Giant resonances: zero sound in cold nuclei and first sound in hot nuclei

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It is shown that zero-sound resonances are excited in nuclei for temperatures $T \lesssim 4.5$ MeV and that hydrodynamic giant resonances are excited for $T \gtrsim 4.5$ MeV. A simple analytic expression is obtained for the width of the hydrodynamic giant resonances. The width of giant dipole resonances is investigated as a function of temperature.

1. Giant multipole resonances were investigated[1,2] in "cold" nuclei between the middle 1940s and the late 1970s. At the beginning of the present decade, advances in experimental techniques had resulted in extensive studies of isovector giant dipole resonances (GDR) in hot nuclei at temperatures of 1–2 MeV (Refs. 3 and 4). At $T \simeq 0$–2 MeV, the GDR were Lorentzian in shape and their width was found to increase with increasing nuclear temperature.[3,4]

GDR properties of ^{110}Sn were recently investigated experimentally with maximum excitation energy of 360 and 610 MeV (Ref. 5). The corresponding nuclear temperatures were 3.5 (Ref. 5) and 6 MeV. We note, by the way, that ^{110}Sn was produced as a result of the complete fusion of two heavy ions, so that, when the temperature was calculated, allowance was made for the fact that about 80% of the maximum energy[5] was associated with the thermal excitation of the nucleus. This estimate was made using the standard value of the level-density parameter, i.e., $A/8$. When $T \simeq 3.5$ MeV, the GDR shape could be described[5] by a Lorentzian whose width was equal to the resonance excitation energy. This state decays practically in one oscillation period, so that the existence of coherent excitation with these parameters is problematic. When $T \simeq 6$ MeV, the shape of the γ-ray spectrum in the energy range 10–20 MeV, usually associated with photons radiated during the γ-decay of the GDR in a hot nucleus,[3,4] is significantly different from the γ-ray spectrum recorded at lower temperatures. For example, the γ-ray spectrum has an irregular structure that is not satisfactorily described by a Lorentzian, and the strength of the resonance, assuming it exists, is sharply reduced. This behavior of the γ-ray spectrum with increasing nuclear excitation energy in the energy range 10–20 MeV was ascribed in Ref. 5 to the fact that, because of the much greater randomness at higher temperatures, the coherence of the motion of nucleons in the nucleus is lost, and collective excitations are suppressed.

In this paper, we put forward a quantitative justification of the interpretation proposed in Ref. 5, determine the temperatures at which coherent collective excitations are present in the nucleus and elucidate their nature. We show that, in cold and warm nuclei, the GDR is the excitation of zero sound, whereas in hot nuclei it has the usual hydrodynamic origin (first sound).

2. Isovector GDCR in the form of zero sound and hydrodynamic excitation were discussed in Ref. 6 in terms of the gas-drop model of the nucleus.[7] The excitation energy of zero-sound GDR in a nucleus containing A nuclei is given by[6]

$$E_0(A)=2s(\hbar^2\varepsilon_F/2Mr_0^2)^{1/2}x(A)A^{-1/3}, \tag{1}$$

where s is related to the isovector interaction constant F_0^- of quasiparticles by the equation

$$G(s)=F_0^-, \tag{2}$$

where ε_F is the Fermi energy, $R = r_0A^{1/3}$ is the nuclear radius, M is the nucleon mass, $x(A)$ is the first nonzero root of the equation

$$j_1'(x)=(3\varepsilon_F x/4B^-A^{1/3})[(1-3s^2+G(s))j_1''(x)+(1-s^2+(2F_0^-+G(s))/3)j_1(x)]. \tag{3}$$

Here $j_1(x)$ are spherical Bessel functions, primes denote derivatives of $j_1(x)$, $B^- = 43.5$ MeV is the isovector surface shear stiffness, and

$$G(s)=[(s/2)\ln((s+1)/(s-1))-1]^{-1}.$$

According to Ref. 6, the width of the zero-sound GDR is related to the excitation energy and nuclear temperature by[1)]

$$\Gamma_0(A)=a_0(E_0^2(A)+(2\pi T)^2). \tag{4}$$

The coefficient $a_0 = 0.02$ MeV^{-1} is inversely proportional to the coefficient η_0 in the quasiparticle viscosity $\eta = \eta_0/T^2$:

$$a_0=\hbar\bar{\rho}\varepsilon_F/(10\pi^2\eta_0), \tag{5}$$

where $\bar{\rho} = 3/(4\pi r_0^3)$ is the nuclear density. In the nculear case, $\eta_0 = 1.84\cdot10^{-21}$ MeV$^3\cdot$c/fm^3 (Ref. 6) and the mean free time of quasiparticles is

$$\tau=5\eta_0/(2\bar{\rho}\varepsilon_F T^2). \tag{6}$$

The excitation energies, widths, and the extent of exhaustion of the model-independent energy-weighted sum rule for the GDR, calculated in Refs. 6 and 8 for zero-sound oscillations, are in good agreement with experimental data on spherical and deformed nuclei.

The hydrodynamic GDR excitation energy can be found from (1) and (3) after formally introducing replacements that transform from zero to first sound: $s = 1/\sqrt{3}, G(s) = 0$. The isovector bulk compressibility is related to the isovector interaction constant of the quasiparticles[2] and is given by $K^- = 6\varepsilon_F(1 + F_0^-)$. (We note that, in Refs. 6 and 8, K^- was not related to ε_F and F_0^- because first sound was not related in these publications to the quasiparticle excitations of the nculeus.) If we introduce the above replacements in (1) and (3), we obtain the relationships for the hydrodynamic GDR excitation energies reported in Refs. 6 and 8.

Using the theory of the Fermi liquid,[9] we can now write

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down the collision integral in the kinetic equation for acoustic excitations in the form of a superposition of plane-wave solutions of the kinetic equation over the different directions of the wave vector. Then, having employed the procedures used in Ref. 6 to evaluate the width of the zero sound GDR, we find the width Γ_1 of hydrodynamic GDR in the limit of acoustic frequencies ω that are small in comparison with the quasiparticle collision frequency $(1/\tau)$ $(\omega\tau \ll 1)$:

$$\Gamma_1(A) = a_1 E_1^2(A)/T^2, \qquad (7)$$

where

$$a_1 = \eta_0/((1+F_0^-)\varepsilon_F \bar{p}\hbar).$$

Substituting the parameter values $F_0^- = 1.6$, $\varepsilon_F = 40$ MeV, $r_0 = 1.2$ fm, employed in Ref. 6, we obtain $a_1 = 0.2$ MeV.

Zero sound of frequency ω propagates in Fermi systems if $\omega\tau \gg 1$, whereas first sound propagates in such systems if $\omega\tau \ll 1$ (Ref. 9). Let us determine the critical temperature T_{cr} for which the quasiparticle collision frequency is equal to the frequency of acoustic oscillations, i.e., $\omega\tau = 1$. We find from (6) that

$$T_{cr} = (5\eta_0 E(A)/2\bar{p}\varepsilon_F \hbar)^{1/2} \simeq 1.12 E^{1/2}(A), \qquad (8)$$

where $E(A)$ is in MeV and the coefficient in front of $E^{1/2}(A)$ was calculated for the above parameters values. Since for intermediate and heavy nuclei $E(A) \sim 16$ MeV for both zero and first sounds, we obtain $T_{cr} \sim 4.5$ MeV.

Since, according to (6), the mean free time τ of quasiparticles is inversely proportional to the square of the nuclear temperature, zero-sound excitations are present in the nucleus for $T \lesssim \frac{1}{2}T_{cr}$, whereas hydrodynamic oscillations are observed for $T \gtrsim 2T_{cr}$. The widths of these excitations are described by (4) and (7), respectively. We note that the zero-sound width increases with increasing temperature, whereas the first-sound width is found to decrease. The reduction in the first-sound width with increasing temperature is due to the reduction in the viscosity of a Fermi liquid with increasing temperature at low temperatures $T \ll \varepsilon_F$. We note that the coefficient η_0 varies as the temperature increases and, at high temperatures $T \gg \varepsilon_F$, is proportional to $T^{5/2}$; the viscosity η is proportional to $T^{1/2}$ (Ref. 10). When $T \sim T_{cr}$, the acoustic wave propagating in nucleus is intermediate between zero and first sound. Its width is not described by (4) and (7) for $T \sim T_{cr}$. The sound is highly damped because its frequency is equal to the quasiparticle collision frequency, leading to a loss of coherence in the motion of nucleons in the interior of the nucleus. It is precisely for this reason that the GDR strength at $T \simeq 6$ MeV was found to be small in Ref. 5, and a highly damped aperiodic GDR-type state was found at $T \simeq 3.5$ MeV. It is important to note at this point that GDR can be excited in a nucleus after the emission of particles by it, i.e., at temperatures that are small in comparison with T_{cr}. This can lead to the appearance of the GDR strength at high temperatures.

The figure shows the width as a function of the nuclear temperature, calculated for ^{110}Sn from (4) and (7), and the experimental data taken from Refs. 3 and 4. It is clear from the figure that the theoretical, GDR widths are in good agreement with experimental values for $T \lesssim 2$ MeV. The calculations based on (1)–(4) and (7) were carried out for the parameter values given above. The calculated zero-sound

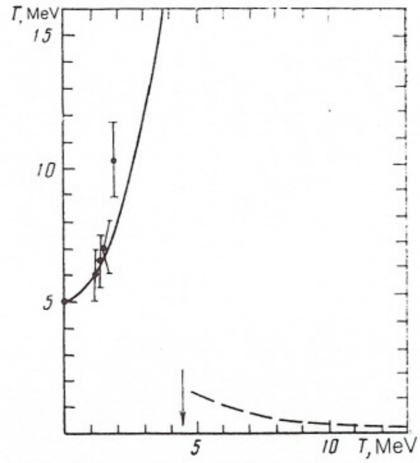

FIG. 1. GDR width as a function of nuclear temperature. Points—experimental data, solid curve—calculated from (4), dashed curve—calculated from (7). The arrow marks the value of the critical temperature.

excitation energy in the case of tin ($E_0 = 15.8$ MeV) is not very different from the first-sound excitation energy ($E_1 = 13.7$ MeV). The magnitude of E_0 differs slightly from the experimental values of GDR energies in "cold" and "warm" nuclei reported in Refs. 3 and 4 ($E_0 = 15.5$–16 MeV).

3. The above discussion of isovector GDR can readily be generalized to the case of isoscalar and isovector giant resonances of different multipolarity in spherical or deformed nuclei. Studies of hydrodynamic resonances provide unique information on the various properties of "hot" nuclei, e.g., their deformation.

We note that we have assumed that the usual static model remains valid at very high temperatures up to $T \gtrsim T_{cr}$. This question remains relatively complex and unresolved. It will be necessary to perform a detailed analysis of the thermodynamic properties of nuclei at such temperatures and, whenever necessary, introduce corrections to the above analysis of hydrodynamic oscillations. We note that the theory of Fermi liquids, developed in Ref. 9, is valid for $T \ll \varepsilon_F$ (Refs. 10 and 11), i.e., in other words, it is valid for $T \gtrsim T_{cr}$, $T \ll \varepsilon_F$.

The problem of the lifetime of a nucleus at high temperatures is important from the point of view of experimental detection of hydrodynamic resonances. The necessary condition for a resonance to be detected experimentally is that the lifetime of the highly excited nucleus be longer than or comparable with the resonance lifetime. The lifetime of a nucleus at excitation energy equal to the nuclear binding energy is approximately equal to the time taken by a nucleon to cross the nuclear diameter ($\sim 10^{-22}$ sec). This time is shorter at lower excitation energies, and is comparable with the lifetime of the hydrodynamic GDR (10^{-21}–10^{-22} sec.).

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[1)]Several workers have used this relation to calculate the resonance excitation energy in other approximations. However, both the excitation energy and the GDR width were calculated in Ref. 6 in the same approach, i.e., in the zero-sound approximation.

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