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Splitting of the Giant Monopole Resonance with Deformation in Sm Nuclei

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In (α,α') measurements on spherical ^{144}Sm and deformed ^{154}Sm, the cross sections and energies of the two components of the isoscalar giant resonance are found to be consistent with a splitting of the giant monopole resonance in ^{154}Sm into two components of roughly equal strength. One component remains close to the giant-monopole-resonance energy of ^{144}Sm while the second is coincident with the giant quadrupole resonance. This is shown to be consistent with simple schematic-model predictions.

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The effects of ground-state deformation on the parameters of the giant resonances (GR) have been of considerable experimental and theoretical interest in recent years. It is well established that the giant dipole resonance (GDR) is split into two components in the deformed nuclei; this splitting has been attributed to different frequencies of dipole oscillations along the major and minor axes of a deformed nucleus.[1] The giant quadrupole resonance (GQR), on the other hand, shows only a small broadening due to deformation, because it splits into three closely spaced components corresponding to $K=0$, 1, and 2.[2] Naively, one might expect the $L=0$ giant monopole resonance (GMR) to be unaffected by the deformation of the nuclear ground state, and a reanalysis of (p,p') data involving the GMR, GDR, and GQR in ^{154}Sm has employed this assumption.[3] Zawischa *et al.*,[4] however, on the basis of microscopic random-phase–approximation calculations, have predicted that the GMR will split into two components in deformed nuclei; the splitting between the two components is predicted to be ~8 MeV in ^{170}Yb. In this Letter, we report the first experimental evidence for splitting of the GMR due to deformation, obtained from a comparison of cross sections and energies of the components of the isoscalar GR peak in the deformed nucleus ^{154}Sm with those in the spherical nucleus ^{144}Sm.

Inelastic α-scattering data have been reported previously for both Sm isotopes taken at a bombarding energy of 115 MeV (Youngblood *et al.*[5]) the angular range 14°–25°, and for ^{144}Sm at 96 MeV (Youngblood *et al.*[6]) over 3°–8°. Data were also obtained for ^{154}Sm at 96 MeV. These data have been analyzed by fitting the GR regions in the spectra, after a smooth continuum background subtraction, with two components of a Gaussian shape with use of a least-squares multipeak fitting routine (see Rozsa *et al.*[7]). The angular distributions obtained at 96 MeV are shown in Fig.

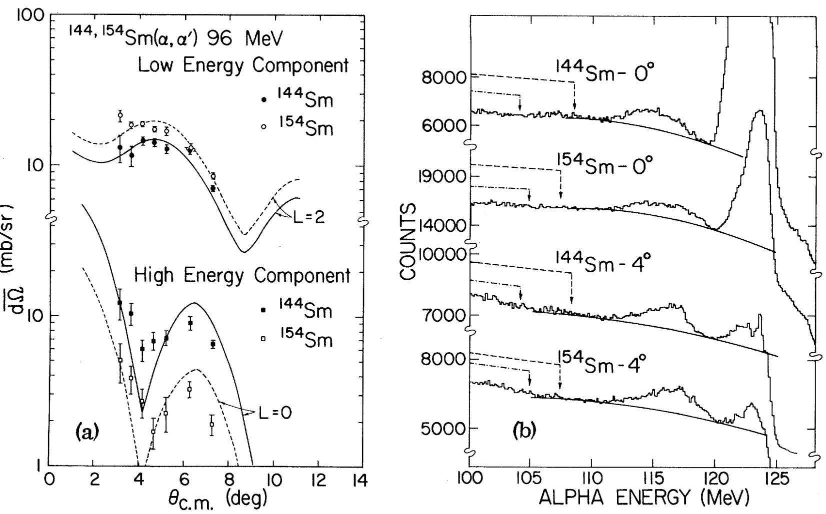

FIG. 1. (a) Angular distributions obtained for the two components of the GR peaks at $E_\alpha = 96$ MeV. The lines are distorted-wave Born-approximation predictions. (b) Spectra at $E_\alpha = 129$ MeV. The solid lines indicate the chosen continuum. The regions where ^{5}Li (dashed lines) and ^{5}He (dot-dashed lines) breakup would contribute are also indicated.

1(a) where the total GR peak cross section of ^{154}Sm has been arbitrarily normalized to that of ^{144}Sm (the ^{154}Sm target utilized in these measurements was destroyed before the thickness could be measured). The angular distributions for the upper components in both nuclei are consistent with $L = 0$ transfer (the GMR), while those for the lower components are consistent with an $L = 2$ transfer (the GQR); the ratio of the GMR to the GQR cross sections in ^{154}Sm is about half the ratio in ^{144}Sm, however. A two-peak analysis of the 115-MeV data also yielded the same result; moreover, the total GMR + GQR cross section was found to be the same within the errors.

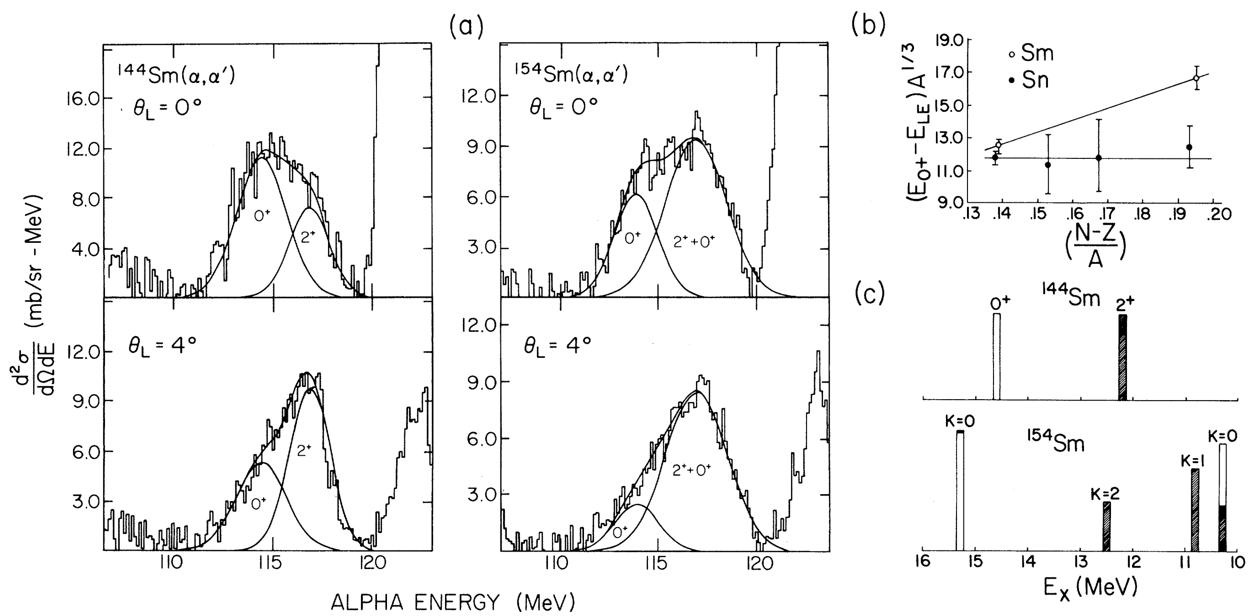

FIG. 2. (a) Spectra at $E_\alpha = 129$ MeV after background subtraction. The lines show two-peak fits. (b) $(E_0 + - E_{\rm LE})A^{1/3}$ plotted vs $(N - Z)/A$ for Sm and Sn isotopes. The errors shown do not include systematic errors. (c) Predicted giant-resonance strength distributions in a spherical (^{144}Sm) and a deformed (^{154}Sm) nucleus.

In an attempt to understand this phenomenon, data were taken on ^{144}Sm and ^{154}Sm at 129 MeV where the GMR– and GQR–to-continuum ratios are considerably enhanced. In these experiments, α-particle beams from the Texas A& M University cyclotron bombarded self-supporting metal-foil targets of ^{144}Sm and ^{154}Sm (enriched to ~ 99% of the desired isotope) placed at the center of the target chamber for the Enge split-pole magnetic spectrograph. The experimental techniques including data reduction and distorted-wave Born-approximation calculations have been described in detail in Ref. 7. In these experiments a pulser signal was also fed through the signal manipulation circuits and the computer to determine the intrinsic dead time of the system.

Data were obtained for ^{144}Sm at 0° and 4°, and for ^{154}Sm at 0° and at 3°, 3.5°, 4°, 5°, 6°, and 7°. One experimental run was devoted to a careful comparison of cross sections between ^{144}Sm and ^{154}Sm. In this run, spectra were taken at 0° and 4° [Fig. 1(b)] where the GMR cross sections are expected to be at maximum and minimum, respectively. Data were also taken for ^{12}C for an absolute cross-section check. Sm target thicknesses were measured with an α gauge and checked by weighing. Considerable care was taken in the preparation and handling of the Sm targets to minimize contamination; the spectra show no peaks in the GR region attributable to target contaminants.

The spectra obtained after subtraction of the continuum, along with the two-peak multispectra fits to the data, are shown in Fig. 2(a). The energies, widths, and sum-rule fractions extracted from all the data, as well as the relative cross sections for the 129-MeV data are summarized in Tables I and II. As in the lower-energy data, the observed GMR cross section in ^{154}Sm is about 50% of that in ^{144}Sm; moreover, the total GR cross section at each angle is the same for both nuclei, thus the decrease in the GMR cross section is balanced by an increase in the cross section of the lower–excitation-energy peak. Such an effect implies that the GMR has split into two components in ^{154}Sm and that one of these components coincides in excitation energy with the GQR. The angular distribution of the lower–excitation-energy (LE) peak in ^{154}Sm is consistent with about 50% $E2$ energy-weighted sum rule (EWSR) plus 50% $E0$ EWSR; unfortunately the 0^+ component is sufficiently weak that the angular distribution would deviate significantly from $L=2$ only inside 2°. The 0° and 4° data [Table II and Fig. 2(a)] confirm this deviation at 0°, the only angle we can measure where it will be apparent.

The width of the observed GMR in both nuclei is the same within experimental error limits, while the LE peak shows a 1.3-MeV broadening in ^{154}Sm when compared with ^{144}Sm. The differences between the excitation energies of the two peaks (times $A^{1/3}$) for each nucleus are compared in Fig. 2(b) with those observed for the Sn isotopes.[8] The values obtained for ^{154}Sm and ^{144}Sm differ by 4.2 ± 0.8 MeV while for the Sn isotopes this quantity is constant within the errors, as is expected (for ^{124}Sn-^{116}Sn the difference is 0.8 ± 1.5 MeV).

Both the decrease in the GMR cross section and the increased energy difference between the two peaks in deformed ^{154}Sm can be understood with an extension of the model applied to the splitting of the GQR.[2,9] In this model, a rigorous self-consistency is applied which results in a modification of the usual quadrupole-quadrupole interaction. The resulting strength distributions are illustrated schematically in Fig. 2(c). In a nucleus with a deformed ground state, the $K=0$, 1, and 2 components of the GQR split apart; also the vibrations, which in a spherical nucleus correspond to quadrupole and monopole, no longer have unique J^π, but each contains a mixture of 2^+ and 0^+. Thus there are two $K=0$ states, the lower predominantly $J^\pi=2^+$ but containing significant

TABLE I. Parameters obtained for the GR peaks in ^{144}Sm and ^{154}Sm.

Nucleus	E_{LE}[a] (MeV)	Γ_{LE} (MeV)	(sum-rule fractions)$_{LE}$ (%)	E_{0^+} (MeV)	Γ_{0^+} (MeV)	(sum-rule fractions)$_{0^+}$ (%)
^{144}Sm	12.2 ± 0.2	2.4 ± 0.2	45 ± 15	14.6 ± 0.2	3.0 ± 0.3	140 ± 40
^{154}Sm	11.8 ± 0.3	3.7 ± 0.3	b	14.9 ± 0.3	2.6 ± 0.4	55 ± 15

[a]For ^{144}Sm, LE denotes the GQR. For ^{154}Sm, LE corresponds to the lower–excitation-energy component of the GR.
[b]See text.

TABLE II. Relative giant-resonance cross sections. Cross sections are relative to the total GR cross section ($\sigma_{LE}+\sigma_{0^+}$) in ^{144}Sm.

Angle	Nucleus	σ_{LE}[a]	σ_{0^+}	$\sigma_{LE}+\sigma_{0^+}$
0°	^{144}Sm	0.34 ± 0.09	0.66 ± 0.13	1.00
0°	^{154}Sm	0.66 ± 0.10	0.31 ± 0.07	0.97 ± 0.15
4°	^{144}Sm	0.60 ± 0.09	0.40 ± 0.08	1.00
4°	^{154}Sm	0.78 ± 0.10	0.17 ± 0.05	0.95 ± 0.13

[a]For ^{144}Sm, LE denotes the GQR. For ^{154}Sm, LE corresponds to the lower-excitation-energy component of the GR.

$J^\pi=0^+$ strength; the upper predominantly $J^\pi=0^+$ but with a small amount of $J^\pi=2^+$ strength. In the model approximately 25% of the 0^+ strength would appear in the lower component, while only 2% of the 2^+ strength would appear in the upper component. The data, however, suggest that approximately half of the 0^+ strength is in the lower component. The upper $K=0$ component is also repelled somewhat by this mixing, consistent with the results seen in Fig. 2(b). It appears that the random-phase-approximation calculations of Zawischa *et al.*[4] obtain too high an incompressibility, resulting in the upper component of the GMR being located too high in excitation. Unfortunately they do not report similar calculations for a spherical nucleus for comparison. Detailed calculations for both ^{144}Sm and ^{154}Sm would be valuable.

The differences between the sum-rule fractions for ^{144}Sm in Table I and those reported in Ref. 6 are due to different assumptions about the shape of the GQR; the analysis of the 96-MeV ^{144}Sm data, reported in Ref. 6, utilized a Breit-Wigner shape with an energy-dependent width for the GQR. The behavior of the GMR in ^{154}Sm relative to ^{144}Sm as reported here is not qualitatively dependent on such assumptions, however.

Although the observed splitting of the GMR is qualitatively similar to that of the GDR in the deformed nuclei, there are compelling arguments against identifying the observed resonance as the GDR. Firstly, the excitation energy of the GDR is 1 MeV lower, and the widths of the GDR in ^{144}Sm and ^{154}Sm (4.4 and 5.3 MeV, respectively)[10] are considerably larger than those of the observed resonance. Secondly, the angular distribution of the observed peak is consistent with an $L=0$ assignment and is out of phase with the predicted angular distribution for an $L=1$ transfer.

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