EXPERIMENTAL DETERMINATION OF MONOPOLE STRENGTH IN ^{40}Ca BETWEEN 10 AND 20 MeV EXCITATION ENERGY

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The distribution of isoscalar monopole strength in ^{40}Ca was determined from singles ^{40}Ca(α, α') and from coincident ^{40}Ca($\alpha, \alpha'\alpha_0$) data at E_α = 120 MeV and scattering angles from 0° to 3°. Between 10.5 and 15.7 MeV excitation energy (23 ± 5)% of the E0 EWSR was located from the singles and from the coincidence measurements independently, while (30 ± 6)% of the E0 EWSR was found in the interval 10.5–20 MeV from the singles data only.

The existence of an isoscalar giant monopole resonance (GMR) has been well established for nuclei with mass $A > 60$ [1–7]. However, for nuclei with $A < 60$ no compact resonance exhausting an appreciable fraction of the E0 energy weighted sum rule (EWSR) has yet been found. The reason for this could be twofold. In the first place it is known that in light nuclei ($A < 40$) the isoscalar quadrupole resonance is strongly fragmented and spread out over a large energy interval [7]. It is quite reasonable to assume that the same happens to the monopole (and other multipole $2\hbar\omega$) strength. Secondly, there are theoretical arguments [8] that the phenomenological relation between the monopole excitation energy E_x(GMR) and the mass number A, $E_x(\mathrm{GMR}) = 80 \times A^{-1/3}$ MeV, is too simple for light nuclei and that additional terms, for instance due to surface effects, have to be included. The effect of these additional terms is that the effective excitation energy E_x(GMR) is lower than predicted by the simple relation given above. In fact it has been suggested by Buenerd [4] that for nuclei with $A \simeq 60$ the isoscalar monopole strength coincides in excitation energy with the isoscalar quadrupole strength, located at approximately $E_x(\mathrm{GQR}) = 65 \times A^{-1/3}$ [7] and that for still lighter nuclei one has $E_x(\mathrm{GMR}) < E_x(\mathrm{GQR})$. Thus one is faced with the possibility that for light nuclei with $A \leqslant 40$ the isoscalar monopole strength and quadrupole strength both are strongly fragmented and intermingled. Thus the fact that in these nuclei no appreciable amount of monopole strength has yet been found might well be due to the experimental problem of locating pieces of monopole strength amidst fragmented strength of other multipolarities, especially quadrupole strength.

The present experiment was especially designed to locate such fragmented monopole strength in the giant quadrupole region of ^{40}Ca, that is between 10 and 20 MeV excitation energy. The nucleus ^{40}Ca is interesting for two reasons. In the first place previous RPA calculations [8,9] predict that there should be a compact monopole resonance located somewhere between 20 and 25 MeV excitation, while a more recent calculation in the framework of the selfconsistent continuum RPA predicts that the monopole strength in ^{40}Ca should be fragmented [10]. The other reason is that nearly all experiments [1,6,11–17] on ^{40}Ca, largely stimulated by the prediction that considerable monopole strength should be present around E_x = 21 MeV [18], failed to locate an appreciable amount of such strength. In fact, all that is definitely known is that around E_x = 14 MeV about 6% of the E0 EWSR is present, while there is some evidence for about 8% of

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the E0 EWSR in the region between 16 and 20 MeV excitation energy [1,6].

We have used two independent methods to determine monopole strength, both of which have been used previously, but only separately or at least not independently as in the present experiment: singles measurements and coincidences with α-decay to the 0^+ ground state of the residual nucleus ^{36}Ar at very forward scattering angles. For the coincidence measurements this has the advantage that in this way the E0 strength is relatively very strongly excited compared to strength of other multipolarities. In the singles experiment the typical behaviour of the E0 angular distribution as compared to other multipolarities has been used. As will be clear from fig. 1, the main difference between a spectrum obtained from inelastic α-particle scattering for angles between 0° and 1.5° and one taken for angles between 1.5° and 3° is due to E0 excitation. Thus by comparing such spectra, properly normalized, one can directly determine excitation energy and strength of monopole excitations.

In the coincidence measurements the angular correlation of α-decay of multipolarity l to the 0^+ ground state of the residual nucleus is to good approximation

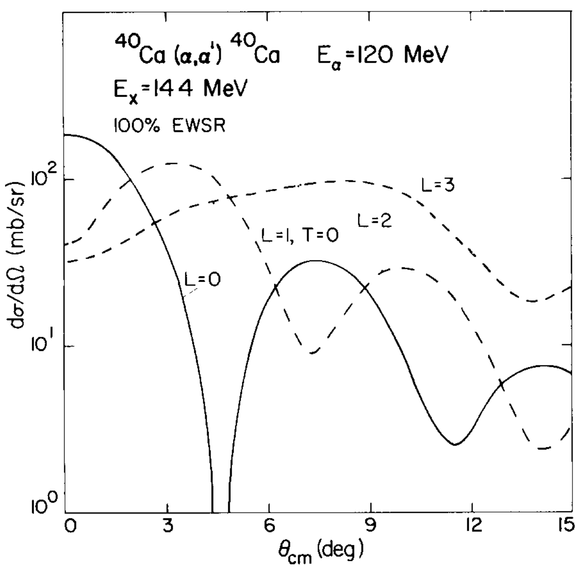

Fig. 1. DWBA predictions of the differential cross sections for the ^{40}Ca(α, α') reaction at E_α = 120 MeV for various isoscalar electric multipoles. The calculations have been normalized to 100% of the appropriate energy weighted sum rule (EWSR) at an excitation energy of 14.4 MeV in ^{40}Ca.

given by the Legendre polynomial $|P_l(\cos\theta)|^2$. Thus the angular correlation for strength of multipolarity $l \neq 0$ is peaked around the recoil direction of the decaying nucleus, to be compared with the isotropic angular correlation for E0 strength.

The momentum analyzed 120 MeV α-particle beam of the KVI cyclotron was used to bombard a 750 μg/cm^2 metallic Ca target, which was nearly free of carbon and oxygen contaminants. The inelastically scattered α-particles were detected with the QMG/2 magnetic spectrograph [19] at 0°, using the full 10.3 msr solid angle, which corresponds to an opening angle of 6°. The beam was stopped in the focal plane of the spectrograph in a movable Faraday cup adjacent to the detection system. The setup was such that the detector covered the excitation energy range between 10.5 and 20 MeV. Since the detection system [20] determines both the horizontal and vertical angles of incidence of the particle, the scattering angle can be reconstructed. It is therefore possible to eliminate spurious events due to slit scattering and to construct spectra for different scattering angle intervals. In the present case two intervals were used. θ = 0°–1.5° ("small" angles) and θ = 1.5°–3.0° ("large" angles). The energy resolution in the experiment was 60 keV, similar to the width expected for E0 fragments on the basis of the observed behaviour of the quadrupole strength. The charged particles originating from the decay of the excited ^{40}Ca nuclei were detected in coincidence with the inelastically scattered projectile at various angles using solid state particle telescopes, consisting of a 13.6 μm ΔE, a 2 mm E and a 2 mm veto detector.

Figs. 2a–2d show the singles data obtained. In fig. 2a the spectrum for the full 10.3 msr solid angle is displayed. No background has been subtracted. In fig. 2b and 2c the properly normalized spectra for "small" and "large" scattering angle are given, while fig. 2d shows the spectrum resulting from subtraction of the spectra of fig. 2b and 2c. It is clear from fig. 1 that multipolarities other then E0, which have nearly flat angular distributions at the forward scattering angles involved, will be approximately canceled by this subtraction procedure, while the presence of isoscalar E1 strength would give rise to negative peaks. Fig. 2d shows that the GQR bump at E_x = 18 MeV which is known to exhaust (40–60)% of the E2 EWSR [12,21] vanishes in the subtraction as does the peak at E_x = 10.9 MeV, which has previously been reported to exhaust 5% of the E2 EWSR [21]. No negative peaks occur, indicating that no isoscalar E1 strength is present, in agreement with the results of refs. [12,17,21].

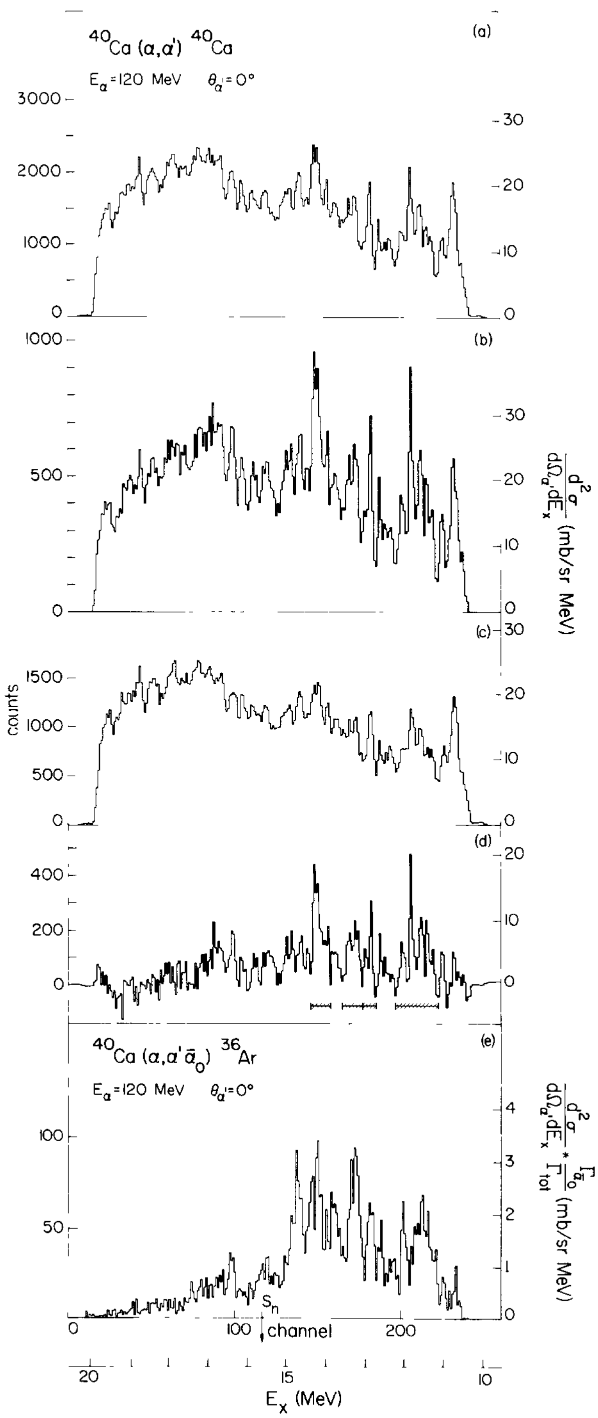

Fig. 2. (a) Singles α-particle spectrum at 0° for the full opening angle of the spectrograph (10.3 msr, $\theta < 3°$). (b) Same as in (a) but for the central part of the solid angle ("small" scattering angles, $\theta < 1.5°$). (c) Same as (a) but now for the remaining part of the solid angle ("large" scattering angles, $\theta > 1.5°$), obtained by subtracting the spectrum of fig. 2b from that of fig. 2a. (d) E0 strength distribution obtained by subtracting the spectrum of fig. 2c from that of fig. 2b with the proper normalization factor. (e) Alpha-particle spectrum at 0° in coincidence with decay to the 0^+ ground state of ^{36}Ar, averaged with the proper weighing factors over all angles for the decay α-particle.

At E_x = 14.2 MeV a clear structure with a width of about 300 keV is seen. According to our singles data it exhausts (5.4 ± 1.0)% of the E0 EWSR. If we assume that all the strength in the spectrum of fig. 2d is due to E0 excitation, the total fraction of the E0 EWSR exhausted in the excitation region between 10.5 and 20 MeV is (30.2 ± 6.0)%. The centroid of the strength distribution is located at E_x = 14.4 MeV. In calculating the sum rule strength the form factor version I of ref. [22] was used while the transition rates B(E0) were determined from the multipole moments of the real part of the optical potential [23].

The E0 strength was also determined from coincidence measurements with charged particles, specifically from the α_0 decay to the 0^+ gs of ^{36}Ar. Fig. 3 displays the angular correlation of this decay mode for the most prominent structures of the spectrum of fig. 2d. The fits shown are obtained with a coherent and incoherent addition of E0 and E2 amplitudes, respectively. No contributions from other multipolarities are needed to explain the observed angular correlations, in good agreement with the results of refs. [14] and [21]. For these measurements the full spectrograph solid angle was used. The angular correlation fits were made using m-state populations from DWBA calculations [24]. Experimental distortion of the angular correlations due to the finite opening angle for the inelastically scattered α-particle (±3°) was taken into account. The results of the present experiments are summarized in tabel 1. The total cross section σ_{tot} obtained from the fits to the α_0 angular correlations are nearly independent on whether a coherent or an incoherent addition of E0 and E2 amplitudes has been used, but the E0 fraction deduced is systematically larger for the coherent fit. However, since the E0 strength is dominating in the intervals under consideration, this does not have very large effects on the E0 strength observed.

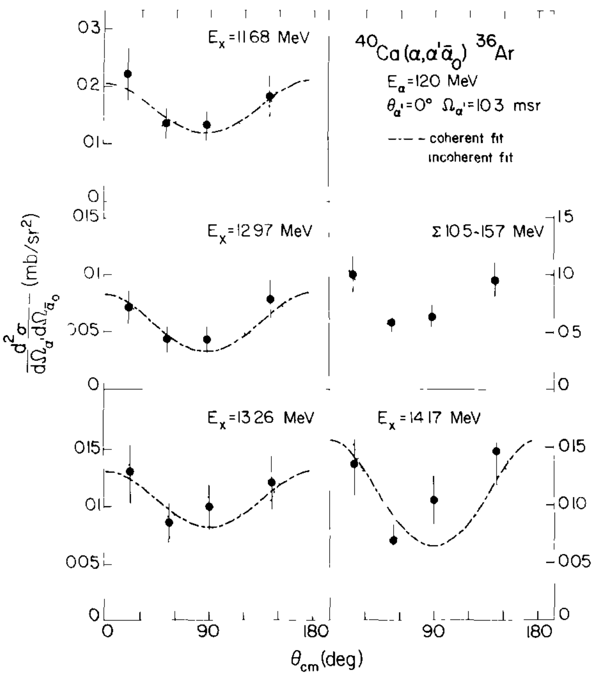

Fig. 3. Angular correlations of the decay to the 0^+ ground state of ^{36}Ar for a few of the most prominent structures in the spectrum of fig. 2d, together with fits with coherent (dot–dash line) and incoherent (dotted line) addition of E0 and E2 amplitudes. See text and table 1 for explanation and results.

The branching ratios $\Gamma(\mathrm{E0}, \alpha_0)/\Gamma_{tot}$ were determined from the experimentally determined branching ratios $\sigma(\alpha_0)/\sigma(\mathrm{coinc.})$, the ratio $\sigma(\mathrm{E0}, \alpha_0)/\sigma(\mathrm{E2}, \alpha_0)$ and the known branching ratios $\Gamma(\alpha_0, \mathrm{E2})/\Gamma_{tot}$ [17].

The large isotropic components observed in the angular correlations for the α_0 decay do not necessarily imply that E0 strength is present, since the decay of a continuum due to multistep excitation could show a similar angular correlation pattern. A substantial contribution from such processes can be excluded though on the basis of the following argument. If a substantial amount of such a continuum would be present, it would have to have a flat angular distribution over the interval 0°–3°, since the subtraction spectrum of fig. 2d does not show a continuum background. Thus its effect on the coincidence measurements which are taken over the full interval 0°–3° would be rather large in comparison with the very forward peaked E0 strength, since for such a flat distribution the contribution from the interval 1.5°–3° is about four times as large as for the interval 0°–1.5°. Yet, if we compare the E0 strength listed in table 1 we see that the results for the coincidences are approximately the same as or even somewhat smaller than those for the singles. Therefore the presence of multistep processes can be excluded. The same conclusion was reached in a similar coincidence experiment previously performed

Table 1
Comparison of the E0 strength found from singles and coincidences with α_0 decay.

E_x	Singles % E0 EWSR a)	Coincidences								Previous results
		σ_{tot} b) (mb/sr)		$\sigma(\mathrm{E0})/\sigma_{tot}$ b) (%)		$\Gamma(\mathrm{E0}, \alpha_0)/\Gamma_{tot}$ b) (%)		% E0 EWSR b)		% E0 EWSR
11.68	5.0	1 9	2.0	98	73	32	35	4.5	3.2	
12.97	1.7	0.6	0.7	95	77	38	40	1.3	1.1	
13.26	3.0	1.2	1.3	99	80	38	41	2.7	2.4	
14.17	5.4	1.2	1.3	79	70	29	26	3.7	3.1	6 +/– 3 c) 6 – 7 d)
sum	15.1							12.2	9.8	
10.5–15.7	23.5		8.7		70		30		22 4	15 e)
10.5–20	30.2									
15.7–20	6.7									8 f)

a) Errors are estimated to be 20% for the singles and 30% for the coincidences.
b) The first value on each row corresponds to the coherent fit, the second to the incoherent fit.
c) Ref. [16]. d) Ref. [12]. e) Ref. [17]. f) Refs. [1,6].

at a scattering angle of 12.5° instead of 0° as is the case for the present experiment In that experiment it was also found that for $E_x < 16$ MeV no continuum due to multistep processes is present [17].

The uncertainties in E0 EWSR fractions listed in table 1 are estimated to be around 20% for the singles and around 30% for the coincidence measurements. The results of the two independent determinations of the E0 strength are in good agreement. Also the agreement with the previously reported values is good: the structure at $E_x = 14.17$ MeV has been reported to exhaust (6 ± 3)% [16] and (6–7)% of the E0 EWSR [12], while the amount of E0 strength found between $E_x = 15.7$ MeV and 20 MeV is in agreement with the suggestions of refs. [1,6,17]. The good agreement between the various results and the consistency of the results from the present singles and coincidence measurements then leads to the conclusion that in ^{40}Ca approximately 30% of the E0 EWSR is located in the excitation region between 10.5 and 20 MeV. The E2 strength deduced from the coincidence data is somewhat lower, but still consistent with the strength reported in ref. [17], taking into account the rather large errors in the E2 strength deduced from the present data.

Thus we have located a substantial but still minor part of the total possible E0 strength, which indeed is strongly fragmented and intermingled with E2 strength. The amount of E0 EWSR located is in good agreement with the calculations of ref. [10]. From this it is reasonable to infer that the remaining E0 strength is located at higher excitation energies, as predicted in ref. [10]. If so, it would probably be even more fragmented which would make it even harder to locate. In this connection it should be pointed out that the very sensitive coincidence measurements described here do not work for $E_x > 16$ MeV since due to the competition of other decay channels $\Gamma(\alpha_0)/\Gamma_{tot}$ decreases strongly with increasing excitation energy. Also the method of comparing singles cross sections in different scattering angle intervals where one uses the typical shape of the E0 angular distribution loses it reliability in case of a very fragmented homogeneous strength distribution due to the errors inherent in such a procedure. Thus if the bulk of the E0 strength is present indeed above $E_x = 20$ MeV it will probably remain undetected at least with the present state of experimental technique. Finally it should be mentioned that it is possible that the calculation of the fraction of the E0 EWSR using the standard form factor as for instance given in ref. [22] cannot be used for such light nuclei as ^{40}Ca, so that the calculated strength of 30% would in fact correspond to a much larger E0 strength.

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