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Deformation effects on the experimental widths of giant dipole resonances

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Using a microscopic semiclassical approach we analyze the effect of deformation on the splitting of giant dipole resonances and consequently on the observed experimental widths. We study the behavior of the width for the Nd, Sm, Sn, and Mo chain of isotopes. Altogether these effects can account for 30—40 % of the observed widths.

Giant resonances are often considered as highly collective modes of nuclear excitation in which an appreciable fraction of the nucleons of a nucleus move together. Indeed, the motion is so collective that it is appropriate to think of these modes of excitation in fluid dynamic terms like the oscillations of a two-fluid drop.

Recently microscopic semiclassical approaches have been introduced, based on the analysis of small amplitude motions of a nuclear system following a Vlasov evolution equation, which is the semiclassical limit of a time dependent Hartree-Fock theory.[1,2] The results, which are fully self-consistent, are of the same quality as complete random-phase approximation (RPA) calculations. However, they require less computational effort and are more transparent in their interpretation. In previous papers[3,4] we presented some calculations on isovector and isoscalar giant resonances performed within a scaling approximation from the study of a linearized version of the nuclear Vlasov equation and the related chain of p-moment equations for the distribution function. The phase space method also allows microscopic calculations to be done for collective motions built on complicated reference states, like a fast rotating nucleus[3] or a dinuclear system,[5] where a full RPA theory is almost impossible to handle. Following the same philosophy in this Brief Report we systematically analyze deformation effects on giant resonances for various isotopic chains. In particular we discuss the influence of the energy splitting on the observed widths of isovector dipole resonances for nuclei which are symmetrically deformed in the g.s. configuration. For such nuclei, assuming the z axis to be the symmetry axis, we have only two possible isovector dipole modes (those along the x and y axes being degenerate), and the frequencies are given by[4]

$$\Omega_{x,z}^2 = C_{x,z}/I_c \ , \tag{1}$$

where, for Skyrme forces, the collective inertial function, I_c, is given by

$$I_c = m \int \frac{\rho_q^{\rm st}}{1+2m\eta\rho^{\rm st}} d^3\mathbf{r} \ , \tag{2}$$

which is independent of the direction of the mode, and the restoring function is

$$\begin{aligned} C_{x,z} = m\eta \int d^3\mathbf{r}[(\mathrm{Tr}\overleftrightarrow{\tau}^{\rm st})\nabla_{x,z}^2\rho_q^{\rm st} + (\mathrm{Tr}\overleftrightarrow{\tau}_q^{\rm st})\nabla_{x,z}^2\rho^{\rm st}] \\ + \int d^3\mathbf{r}\{ [D_q^{\rm st} + \tfrac{1}{2}t_0(1+2x_0)\rho_q^{\rm st} - \tfrac{1}{8}(t_+ + \tfrac{1}{2}t_-)\nabla^2\rho_q^{\rm st}]\nabla_{x,z}^2\rho_q^{\rm st} \\ + \tfrac{1}{12}t_3(1+2x_3)(\rho^{\rm st})^{\sigma-1}[(\sigma-1)\rho_{q'}^{\rm st} - (\sigma+1)\rho_q^{\rm st}](\nabla_{x,z}\rho_q^{\rm st})^2\} \ , \end{aligned} \tag{3}$$

with

$$\begin{aligned} D_q = t_0[(1-x_0)\tfrac{1}{2}\rho_q + (1+\tfrac{1}{2}x_0)\rho_{q'}] - \tfrac{3}{16}t_-\nabla^2\rho_q - \tfrac{1}{4}(\tfrac{1}{2}t_+ + t_-)\nabla^2\rho_q \\ + \tfrac{1}{24}t_3\{(1-x_3)(\sigma+2)\rho_q^2 + [(1-x_3)\sigma + 2(2+x_3)]\rho_q^2 + 2\rho_q\rho_{q'}[(2+x_3)(1+\sigma) + (1-x_3)]\}\rho^{\sigma-1} \ . \end{aligned}$$

σ is 1 for I to VI Skyrme interactions, while it is $\frac{1}{6}$ for the modified Skyrme (SKM). st is used to denote stationary values, m is the nucleon mass, and

$$\eta = \frac{t_+}{4\hbar^2}, \quad t_\pm = t_1 \pm t_2 \ .$$

We need only some knowledge of matter density, $\rho_q^{\rm st}$, and kinetic energy density, $\tau_q^{\rm st}$, distributions in the reference state on top of which we build the giant mode. In this paper all this information is obtained with a self-consistent Hartree-Fock plus Bardeen-Cooper-Schrieffer (BCS) calculation with the same effective interaction. We remark that the major contributions to the integrals (3) come from the nuclear surface. Thus it is not the detailed behavior of the static local density inside the nucleus which is important here, but the shape at the surface. For this reason and in order to emphasize the main effects of the deformation on the dipole frequencies, we can assume a proportional density distribution of neutron and protons and Woods-Saxon spheroidal shapes deformed along the z axis,

$$\rho^{\rm st}(\mathbf{r})=\frac{\rho_0}{1+\exp\{[r-R(\theta)]/a\}}\ , \tag{4}$$

with

$$R(\theta)=R_0(\beta)[1+\beta Y_{20}(\cos\theta)]\ . \tag{5}$$

Assuming for the squared radial first derivative of the total local density a δ structure with a suitable Woods-Saxon normalization

$$\left[\frac{\partial \rho^{\rm st}}{\partial r}\right]^2=\frac{\rho_0^2}{4a}\delta[r-R(\theta)]\ ,$$

in a Thomas-Fermi approximation for the kinetic energy density, we can solve analytically the integrals (2) and (3) and we get the two frequencies[6] $\Omega_{x,z}(\beta)$, which for small values of β assume the simple form

$$\begin{aligned}\Omega_z(\beta)&=\Omega_0\left[1-\frac{2}{\sqrt{5\pi}}\beta\right]\ ,\\ \Omega_x(\beta)&=\Omega_0\left[1+\frac{1}{\sqrt{5\pi}}\beta\right]\ ,\end{aligned} \tag{6}$$

where Ω_0 is the giant dipole resonance (GDR) frequency for spherical nuclei, which is very sensitive to the interaction used. For a SKM force we get a general trend

$$\hbar\Omega_0 \simeq 35A^{-1/6}\ \text{MeV}\ ,$$

which provides a good estimate of the experimental values.[7] Moreover, the energy splitting results are easily related[6] to the deformation parameter β by

$$\frac{\Omega_x-\Omega_z}{2\Omega_x+\Omega_z}=\frac{1}{\sqrt{5\pi}}\beta\ . \tag{7}$$

Similar results are well known in the hydrodynamic model.[8] This is not surprising for the GDR case where distortions in the momentum distribution are not involved in the collective oscillation. In this case, just by chance, the liquid drop model with its locally equilibrated momentum distribution should be in very close agreement with our microscopic phase space approach. The situation would be very different, for instance, for giant quadrupole resonances.[3,9]

We remark that the GDR energies presented here are evaluated self-consistently from Eq. (1) by using a static Hartree-Fock (HF) code for axially deformed nuclei,[10] while we use the approximate Eq. (7) only to estimate the corresponding axial deformation parameter. Now the problem is how to analyze the data, i.e., how to relate the observed widths to the widths Γ_x and Γ_z of the split resonances[3,9] and to a "splitting width," Γ_s, defined by

$$\Gamma_s=\hbar\,|\,\Omega_x-\Omega_z\,|\ . \tag{8}$$

Important information comes from the cases (^{150}Nd,^{152,154}Sm), where the GDR splitting is clearly resolved. A fit of the photoneutron cross section in the GDR region with Lorentz lines[11,12]

$$\sigma=\sigma_1\frac{(E\Gamma_1)^2}{(E^2-E_1^2)^2+(E\Gamma_1)^2}+\sigma_2\frac{(E\Gamma_2)^2}{(E^2-E_2^2)+(E\Gamma_2)^2} \tag{9}$$

gives an area ratio between the two resonances

$$\frac{\sigma_2\Gamma_2}{\sigma_1\Gamma_1}\simeq 2\ . \tag{10}$$

The resonance 2 is the higher energy one, but with

$$\sigma_2\simeq\sigma_1 \tag{11}$$

and

$$\Gamma_2\simeq 2\Gamma_1\ . \tag{12}$$

Since for such prolate nuclei we expect two independent higher energy transverse modes, Eq. (12) means that the intrinsic width of each giant level is approximately the same,

$$\Gamma_x=\Gamma_y=\Gamma_z=\Gamma=\Gamma^{\uparrow}+\Gamma^{\downarrow}\ . \tag{13}$$

Finally from the equality Eq. (11) of the peak values, we

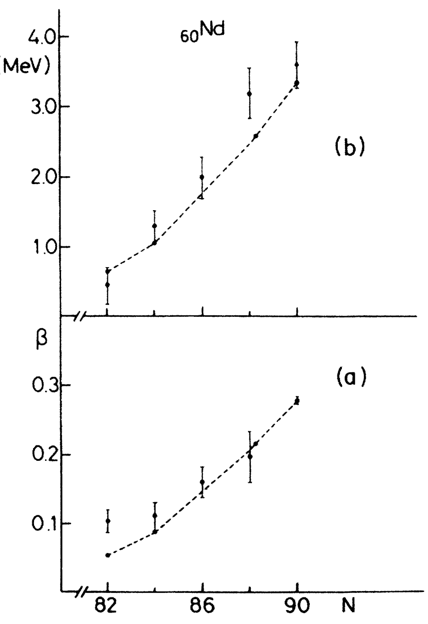

FIG. 1. (a) Comparison between the axial deformation parameters (symbol with filled circle) deduced from the experimental reduced electric quadrupole transition probabilities $B(E2,0\rightarrow 2^+)$ and those obtained by using Eq. (7) for Nd isotopes. (b) Relative comparison between the total experimental GDR width (less 4.0 MeV) and the splitting contribution [Eq. (8)]. The point corresponding to $N=90$ (symbol with filled triangle) is the experimental observed energy splitting. The subtracted width gives an evaluation of the spreading width in this isotopic chain.

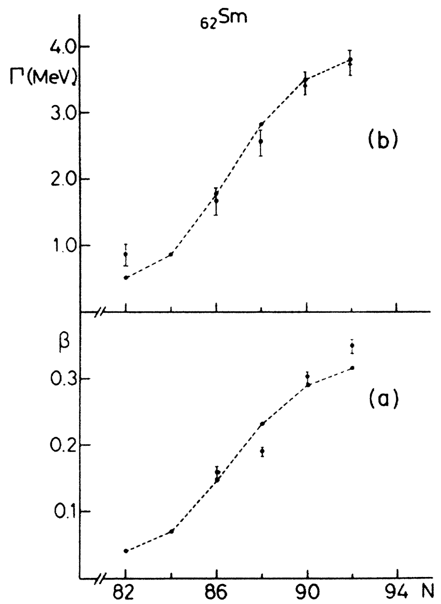

FIG. 2. (a) and (b) are the same as Fig. 1, but for Sm isotopes. Two experimental energy splittings (for $N=90,92$) are observed in this case. The total experimental GDR widths (symbol with filled circle) reported in the figure are lessened by 3.5 MeV. The points corresponding to $N=90,92$ (symbols with filled triangles) are the experimental observed splitting energies.

can safely define a total experimental width, to be used also when the splitting is not resolved:

$$\Gamma_{\text{exp}}=\frac{\Gamma_1}{2}+\frac{\Gamma_2}{2}+\Gamma_s \simeq \Gamma_s+\tfrac{3}{2}(\Gamma^{\uparrow}+\Gamma^{\downarrow}) . \qquad (14)$$

Before going on to the discussion of our results, we would like to make a comment on Eq. (10). A 2:1 weight for the two levels means an equal absorption probability for the

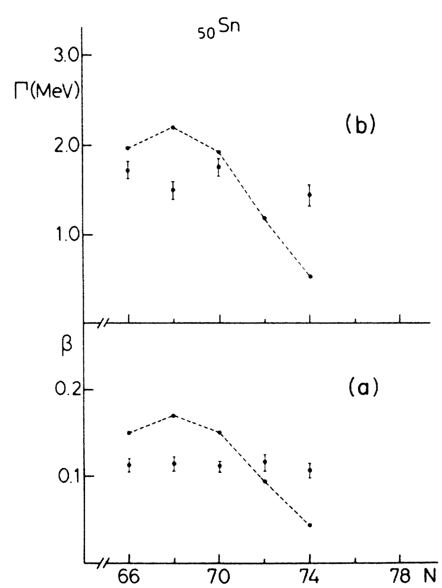

FIG. 3. The same as Fig. 1, but for Sn isotopes. The total experimental GDR widths are subtracted by 3.5 MeV.

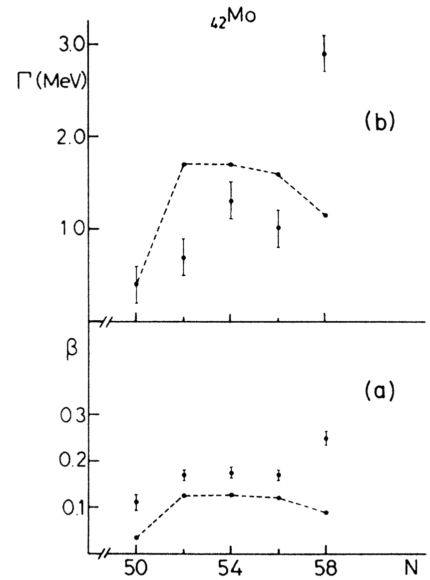

FIG. 4. The same as Fig. 1, but for Mo isotopes. The total experimental GDR widths are subtracted by 5.0 MeV.

three modes. This was predicted by Okamoto and Danos[8] on the basis of the hydrodynamical model. We easily get the same result in our scaling approximation to the Vlasov equation. Indeed we have a reduced transition strength,[3]

$$B(E1,x,y,z) \sim \frac{I_c}{\Omega_{x,y,z}} , \qquad (15)$$

and therefore an equal absorption probability $\sigma \sim EB$ in the resonance region since the collective mass does not depend on the particular mode.

In Figs. 1–4 we show for the Nd, Sm, Sn, and Mo isotopes, respectively, a relative comparison between the experimental width[11–15] and the theoretical splitting width obtained from Eqs. (1)–(3) and (8) (upper parts of the figures). For ^{150}Nd and ^{152,154}Sm, since the GDR splitting is clearly experimentally resolved, we can directly compare absolute experimental and theoretical values. The excellent agreement between observed and theoretical splitting widths for ^{152,154}Sm isotopes gives an indication of the goodness of our method in predicting their absolute behavior with an increasing number of neutrons (or deformation) and supports our conclusions. In the lower parts of the figures we also report a comparison between deformation parameters deduced from the experimental reduced electric quadrupole transition probability[16] by

$$\beta=\frac{4\pi}{3}\frac{[B(E2,0\rightarrow 2^+)]^{1/2}}{ZR_0^2} \qquad (16)$$

and those predicted from Eq. (7). For Nd and Sm isotopes (Figs. 1 and 2), we get good agreement for the β values and almost the same behavior between the scaled experimental widths[11–13] and the theoretical splitting widths, for increasing neutron number out to the closed $N=82$ shell. Since in this mass region the escape width can be neglected,[11–15] our result means that the spreading width contribution to the observed total width is almost constant with increasing deformation parameter, at least for these isotopes. Indeed the subtracted width in Figs. 1–4 gives an approximate measure ($\Delta\Gamma \sim \frac{3}{2}\Gamma^{\downarrow}$) of this spreading width which does not depend much on the g.s. deformations.

In the Sn case (Fig. 3) we have a clear effect of the closure of the 82 neutron shell in the direction of a larger sphericity and a consequent decrease of the splitting. Experimentally this trend is not evident, although there is some disagreement in the data.[13,14] The situation is completely different for the Mo isotopes,[13,15] where the discrepancy is extremely clear (Fig. 4). We think that in this case our description of the ground state properties of these isotopes is inadequate, essentially because we are completely neglecting n-p pairing couplings which are particularly important for 40–50 n-p shell nuclei.[16,17]

The conclusion of our semiclassical analysis of deformation effects on the observed widths of giant dipole resonances is very clear: for unclosed shell nuclei about 30–40% of the width can be directly related to ground state deformation properties. This is essentially a warning for people who are trying to reproduce the experimental resonance widths as being just due to the spreading properties of the collective mode, second order RPA terms, or two-body collision effects.

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