Nonperturbative Study of the Damping of Giant Resonances in Hot Nuclei

F. V. De Blasio,(1) W. Cassing,(2) M. Tohyama,(3) P. F. Bortignon,(4),(5) and R. A. Broglia(1),(5),(6)
(1)*Dipartimento di Fisica, Università di Milano, Milano, Italy*
(2)*Institut für Teoretische Physik, Universität Giessen, Giessen, Germany*
(3)*School of Medicine, Kyorin University, Tokyo, Japan*
(4)*Dipartimento di Ingegneria Nucleare, Politecnico di Milano, Milano, Italy*
(5)*Istituto Nazionale di Fisica Nucleare, sezione di Milano, Milano, Italy*
(6)*The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
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The damping of dipole and quadrupole motion in ^{16}O and ^{40}Ca at zero and finite temperature is studied including particle-particle and particle-hole interactions to all orders of perturbation. We find that the dipole dynamics in these light nuclei is well described in terms of mean-field theory (time-dependent Hartree-Fock), while the quadrupole motion is strongly damped through the coupling to more complicated configurations. Both the centroid and the damping width of the quadrupole and dipole giant resonances show a clear stability with temperature as a consequence of the weakening of the interaction, which contrasts with the increase of the phase space.

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Giant resonances are the nuclear zero sounds. Once excited it takes a few periods before the oscillation relaxes. Empirical evidence from excited nuclei testifies to the fact that the properties of these resonances are remarkably stable with temperature. In fact, the centroid seems not to change with excitation energy, while the conspicuous changes observed in the damping width as a function of temperature can be mainly attributed to deformation effects induced by the fast rotation of the hot nucleus [1].

A variety of studies have identified the coupling to the nuclear surface as the main damping mechanism [2]. Ultimately, this coupling can be traced back to collisions among the nucleons. However, central questions remain unanswered concerning the nature of these processes, the most pressing being its temperature dependence. In what follows we shall address this question in a systematic way. It will be concluded that theory provides a simple explanation of the observations based on the fact that the progressive loss of definition of the Fermi surface as a function of temperature is accompanied by a progressive loss in the definition of the nuclear surface. While the first phenomenon makes collisions more prolific, the second makes each of them less effective.

The Hartree-Fock approximation provides a natural description of the single-particle motion in atomic nuclei. Its time-dependent extension (TDHF) constitutes a powerful tool to study collective motion in many-body systems, and also for going beyond the collisionless regime.

A general formulation of mean-field theories supplemented by collisions has been given in Refs. [3,4], resulting in a set of coupled equations for the one-body density matrix $\rho(1,1';t)$ and the two-body correlation function $c_2(12,1'2';t)$. Because of technical limitations these equations can, at present, only be solved accurately for small-amplitude nuclear motion. In this case one can expand both ρ and c_2 in terms of single-particle states ψ_α fulfilling the TDHF equations,

$$\left[i\hbar\frac{\partial}{\partial t}-h(1)\right]\psi_\alpha(1,t)=0\,, \qquad (1)$$

according to

$$\rho(1,1',t)=\sum_{\alpha,\beta}n_{\alpha\beta}\psi^*_\beta(1',t)\psi_\alpha(1,t)\,, \qquad (2)$$

and

$$c_2(1,2,1',2';t)=\sum_{\alpha,\beta\alpha',\beta'}C_{\alpha\beta\alpha'\beta'}(t)\psi_\alpha(1,t)\psi_\beta(2,t)\psi^*_{\alpha'}(1',t)\psi^*_{\beta'}(2',t)\,. \qquad (3)$$

The quantity $h(i)=t(i)+U(i)$ is the one-body Hamiltonian, i.e., the sum of a kinetic-energy term and the mean field

$$U(i;t)=\mathrm{Tr}_{2=2'}[v(i2)A_{i2}\rho(22';t)]\,. \qquad (4)$$

The quantity $v(12)$ is the two-body interaction acting among nucleons while $A_{12}=1-P_{12}$, where P_{12} denotes the permutation operator between nucleons.

The equations of motion for the occupation matrix $n_{\alpha\beta}(t)$ and $C_{\alpha\beta\alpha'\beta'}(t)$ are

$$i\hbar\frac{\partial}{\partial t}n_{\alpha\beta}=\sum_{\gamma\delta\sigma}[C_{\gamma\delta\beta\sigma}\langle\alpha\sigma|v|\gamma\delta\rangle-C_{\alpha\delta\gamma\sigma}\langle\gamma\sigma|v|\beta\delta\rangle] \qquad (5)$$

and

$$i\hbar\frac{\partial}{\partial t}C_{\alpha\beta\alpha'\beta'}=B_{\alpha\beta\alpha'\beta'}+P_{\alpha\beta\alpha'\beta'}+H_{\alpha\beta\alpha'\beta'}\,, \qquad (6)$$

where

$$B_{\alpha\beta\alpha'\beta'}=\sum_{\lambda_1\lambda_2\lambda_3\lambda_4}\langle\lambda_1\lambda_2|v|\lambda_3\lambda_4\rangle_A[(\delta_{\alpha\lambda_1}-n_{\alpha\lambda_1})(\delta_{\beta\lambda_2}-n_{\beta\lambda_2})n_{\lambda_3\alpha'}n_{\lambda_4\beta'}-n_{\alpha\lambda_1}n_{\beta\lambda_2}(\delta_{\lambda_3\alpha'}-n_{\lambda_3\alpha'})(\delta_{\lambda_4\beta'}-n_{\lambda_4\beta'})] \qquad (7)$$

represents the lowest-order contribution of collisions in the particle-particle channel (Born approximation), while the term P represents the higher-order particle-particle (and hole-hole) contributions,

$$P_{\alpha\beta\alpha'\beta'}=\sum_{\lambda_1\lambda_2\lambda_3\lambda_4}\langle\lambda_1\lambda_2|v|\lambda_3\lambda_4\rangle[\delta_{\alpha\lambda_1}\delta_{\beta\lambda_2}C_{\lambda_3\lambda_4\alpha'\beta'}-\delta_{\lambda_3\alpha'}\delta_{\lambda_4\beta'}C_{\alpha\beta\lambda_1\lambda_2}-\delta_{\alpha\lambda_1}n_{\beta\lambda_2}C_{\lambda_3\lambda_4\alpha'\beta'}-\delta_{\lambda_2\beta}n_{\alpha\lambda_1}C_{\lambda_4\lambda_3\beta'\alpha'}$$
$$+\delta_{\lambda_3\alpha'}n_{\lambda_4\beta'}C_{\alpha\beta\lambda_1\lambda_2}+\delta_{\lambda_4\beta'}n_{\lambda_3\alpha'}C_{\alpha\beta\lambda_1\lambda_2}]\,. \tag{8}$$

The last term,

$$H_{\alpha\beta\alpha'\beta'}=\sum_{\lambda_1\lambda_2\lambda_3\lambda_4}\langle\lambda_1\lambda_2|v|\lambda_3\lambda_4\rangle[\delta_{\alpha\lambda_1}(n_{\lambda_3\alpha'}C_{\beta\lambda_4\beta'\lambda_2}-n_{\lambda_3\beta'}C_{\beta\lambda_4\alpha'\lambda_2}-n_{\lambda_4\alpha'}C_{\lambda_3\beta\lambda_2\beta'}-n_{\lambda_4\beta'}C_{\lambda_3\beta\alpha'\lambda_2})$$
$$+\delta_{\beta\lambda_2}(n_{\lambda_4\beta'}C_{\alpha\lambda_3\alpha'\lambda_1}-n_{\lambda_4\alpha'}C_{\alpha\lambda_3\beta'\lambda_1}-n_{\lambda_3\beta'}C_{\alpha\lambda_4\alpha'\lambda_1}-n_{\lambda_3\alpha'}C_{\alpha\lambda_4\lambda_1\beta'})$$
$$-\delta_{\beta'\lambda_4}(n_{\beta\lambda_2}C_{\alpha\lambda_3\alpha'\lambda_1}-n_{\alpha\lambda_2}C_{\beta\lambda_3\alpha'\lambda_1}-n_{\beta\lambda_1}C_{\alpha\lambda_3\alpha'\lambda_2}-n_{\alpha\lambda_1}C_{\beta\lambda_3\lambda_2\alpha})$$
$$-\delta_{\alpha'\lambda_3}(n_{\alpha\lambda_1}C_{\beta\lambda_4\beta'\lambda_2}-n_{\alpha\lambda_2}C_{\alpha\lambda_4\beta'\lambda_2}-n_{\alpha\lambda_2}C_{\beta\lambda_4\beta'\lambda_1}-n_{\beta\lambda_2}C_{\alpha\lambda_4\lambda_1\beta'})]\,, \tag{9}$$

is the contribution to the equations of motion of collisions in the particle-hole channel, which we loosely address as density fluctuations. The set of coupled equations (5) and (6) provides a nonperturbative description of nuclear motion, known as time-dependent density-matrix (TDDM) theory, which takes into account collisions among nucleons to all orders in the interaction. We note that the theory fulfills the conservation of particle number, momentum, and energy. In what follows we approximate the interaction v appearing in the mean-field potential of Eq. (4) by a Bonche-Koonin-Negele (BKN) [5] or Skyrme II (SKII) [6] force and we use $v(12)=V_0\delta(\mathbf{r}_1-\mathbf{r}_2)$ for the residual interaction appearing in Eqs. (7)-(9). In keeping with the fact that the matrix elements of $v(12)$ at full density are very small due to Pauli blocking—therefore making the nuclear surface the main source of damping of giant resonances—the strength of the interaction V_0 has been determined from the strength of the effective force (BKN or SKII) calculated at density $\rho=\rho_0/2\approx 0.08\ \text{fm}^{-3}$. In modifying the strength of V_0 by 30% we did not find any significant change in the results presented below.

We have solved the coupled equations (5) and (6) for the case of the isovector dipole and the isoscalar quadrupole vibrations in the nuclei ^{16}O and ^{40}Ca as a function of temperature [7]. The correlated ground state is boosted at a certain time (typically after 0.2×10^{-21} s) by applying appropriate phase factors proportional to a strength factor α. In this way the system acquires a well-defined collective energy proportional to α^2. In the case of isoscalar quadrupole motion we have used the BKN force in the calculation of the self-consistent field, Eq. (4), and $V_0=-300$ MeV for the strength of the interaction v responsible for collisions. In the description of the isovector dipole motion the SKII interaction was adopted in Eq. (4) and $V_0=-420$ MeV. The set of single-particle levels used in the calculations includes the $1s$, $1p$, $2s$, and $1d$ in the case of ^{16}O and $1s$, $1p$, $2s$, $1d$, $2p$, and $1f$ in the case of ^{40}Ca.

The evolution of the system, both in TDHF and in TDDM, is followed in time by calculating the mean-square radius, the quadrupole moment $Q_2(t)$, and the dipole moment $Q_1(t)$ of the system. The total energy and number of particles are found to be conserved within 7% and 1%, respectively. The reason for this is to be found in the fact that the single-particle basis used in the calculation has been truncated. In fact, decreasing the energy given to the system in the boosting process, the conservation of energy and particle number is better satisfied. On the other hand, as long as the response of the system is linear, the properties extracted from it concerning giant resonances are independent of the value of the boosting parameter [8]. Furthermore, the fluctuation in the quadrupole moment of ^{40}Ca is found to be less than 1.5 fm^2 for the correlated ground state within a time interval of 3×10^{-21} s. This number is in all cases less than 1% of the quadrupole moment associated with the collective excitation of the system (21 MeV for ^{40}Ca) and testifies to the accuracy of the numerical solutions. Similar results are found in the case of the dipole motion. To carry out calculations at finite temperature, we replace the initial occupation numbers by appropriate Fermi distributions and propagate the system in time to build up its correlations before applying the collective boost of interest. Note that the temperature is not a dynamical constraint but merely enters as a parameter for the initial conditions in the equations of motion which are solved at constant energy.

In Fig. 1(a) we show the time-dependent evolution of the dipole moment of ^{40}Ca calculated at $T=0$ in the TDHF and TDDM approximations, while in Fig. 1(b) two temperatures ($T=0$ and $T=4$ MeV) are directly compared in the full TDDM theory. Two conspicuous features emerge from simple inspection of these results. First, the vibration displays a single frequency mode which is strongly damped already in TDHF, the inclusion of fluctuations and collisions essentially not affecting this behavior. Consequently the relaxation of the giant dipole resonance of ^{40}Ca seems to be determined both by the decay into single-particle motion (like Landau damping in infinite systems) and by the coupling to the continuum, the so-called escape width. Second, the properties of the resonance are unaffected by temperature. This is a natu-

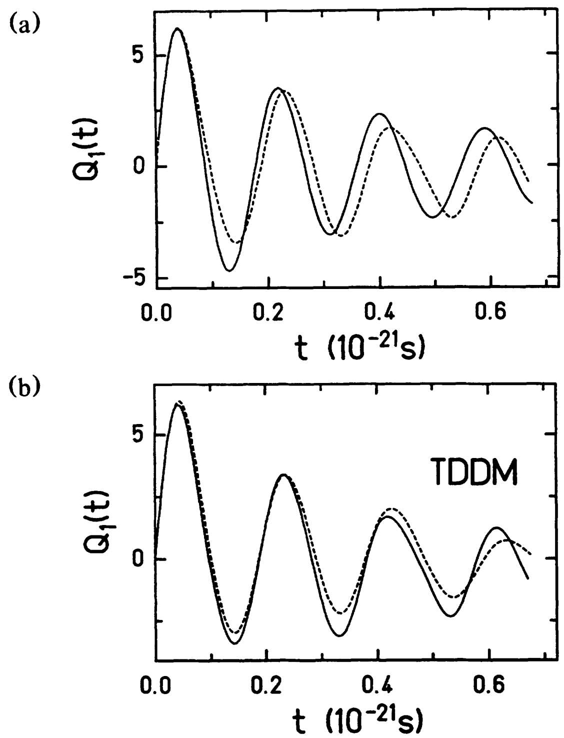

FIG. 1. (a) The dipole moment $Q_1(t)$ in ^{40}Ca at $T=0$ in the limits of TDHF (solid line) and TDDM (dashed line). (b) The dipole moment $Q_1(t)$ in ^{40}Ca in the TDDM limit at temperature $T=0$ (solid line) and $T=4$ MeV (dashed line).

ral consequence of the fact that damping is in this case controlled by mean-field effects.

Fitting the main frequency with a damped oscillator whose coordinate is parametrized according to

$$Q_{\text{test}}(t)=A_0\sin(\omega t)e^{-\gamma t/\hbar}, \tag{10}$$

one obtains a width $\Gamma=2\gamma$ which in all cases is about 4 MeV. Although the purpose of the present Letter is not to provide a detailed description of the experimental finding but to understand the nature of the damping mechanisms, the above number compares well with the experimental value of 5 MeV. Similar results are obtained in the case of ^{16}O where the calculated width is $\Gamma=5$ MeV, essentially independent of the temperature or of the presence of collisions (cf. Table I).

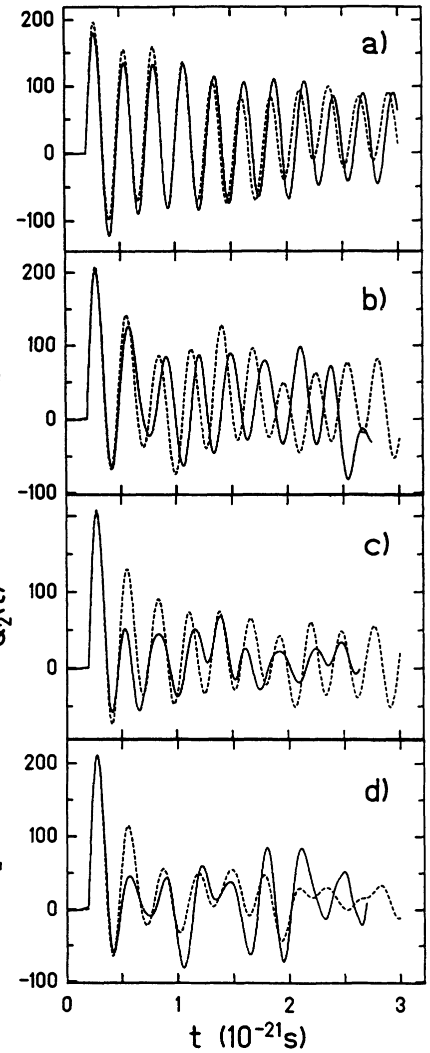

FIG. 2. The quadrupole moment $Q_2(t)$ in ^{40}Ca in the limits of (a) TDHF; (b) TDHF plus residual "two-body collisions," $H=0$; (c) TDHF plus fluctuations, $P=0$; and (d) TDDM. Temperatures $T=0$ (solid lines) and $T=4$ MeV (dashed lines).

In Fig. 2 the time-dependent evolutions of the quadrupole moment associated with ^{40}Ca calculated in mean field and including fluctuations and collisions are shown for two temperatures ($T=0$ and $T=4$ MeV) for TDHF, $H=0$, $P=0$,

TABLE I. Theoretical values for the width of quadrupole and dipole modes as extracted [as in Eq. (10)] from the decay constant relative to the first three maxima. The columns p-p (particle-particle) and p-h (particle-hole) contain the results obtained respectively by putting $H=0$ and $P=0$ in Eq. (6) as discussed in the text. The corresponding columns in the case of the dipole motion are left free as the corresponding damping arises mainly from mean-field effects.

	$T=0$ MeV				$T=4$ MeV			
	TDHF	p-p	p-h	TDDM	TDHF	p-p	p-h	TDDM
2^+ ^{40}Ca	0.80	1.86	5.60	5.50	0.52	1.97	2.02	2.89
1^- ^{40}Ca	3.56			4.12	4.37			4.33
1^- ^{16}O	6.00			5.53	5.00			4.90

and TDDM. Again simple inspection allows us to extract the main features of the results. The giant quadrupole resonance (GQR) corresponds in TDHF [Fig. 2(a)] to a single mode which is only slightly damped and whose properties are independent of temperature. The presence of collisions and fluctuations changes this picture in a qualitative way by producing a strongly damped vibration which now displays a complicated beating pattern, pointing to the existence of a variety of normal modes. These effects are mainly controlled by fluctuations [cf. Fig. 2(c)] while collisions in the particle-particle and hole-hole channels [Fig. 2(b)] play a minor role. In any case, the role of these channels cannot be neglected in a quantitative description of the damping processes, because of the interference with the particle-hole channel [cf. Fig. 2(d)].

Making use of a fit as in Eq. (10) for the main peak, representative damping widths for the GQR in ^{40}Ca were obtained. The results are displayed in Table I. We have also studied the collective dipole and quadrupole response of ^{16}O and ^{32}S, obtaining results which are consistent with those of ^{40}Ca.

We conclude that the giant dipole and quadrupole resonances of light nuclei provide textbook examples of the workings of the main relaxation mechanisms found in many-body systems, namely, the escaping of particles in the continuum, Landau damping, and the collisional damping arising from density fluctuations and particle collisions. The first two damping mechanisms are found not to vary with temperature, as expected for mean-field phenomena. Remarkably, the last mechanism is also found to be essentially independent of temperature. This is because temperature leads to a simultaneous and progressive smearing of the Fermi surface (thus enhancing the role of collisions by neutralizing the limitations imposed by the Pauli principle) as well as of the nuclear surface (thus making the role of collisions, which essentially all take place at low density, less effective). The empirically found almost total cancellation between these two effects does not appear necessary, and some temperature dependence may occasionally be found for other nuclei or collective modes. This last result is intimately connected with the finite size of the atomic nucleus and the special role that the nuclear surface plays in the relaxation processes.

Summing up, the results presented above answer a long-standing problem found [9] in the study of collective motion in hot nuclei; the answer which can be summarized simply as follows: The damping width of giant resonances associated with quantal small-amplitude fluctuations is independent of the temperature of the system.

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