Isoscalar Compression Modes Within Fluid Dynamic Approach

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We study the isoscalar compression excitations, the isoscalar giant monopole resonance (ISGMR) and the isoscalar giant dipole resonance (ISGDR), within the nuclear fluid dynamic approach (FDA) [1], with and without the effect of relaxation (collisional damping with memory effect). Assuming sharp particle density distribution and quadrupole distortion of the Fermi surface and neglecting the relaxation effects, the FDA energy of the compression modes is given by

$$\hbar\omega = \sqrt{\hbar^2 \frac{K + (24/5)\ \epsilon_F}{9mR_0^2}} qR_0, \qquad (1)$$

where $R_0 = r_0 A^{1/3}$ is the nuclear radius, ϵ_F the Fermi energy and the wave number q is given by the boundary conditions for the liquid pressure on the free nuclear surface. The additional term with ϵ_F in Eq. (1) is due to the Fermi surface distortion effect. The incompressibility K was determined from the experimental energy E_{0+}^{exp} of the giant monopole resonance by using the scaling model definition. Namely,

$$K = \frac{m < r^2 >}{\hbar^2} \left(E_{0+}^{exp}\right)^2. \qquad (2)$$

We point out that the classical liquid drop model (LDM) energy of the compression modes can be obtained from Eq. (1) by neglecting the Fermi surface distortion effects and it is given by

$$\hbar\omega = \sqrt{\frac{\hbar^2 K}{9mR_0^2}} qR_0. \qquad (3)$$

In Fig. 1 we have plotted both the FDA and the LDM energies of the ISGDR and the ISGMR as obtained from Eqs. (1) and (3). A significant shift up of the FDA curves with respect to the corresponding LDM curves is due to the Fermi surface distortion effect. In contrast to the ISGDR case, the relative shift between the FDA and the LDM energies is suppressed for the ISGMR due to the Fermi surface distortion effects in the boundary condition, see also Ref. [2]. In Fig. 1 we have also plotted the ISGDR energy for the scaling model of Ref. [3]. The relative location of the dipole, $E1$, and monopole, $E0$, energies for four nuclei presented in Fig. 1 is given by

$$(E1/E0)_{FDA} = 1.78 \div 1.86,$$

$$(E1/E0)_{scaling} = 1.76 \div 1.80. \qquad (4)$$

Both these ratios exceed significantly the LDM estimate $(E1/E0)_{LDM} = 1.43$ and the experimental data $(E1/E0)_{\rm exp} = 1.5 \pm 0.1$ of Ref. [4]. We point out that both ratios $(E1/E0)_{FDA}$ and $(E1/E0)_{scaling}$ have different asymptotic limits at $K \to \infty$. Namely, it can be seen from Eqs. (1) and (3), that $(E1/E0)_{FDA} = 1.43$ if $K \to \infty$, i.e., the Fermi-liquid drop ratio $(E1/E0)_{FDA}$ goes to the liquid drop model limit $(E1/E0)_{LDM}$ at $K \to \infty$. This fact is important from the point of view of a consistent description of the compression modes in the Fermi liquid. It is well-known that the zero sound velocity goes to the first sound limit at $K \approx 6\epsilon_F(1 + F_0) \to$

∞ , where F_0 is the Landau scattering amplitude, and both energies $E0$ and $E1$ have to go to the corresponding LDM predictions. In this respect, the scaling model is incorrect because it predicts the limit $(E1/E0)_{scaling} = \sqrt{7/3}$ at $K \to \infty$, see Ref. [3]. Our numerical calculation also gives that for the mass number A presented in Fig. 1 the ISGDR exhausts about 89% of sum m_1.

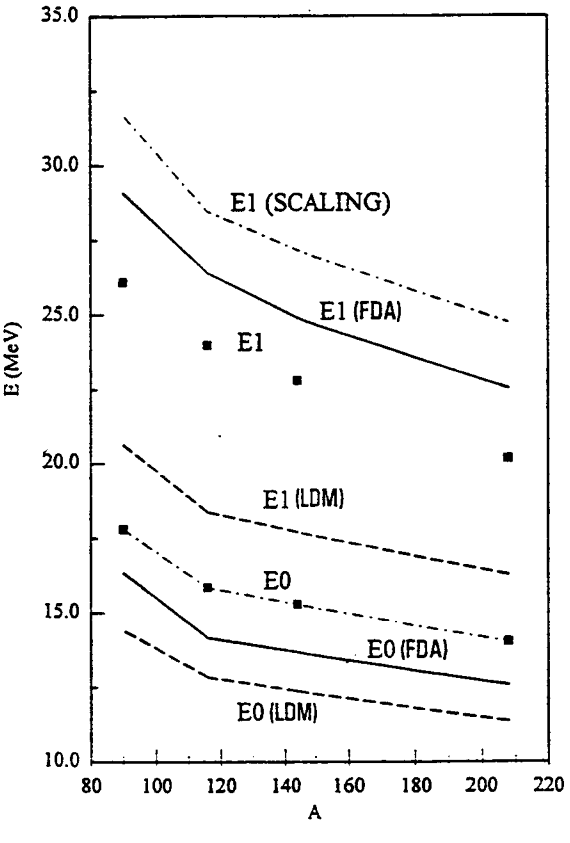

Figure 1. Energies of the isoscalar giant monopole ($E0$) and dipole ($E1$) resonances as functions of the mass number A. The dashed lines are related to the traditional liquid drop model and the solid lines are for the fluid dynamic approach (FDA) of the present work neglecting the effects of damping. The dot-dashed lines show the result of the scaling model [3]. The full squares are the experimental data from Ref. [4].

The position, $\hbar\omega_0$, and the width, $\Gamma = \hbar\gamma q^2$, of the compression mode depend on the relaxation time τ because of the Fermi surface distortion effect. The relaxation time is assumed to be frequency and temperature dependent and is taken in the form

$$\tau = 4\pi^2\beta\hbar/[(\hbar\omega_0)^2 + 4\pi^2T^2], \qquad (5)$$

where β is the constant related to the differential cross section for the scattering of two nucleons in the nuclear interior, and T is the temperature (here, $T = 0$). The dependence of the ISGDR and ISGMR energies and the corresponding widths on the collisional parameter β is shown in Fig. 2. In frequent collision regime ($\omega_0\tau \ll 1$, small β), the contribution to the sound velocity c_0 from the Fermi surface distortion effect is washed out and both energies $E0$ and $E1$ reach the first sound limit (i.e., the LDM regime). The non-monotonic behavior of the width in Fig. 2 is due to the memory effect (ω-dependence) in the relaxation time of Eq. (5). It shows the transition from the rare collision regime with $\Gamma \sim 1/\tau$ to the frequent collision regime with $\Gamma \sim \tau$.

Considering for ^{208}Pb the dependence of the energy ratio $E1/E0$ and the widths $\Gamma 0$ and $\Gamma 1$ for the ISGMR and the ISGDR, respectively, on the damping parameter β (see Eq. 5), we find a good agreement between experimental data [4] and the results of the FDA model calculations for the value of $\beta \sim 0.5$, see Fig. 2. We add that for ^{208}Pb, the effect of collisions is to reduce the values of $E0$ and $E1$ by about 0.7 and 3.0 MeV, respectively, i.e., increasing the value of K by about 20 MeV. This value of $\beta \sim 0.5$ is significantly smaller than the values of 4.25 obtained for nuclear matter in Ref. [5]. We point out, however, that for a finite system the collisional parameter β can absorb an additional contribution associated with the one body relaxation on the sharp potential surface. This fact leads to an effective decrease of the value of β with respect to the one for nuclear matter [6].

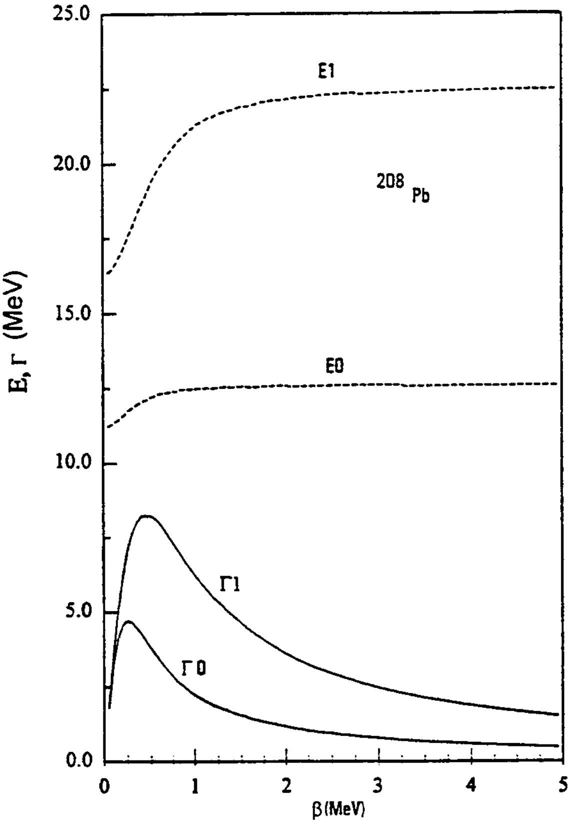

Figure 2. Dependence of the FDA energies E1 and E0 and the width Γ1 and Γ0 for the isoscalar giant dipole and monopole resonances on the damping parameter β, see Eq. 5, for ^{208}Pb.

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