Giant quadrupole resonance in ^{24}Mg, ^{27}Al, and ^{28}Si †

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The giant-resonance region of ^{24}Mg, ^{27}Al, and ^{28}Si was studied by inelastic scattering of 126-MeV α particles. In contrast to results at 96 MeV, considerable clustering of $E2$ strength was observed for ^{27}Al at $E_x \sim 20.1$ MeV with $\Gamma \sim 7.6$ MeV exhausting about 35% of the $E2$ energy weighted sum rule. $E2$ strength was also located in ^{24}Mg in two clusters of states at $\bar{E}_x \sim 18.2$, 24.4 MeV; however, contributions from other multipoles cannot be neglected. In ^{28}Si a multipeaked group was observed at $E_x \sim 19.4$ MeV with $\Gamma \sim 4$ MeV but no L assignment was made. The energy dependence of the cross section for the giant quadrupole resonance was found to be consistent with distorted-wave Born approximation predictions.

[NUCLEAR REACTIONS ^{24}Mg, ^{27}Al, ^{28}Si(α, α'), $E = 126$ MeV; measured $\sigma(\theta)$
giant resonances, deduced l, sum rule fraction.]

INTRODUCTION

The giant quadrupole resonance (GQR) is now well established[1-4] for nuclei with $A > 32$. A systematic study with 96- and 115-MeV inelastic α scattering has revealed its properties in many nuclei. For nuclei lighter than $A \sim 32$, however, clustering of the $E2$ strength into a single, structureless peak was not observed.[5] In fact, no significant grouping of $E2$ strength was identified in the data taken at $E_\alpha = 96$ MeV, although Lewis and Bertrand[2] had earlier suggested the presence of a GQR in ^{27}Al. Recently, in work at Jülich[6] utilizing a higher-energy α particle beam ($E_\alpha \sim 150$ MeV), a significant fraction of the $E2$ strength in ^{16}O has been located in a multipeaked group between 16–25 MeV. Preliminary results on ^{20}Ne and ^{28}Si at the higher energy[7] have also suggested the presence of a GQR somewhat like that in calcium. Investigations utilizing inelastic proton scattering at Oak Ridge[2,8] and Orsay[3] have revealed considerable structure in the giant-resonance region for ^{27}Al and ^{28}Si and a portion has been attributed to $E2$ strength although there is some ambiguity in removing contributions of the giant dipole resonance (GDR). On the basis of inelastic deuteron scattering data Chang *et al.*[9] have suggested that considerable $E2$ strength exists between 15–25 MeV in ^{24}Mg and ^{27}Al. An α scattering experiment[10] on ^{24}Mg at 70 MeV located 36% of the $E2$ strength below $E_x \sim 16$ MeV, while above 16 MeV little structure was seen in the spectra.

We have investigated the giant-resonance region for the nuclei ^{24}Mg, ^{27}Al, and ^{28}Si utilizing inelastic α scattering at 126 MeV (30 MeV higher than our previous work on these nuclei). The $E2$ strength seen is compared with that seen in other reactions and the (apparent) energy dependence of its excitation is explored.

EXPERIMENTAL PROCEDURE

The experimental techniques used differed little from those previously described.[1] A 126-MeV α beam was used to bombard solid targets. The ^{24}Mg target was a rolled foil 2.0 mg/cm^2 thick enriched to > 95% in ^{24}Mg. The Al target was a commercially available, high-purity 6-μm Al foil. A 25-μm thick silicon wafer was obtained from ORTEC and served as the ^{28}Si target. Unfortunately, this wafer shattered after measurements were obtained at two angles. Two ΔE-E silicon detector telescopes with a constant angular separation of 5° were used to detect the inelastically scattered α particles. Surface barrier detectors 1 mm thick (ΔE) and Si(Li) detectors 5 mm thick permitted observation of outgoing α particles corresponding to a wide range of excitation ($E_x \lesssim 65$ MeV). Experimental tests necessary to assure that the spectra contained negligible spurious events were performed as described previously.[1]

EXPERIMENTAL RESULTS

Sample ^{24}Mg, ^{27}Al, and ^{28}Si spectra are shown in Fig. 1. In contrast to the data taken[5] at 96 MeV, a prominent clustering of events is apparent above the continuum at ~ 20 MeV with a width of ~ 7.6 MeV in ^{27}Al, and considerable structure is apparent in ^{28}Si in the same region of excitation. The ^{24}Mg spectra show two "clusters" of levels, one between 15.8 and 20.6 MeV and a second from 20.6 to ~ 28 MeV. In order to obtain angular distributions, the nuclear continuum was separated from the peaks utilizing much the same criteria discussed in Ref. 1. The "backgrounds" chosen are indicated by the dashed lines on the spectra. Angular distributions obtained for the 20-MeV group in ^{27}Al and the clusters of states in ^{24}Mg

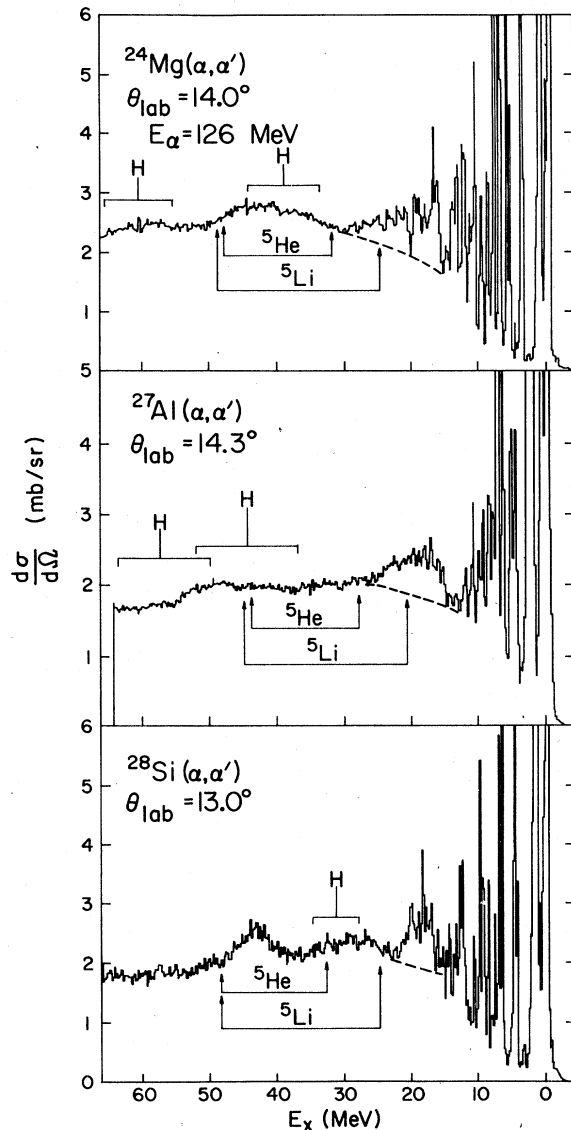FIG. 1. Inelastic α spectra from ^{24}Mg, ^{27}Al, and ^{28}Si taken at 126 MeV. The dashed lines indicate the background chosen for analysis. The regions where H(α, α)H and breakup α particles from ^{5}He and ^{5}Li would appear in the spectra are indicated.

$L = 2$ strength. The cluster of states from 15.8 to 20.6 MeV was fitted after subtraction of background using a multiple Gaussian peak fitting program. Consistent fits at all of the angles taken could be obtained assuming there were 10 peaks in this region with natural widths of ~240 keV below and ~280 keV above 19 MeV. The uncertainties inherent in this procedure are quite large as the assumption of similar widths for all of the states is dubious, the background is large, and the statistics are not really satisfactory. Nonetheless, angular distributions obtained for four of the peaks are indicative of $L = 2$ transfer, while the
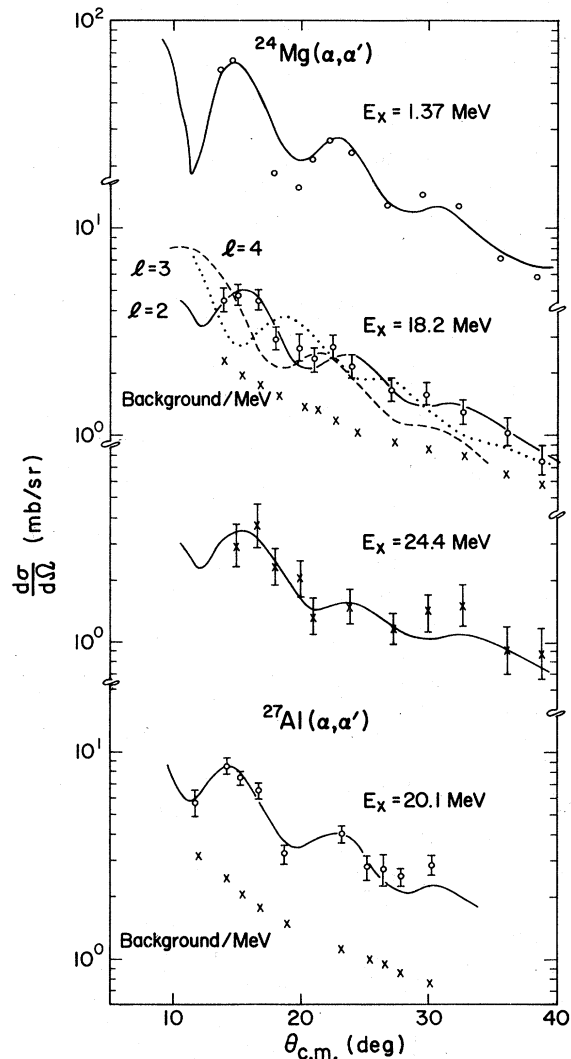

FIG. 2. Angular distributions obtained for the 1.37-MeV state, the 18.2- and 24.4-MeV groups of ^{24}Mg, and the 20.1-MeV group in ^{27}Al. Also shown is the background/MeV. The curves are DWBA calculations for the L transfer indicated.

are shown in Fig. 2. Also shown are distorted-wave Born approximation (DWBA) predictions obtained as described in Ref. 1, using the parameters shown in Table I. The agreement with the L = 2 calculation is quite good for ^{27}Al, suggesting that most of the strength in this group should be attributed to $E2$ strength. For both groups of levels in ^{24}Mg an $L = 2$ prediction [representing 26% of the $E2$ energy-weighted sum rule (EWSR)] fits the data considerably better than the $L = 3$ or 4 calculations, indicating the presence of significant

TABLE I. Optical-model parameters used in the DWBA calculations (in MeV fm).

Nucleus	E	V	W	r_R	a_R	r_i	a_i
^{24}Mg	126	171.1	30.1	1.25	0.70	1.47	0.82
^{27}Al	126	182.7	37.1	1.22	0.69	1.38	0.68

TABLE II. Parameters obtained from inelastic α scattering. Both isoscalar (IS) and electromagnetic (EM) EWSR strengths [A. M. Bernstein, Advan. Nucl. Phys. 3, 325 (1969)] are given for the first-excited states. $\Gamma = \Gamma_{\mathrm{rms}} \times 2.35$.

Nucleus	E_x (MeV)	Γ (MeV)	$\beta^2 R^2$	S (IS) (%)	S (EM) (%)
^{24}Mg	1.37		3.09	10 ± 2	12 ± 1
	18.2 ± 0.3	3	0.51	26	
	~24.4	5.5	0.51	~26	
^{27}Al	20.1 ± 0.3	7.6 ± 0.3	0.55	34	
^{28}Si	1.78		1.85	10	9.2 ± 0.9
	~19.4	4	~0.38	~25	

other six yield nondescript angular distributions. The four $L = 2$ states ($E_x = 16.60$, 16.99, 17.40, and 18.20 MeV) contain about half of the strength in the group at the $L = 2$ maximum, or about 12% of the $E2$ EWSR. The remaining groups ($E_x = 17.86$, 18.67, 19.13, 19.51, 19.87, and 20.23 MeV) might still contain significant $L = 2$ strength, however, it is clear that not all of the yield above the background shown in Fig. 1 is attributable to $L = 2$. Such an analysis was not practical for the higher group, due in part to insufficient statistical accuracy, but it is likely that a significant portion of the strength in this region is also not quadrupole.

The parameters obtained for the groups in the three nuclei are given in Table II. In ^{28}Si data were obtained at two angles only, hence no assignment can be inferred. However, an $E2$ EWSR estimate was obtained by normalizing the two points to DWBA calculations for comparison with other work. Data were also obtained for the 1.37-MeV 2^+ state in ^{24}Mg and the angular distribution and DWBA fit for this state are shown in Fig. 2. The fit is adequate, and the sum-rule fraction extracted is in agreement with that obtained by Yang et al.[10] at 70-MeV bombarding energy. The two points obtained for the 1.78-MeV 2^+ state in ^{28}Si when normalized to the DWBA calculation result in a sum-rule fraction in good agreement with the electromagnetic value.

DISCUSSION

With the 126-MeV α beam, a GQR peak in ^{27}Al containing 35% of the $E2$ EWSR is very clear in the spectrum, but at 96 MeV, although some enhancement was seen in the giant-resonance region (Fig. 6, Ref. 1), this peak was not apparent. This can be understood if the bombarding energy dependence of the GQR and the continuum in the vicinity of the GQR are explored. The DWBA cross sections at the second maximum in the angular distribution of $L = 2$ states located at $E_x = 1.37$ MeV and $E_x = 18$ MeV in ^{24}Mg are plotted as a function of bombarding energy in Fig. 3. The calculations were performed with optical parameters from the literature[11] appropriate to the bombarding energy, and with the 126-MeV parameters given in Table I; however, the results are qualitatively independent of the choice of parameters. The cross sec-

tion for the 18-MeV state increases dramatically as the bombarding energy increases, and is about twice as high at 126 MeV as at 96 MeV, whereas a much smaller increase is predicted for the 1.37-MeV state. At the same angles, the nuclear continuum remains about the same. Thus the ratio of GQR to continuum yield increases considerably as the energy increases.

Of particular importance at smaller angles ($\theta_{\mathrm{lab}} \lesssim 15°$) are the broad peaks in the spectra due
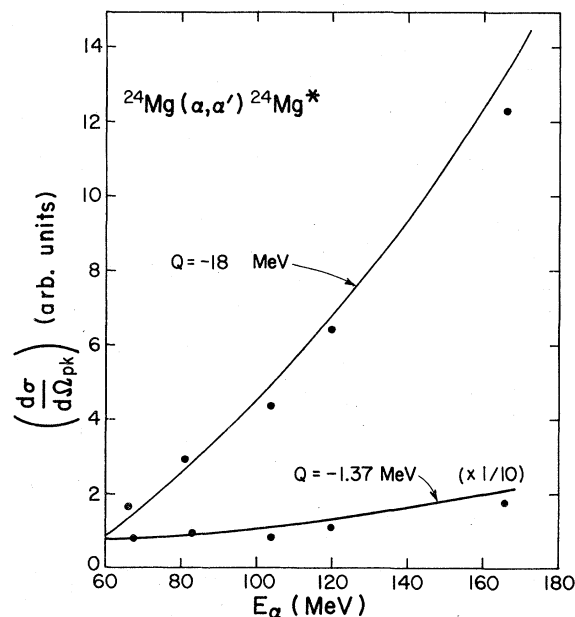

FIG. 3. The solid lines are the calculated cross section at the second maximum in the $L = 2$ angular distribution for ^{24}Mg(α, α') at $E_x = 1.37$ and 18 MeV using the optical parameters of Table I plotted as a function of bombarding energy. The circles are cross sections calculated using optical potentials from the literature (Ref. 11). These have been divided by r_R^2 to normalize to a constant sum-rule fraction.

to α particles from breakup of unstable ^{5}He and ^{5}Li formed in pickup reactions. These processes have been shown[1,12] to contribute a significant portion of the yield in the region just above the GQR in heavier nuclei, and the contributions from this process are apparent in the spectra at both 96 and 126 MeV. At 96 MeV the higher α energy "bump" due to the ^{5}He breakup is immediately adjacent to the GQR peak, while the bump from ^{5}Li is essentially at the GQR position. In the 126-MeV data, the ^{5}He and ^{5}Li bumps have moved in the spectrum relative to the GQR peak due to the increased energy carried off by the unobserved n (or p). The increased GQR yield, almost constant continuum yield, and the shift in the ^{5}He and ^{5}Li positions combine to make the GQR peak much more apparent at 126 MeV. When the GQR peak observed at 126 MeV is substracted from the 96-MeV spectrum after scaling by the cross-section ratio predicted by DWBA, a reasonable shape for the upper edge of the ^{5}He breakup peak is obtained. Thus the 96-MeV results are consistent with the 126-MeV data, even though a rather special background shape must be picked. The S/Γ ratio of 4.6%/MeV observed in ^{27}Al at 126 MeV is somewhat higher than the ~3.5%/MeV limit (established for a Gaussian peak shape) inferred[5] from the 96-MeV data. The suggestion (from Fig. 3) that further increases in bombarding energy would produce a still clearer separation of the GQR peak and the continuum is borne out by work from Jülich[13] at 145 and 172 MeV, reported while this manuscript was being prepared.

Now that there is some understanding why this peak in ^{27}Al was not identified at 96 MeV, it is fruitful to compare with other work. In inelastic proton scattering at Oak Ridge[8] (61 MeV) and at Orsay[3] (155 MeV) a peak was identified at about 20 MeV with[8] 30±10% of the $E2$ EWSR. From 70-MeV inelastic deuteron scattering data Chang et al.[9] obtain $E_x = 21$ MeV, $\Gamma = 8 \pm 1$ MeV, and 46±15% of the $E2$ EWSR for the GQR peak, while from 145- and 172-MeV α scattering data Kiss et al.[13] obtain $E_x = 18.6$ MeV, $\Gamma = 7.6$ MeV width, and an $E2$ EWSR depletion estimated to be between 40–70%. A careful comparison of the spectra reveals that essentially the same fine structure is seen with the different reactions. The somewhat higher excitation energy obtained in our work compared with that done at higher α energy appears to be due to greater yield in the peak above 20 MeV. This might be due to the inclusion of some of the ^{5}Li breakup peak in the GQR yield or a difference in continuum shapes at the different energies.

For ^{24}Mg approximately 36–42% of the $E2$ EWSR strength has been identified[10,14] below E_x

~16 MeV. Between 16–28 MeV our analysis of the gross structure would yield 52% of the $E2$ EWSR if all of the strength above the continuum in this region were attributed to the GQR. This is in agreement with the recent Jülich[13] estimate of 40–70% for this region. Our analysis of the individual peaks, however, suggests the actual number may be somewhat less, possibly on the order of 25–30% over this region, but a careful analysis of good statistics, high-resolution data
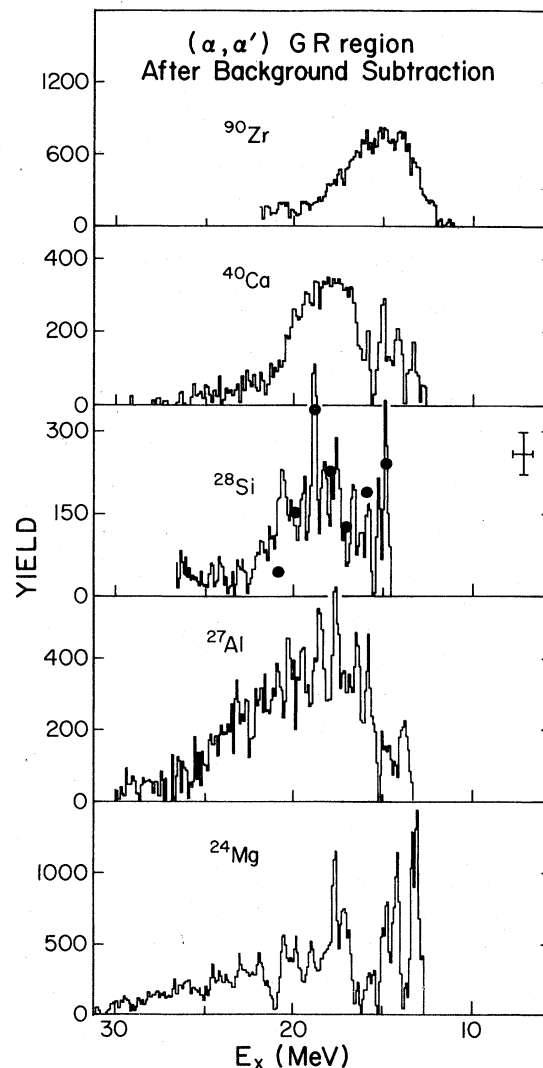

FIG. 4. The spectra in the giant-resonance region after background subtraction are shown for ^{90}Zr, ^{40}Ca (both at $E_\alpha = 96$ MeV from Ref. 1), and for ^{28}Si, ^{27}Al, and ^{24}Mg. The closed circles represent the $E2$ strength seen in ^{28}Si with the ^{24}Mg(α, γ) reaction (Ref. 14), arbitrarily normalized to the (α, α'). These points are averages over 1-MeV wide bins; the uncertainties are indicated by the error bar in the upper right corner of the ^{28}Si spectrum.

will be necessary to accurately determine the $E2$ strength in this region.

Structure similar to the low-energy group is apparent in the ^{24}Mg(p,p') spectrum from Oak Ridge[8]; however the presence of the upper group is not obvious. Chang et al.[9] utilizing inelastic deuteron scattering extract a "resonance-like structure peaked at $E_x \sim 60/A^{1/3}$ MeV with a width of about 10 MeV" for ^{24}Mg. In the 70-MeV α data of Yang et al.,[10] the structure between 16 and 20 MeV was at best just discernible. This can be understood (for the α data) from the energy dependence of the cross section. In the region from 16–20 MeV after subtracting an interpolated background they find a residual yield, the angular distribution of which is fitted by an $L = 2$ calculation exhausting $\sim 30\%$ of the $E2$ EWSR.

Knöpfle et al.[7] investigated ^{28}Si utilizing 150-MeV inelastic α scattering and they have identified a GQR peak at 19.7 MeV with a width of 5.1 MeV exhausting $\sim 31\%$ of the $E2$ EWSR. They did have to use an abnormal background to get a good $L = 2$ shape for the angular distribution and conclude that other multipolarities also contribute in the giant-resonance (GR) region. Our ^{28}Si spectra have much better resolution (~ 210 keV full width at half maximum compared with ~ 350 keV) and what appears as a slightly structured bump in the 150-MeV data shows up as at least five peaks in our data. Similar structure is seen in the ^{28}Si(p,p') data from Oak Ridge National Laboratory,[8] however, the possible presence of dipole excitation complicates the analysis. The $E2$ strength distribution above 15 MeV in ^{28}Si observed in the ^{24}Mg(α,γ) reaction[14] is in agreement with our (α,α') results as may be seen in Fig. 4. Above $E_x \sim 15$ MeV, $\sim 10\%$ of the $E2$ EWSR strength has been located with the (α,γ) reaction[14] while 32–40 % was observed[15] below 15 MeV. If the states above 15 MeV on the average have $\Gamma_{\alpha_0}/\Gamma \sim \frac{1}{3} - \frac{1}{2}$ then the total strength observed would agree with (α,α'). It is also possible that Γ_{α_0}/Γ may be quite different for the different components of the peak. For example, a recent study[16] of the α decay of the GQR in ^{40}Ca revealed that although a 2^+ state at $E_x \sim 14$ MeV decays almost exclusively through the α_0 channel, the group containing the major portion of the $E2$ strength (located at 18 MeV) has at most a small α_0 decay branch. Thus differences between the (α,α') and (α,γ) results are likely a measure of the relative α_0 branches.

CONCLUSIONS

Considerable $E2$ strength has been located at high excitation in ^{27}Al, ^{24}Mg, and ^{28}Si with 126-MeV inelastic α scattering, and the results are in reasonable agreement with those from other inelastic scattering experiments. This strength could not be reliably identified at $E_\alpha = 96$ MeV due primarily to the considerably smaller $E2$ cross section relative to the continuum. A comparison of the spectra in the giant resonance region after background subtraction with those for ^{90}Zr and ^{40}Ca is shown in Fig. 4. There is considerably more structure in ^{28}Si, ^{27}Al, and ^{24}Mg than in the heavier nuclei. Analysis of the individual peaks seen in the giant resonance region in the ^{24}Mg (α,α') data leads to the conclusion that not all of the strength seen in this region is quadrupole; in fact for the cluster of states analyzed only about half of the strength was in individual peaks which could reasonably be identified as quadrupole.

Utilizing inelastic α scattering where only the isoscalar modes are excited, $E2$ strength has now been located[6,7,12] in ^{28}Si, ^{20,22}Ne, ^{16}O, ^{27}Al, and ^{24}Mg. In heavier nuclei most of the $E2$ EWSR (~ 80–100% for $A > 100$) is located[1] in a collective peak of several MeV width with little fine structure when observed with a resolution of ~ 150 keV or greater, while in light nuclei ($16 \geqslant A \geqslant 32$) the strength is considerably more fragmented with 25–40 % distributed among levels below $E_x \approx 15$ MeV and a comparable amount located in the GR region (15–25 MeV). As is the case for the GDR, the $E2$ strength in the giant-resonance region for light nuclei is not generally in one strong coherent state, but is spread over several groups, exhibiting a qualitatively different structure from the GQR in heavier nuclei.

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