{\mathbf{x}}$ in the electron scattering plane, as defined, for example, in Ref. [12]). The array of telescopes permitted measurements of the decay correlation angle, the polar angle ϑ_α, in the detector plane, from 0° (along q) to 180° (opposite to q) and beyond, to $\vartheta_\alpha=240°$ (equivalent to $\vartheta_\alpha=120°$ at $\varphi=-45°$) in steps of 10°. Data were accumulated for excitation energies of $\omega=18$–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 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 detailed shape of the correlations is very sensitive to interferences from different multipoles, and a large gap in that correlation can lead to significant errors in interpretation. The other advantage is a simplification in the analysis.

The angular correlations have been analyzed by fitting them to a series of Legendre polynomials. In the general theory of $(e,e'x)$ reactions [12], the cross section is the Mott cross section σ_M times a sum of bilinear products of kinematic factors V_L, V_T, V_{LT}, and V_{TT} and corresponding structure functions W_L, W_T, W_{LT}, and W_{TT}. The subscripts L and T refer to the interaction of the electron with the longitudinal 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 [13]

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

The response functions W_L and W_T both contribute to the A_k^0 coefficients. The A_k^1 coefficients constitute a multipole decomposition of the third response function, W_{LT}. The out-of-plane geometry allows us to choose $\varphi=135°$ to 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 simplifies the analysis by removing an ambiguity in the fits.

In the approximation that the reaction amplitudes are resonance dominated, the structure functions W_i can be factored into products of excitation form factors and decay angular correlation coefficients [13–16]. Following Kleppinger and Walecka [13], 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 (and, therefore, equal to those measured in photonuclear decay). We can 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.

If we restrict our discussion for the moment to the $(e,e'\alpha_0)$ channel leaving ^{8}Be in its 0^+ ground state, then the q-independent 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 $C(2)$ and $T(2)$ from the fit as the only free $E2$ parameters.

The contribution from other multipoles can be uniquely determined for $(e,e'\alpha_0)$ in a similar fashion. The effect of $E1$ and/or $E3$ is to produce an asymmetry between 0° and 180°, which is seen in Fig. 1. The $E1$ and $E3$ contributions were determined by demanding that $C(1)$ and $T(1)$ and $C(3)$ and $T(3)$ are related, respectively, by Siegert's theorem, i.e., $T(L)=(-1)\sqrt{(L+1)/L}\,(\omega/q)\times C(L)$. There is little loss of accuracy here because it is evident from the correlations that the dominant multipole is $E2$, and we expect $|C(L)|^2\gg|T(L)|^2$ for all the giant electric resonances in these kinematics. The $C(0)$ contribution from $E0$ is uniquely determined from the isotropic component. Magnetic multipoles are forbidden, of course, by parity conservation.

The results of the fits to the $(e,e'\alpha_0)$ correlations are shown by the solid curves through those data in Fig. 1 and include contributions from $E0$, $E2$, and $E3$ multipoles. The inclusion of $E1$ produced no significant strength, as expected by isospin conservation, but larger

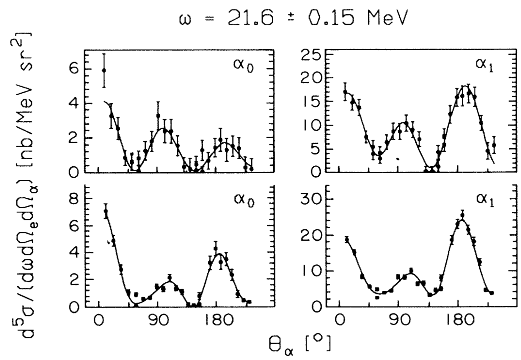

FIG. 1. Angular correlations for ^{12}C$(e,e'\alpha_0)$ and ^{12}C$(e,e'\alpha_1)$ at the resonance energy of 21.6 MeV for two values of q, 0.24 and 0.61 fm^{-1}. The fits, described in the text, indicate dominant $E2$.

uncertainties in the fitted parameters. Hence its contribution was assumed to be negligible. The shape of the dependence on ϑ_α is characteristic of 2^+ and confirms that the cross sections are dominated by decay of the GQ$_0$R.

In Fig. 2, we compare total cross sections for the $(e,e'\alpha_0)$ channel, and their $E2$ components, with total cross sections from ^{12}C$(\alpha,\alpha'\alpha_0)$ [8] and ^{12}C$(p,p'\alpha_0)$ [9]. The structure seen in $(e,e'\alpha_0)$ is qualitatively similar to

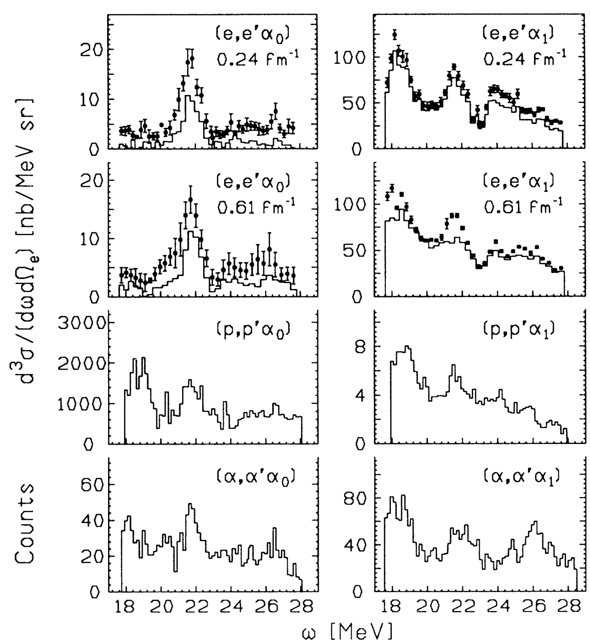

FIG. 2. On the left, the total cross section for ^{12}C$(e,e'\alpha_0)$ for $q=0.24$ and 0.61 fm^{-1} compared to that for ^{12}C$(\alpha,\alpha'\alpha_0)$ [8] and ^{12}C$(p,p'\alpha_0)$ [9]. The histograms under the $(e,e'\alpha_0)$ cross section show the $E2$ component. On the right is shown a similar comparison for the α_1 channels.

both of these in this excitation energy range of $\omega = 18-28$ MeV in that the cross sections are characterized by a resonance at $\omega \approx 21.6$ MeV. However, in the $(e,e'\alpha_0)$ reaction, the relative cross section off-resonance is significantly smaller than that for $(\alpha,\alpha'\alpha_0)$. For the $(p,p'\alpha_0)$ reaction, the shape is similar to what we see for $\omega > 20$ MeV but is dominated by a larger resonance near 19 MeV. Both of these observations suggest that while the correlated peaks seen in these other reactions are $E2$, the additional background and other peaks must be due to other multipoles, particularly in light of our multipole decomposition.

At the largest value of q, the $E3$ contribution is $\sim 30\%$ of the total cross section for a resonance unresolved from the $E2$ structure at 21.6 MeV. Extensive checks were made that the proximity of these two resonances was not due to some pathological systematic error in the analysis. After varying all the fitted coefficients in an effort to test the reproducibility of the $E3$ resonance, we conclude that it is real. The most convincing evidence is shown by the form factors in Fig. 3. The $E2$ and $E3$ form factors are obtained from independent fits at each individual value of q. However, the q dependence of both are consistent with the Tassie model for reasonable fitted values of the $B(EL)$'s and transition radii. It is interesting to note that $E3$ strength had been reported previously in the $^{11}B(p,\alpha_0)$ reaction [17].

The $E0$ strength in the $(e,e'\alpha_0)$ reaction is rather monotonically distributed, although there is some evidence for a peaking near 20.5 MeV. A similar peaking of $E0$ strength near 20 MeV has been reported from earlier $(e,e'p_0)$ measurements [18].

We have also performed a similar decomposition of the strength in the $(e,e'\alpha_1)$ channel in the region from 18 to 28 MeV. This analysis is more model dependent than that for the α_0 channel because $a_2(2)$ and $a_4(2)$ are not similarly uniquely constrained by simple coupling of angular momenta. As a result, we cannot resolve an ambiguity between $E0$ and $E2$ which arises because of the well known similarity of the $C(0)$ and $C(2)$ form factors, and because the effect of adding $C(0)$ is simply an additional contribution to a_2 through $C(0)/C(2)$ interference. We have, therefore, determined the $E2$ strength under two extreme assumptions: (a) the $C(0)$ strength function is allowed to be free; and (b) the $C(0)$ strength is constrained to be negligible. The $C(0)$ strength distribution under the first assumption is clearly wrong because it looks like a rather uniform fraction of the total cross section, including the $E2$ resonance at 21.6 MeV. The true $E2$ strength most likely corresponds to a value of $C(0)$ between these two limits. In fact, because the branching ratios for α_0 and α_1 are independent of q within statistical uncertainties, we have assumed that the fraction of the cross sections due to $E2$ is the same for both decay channels. This gives a best value for the $E2$ strength approximately half way between the extreme limits. The $E3$ strength is independent of the assumption regarding $C(0)$.

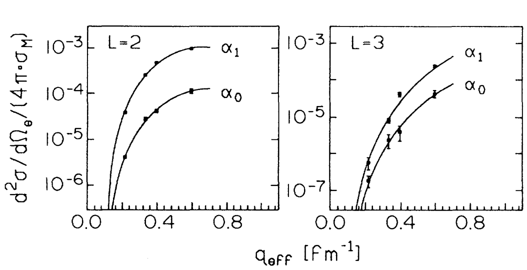

FIG. 3. The form factors for the extracted $E2$ and $E3$ strength at 21.6 MeV for both $(e,e'\alpha_0)$ and $(e,e'\alpha_1)$. The lines are Tassie model fits.

From these fits, also shown in Fig. 1, we have obtained the α_1 form factors shown in Fig. 3 for both $E2$ and $E3$ multipoles for the resonances near 21.6 MeV. The q dependence of the $E2$ form factor is independent of the assumptions concerning the $E0$ strength. The consistency of the α_1 results with those from α_0 is strong evidence for their validity. The extracted form factors have the same q dependence, within fitting uncertainties, as those for α_0, as would be expected for resonance decay to various allowed channels. The total α_1 cross sections (and $E2$ components) are shown in comparison with those from $(\alpha,\alpha'\alpha_1)$ [8] and $(p,p'\alpha_1)$ [9] in Fig. 2. The $(e,e'\alpha_1)$ and $(p,p'\alpha_1)$ are very similar in shape, while the $(\alpha,\alpha'\alpha_1)$ exhibits a significantly larger structure near 26 MeV.

Our integrated $E2$ strength, obtained from the Tassie model fits to the form factors, is summarized and compared to the $(\alpha,\alpha'\alpha)$ and $(p,p'\alpha)$ results in Table I. The errors on the α_0 results primarily reflect the statistical uncertainty in the data and the restricted range of q we were able to obtain for this experiment. The statistical accuracy of the α_1 data is much better, and the errors on the $E2$ strength are essentially the systematic uncertain-

TABLE I. Fraction of the GQ_0R EWSR exhausted in the α_0 and α_1 channels from $^{12}C(e,e'\alpha)$ compared to that for $^{12}C(\alpha,\alpha'\alpha)$ [8] and $^{12}C(p,p'\alpha)$ [9]. Reference [8] quoted neither the integration region over the 21.6 MeV resonance nor the uncertainties on the estimated $E2$ strength.

Reaction	Energy interval (MeV)	$B(E2)$ (e^2fm^2)	% $E2$ EWSR
$(p,p'\alpha_0)$	20.95-22.65		1.4 ± 0.7
$(p,p'\alpha_0)$	20.95-25.25		2.9 ± 1.4
$(\alpha,\alpha'\alpha_0)$	21.6		0.6
$(e,e'\alpha_0)$	20.6-22.6	0.74 ± 0.07	1.09 ± 0.11
$(e,e'\alpha_0)$	18.0-28.0	1.36 ± 0.13	2.00 ± 0.18
$(p,p'\alpha_1)$	20.95-22.65		5.0 ± 2.5
$(p,p'\alpha_0)$	20.95-28.15		15.8 ± 7.9
$(\alpha,\alpha'\alpha_1)$	21.6		1.4
$(\alpha,\alpha'\alpha_1)$	20.0-30.0		6.4
$(e,e'\alpha_1)$	20.6-22.6	5.6 ± 1.6	8.2 ± 2.3
$(e,e'\alpha_1)$	18.0-28.0	23.6 ± 4.7	34.7 ± 6.9

ties due to the $E0/E2$ ambiguity, which we have conservatively taken to span the difference in the two extremes for $C(0)$.

The $E2$ strength is the same for $(e,e'\alpha_0)$ and $(p,p'\alpha_0)$ within the quoted uncertainties. The $(e,e'\alpha_1)$ $E2$ strength appears to be larger than that for $(p,p'\alpha_1)$, but just outside the quoted systematic uncertainties. However, since $E2$ only accounts for part of the total cross section in $(e,e'\alpha)$, one expects similar amounts of other multipoles in the $(p,p'\alpha)$ because the $(p,p'\alpha)$ data were taken at a q very similar to our highest value. Thus, to assume that all the $(p,p'\alpha)$ cross section is due to $E2$ clearly gives an upper limit. The absolute strength seen in our $(e,e'\alpha)$ analysis is approximately a factor of 5 more than quoted from the $(\alpha,\alpha'\alpha)$ work for the 21.6 MeV resonance summed over both channels, and a factor of 4 larger when integrated over a comparable energy range [the $(\alpha,\alpha'\alpha_0+\alpha_1)$ exhausts $\sim$10.2% of the energy-weighted sum rule (EWSR) [19] in the region 20–30 MeV [8]]. Thus we conclude that the isoscalar $E2$ strength quoted from the $(\alpha,\alpha'\alpha)$ analysis is too small and that, while we are in reasonable agreement with the values reported from $(p,p'\alpha)$, we find a significant strength for other multipoles in this excitation region which is not taken into account in either of the hadron induced reactions. We note also that in both Refs. [8] and [9], the detailed fits to the angular correlations do not agree with the data over the full angular range, particularly in the region of the small maximum near 90°, indicating the presence of other multipoles. Finally, we conclude that while we do not see a "compact" GQ_0R in ^{12}C, we do report considerable $E2$ strength ($\sim$37% of the EWSR) between 18 and 28 MeV.

This work has been supported, in part, by the Deutsches Forschungsgemeinschaft (SFB 201). The UNH group gratefully acknowledges support by the U.S. Department of Energy (DE-AC02-79ER10330) and the National Science Foundation (INT-821360).

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