Giant Quadrupole Resonance in ^{24,26}Mg: A Comparison of Inelastic-Scattering and α-Capture Experiments

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The distribution of giant quadrupole resonance strength in ^{24,26}Mg obtained from inelastic α- and proton-scattering experiments and α-capture experiments have now been shown to be compatible. The results show that the giant quadrupole resonance strength in ^{24}Mg and ^{26}Mg is fragmented into several states or clusters of states and suggest that the giant quadrupole resonance states have very different α_0-decay strength.

Several papers have recently been published concerning the excitation of giant multipole resonances in *sd*-shell nuclei. The existence of localized isoscalar quadrupole strength in the giant-resonance region of these nuclei has for several years been a topic of considerable controversy. The historical background of this controversy has been described elsewhere.[1] It is important to note, however, that part of the controversy has arisen from apparent differences between quadrupole strength observed in the continuum of *sd*-shell nuclei through inelastic scattering and through radiative α capture.

In this Letter we present a comparison of the giant-quadrupole-resonance (GQR) strengths for ^{24}Mg and ^{26}Mg, as obtained from high-resolution inelastic α- and proton-scattering experiments and from an α-capture measurement. The results show that the GQR in these nuclei is fragmented into many different states or clusters of states. All GQR states observed in the α-capture reaction are observed in the (α, α') spectra, while several other $L=2$ states observed in the (α, α') work are not observed in the α-capture reaction.

Some established characteristics of the excitation of giant multipole resonances in *sd*-shell nuclei by inelastic α scattering are the following. (i) Only for incident energies well above 100 MeV is a distinct localization of GQR strength observed. This is due to both a cross-section enhancement at the higher energies[2,3] and to a decreased overlap[4] in the spectra with the α particles from the break-up of ^{5}He and ^{5}Li. (ii) The giant-resonance region, when studied with good energy resolution, is found to be fragmented into a considerable number of states or clusters of states.[5-7] (iii) The resonance region contains, in addition to $E2$ strength, certainly $E3$ and possible $E0$ strength.[5,7]

The inelastic α-scattering data were obtained with an overall energy resolution of about 100 keV (full width at half-maximum) using 120-MeV α particles from the Kernfysisch Versneller Instituut, Groningen, cyclotron in an experimental arrangement similar to the one described in Ref. 7. Data were taken from 6° to 22° in 1° steps. Typical (α, α') spectra for ^{24}Mg and ^{26}Mg are shown in Figs. 1(a) and 1(b), respectively. The proton data shown in Fig. 1 were obtained earlier using 60-MeV protons and have been reported elsewhere.[6]

In Fig. 1 we also show the results of α-capture experiments to the GQR in ^{24,26}Mg which have recently been published.[8] In these measurements only 2^+ states that have an α-decay branch to the ^{20,22}Ne ground states can be observed, hence more $E2$ strength may be present but unobserved in the capture experiments. Therefore the $E2$ strengths obtained from the capture measurements should be considered as well-established lower limits.

The (α, α') angular distributions have been compared with distorted-wave Born-approximation (DWBA) calculations using a collective form factor and reported optical parameters.[9] The peaks shown in Fig. 1 for ^{24}Mg and ^{26}Mg have an angular distribution characteristic of $L=2$, except for those in the shaded regions for which the angular distributions indicate that other multipolarities can contribute. The quality of the fits for the states assigned as 2^+ is similar to that obtained in our recent measurement[5] on ^{28}Si. The (α, α') spectrum and the (α,γ_0) excitation function for ^{24}Mg in Fig. 1(a) show a striking agreement. All

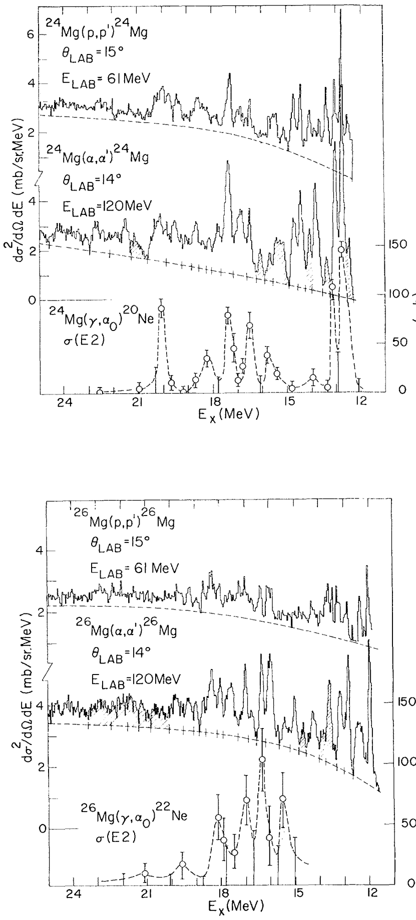

FIG. 1. Spectra of (α,α') at 14° and (p,p') at 15° are compared with the $E2$ (γ,α_0) excitation functions for ^{24,26}Mg. In the inelastic scattering spectra the assumed shape of the continuum is indicated together with the energy bins for which angular distributions are obtained. The shaded regions of the (α,α') spectra possibly contain other than 2^+ states.

the strong resonances seen in the (α,γ_0) reaction can be correlated with $L=2$ excitations in the (α,α') spectrum, indicating that even at high excitation energy multipolarity assignments based on DWBA fits are reliable. However, some peaks in the (α,α') spectrum of ^{24}Mg, like the ones at $E=17.0$ and 19.4 MeV which have distinctly $L=2$ angular distributions, are not observed in the capture excitation function. This can be explained if it is assumed that 2^+ states seen in (α,α') but not in α capture have a very weak (or zero) α-decay branch to the ground state. The ^{26}Mg data show a similar pattern as is clear from Fig. 1(b).

The isoscalar quadrupole strengths $S_\alpha(E_x)$, expressed as a percentage of the $T=0$, $E2$ energy-weighted sum rule (EWSR) for ^{24,26}Mg were obtained by normalizing the $(\beta R)^2$ values deduced from DWBA fits to the strengths of the lowest 2^+ states in ^{24}Mg and ^{26}Mg, respectively, as obtained from their adopted[10] half-lives. The capture data measured by Kuhlmann *et al.* were integrated and converted to $S_{\rm capt}(E_x)$ values by using the reaction[11]

$$S_{\rm capt}(E_x)=(10^7/3.1)E_x^{-2}\int_{\rm res}\sigma(E_x)\,dE_x.$$

Table I summarizes the GQR strength distribution in ^{24}Mg.

In the range of excitation energy between 15 and 24 MeV in ^{24}Mg we find $(60\pm15)\%$ of the $T=0$, $E2$ EWSR (see Table I). Proton-capture experiments indicate that (10–15)% of the EWSR is accounted for by direct proton capture to the ground state.[12] This additional strength cannot be distinguished, in our experiments, from the underlying continuum because of its flat energy distribution. In addition we find in the range of excitation energy below 15 MeV about 45% of the

TABLE I. $T=0$, $E2$ strength in the GQR of ^{24}Mg.

E_x [a] (MeV)	βR	S_α [b] (%EWSR)	$S_{\rm cap}$ [c] (%EWSR)
1.37	1.59	18.6 [d]	
12.8	0.23	3.5	4.0
13.1	0.23	3.6	2.8
13.9	0.20	3.0	0.4
14.5	0.20	3.3	
14.9	0.18	2.5	
16.6	0.16	2.3	1.1
17.0	0.24	5.3	
17.4	0.30	8.4	1.2
17.8	0.17	3.1	
18.2	0.16	2.5	0.5
18.8	0.22	4.8	
19.1	0.14	2.0	
19.6	0.22	5.2	
20.0	0.15	2.3	1.0
20.4	0.25	6.8	
21.1	0.16	(2.7)	
21.4	0.10	(2.8)	
22.7	0.21	5.4	
24.0	0.25	7.9	
$\sum$ 1.37–15		45 ± 10	
$\sum$ 15–24		60 ± 15	

[a] As obtained from this experiment.
[b] Obtained from a collective-model analysis normalizing to the 1.37-MeV 2^+ state. Relative error is estimated to be 20%.
[c] Obtained from Ref. 8. Relative error is estimated to be 20%.
[d] Obtained from adopted half-life (see Ref. 10).

EWSR in good agreement with an earlier (α, α') experiment.[13] Thus using the normalization procedure as described above we can account for the full $T=0$, $E2$ EWSR strength in ^{24}Mg. For ^{26}Mg, we measure $(50\pm10)\%$ of the $T=0$, $E2$ EWSR in the excitation energy range between 15 and 22 MeV.

Comparison of the $S_\alpha(E_x)$ and $S_{\rm capt}(E_x)$ values for the 12.8 and 13.1 MeV $J^\pi=2^+$ states in ^{24}Mg shows that these values are approximately equal. Since for these states $\Gamma_{\alpha 0}/\Gamma_{\rm tot}$ is nearly unity[8] the corresponding $S_{\rm capt}$ values should provide nearly the total percentage of the EWSR depleted in these states. This implies that the (α, α') normalization procedure described above is approximately correct.

Based on the strength obtained in their (α,γ_0) measurements Kuhlmann *et al.*[8] have calculated the total cross section expected for $E2$ excitation if the capture reaction proceeds only through the formation of a compound nucleus and subsequent statistical decay into various channels. Their calculations show that under these assumptions about $(120\pm30)\%$ of the $T=0$, 2^+ EWSR in ^{24}Mg should be present in the region between $E_x=12$ and 22.5 MeV. We find in this energy region an upper limit of 65%. Thus, for ^{24}Mg, noncompound, semidirect, contributions to the α-capture reaction are important. The same conclusion is reached by comparing $S_{\rm capt}$ and S_α for those states mutually excited in the 16.5- to 21-MeV excitation range of ^{24}Mg. If S_α gives the total EWSR for each level then it is seen from Table I that the α_0-decay branch observed in the capture reaction accounts for only (15–50)% of the total decay of the various levels. However, if the reaction is assumed to be completely compound nuclear then the α_0-decay branch can provide no more than 10% of the total decay for any of the observed levels; a value inconsistent with the data listed in Table I.

For ^{26}Mg the assumption that the (α,γ_0) reaction proceeds only through a compound process leads to an expected $E2$ strength of 300% in the region between $E_x=15$ and 22 MeV. Since at most 100% of the EWSR can be present it was already concluded in Ref. 8 that in ^{26}Mg large noncompound contributions exist. As we find only $(50\pm10)\%$ EWSR strength in this interval the discrepancy between the strength expected on basis of a pure compound process and the observed strength is even more dramatic.

The suggestion that some GQR states in ^{24}Mg do and others do not have a strong α_0-decay branch to the ^{20}Ne ground state can be qualitatively understood. The GQR in ^{24}Mg can be formed from $2\hbar\omega$ one-particle-one-hole excitations with the holes in the sd shell or in the $1p$ shell. Only those particle-hole components with the hole in the sd-shell can have an overlap with the ^{20}Ne ground state via α transfer. Particle-hole components with a $1p$ hole can be only connected via α transfer to particle-hole excited states in ^{20}Ne. Our observation indicates that the GQR states in ^{24}Mg have a predominance of one or the other type of particle-hole components. However, coincidence experiments which observe the particle decay of the GQR states are needed to confirm this suggestion.

The close agreement between the giant-resonance regions of the (α, α') and (p,p') spectra for ^{24,26}Mg and also for ^{28}Si (Ref. 5) is surprising. Calculations indicate that in the (p,p') spectra an appreciable fraction of the inelastic cross section in the giant-resonance region should be due to giant-dipole-resonance (GDR) excitation.[14] For ^{24}Mg at 15° this fraction is calculated to be about 40% using the Goldhaber-Teller (GT) model and nearly 100% if the Jensen-Steinwedel (JS) model is used.[1] Clearly the calculations based on the JS model predict too much GDR strength as has been reported before.[5] A careful analysis even indicates that calculations based on the GT model overestimate the GDR strength in inelastic proton scattering,[15] an effect that is not yet understood.

In conclusion a careful comparison of the energy and the strength of the GQR fine structure observed in (α, α') and (α_0,γ) experiments in ^{24,26}Mg shows that the results of both experiments are fully compatible. Comparison between the inelastic scattering and capture data indicates that some of the observed 2^+ states have no ground-state α-decay branch and for those having such a branch the strength of the α_0 decay varies considerably among the states. The conclusion previously reached for ^{26}Mg that GQR excitation by α capture cannot be completely compound nuclear is made stronger and extended to ^{24}Mg through use of the EWSR measured in the (α, α') experiment. It is interesting to compare these results with a recent experiment[16] on ^{16}O in which it was found that nearly the entire GQR resonance decays by α_0 and α_1 decay and another[17] on ^{40}Ca for which p decay of the GQR at 18 MeV was found.

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Partial Radiative Muon Capture on ^{12}C

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I report on a calculation of radiative muon capture on ^{12}C(g.s.) to ^{12}B(g.s.), done within the framework of the impulse approximation and a standard shell-model description of the nucleus. It is shown that the photon asymmetry as well as polarization and alignment of the ^{12}B nucleus depends strongly on the magnitude of the induced pseudoscalar coupling. The effects of possible contributions of second-class axial currents are also studied.

The long-standing problem of determining the pseudoscalar form factor and testing its momentum dependence predicted by partial conservation of axial-vector current (PCAC) may be settled by measuring either radiative muon capture on the proton or an exclusive capture process on a suitable nucleus. Both experiments seem to be of similar difficulty. In this Letter I show that exclusive radiative capture on ^{12}C is a good candidate for this matter. I show, specifically, that alignment and polarization of the daughter nucleus ^{12}B determine g_P if second-class currents are assumed to be absent, rather independently of the uncertainties inherent in the theoretical treatment.

In a radiative capture process $\mu^- + (Z,A) \to (Z-1,A) + \nu_\mu + \gamma$ one expects polarizations and asymmetries to depend strongly on the spins and parities of initial and final nuclear states. Therefore it is important to study exclusive radiative capture, i.e., radiative capture into definite final nuclear states, rather than integrated capture rates. I have investigated two typical examples of such partial transitions, ^{12}C(g.s.) with $I^P = 1^+$ to ^{12}B(g.s.) with $I^P = 1^+$, and ^{16}O(g.s.) with $I^P = 0^+$ to ^{16}N(120-keV level) with $I^P = 0^-$. In this Letter I report on some of my results for the first of these processes

$$\mu^- + {}^{12}C(g.s.) \to {}^{12}B(g.s.) + \nu_\mu + \gamma \quad (1)$$

and comment briefly on the capture process on oxygen. A more detailed account of these calculations for both cases will be presented elsewhere.

Inclusive radiative capture has been investigated by Rood and Tolhoek for the example of ^{40}Ca.[1] In particular, these authors study the effects of varying the induced pseudoscalar and second-class tensor contributions as well as the dependence of the predicted capture on nuclear-model uncertainties. Their treatment is based, however, on the closure approximation over nuclear final states.[2]

