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Temperature dependence of the damping width of single-particle states in hot nuclei

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Abstract. The temperature dependence of the damping width $\Gamma^{\downarrow}_{sp}$ of single-particle levels of atomic nuclei is calculated as a function of temperature T. It is found that $\Gamma^{\downarrow}_{sp}$ displays a linear dependence with temperature in the range $0.5\,\mathrm{MeV} \leq T \leq 3$ MeV.

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The basic element in the description of the nuclear structure is the existence of a mean field where nucleons move independently of each other. Beyond mean field, collisions among the nucleons renormalize in an important way the single-particle motion, in particular in hot nuclei (cf. e.g. [1–5]). In a collision, a nucleon can change its state of motion by promoting a particle moving in the Fermi sea, to a state above the Fermi surface. Particle-particle, pairing-like correlations are, in the nuclear case, considerably weaker than the particle-hole correlations. Furthermore, Pauli principle makes it more favorable for a collision among nucleons to take place on the nuclear surface than in the volume of the nucleus. This is the reason why, an accurate description of collisions among nucleons is provided by the coupling of nucleons to collective vibrations of the nuclear surface. In fact, quantum-mechanical, non-perturbative studies of the role played by collisions on the nuclear structure have been carried out within the framework of time-dependent-density-matrix theory [5]. The results obtained were found, at all temperatures, to be very similar to those obtained treating collisions perturbatively within the particle-vibration coupling model [4], where the motion of particles in levels close to the Fermi energy ϵ_F is dressed through couplings to the nuclear surface. The associated "dressing" leads only to virtual transitions and thus to an effective mass, the so-called ω-mass (cf. e.g. [6]). For particles moving in single-particle levels with energies progressively larger in absolute value, from that of the Fermi energy, both virtual and real transitions are possible, and the single-particle levels acquire a width [7]. The above arguments are also valid in the case of open shell superfluid nuclei, exception made that in this case the minimum energy a quasiparticle state can have is Δ, that is, an energy equal to that of the pairing gap. Consequently, in superfluid nuclei, particles moving in a single-particle level with energy ϵ_F can still experience real transitions and thus display a finite lifetime.

Heating up the nucleus has a number of implications. In particular, the Fermi surface becomes diffuse over an energy range of the order of the temperature T of the system. A consequence of this fact is that a nucleon at the Fermi surface, also in nuclei that are closed shell at T= 0 MeV, can now undergo real transition and thus acquire a width. In the present paper we shall calculate the damping width $\Gamma^{\downarrow}_{sp}$ of a nucleon at the Fermi energy as a function of temperature. We shall conclude that the results can be parametrized by a linear function.

The calculations have been carried out making use of Matsubara's formalism of thermal many-body Green functions (cf. e.g. [4, 8]). The single-particle self-energy is, to second order in the matrix element V coupling the single-particle motion to surface vibrations, given by

$$\Sigma_{(2)}(1,\omega+i\eta,T) = \sum_{2,\lambda_n} V^2(1,2;\lambda_n) \left(\frac{1+n_B(\lambda_n)-n_F(2)}{\omega+i\eta-\epsilon_2-\omega_{\lambda_n}} + \frac{n_B(\lambda_n)+n_F(2)}{\omega+i\eta-\epsilon_2+\omega_{\lambda_n}} \right). \quad (1)$$

The labels 1 and 2 are the quantum numbers of the single-particle states involved in the process, with energies ϵ_1 and ϵ_2 respectively. The collective vibration is labeled by the subindexes λ and n. The first indicates the multipolarity of the vibration. For each multipolarity there are many roots, solutions of the quasiparticle random phase approximation (QPRPA) equations. That is, there are many vibrations, some collective, others not, for each spin and parity. The label n (with n=1,2 $\cdots$) identifies each of them, the lowest one in energy carrying the label n=1, the second n=2, etc $\cdots$. The quantities $n_B(\lambda_n)$ and $n_F(i)$ are Bose-Einstein and Fermi occupation numbers respectively. Finally, the interval of energy over which averages are taken is indicated by η. Values ranging in the interval 0.2 MeV–0.5 MeV were used in the calculations.

From (1) one can calculate the imaginary and the real parts of the self-energy, that is

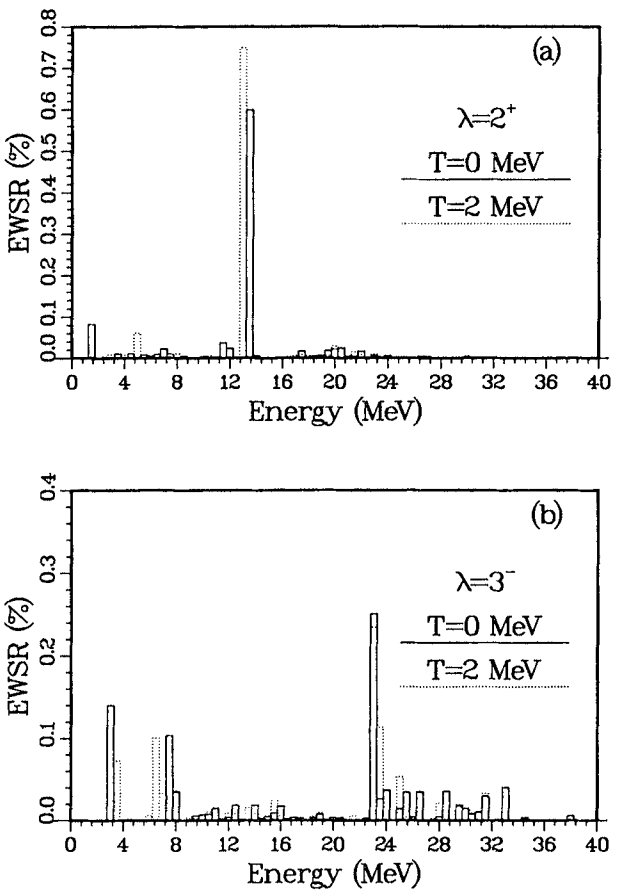

Fig. 1a,b. Multipole response of ^{98}Mo at T = 0 MeV and at T = 2 for multipolarities $\lambda^{\pi} = 2^{+}$ (**a**) and $\lambda^{\pi} = 3^{-}$ (**b**)

$$W(1,\omega,T) = \mathrm{Im}\Sigma_2(1,\omega + i\eta, T), \tag{2}$$

$$\Delta E(1,\omega,T) = \mathrm{Re}\Sigma_2(1,\omega + i\eta, T). \tag{3}$$

With these quantities one can construct the single-particle strength function (cf. e.g. [9] app.2D)

$$P_1(1,\omega,T) = \frac{1}{2\pi}\frac{\Gamma + I}{(\epsilon_1 + \Delta E - \omega)^2 + \frac{1}{4}(\Gamma + I)^2}, \tag{4}$$

where Γ=2×W(1,ω,T) and I=2×η.

The calculations have been carried out for a number of spherical nuclei, in particular ^{98}Mo and ^{64}Zn. The unperturbed single-particles energies ϵ_i were determined as solutions of a Woods-Saxon potential

$$U(r) = V_0\left(1 + exp\left(\frac{r - R_0}{a}\right)\right)^{-1}, \tag{5}$$

where R_0=1.25$A^{1/3}$ fm is the radius and a=0.65 fm is the diffusivity. On this basis the BCS solution for a pairing force with constant matrix element was calculated. Allowing the nuclear radius to oscillate, one obtains, in first order in the deformation parameters $\alpha_{\lambda\mu}$, an extra contribution to the energy given by

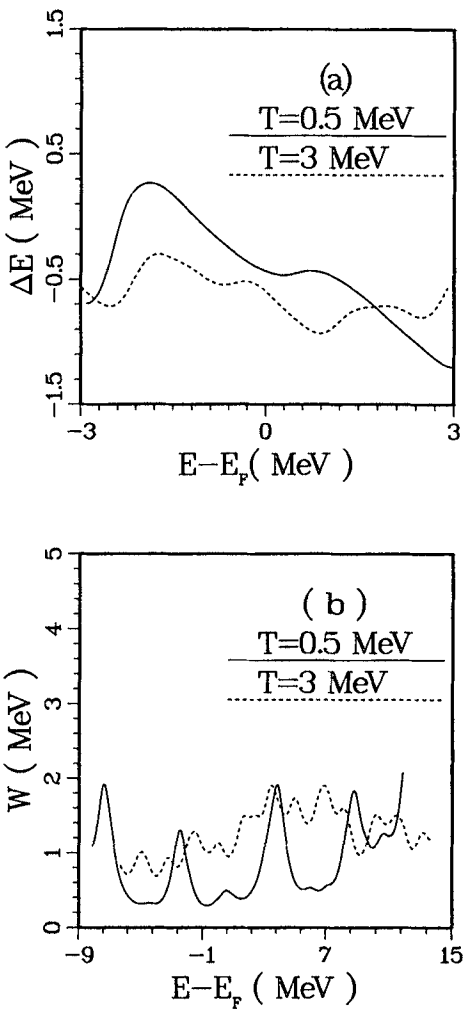

Fig. 2a,b. Average values of the real (**a**) and imaginary (**b**) part of the self-energy for the nucleus ^{98}Mo at T = 0.5 MeV and at T = 3MeV. A value η=0.5 MeV was used in the calculations

Table 1. Parameters α and β of the linear fitting to $\Gamma^{\downarrow}_{sp}$ as a function of T, calculated for different value of the averaging parameter η (I=2η). In the last line of each group of results the average values of α and β are written with the corresponding errors

Nucleus	I (MeV)	α (MeV)	β
^{98}Mo	0.4	0.0	0.65
	0.6	0.0	0.90
	0.8	0.2	0.90
	1.0	1.0	0.70
		$0.3^{+0.7}_{-0.3}$	$0.8^{+0.10}_{-0.15}$
^{64}Zn	0.4	0.9	0.3
	0.6	1.2	0.2
	0.8	1.4	0.2
	1.0	1.0	0.5
		$1.1^{+0.3}_{-0.2}$	$0.3^{+0.2}_{-0.1}$

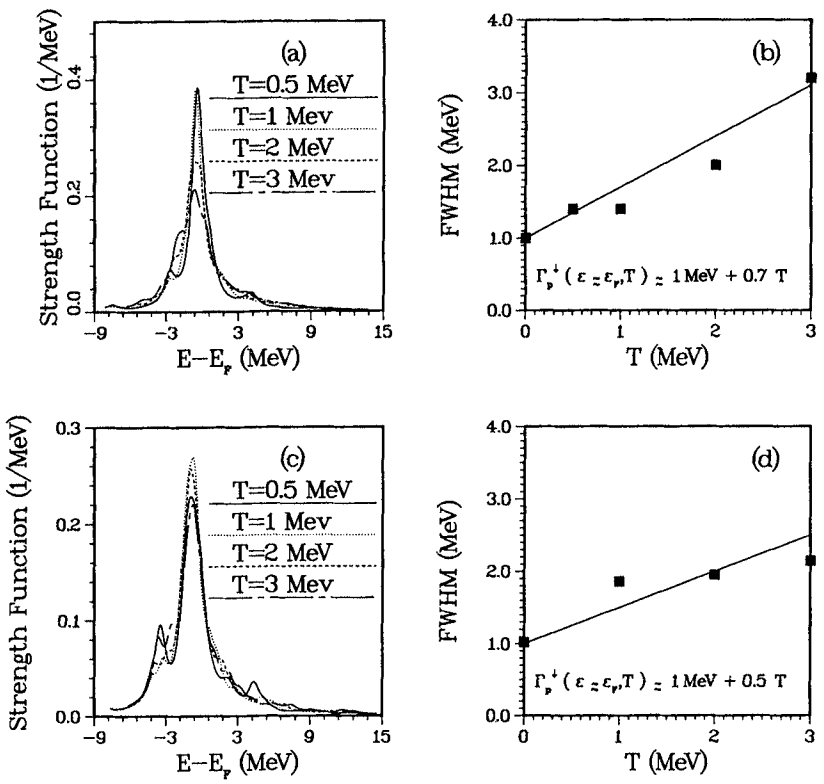

Fig. 3. (**a**) Strength functions and (**b**) full widths at half maximum (**b**) for a number of temperatures in the range 0.5 MeV $\leq$ T $\leq$ 3 MeV for the case ^{98}Mo. Graphs (**c**) and (**d**) show the same quantities but for the nucleus ^{64}Zn. A value of η=0.5 MeV was used in the calculations

$$\delta U = -R_0 \frac{\partial U(r)}{\partial r} \sum_{\lambda\mu} \alpha_{\lambda\mu} Y^*_{\lambda\mu}(\hat{r}). \tag{6}$$

This potential provides a coupling between the single-particle motion and the collective vibrations of the surface [9]. The corresponding matrix elements $\langle 2, \lambda_n | \delta U | 1 \rangle$ are denoted V(1,2;λ_n) in (1). Making use of these matrix elements and of the single particle energies ϵ_i, one can calculate the properties of the collective modes λ_n. This has been done within the framework of linear response theory, the QPRPA for T=0 MeV ($\Delta \neq 0$) and in the so-called finite temperature random phase approximation for T$\neq$0 (Δ =0) [10]. Results for the nucleus ^{98}Mo corresponding to λ^π=2$^+$ and λ^π=3$^-$, that is quadrupole and octupole surface vibrations and for a couple of temperatures are displayed in Fig. 1.

The existence, at low-temperature (T=0 MeV), of low-lying collective vibration carrying a sizable fraction of the energy-weighted sum rule (EWSR) is apparent from the figure. In particular the low-lying quadrupole surface vibration of ^{98}Mo carries $\approx$ 10% of the EWSR and an associated B(E2) value corresponding to $\approx$ 20 Weiskopf units (W.u) while the lowest 3$^-$ carries 14% of the EWSR and 33 W.u. These are the states which play the most important role in the renormalization processes described by (1). Similar results are obtained in the other nuclei calculated. Increasing the temperature of ^{98}Mo to T=2 MeV has essentially no consequences for the high lying modes with excitations energies larger than 10 MeV, corresponding to the region of the giant resonances, while significant changes are observed at low excitations energies ($\leq$ 3 MeV), where temperature essentially quenches the correlations of surface vibrations, leading also to a conspicuous fragmentation of the strength.

Making use of the elements discussed above, the real and imaginary part of the self-energy associated with single-particle levels lying around the Fermi energy have been calculated. For each temperature, an average value has been defined according to the relation

$$\overline{A}(\omega, T) = \frac{\sum_n (2j_n + 1) A_{j_n}(j_n, \omega, T)}{\sum_n (2j_n + 1)}, \tag{7}$$

where A(j_n, ω, T) stands for any of the quantities defined in (2) and (3). The single-particle states used to calculate this average are $2d_{5/2}$, $3s_{1/2}$, $1g_{7/2}$, $2d_{3/2}$, $1h_{11/2}$ for the nucleus ^{98}Mo and $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, $1g_{9/2}$, $2d_{5/2}$ for the case of ^{64}Zn. Examples of $\overline{W}$ and $\overline{\Delta E}$ in the temperature range of 0.5 $\leq$ T $\leq$ 3 MeV, are shown in Fig. 2 for the case of the valence orbitals of ^{98}Mo. Inserting these average values in (4), one obtains an average single-particle strength function (cf. Figs. 3a and c). The corresponding full width at half maximum (FWHM) are shown in Fig. 3b and d. The results can be parametrized in terms of the sum of the value of $\Gamma^{\downarrow}_{sp}$ at T=0 MeV, plus a linear function of T (cf. also [4, 11])

$$\Gamma^{\downarrow}_{sp} = \alpha + \beta T. \tag{8}$$

A value of η=0.5 MeV (I=1 MeV) was used in the calculations reported in the figures. To test the uncertainty introduced in the value of $\Gamma^{\downarrow}_{sp}$ by the averaging parameter, we have repeated the calculations for other values of η, namely 0.2, 0.3 and 0.4 MeV. The results can again be parametrized by the function given in (8), the corresponding parameters α and β being collected in Table 1. As expected, the main uncertainty is found in connection with the value of $\Gamma^{\downarrow}_{sp}$ at T=0 MeV (α coefficient). In any case, the linear dependence of $\Gamma^{\downarrow}_{sp}$ with T emerges in all cases. This result is very different from the one expected in the case of infinite systems, where $\Gamma^{\downarrow}_{sp}$ depends quadratically on temperature [12], reflecting the increase in the number of collisions due to the relaxation of the Pauli principle. The reason for this difference is that in the finite (infinite) system, the most important dressing process is that associated with the coupling of a particle to the correlated (uncorrelated) particle-hole excitations. The intermediate states describing the corresponding process are liner (quadratic) in the occupation numbers. The linear (quadratic) temperature dependence ensues.

We conclude that the damping width of single-particle states close to the Fermi energy displays a linear dependence with temperature.

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