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Damping of nuclear motion in hot nuclei

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Abstract

The calculated damping width of single-particle states is found to depend linearly with the temperature of excited nuclei, while the damping width of giant resonances seems to be independent of temperature. This result is understood in terms of the correlation existing between the particle and the hole participating in the vibration.

During the past few years the giant dipole resonance (GDR) has been systematically studied in the decay of compound nuclei [1-6]. A central question addressed in these studies concerns the evolution of the damping width $\Gamma^{\downarrow}_{\mathrm{GDR}}$ of the vibration as a function of the temperature of the compound system. The quest has become of particular relevance after it has been found [7–11] that there exist a critical temperature ($T \approx$ 4–5 MeV) above which the multiplicity of the γ-rays associated with the decay of thermally excited GDR saturates, and the mode is not observed in the associated compound nucleus γ-decay. Two scenarios have been proposed to explain this phenomenon:

1) The damping width of the GDR is essentially independent of temperature, and consequently, the time ($\approx \hbar/\Gamma^{\downarrow}_{\mathrm{GDR}}$) it takes for the GDR to be present as a thermal excitation of the composite system is also independent of temperature. On the other hand, the particle-decay width, $\Gamma^{\uparrow}_{\mathrm{CN}}$, is expected to increase as a function of the excitation energy of the compound nucleus. Therefore, the temperature at which $\Gamma^{\uparrow}_{\mathrm{CN}} \approx \Gamma^{\downarrow}_{\mathrm{GDR}}$ defines the critical temperature [12] above which the primary decay mode of the compound nucleus is through particle decay, and the GDR is unable to come into thermal equilibrium with the other degrees of freedom of the compound nucleus.

2) The damping width of the GDR increases strongly with temperature, eventually becoming so large that the vibration ceases to exist as a well defined mode of excitation [9,13-16].

The fact that these two completely opposite scenarios have been proposed, reflects the confusion existing concerning the outcome of microscopic calculations of $\Gamma^{\downarrow}_{\mathrm{GDR}}$, such as those reported in Ref. [17]. The corresponding results are involved to obtain and are not easily explained in simple terms. In the present paper, we present, for the first time, general arguments, based on detailed analysis of microscopic calculations, which testify to the fact that $\Gamma^{\downarrow}_{\mathrm{GDR}}$ is essentially independent of temperature. This result is quite general and depends only on the central role played by the nuclear surface in the damping of nuclear motion.

Collective vibrations can be viewed as a correlated particle above the Fermi surface and of a hole in the Fermi sea. Consequently, the damping width of the giant resonance is intimately connected with the width

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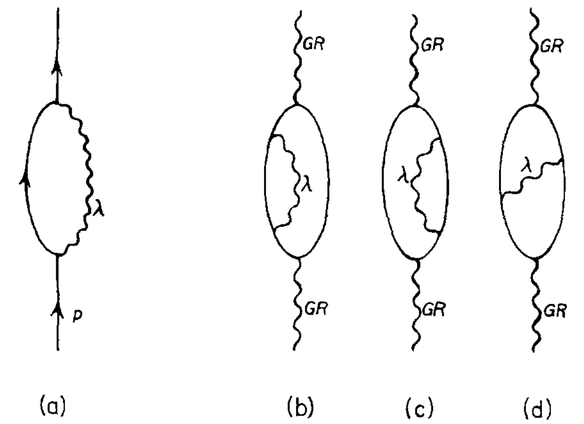

Fig. 1. Self-energy diagram for the single-particle state (a) and for the giant resonance (b), (c) and (d). An arrowed line pointing upwards(downwards) describes the particle (hole) propagation. A wavy line, labeled λ, describes the surface vibration while GR the giant vibration.

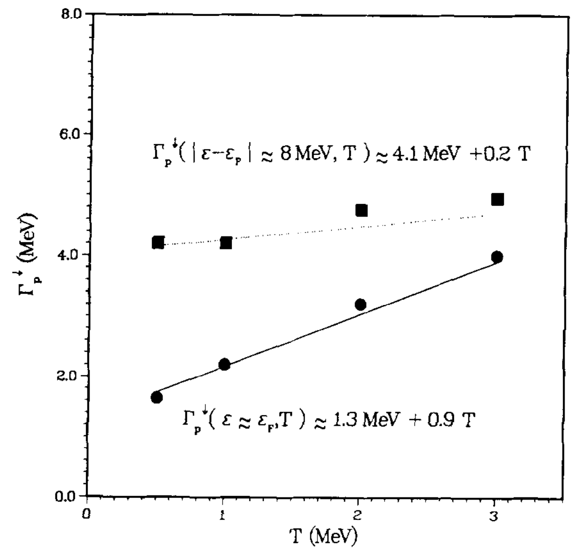

Fig. 2. Single-particle damping width plotted as a function of temperature and associated with a particle at the Fermi energy in ^{120}Sn (solid dots) and at 8 MeV away from it (solid squares). The lines are to guide the eye.

of single-particle states. A nucleon can change its state of motion by colliding with another nucleon and exciting it to a state above the Fermi surface, thus leaving behind a hole in the Fermi sea. Because in the nuclear case, particle-hole correlations are conspicuously more important than particle-particle correlations, the above process can be accurately described in terms of the coupling of a nucleon to vibrations of the nuclear surface (cf. e.g. Refs. [18,19]).

In the present work, the calculation of the particle damping width was carried out in lowest order perturbation theory. The basic parameter of the theory is the strength with which the particle couples to surface vibrations [20]. The Matsubara formalism of thermal Green's function was used in the calculations. The corresponding correction to the self-energy of the particle is shown in Fig. 1(a). The associated rules for the calculations of this type of process and the resulting expression are well known, and we refer the reader to [17,21] for details. From the knowledge of the real and imaginary part of the single-particle self-energy, one can construct the strength function, and the full width at half maximum of this function is identified with the single-particle damping width (FWHM $= \Gamma_p^{\downarrow}$).

The calculation of $\Gamma_p^{\downarrow}$ has been carried out for a number of spherical nuclei, among them ^{120}Sn. The unperturbed single-particle energies were determined in terms of a Woods-Saxon potential. In keeping with the fact that all the calculations were carried out for temperatures larger than 0.5 MeV, pairing correlations were not taken into account. The vibrations of the system were obtained using multipole-multipole effective forces within the framework of the random phase approximation (RPA). The corresponding results provide all the elements needed to calculate the process displayed in Fig. 1(a), and the associated response functions of the valence single-particle orbitals $2d_{3/2}$, $1h_{11/2}$, $3s_{1/2}$, $2d_{5/2}$ and $1g_{7/2}$. The resulting average FWHM is shown in Fig. 2 as a function of temperature. The results are well fit by the relation

$$\Gamma_p^{\downarrow}(\epsilon \approx \epsilon_F, T) \approx \alpha + \beta T, \qquad (1)$$

where $\alpha \approx 1.3$ MeV and $\beta \approx 0.9$. Similar results have been obtained in [17] for the nucleus ^{208}Pb. The behavior of $\Gamma_p^{\downarrow}$ with temperature described by Eq. (1) can be understood in terms of the following consideration: a) in a hot nucleus, temperature can be viewed as the energy available to nucleons at the Fermi energy to undergo real transitions to more complicated configurations, and b) the low-energy RPA response is essentially constant with energy, due to the presence of a number of low-lying collective surface vibrations (cf. the Appendix of Ref. [17]). For later use we also display in Fig. 2 the average FWHM as a function of

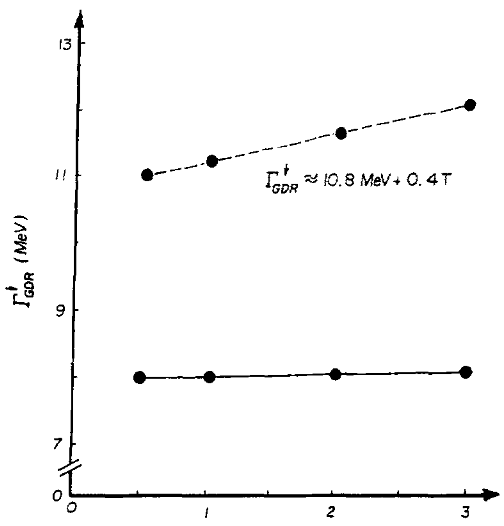

Fig. 3. Damping width of the GDR of ^{120}Sn as a function of temperature. The continuous line joins the values calculated taking into account all three processes (b)–(d) displayed in Fig. 1. The dashed line joins the results obtained taking into account only the processes displayed in Fig. 1(b) and 1(c) (self-energy contributions).

temperature of the single-particle strength functions associated with the orbitals $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$ lying at an energy $|\epsilon - \epsilon_F| \approx 8$ MeV. In this case $\alpha \approx 4.1$ MeV and $\beta \approx 0.2$.

A naive model of the damping of giant resonances is based on the assumption that the particle and the hole decay independently [18,20,22–24]. Within such a model one expects

$$\begin{aligned}\Gamma^{\downarrow}_{\mathrm{GR}}(\hbar\omega_v, T) \\ &\approx \Gamma^{\downarrow}_p(\epsilon \approx \tfrac{1}{2}\hbar\omega_v, T) + \Gamma^{\downarrow}_h(\epsilon \approx \tfrac{1}{2}\hbar\omega_v, T) \\ &\approx 2\Gamma^{\downarrow}_p(\epsilon \approx \tfrac{1}{2}\hbar\omega_v, T),\end{aligned} \tag{2}$$

where $\hbar\omega_v$ is the energy centroid of the vibration. To make this relation quantitative, we calculate the correction to the unperturbed Green function of the vibration associated with the decay of the particle or of the hole (cf. Figs. 1(b) and 1(c)). Making use of the elements discussed above in connection with the calculation of $\Gamma^{\downarrow}_p$, the real and imaginary part of the vibration self-energy and the corresponding strength function have been worked out. The associated FWHM is shown in Fig. 3 as a function of temperature. The results can be parametrized by the function 10 MeV + 0.4 T, as expected from Eq. (2) and the results for $\Gamma^{\downarrow}_p(|\epsilon - \epsilon_F| \approx 8\ \mathrm{MeV}, T)$ displayed in Fig. 2, in keeping with the fact that $\hbar\omega_v \approx 16$ MeV.

On the other hand, it is well known that Eq. (2) overestimates the observed damping width of giant resonances already at $T = 0$ MeV. This is because the full self-energy operator of the vibration contains, aside from the contribution displayed in Figs. 1(b) and 1(c), the correction shown in Fig. 1(d). This graph takes into account the fact that the decay of a particle in the presence of a hole allows for an exchange of the vibration between the particle and the hole, a process known as vertex-correction [21]. This boson exchange acts as an effective glue between the particle and the hole, and cancels much of the contribution to the damping phenomenon associated with processes (b) and (c) of Fig. 1. The FWHM of the strength function calculated taking into account all the contributions to the self-energy of the vibration is shown in Fig. 3 as a function of T. The result is essentially independent of temperature [1] (cf. also [17,25]), and can be understood in simple terms that are also quite general. In fact, because the energy of the surface vibrations are of the order of 1–2 MeV, no real transitions of a particle at the Fermi level to more complicated states are possible, in particular, to states containing a particle and a vibration. For particles moving in levels progressively removed from the Fermi energy, real transitions become progressively more prolific. Consequently, and in keeping with the fact that temperature can be viewed as the energy available to a particle at the Fermi energy to make real transitions, temperature is expected to have a more conspicuous effect for a single-particle level at the Fermi energy than for a single-particle level far away from the Fermi surface (cf. Fig. 4). In fact, as shown above in connection with Eq. (1), $\beta(\epsilon_{\mathrm{sp}} - \epsilon_F = 0) \approx 0.9$ and $\beta(|\epsilon_{\mathrm{sp}} - \epsilon_F| \approx 8\ \mathrm{MeV}) \approx 0.2$, where $|\epsilon_{\mathrm{sp}} - \epsilon_F| \approx 8$ MeV is the typical energy for a particle or a hole participating in a GDR, in keeping with the fact that the centroid of the vibration lies at ≈ 16 MeV. Because of the cancellation existing between the particle and

[1] The fact that we predict a value of ≈ 8 MeV for the damping width of the GDR of ^{120}Sn at $T = 0$ MeV (as compared with the experimental value of 5 MeV), is connected with the rather large fragmentation of the resonance observed already at the RPA level (Landau damping) a result which is to be adscribed to the single-particle basis used in the present calculation.

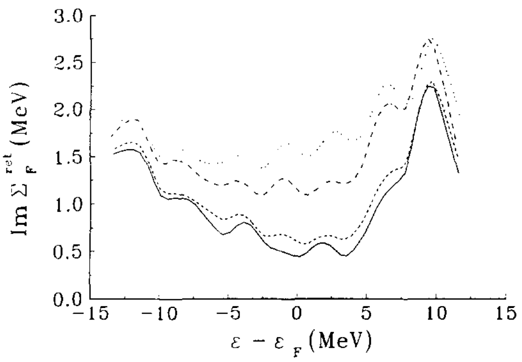

Fig. 4. Imaginary part of the single-particle retarded self-energy for a particle at the Fermi surface as a function of the energy, displayed for T = 0.5 MeV (solid), 1 MeV (dash), 2 MeV (dash-dot) and 3 MeV (dots).

the hole contributions to $\Gamma^{\downarrow}_{\mathrm{GDR}}$, the β coefficient associated with the temperature dependence of $\Gamma^{\downarrow}_{\mathrm{GDR}}$ is expected to be a fraction of $\beta(|\epsilon_{sp} - \epsilon_F| \approx 8$ MeV), a quantity typically of the order of 0.1 or less. Consequently, within the range of temperature $0 \leq T \leq$ 4 MeV, the width of the GDR is expected to increase at most by 0.4–0.5 MeV, an increase to be compared to the value $\Gamma^{\downarrow}_{\mathrm{GDR}}(T = 0) \approx$ 5–6 MeV.

In summary, one can state that although $\Gamma^{\downarrow}_{\mathrm{GDR}}$ increases linearly with T, its variation within the temperature interval of interest is so weak that $\Gamma^{\downarrow}_{\mathrm{GDR}}$ can be considered, for all practical purposes, to be independent of temperature. This result, combined with that of Ref. [26], stating that the coupling of the giant vibration to the compound nucleus (CN) leads to a damping width that is also temperature independent, gives quantitative support to the suggestion advanced in previous occasions [27–29], namely, that the GDR should exist in hot nuclei as a well defined excitation at all temperatures. A different question is, whether its possible γ-decay in competition with CN-particle decay, can be observed at all values of T.

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