with another example, ^{162}Er, the octupole phonon in ^{180}W retains its collective character to a much larger value of the core rotation. Since the rotational frequencies of these two nuclei should be rather similar, this implies that the octupole correlation energy in ^{180}W is significantly larger than that in Er. By comparing Fig. 3 with a similar diagram for the $i_{13/2}$ orbital in ^{181}W,[1] one observes that the collective octupole phonon decouples more swiftly and completely than a single-particle state which is a major component of the phonon. This is particularly surprising since the $i_{13/2}$ orbital has more than twice the angular momentum of the octupole phonon. Finally, we observe that since the experimental ratios approach asymptotically so closely to unity, if our interpretation is correct, the octupole phonon does not affect the rotational properties of the core at large angular momenta.

The authors are grateful to Dr. F. M. Bernthal for permission to quote unpublished results on the ^{180}W level scheme and to Dr. P. Vogel for a stimulating discussion. We also wish to thank the crew of the cyclograaff for their efforts in producing the beams used in the experiments. This research was supported by the U. S. Department of Energy and in part by the National Science Foundation, Grant No. PHY77-12876.

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Is There an Isoscalar "Giant" Quadrupole Resonance in ^{12}C?

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(Received 22 May 1978)

Apparent discrepancies in the amount of $E2$ strength located in the giant resonance region of ^{12}C are resolved by a ^{12}C($\alpha,\alpha' c$) coincidence experiment at 104 MeV. The summed $E2$ strengths in the dominant decay channels $c=\alpha_0$, α_1, and p_0 in the range $20 \leq E_x \leq 30$ MeV exhaust less than 15% of the energy-weighted sum rule. So far ^{12}C is the only investigated nucleus which does not exhibti a giant quadrupole resonance.

The intense search[1-8] for an isoscalar giant quadrupole resonance (GQR) in ^{12}C, prompted by its occurrence in all other investigated nuclei, has resulted in reports of widely differing amounts of $E2$ strength in the energy region between 20 and 30 MeV: (80 ± 30)% of the energy-weighted sum rule (EWSR) deduced[1] from semidirect reaction amplitudes contributing to inelastic proton scattering; (26^{+15}_{-10})% from (d,d') reactions[2] at 70 MeV; ~19% from (^{3}He, ^{3}He$'$) reactions[3] at 130 MeV; (30–50)% from 96-MeV[4] and <(16 ± 5)% from 150-MeV[5] α scattering. An analysis of the reaction[6] ^{11}B($\vec{p},\gamma_0$)^{12}C yielded ~40% (lower limit 15%) in the p_0 channel alone.

To explain these discrepancies we performed a ^{12}C($\alpha,\alpha' c$) experiment with 104-MeV α particles from the Karlsruhe cyclotron. Scattered α' particles and charged decay products c from the giant-resonance region were detected in coincidence by semiconductor telescopes. The setup, very similar to the one described previously,[9] allowed a unique identification of protons (p_0) decaying to the ground state of ^{11}B [for $18 \lesssim E_x(^{12}\mathrm{C}) \lesssim 30$ MeV] and of α_0 and α_1 decays to the ground and first excited states of ^{8}Be. The α' telescope was kept fixed at $\theta_{\alpha'} = 17°$ or 22°, i.e., in the second maximum of $L=2$ or $L=3$ (α, α') angular distributions, respectively. In-plane angular correlations were obtained for lab angles θ_c between −28° and −140°.

Figure 1(a) shows the singles (α, α') spectrum at $\theta_{\alpha'} = 17°$ which is very similar to that obtained at 96 MeV.[4] On top of a large continuum one observes a broad double-peaked group between $25 \leqslant E_x \leqslant 32$ MeV, which had been interpreted[4] as the GQR. However, the kinematic coincidence data (i.e., coincidences between light reaction products and corresponding recoil nuclei) in Fig. 1(b) demonstrate that a large fraction of the alleged GQR and the groups at apparent excitation energies of ~43, 46, and 58 MeV originate from pickup reactions leading to ^{5}He, ^{5}Li, and a particle-unstable state of ^{6}Li, respectively, which redecay into the α' channel. Ironically, the $(\alpha, {}^5\mathrm{He})$ and $(\alpha, {}^5\mathrm{Li})$ reactions which simulated a GQR in ^{12}C are known[10] to have prevented its observation by 100-MeV α particles in the case of ^{16}O and $2s$, $1d$ shell nuclei.[11]

If a coincidence requirement is imposed with α_0, α_1, and p_0 particles the resulting spectrum [Fig. 2(a)] is in close agreement with that observed[5]

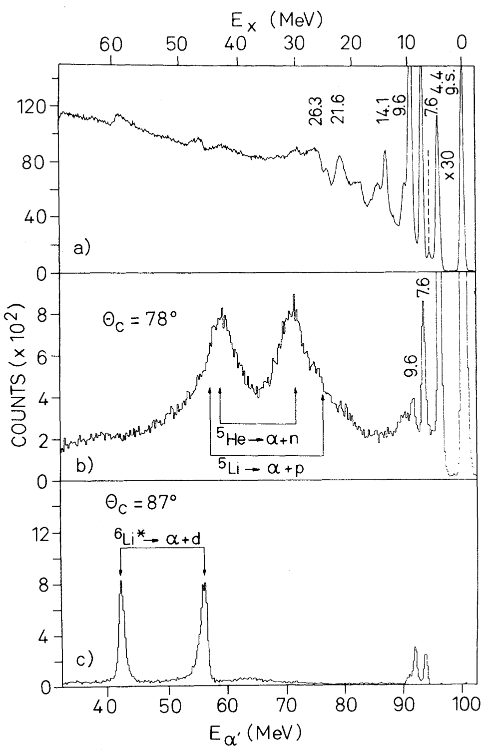

FIG. 1. Spectrum of the $^{12}\mathrm{C}(\alpha,\alpha')$ reaction at $E_\alpha = 104$ MeV and $\theta_{\alpha'} = 17°$; (a) singles; (b) in kinematic coincidence with ^{11}B and ^{11}C recoil nuclei from the reactions $^{12}\mathrm{C}(\alpha, {}^5\mathrm{Li} \rightarrow \alpha' + p)^{11}\mathrm{B}$ and $^{12}\mathrm{C}(\alpha, {}^5\mathrm{He} \rightarrow \alpha' + n)^{11}\mathrm{C}$ (and also with ^{12}C recoiling from elastic and inelastic scattering); (c) in kinematic coincidence with ^{10}B recoil nuclei from the reaction $^{12}\mathrm{C}[\alpha, {}^6\mathrm{Li}(2.18\ \mathrm{MeV}) \rightarrow \alpha' + d]^{10}\mathrm{B}$ (g.s.). The kinematic limits for breakup α' particles were calculated neglecting Coulomb repulsion.

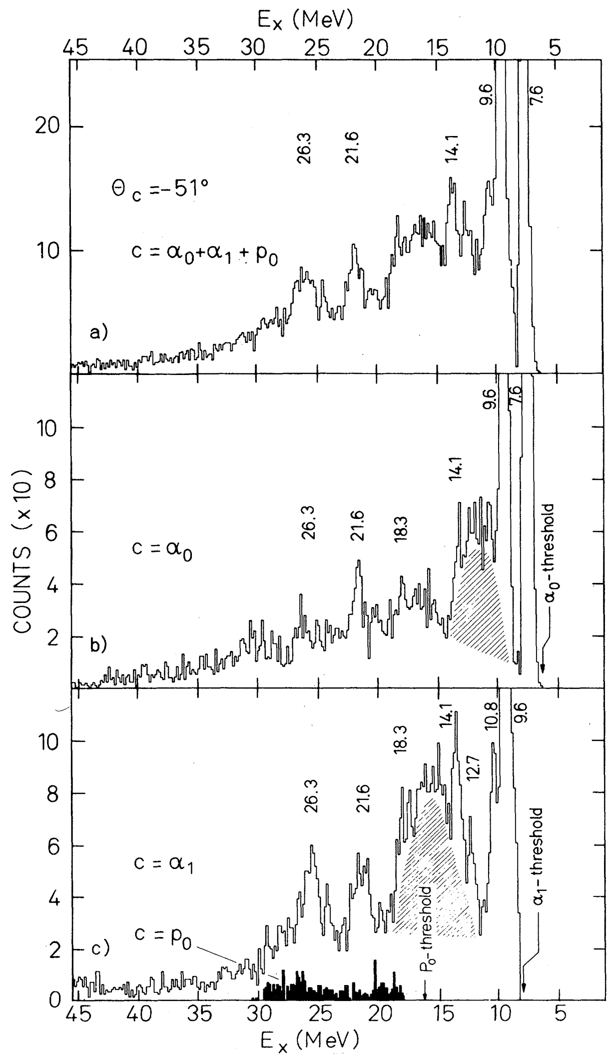

FIG. 2. Spectrum of inelastically scattered α' particles ($\theta_{\alpha'} = 17°$) measured in coincidence with (a) α_0, α_1, and p_0 decay; (b) α_0 decay alone; and (c) α_1 or p_0 (black area) decay, respectively. The hatched areas represent quasifree $^{12}\mathrm{C}(\alpha, 2\alpha)$ groups (see text).

in the $^{12}C(\alpha, \alpha')$ reaction at 150 MeV where the α particles from the breakup of ^5He and ^5Li occur at $E_x > 31$ MeV. Figures 2(b) and 2(c) qualitatively show that the high-lying resonances at 21.6 and 26.3 MeV mainly decay by α emission. The existence of these resonances is, however, not reflected in the small fraction of the α' spectrum which is coincident with p_0 protons. This nonresonant behavior was also observed in a $^{11}B(p, \gamma_0)^{12}C$ experiment.[7]

Angular correlations for α_0 and α_1 decay (Fig. 3) have been obtained after subtracting a background specified through connection of the main minima in Figs. 2(b) and 2(c). This background originates predominantly from nonsequential processes; e.g., the broad structures near 13 and 16 MeV [Figs. 2(b) and 2(c)] were identified from their kinematic behavior as arising from quasifree $^{12}C(\alpha, 2\alpha)$ scattering leading to the ^8Be(g.s.) and ^8Be(2.9 MeV) states, respectively. The measured α_0 and α_1 angular correlations for various low-lying states of known spins are well reproduced by the calculations (Fig. 3) based on the m-state populations obtained from a DWBA (distorted-wave Born-approximation) calculation with Woods-Saxon parameters $V = 97$ MeV, $r_v = 1.37$ fm, $a_v = 0.75$ fm, $W = 16$ MeV, $r_w = 1.92$ fm, and $a_w = 0.47$ fm. As in an $^{16}O(\alpha, \alpha' c)$ experiment,[9] $L = 4$ partial waves produce sizable contributions to the $2^+ \to 2^+$ decays. The calculated correlation functions were used to extrapolate the measured correlations over the full sphere. This is justified by (1) the quality of the fits and (2) the branching ratios $(\Gamma_{\alpha_0} + \Gamma_{\alpha_1})/\Gamma$ obtained for the 9.6-, 10.8-, and 14.1-MeV states, which equal the required value of 1.0 within 15%. The α_0 angular correlations allow a unique 2^+ assignment to the 21.6- and 26.3-MeV groups but no assignment could be obtained for the weak (Fig. 2) 29-MeV group. For these states extraction of the branching ratios Γ_c/Γ is no longer meaningful, since they explicitly depend upon the singles (α, α') yield, which is obscured by the breakup processes as discussed above. Quantities independent of the background assumption in the singles spectrum are rather the partial differential cross sections[9] $d\sigma_c(\theta_{\alpha'} = 17°, 22°)/d\Omega_{\alpha'}$ obtained by integrating the angular correlation in channel c over 4π. By comparison with real-coupling DWBA calculations and following the method described by Knöpfle *et al.*,[12] we extracted the $E2$ EWSR fractions contained in the various decay channels c (Table I). The p_0 angular correlations show little structure. No background was subtracted in this weak

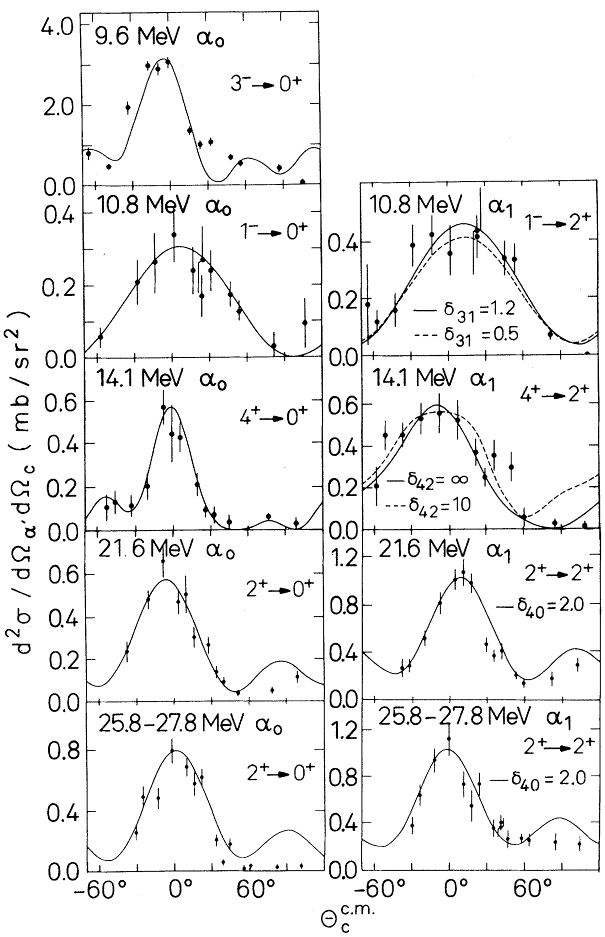

FIG. 3. Angular correlations for α_0 and α_1 decay of several resonances in ^{12}C; $\theta_{\alpha'} = 17°$. Angles are measured with respect to the ^{12}C recoil axis. The fitted curves are based on m-substate populations from DWBA. The mixing parameters $\delta_{LL'} = (\Gamma_L/\Gamma_{L'})^{1/2}$ found to reproduce the α_1 correlations are inserted.

TABLE I. Percentage S of isoscalar $E2$ EWSR strength contained in various decay channels c for ^{12}C states in the giant-resonance region. The quoted values are an average of the two measurements at $\theta_{\alpha'} = 17°$ and 22°, which agree within 15%. Values in parentheses are upper limits assuming pure $L = 2$ excitation while the α_0 angular correlation for this energy interval indicates the presence of other multipolarities.

E_x (MeV)	$S(\alpha_0)$	$S(\alpha_1)$	$S(p_0)$	Total
21.6	0.6	1.4	< 0.3	2.3
25.8–27.8	1.7	3.2	< 1.6	6.5
27.8–30.5	(1.5)	(1.8)	(< 2.0)	(5.3)

channel and therefore for p_0 only upper limits are given in Table I. No sizable strength was found in the other proton channels.

For $20 \leq E_x \leq 30$ MeV the total observed $E2$ strength of <15% of the EWSR in the p_0, α_0, and α_1 channels compares favorably with the <(16 ± 5)% of Ref. 5 if one assumes comparable contributions from proton and neutron decay. As in the case of ^{16}O (Ref. 9), the strength in the p_0 channel is at least a factor of 4 lower than that deduced from polarized-proton capture.[6] The simplest explanation, of course, would be that the predominant part of the $E2$ strength deduced from reactions[1] ^{11}B($\vec{p}$, γ_0)^{12}C and ^{12}C(p, p') is of isovector character. This conjecture is supported by the result of a 1p-1h (one-particle, one-hole) + 2p-2h RPA calculation,[13] in which the strongest 2^+ state at $E_x \simeq 30$ MeV is predominantly $T = 1$. The wide resonant structures centered at $E_x \sim 27$ MeV in ^{11}B(p, α_0)^{8}Be and at $E_x \sim 28.5$ MeV in ^{10}B(d, α_0)^{8}Be excitation functions[8] are not visible in the ^{12}C(α, $\alpha'\alpha_0$) spectrum [Fig. 2(b)]. Thus, contrary to the conclusion of Ref. 8, the backward α_0 yields do not reflect the isoscalar $E2$ strength distribution.

The present experiment has shown that the inelastic-scattering experiments[2–5] yield fully compatible $E2$ strengths if background processes are taken into account. Moreover, for low-lying states we have found a fair agreement with electromagnetic transition rates (see also Refs. 3 and 5). We conclude that the isoscalar $E2$ resonances in the region $20 \leq E_x \leq 30$ MeV of ^{12}C exhaust about 15% of the EWSR. The observation of these "pygmy" quadrupole resonances in ^{12}C is in striking contrast to the compact "giant" quadrupole resonances ($S > 30\%$ of the EWSR) in all previously investigated (e.g., Refs. 5, 10–12), heavier ($A \geq 16$) nuclei. Thus we have encountered an A limit for the existence of the isoscalar GQR whose disappearance as a collective phenomenon is not unexpected for sufficiently light systems.

This work was supported in part by Gesellschaft für Kernforschung, GmbH, 75 Karlsruhe, West Germany. We thank Dr. U. Scheib for his angular correlation code.

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