Evidence for Deformation Effect on the Giant Monopole Resonance

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The giant monopole resonance in the region of deformed nuclei has been investigated by inelastic scattering of 108.5 MeV ^{3}He at very small scattering angles. Evidence is reported for coupling between the giant monopole and giant quadrupole vibrations, based both on energy shift and transition strength.

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The existence of the giant monopole resonance (GMR) in nuclei has been firmly established within the last few years.[1,2] Whereas the experimental study is being performed systematically,[3,4] the theoretical aspects are extensively discussed.[5] One question opened recently[6] concerns the coupling between the GMR and the giant quadrupole resonance (GQR). The aim of this paper is to report on an experimental evidence for such a coupling in deformed nuclei. The expected effect is rather small and requires a fairly accurate determination of excitation energies. It has been shown recently that such a requirement could be met very satisfactorily by overcoming experimental difficulties in very small scattering angle measurements.[2]

The experiments were performed at Institut des Sciences Nucléaires, Grenoble, using the analyzed beam of 108.5 MeV ^{3}He particles from the variable energy cyclotron. Inelastically scattered particles were detected in a position sensitive detector on the focal plane of the spectrometer. The study was performed at very small scattering angles including zero degrees, where the cross section for GMR excitation is expected to be maximum. This was made possible by means of an active collimator system to reject slit scattered events. The principle of this design has been described in Ref. 2, where the basic justifications of these experiments were also given. This system was further improved to subtract from the spectra the remaining instrumental background due to the small residual inefficiency of the active collimator. A more complete description of the experimental setup is reported in Ref. 3. This paper will focus on the region of deformed nuclei. Results on other regions of mass are only mentioned here to show the general trends of the data. Preliminary results have been previously reported,[3] and the whole set of data will be discussed in a forthcoming more comprehensive paper. Meanwhile we are concerned here with the following nuclei: ^{140}Ce, ^{144,150,152}Sm, ^{159}Tb, ^{165}Ho, ^{169}Tm, ^{175}Lu, ^{181}Ta, ^{197}Au, ^{208}Pb, and ^{232}Th. Figure 1 illustrates the data obtained on ^{181}Ta.

Figure 2(a) displays the measured excitation energy as a function of the nuclear mass for all the nuclei investigated so far in these experiments. A first examination of these data leads to the following remarks: (1) The experimental values of E_x decrease smoothly with the increasing mass. They are clustered around an average value in the region of mass 90–130. (2) In the region of deformed nuclei ($144 \lesssim A \lesssim 200$), the values of E_x are enhanced compared to those of the nearby spherical nuclei ($A \sim 140$ and $A \sim 200$) and they make a bump on the average shape of the systematics. The numerical values are given in Table I. The scattering of the experimental values around the average in the region $90 \lesssim A \lesssim 130$, where nuclei are nearly spherical, can be attributed to asymmetry and possibly shell effects, the former of which will be discussed in a further publication, whereas there is no available information on the latter. Indeed, the asymmetry of the nuclei studied in this region of mass varies markedly for neighboring nuclei and this is likely to affect the monopole frequency (see relations below). For the upper masses the above-mentioned effects might also affect the GMR excitation energy. However, the studied deformed nuclei lie along the stability line. Then any effect due to the asymmetry should be smooth and no local effect is to be expected.

The experimental values on Fig. 2(a) are compared to a curve obtained from a hydrodynamical relation[7]:

$$E_x = \hbar [K_A / m \langle r^2 \rangle]^{1/2}, \tag{1}$$

where K_A is the compression modulus of the nu-

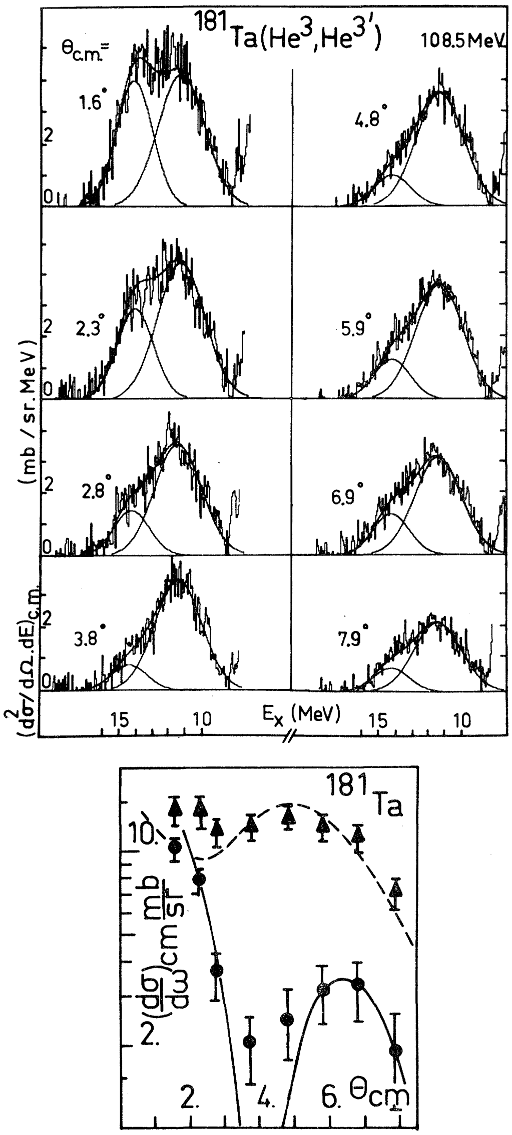

FIG. 1. Upper part: Example of difference spectra measured at forward angles, unfolded into GMR and GQR components. The total spectra (not shown) contain a very small amount of instrumental background (see Refs. 2 and 3). Lower part: Corresponding angular distributions derived for GMR (solid circles) and GQR (triangles) compared to DWBA calculations assuming 74% and 78% EWSR, respectively.

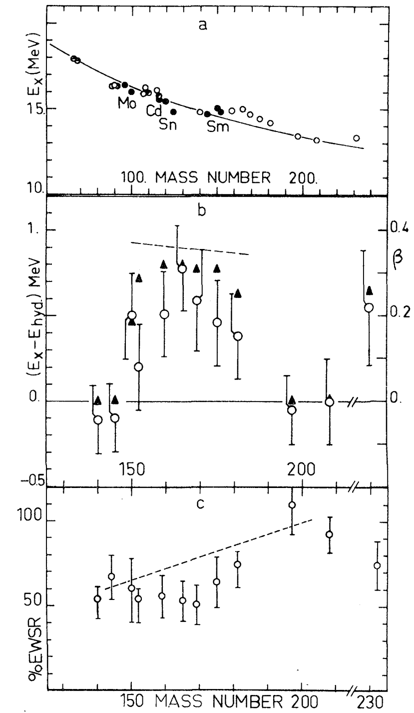

FIG. 2. (a) Systematics of the excitation energies of the GMR measured in this work. The families of iostopes studied are indicated by solid or half-solid circles and the corresponding elements indicated below. The solid line is a fit as described in the text, with an asymmetry $(N-Z)/A$ following the stability line. (b) Difference between the experimental and hydrodynamical values (left scale) of the GMR excitation energy (open circles). The errors bars correspond to the experimental uncertainties. The triangles are the corresponding static deformations β of the nuclei studied (right scale). (c) GMR transition strengths as EWSR percentages. The error bars arise from DWBA fits and from averaging over values obtained with sets of optical model parameters from $A = 120$ and 208. The horizontal scale is the same for (b) and (c).

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$$K_A = K_\infty + K_{\text{surf}} A^{-1/3} + K_{\text{sym}}[(N-Z)/A]^2 + 1.4Z^2A^{-4/3};$$

the other notations are the same as in Ref. 7.

The value $K_\infty = 210$ MeV was obtained in Ref. 7 from fitting random-phase approximation (RPA) calculations. Using this value to fit the data on spherical nuclei near the stability line leads to $K_{\text{surf}} = -420 \pm 40$ MeV and $K_{\text{sym}} = -450 \pm 100$ MeV in reasonable agreement with both the theory[7] and the recent analysis of some experimental data.[4] The resulting curve is shown on Fig. 2(a). It reproduces satisfactorily the average data for spherical or nearly spherical nuclei in the range of mass investigated. On the contrary, it is clear from the relations above that no set of parameters can reproduce the bumps in the deformed region and the other regions as well. In the deformed nuclei, it is seen that E_x(GMR) is somewhat larger than the hydrodynamical values.

TABLE I. GMR excitation energies, widths (in megaelectronvolts) and transition strengths (in percent EWSR) for the studied nuclei.

Nucleus	E_x	Γ	% EWSR
^{140}Ce	14.8 ± 0.2	3.0 ∓ 0.2	53 ± 10
^{144}Sm	14.7 ± 0.2	2.9 ∓ 0.2	67 ± 13
^{150}Sm	15.1 ± 0.25	3.0 ∓ 0.25	60 ± 19
^{152}Sm	14.8 ± 0.25	3.1 ∓ 0.25	54 ± 9
^{159}Tb	14.85 ± 0.25	3.4 ∓ 0.25	56 ± 13
^{165}Ho	15.0 ± 0.25	2.7 ∓ 0.3	53 ± 12
^{169}Tm	14.7 ± 0.3	2.5 ∓ 0.3	51 ± 12
^{175}Lu	14.4 ± 0.3	3.0 ∓ 0.3	65 ± 15
^{181}Ta	14.2 ± 0.25	2.5 ∓ 0.25	74 ± 11
^{197}Au	13.45 ± 0.2	2.4 ∓ 0.2	109 ± 17
^{208}Pb	13.2 ± 0.3	2.8 ∓ 0.25	92 ± 12
^{232}Th	13.35 ± 0.4	2.3 ∓ 0.4	74 ± 12

This is better seen on Fig. 2(b) where the difference $\Delta E_x = (E_x - E_{\text{hyd}})$ is displayed through the regions of deformation. E_x stands for the experimental value, and E_{hyd} for the prediction of relation (1) [solid curve on Fig. 2(a)]. It is seen that ΔE_x is around zero for spherical nuclei (^{140}Ce, ^{144}Sm, ^{197}Au, ^{208}Pb), whereas it is consistently positive for all the deformed nuclei studied. Also shown on the same figure are the experimental static deformation parameters β taken from Ref. 8. There is a clear correlation between ΔE_x and β for all the nuclei studied except for ^{152}Sm. The average value of the ratio $\Delta E_x/\beta$ is 1.8 ± 0.9 MeV. This correlation between the monopole frequency and the ground-state nuclear deformation can be understood in terms of coupling between the giant quadrupole and monopole modes. In a cranking-model approach of the problem, Abgrall *et al.*[6] have estimated that one effect of such a coupling on the GMR in prolate nuclei should be to shift its excitation energy from around 80 $A^{-1/3}$ up to 85 $A^{-1/3}$ MeV, assuming a deformation $\beta = 0.3$. This transition carries most [79% energy-weighted sum rule (EWSR)] of the $E0$ strength and a small amount (3% EWSR) of the $E2$ strength. For $A = 165$, this leads to $\Delta E_x^{\text{th}} \sim 0.9$ MeV [dashed line on Fig. 2(b)]. The experimental values corresponding to approximately the same β are scattered between 0.5 and 0.8 MeV, thus slightly smaller than the estimate of Ref. 6. However, the agreement may be considered as reasonable, and good enough to establish the energy shift observed experimentally as being due to the coupling between GMR and GQR. The authors of Ref. 6 also predict a small amount (21% EWSR) of $E0$ strength at 56 $A^{-1/3}$ MeV. However, no indication for this strength has yet been found experimentally. The RPA approach of Zawischa, Speth, and Pal[9] also predicts the main strength of the GMR to shift to higher E_x. However this predicted shift is much larger than observed in the present work. From the same coupling, one expects to observe the GQR as a wider bump[6] with its centroid almost unaffected, which is confirmed experimentally.

A DWBA analysis of the data has also been undertaken in the same way as in Ref. 2. It was performed using optical model parameters from Ref. 10, determined on $A = 24$, 90, 120, and 208 nuclei. This means inaccuracies in analyzing the data for masses in between these values. Nevertheless some trends appear quite clearly: The GMR strength amounts to around 100% EWSR for $A \sim 200$, but decreases continuously down to around 20% in the ^{66,68}Zn isotopes. Figure 2(c) displays the strength extracted from DWBA fits for the nuclei studied here; the numbers are given in Table I. As mentioned above, the work of Abgrall *et al.*[6] also predicts that the upper component of the coupling multiplet carries only 79% EWSR of the $E0$ strength, the remaining 21% being carried by a lower component. The trend observed on Fig. 2(c) confirms this prediction: The dashed line is a linear interpolation between the average values of the strength found in spherical nuclei ^{140}Ce, ^{144}Sm and ^{197}Au, ^{209}Pb. The slope is due to the decrease of the strength observed with the decreasing mass through the table. It is seen that in all deformed nuclei the strength is found consistently smaller than the linear interpolation predicts it, by around 10% to 25% EWSR, again in reasonable agreement with Ref. 6. It is also to be noted that for the Sm isotopes the $E0$ strength decreases consistently with the increase of the deformation as recently observed in another work.[11] Beyond $A \sim 200$, the strength is again found smaller for the deformed ^{232}Th than for Au and Pb.

From the present study, it is concluded that there is evidence for a deformation effect on the GMR excitation energies due to a coupling with the GQR. This interpretation is supported by the behavior of the GMR strength measured through this region of nuclear mass.

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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.

