Isoscalar Giant Resonance in Light Nuclei ($A \leqslant 40$)*

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The giant-resonance region was studied for ^{40}Ca, ^{40}Ar, ^{36}Ar, ^{32}S, ^{28}Si, ^{27}Al, ^{20}Ne, and ^{16}O by inelastic scattering of 96.6-MeV α particles. A systematic broadening of the isoscalar giant resonance at $E_{exc} \simeq 63/A^{1/3}$ MeV occurs as A decreases. The width for ^{40}Ca is 3.5 ± 0.3 MeV, for ^{32}S it is 7.1 ± 0.5 MeV, and for nuclei below $A = 32$ the resonance is too diffuse to be observed.

Evidence from the scattering of electrons,[1] protons,[2] and helium ions[3-5] indicates the existence of a systematically occurring state with $J^\pi = 2^+$ or 0^+ at an excitation energy of about $63/A^{1/3}$ MeV in nuclei ranging from ^{40}Ca to ^{238}U. Model calculations predict a concentration of $E2$ strength in this region. If, as is commonly assumed, this state has $J^\pi = 2^+$ (in even-even nuclei) then it contains 30–100% of the isoscalar $E2$ energy-weighted-sum-rule (EWSR) strength. Since this strength is concentrated in a region 3 to 6 MeV wide it has been referred to as the giant quadrupole reso-

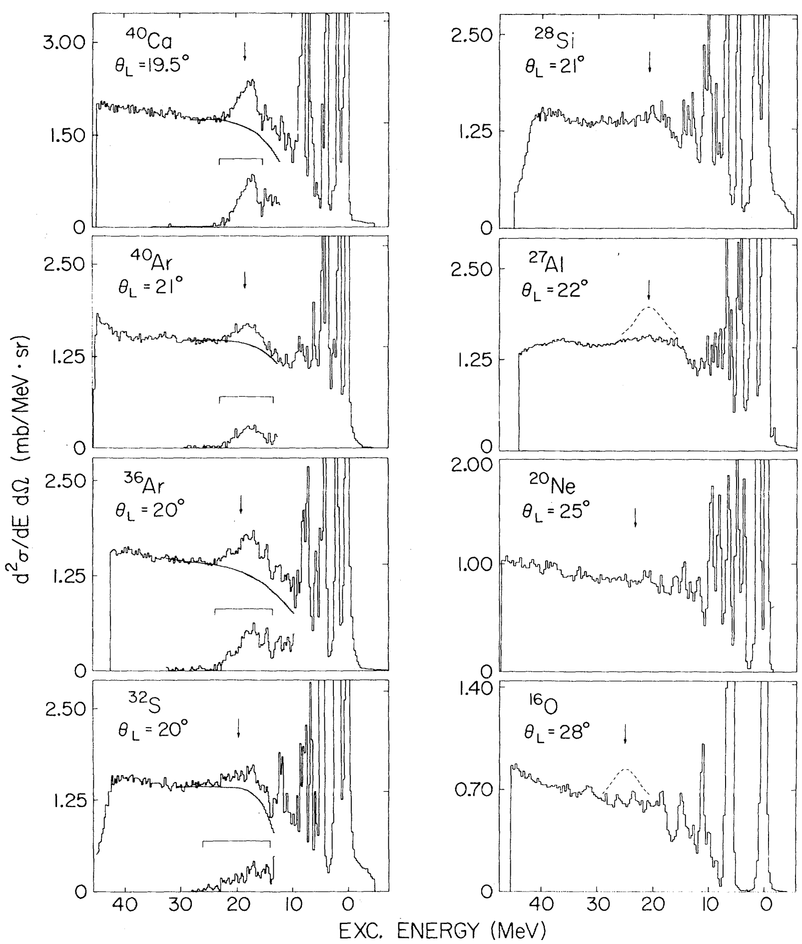

FIG. 1. Spectra from the (α, α') reaction at $E_\alpha = 96.6$ MeV, at angles near the expected maximum for $L = 2$ angular distributions. The smooth curves are backgrounds as described in the text. The GQR's with background subtracted are shown at the bottom of the spectra for selected nuclei. The arrows are located at $63/A^{1/3}$ MeV. The dashed peaks in ^{27}Al and ^{16}O are hypothetical GQR's which have $\Gamma = 6$ MeV and exhaust 25% of the EWSR.

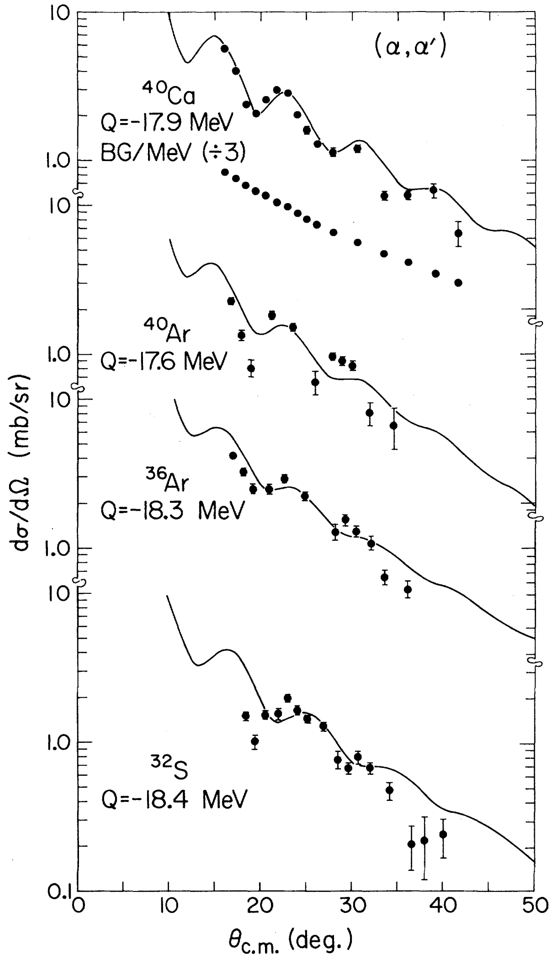

FIG. 2. Angular distributions for (α, α') reactions exciting the GQR. The error bars are statistical. The DWBA calculations are normalized to the data. Also shown is the background per MeV underlying the GQR in ^{40}Ca.

nance (GQR) in analogy to the giant dipole resonance (GDR). The existence of a well-defined GQR for $A > 40$ is in apparent contradiction with radiative-capture experiments for $A < 40$. Although substantial $E2$ strength is seen in the (α, γ) reaction leading to ^{16}O,[6] ^{24}Mg,[7] ^{28}Si, ^{30}Si,[8] ^{32}S,[9] and ^{40}Ca,[10] it is rather uniformly distributed over a broad energy range. Similarly, radiative capture of polarized protons which yields $E2$ strengths for (γ, p_0) shows no gross structure of width 3 to 6 MeV for ^{16}O[11] and ^{32}S.[12]

In order to determine if any real discrepancy exists between the $E2$ strength seen in radiative capture and inelastic scattering experiments (assuming $J^\pi = 2^+$) we have surveyed the mass region from $A = 16$ to $A = 40$ using the (α, α') reaction. Other projectiles have previously been used to study this region.[2,3] However the results are ambiguous because of the excitation of the GDR, which occurs in the same energy region as the GQR. α particles possess the distinct advantage, with respect to protons, ^{3}He nuclei, and electrons, in that they excite only $\Delta T = 0$ states. Thus in self-conjugate nuclei excitation of the GDR is isospin forbidden. Although in non-self-cojugate nuclei the $T_<$ component of the GDR could conceivably be excited by isoscalar projectiles, it has been shown[5] that such excitation, if it occurs, must be very small.

A beam of 96.6-MeV α particles provided by the Texas A & M cyclotron was used to bombard gas targets of ^{40}Ar, ^{36}Ar, ^{32}S (H_2S), ^{28}Si (SiH_4), ^{20}Ne, and ^{16}O (O_2). The gas cell was a cylinder 8.9 cm in diameter and 2.54 cm high, and was covered with a 0.0001-in. Havar foil. Two $\Delta E + E$ silicon detector telescopes collimated in the conventional fashion viewed the target cell. In order to evaluate the effect of slit scattering, spectra from the reaction ^{4}He$(\alpha, \alpha')^4$He were recorded at forward angles. On the basis of the number of counts observed in the region below 20-MeV excitation energy (which contains no states) it was concluded that slit scattering contributed negligibly to the present data. α spectra were also obtained for solid targets of ^{27}Al and ^{40}Ca. Spectra from all targets are shown in Fig. 1.

It is immediately apparent that there is a transition from a well-defined giant resonance in the heavier nuclei to a flat continuum containing many small peaks in ^{20}Ne and ^{16}O. To be quantitative in assessing this trend we must make some assumptions. First we shall assume that the giant resonance seen in ^{40}Ca and numerous heavy nuclei is $E2$ and that the usual collective-model distorted-wave Born-approximation (DWBA) treatment of the (α, α') reaction may be used to extract $E2$ EWSR strengths. Second, we assume that the continuum background underlying the giant resonance is not coherent with the peak itself and may be simply subtracted. Since there is no adequate theory describing this continuum we must rely on interpolation from regions where no peak exists. In choosing the background we rely on the fact established in Ref. 5 that the (α, α') reaction to the GQR exhibits a diffractionlike structure whereas the background decreases monotonically with angle. This can also be seen in Fig. 2. The shape of the background was determined by a power-series fit to the spectrum above and below the GQR at angles where the l

TABLE I. Excitation energies, widths (full width at half-maximum), and EWSR strengths for GQR's obtained from inelastic α scattering. Also listed are EWSR strengths from radiative-capture experiments.

Nucleus	Exc. energy (MeV)	Γ (MeV)	S (%)	$S_{\text{rad cap}}$ (%)
^{40}Ca	17.9	3.5 ± 0.3	44 ± 10	19[a]
^{40}Ar	17.6	4.7 ± 0.3	29 ± 10	
^{36}Ar	18.3	5.6 ± 0.3	49 ± 15	
^{32}S	18.4	7.1 ± 0.5	32 ± 15	20[b], 35[c]

[a]Ref. 10. $E2$ strength in the α_0 channel from 13 to 19 MeV.

[b]Ref. 12. $E2$ strength in the α_0 channel from 12 to 20 MeV.

[c]Ref. 12. $E2$ strength in the p_0 channel from 12 to 20 MeV.

$=2$ contribution is at a minimum. This function was then renormalized at an excitation energy above the GQR to determine the background at other angles. This procedure is based on the assumption that the shape of the background does not vary much with angle, which seems to be justified experimentally.

The spectra with background subtracted are shown in Fig. 1. In analyzing the multipole strength we consider only the area in brackets. The results of the analysis are given in Tables I and II and Fig. 2. The sum-rule fraction for a state with energy E_i defined in terms of a uniform matter distribution is

$$S = (\beta R)_{\exp}{}^2/(\beta R)_i{}^2,$$

with $(\beta R)_i{}^2 = l(2l+1)(\hbar/2m)4\pi/3AE_i$ and $\beta_{\exp} = d\sigma(\theta)_{\exp}/d\sigma(\theta)_{\text{DWBA}}$. In order to assess the accuracy of the correspondence between transition strengths derived from (α,α') and those obtained from electromagnetic measurements we also list $B(E2)$ values in Weisskopf units for several of the low-lying 2^+ states. These are evaluated in the manner described by Bernstein.[14] The errors given for S and $B(E2)$ include the estimated uncertainty in choosing the background and in the DWBA normalization. The widths are rms deviations from the centroids multiplied by 2.35 and are thus comparable to the full width at half-maximum of a Gaussian or Lorentzian function. The errors on the widths are rms deviations from the mean of at least eight different angles and do not include uncertainties in the choice of background.

The widths from Table I support the visual observation that a transition occurs between ^{36}Ar and ^{28}Si from a well-defined GQR to a more uniform distribution of quadrupole strength. For the nuclei lighter than ^{32}S the quadrupole strength in the continuum is too diffuse to be seen, hence the present experiment yields only an upper limit. This limit is obtained by estimating the minimum strength which would be clearly observable in ^{27}Al and ^{16}O (see Fig. 1). Assuming a Gaussian peak the limit is $S/\Gamma \sim 3.5\%$ per MeV (peak strength $\sim 6.5\%$ per MeV). Any $E2$ strength which is more diffuse than this would not be detectable. Radiative-capture experiments on nuclei below ^{32}S invariably yield uniform $E2$ strength distributions with strengths on the order of 1% per MeV. Thus there is no discrepancy between these experiments and the present results.

Comparison of the absolute $E2$ strengths of Table I with those from radiative capture is not straightforward. Radiative capture measures the $E2$ strength in only the α_0 or p_0 channel whereas the total strength (model dependent) is measured in the present work. Additionally the polarized-proton-capture experiments could have

TABLE II. Optical-model parameters used in the DWBA calculations. Also given are deformation lengths (βR) and $B(E2)$ values for the GQR's and low-lying 2^+ states derived from the DWBA fits.

Nucleus	Exc. energy (MeV)	Optical model parameters: V (MeV)	W (MeV)	r_0 (fm)	a (fm)	βR (fm)	$\beta(E2)$ values (Weisskopf units): Present work	Other values
^{40}Ca	17.9	121.9	62.7	1.35	0.70	0.73	5.8 ± 1.3	4.6[a]
^{40}Ar	1.46	120	68.6	1.20	0.85	0.87	6.7 ± 2.0	12.5 ± 3[b]
	17.6					0.60	3.2 ± 1.1	
^{36}Ar	1.97	104.4	56.5	1.24	0.85	0.88	7.5 ± 2.0	9.4 ± 1.0[b]
	18.3					0.80	6.3 ± 1.9	
^{32}S	2.24	75.2	46.8	1.36	0.76	1.16	11.5 ± 2.0	8.8 ± 1.5[b]
	18.4					0.68	4.0 ± 1.9	

[a]Ref. 4 derived from (α, α').

[b]Ref. 13 derived from electromagnetic measurements.

contributions from $T=1$ $E2$ strength which is not seen in (α,α'). With these limitations in mind it is not hard to reconcile the $E2$ strengths from (α,α') with those from radiative capture leading to ^{32}S and ^{40}Ca (see Table I). No peaking of $E2$ strength was seen in the reactions ^{28}Si$(\alpha,\gamma)^{32}$S or ^{31}P$(p,\gamma)^{32}$S.[9,12] This is quite consistent with our observation of a very broad GQR in ^{32}S. The $E2$ strength seen in the reaction ^{36}Ar$(\alpha,\gamma)^{40}$Ca has been found by Branford[10] to be consistent with the existence of a GQR, in spite of the fact that the (α,γ) excitation function does not exhibit the expected resonance structure. It should be noted however that the (α,γ) excitation function to the giant dipole resonance in ^{40}Ca likewise does not bear much resemblance to the Lorentzian peak seen in γ-ray absorbtion experiments.[15] Quadrupole-strength information from the reaction[16] ^{39}K$(p,\gamma)^{40}$Ca is not sufficiently precise to confirm or contradict the present (α,α') data.

We conclude that there is a striking transition in the character of the peak at $63/A^{1/3}$ MeV in the s-d shell nuclei. Assuming $J^{\pi}=2^{+}$, in ^{40}Ca 44% of the $E2$ EWSR is found in a peak of width $\Gamma=3.5$ MeV. In ^{32}S, 32% is found over a region of width $\Gamma=7.1$ MeV. A high-resolution study of the reaction[17] ^{24}Mg(α,α') shows no evidence of a GQR but does indicate considerable $E2$ strength ($S=40\%$) in discrete states below 18 MeV. The isoscalar $E2$ strength in ^{16}O, which has been located in radiative-capture and electron-scattering experiments,[6,11,18] is very fragmented with a width of 15 MeV. This behavior is significantly different from that of the GDR where the corresponding widths for ^{40}Ca and ^{16}O are 4.2 and 6.3 MeV.[15] It is important to know if the dispersion of $E2$ strength as A decreases can be understood in terms of existing theories.

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