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Nuclear Collective Excitations at Finite Temperature

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The nuclear collective response at finite temperature is investigated in the quantum framework of the small amplitude limit of the extended TDHF approach, including a non-Markovian collision term. By employing a Skyrme force, the isoscalar monopole, isovector dipole and isoscalar quadrupole excitations in ^{40}Ca are calculated. The collisional damping due to decay into incoherent 2p-2h states is small at low temperatures but increases rapidly at higher temperatures.

Introduction

During last several years, a systematic effort has been made to investigate the properties of giant dipole resonance built on excited states. These investigations indicate that as a function of the excitation energy or temperature, the mean resonance energy does not change much but the resonance becomes broader as observed in giant dipole resonance in ^{120}Sn ¹⁾²⁾ and ^{208}Pb nuclei ³⁾, and it appears to saturates at large excitations. On theoretical side much work has been done to understand the properties of collective vibrations at finite temperature ⁴⁾⁵⁾. These calculations are based on different damping mechanisms, such as the mechanism due to coupling with the surface modes ⁶⁾⁷⁾, the damping due to incoherent 2p-2h doorway states which is usually referred to as the collisional damping ⁸⁾. These calculations have been partially successful for explaining the broadening of the giant dipole resonance with increasing temperature, but the saturation is still an open problem.

The small amplitude limit of the extended TDHF provides an appropriate basis for investigating collective response, in which damping due the incoherent 2p-2h decay is included in the form of a non-Markovian collision term ⁹⁾¹⁰⁾¹¹⁾. Based on this approach, the incoherent contribution to damping at finite temperature has been calculated in Thomas-Fermi approximation in refs. ¹²⁾¹³⁾. In this work, we carry out a quantal investigation of the nuclear collective response at zero and finite temperature on the extended TDHF framework in small amplitude limit, which may be referred as an extended RPA approach ¹⁴⁾. In contrast to the semi-classical treatments, the shell effects are incorporated into the strength distributions as well as the collisional damping widths. We present calculations for the isoscalar monopole, isoscalar quadrupole and isovector dipole strength distributions in ^{40}Ca at finite temperature by employing an effective Skyrme force.

Collective response at finite temperature

The formal basis of the extended TDHF theory has been developed some years ago ¹⁵⁾, and it provides an effective quantal transport description for the evolution of the single particle density matrix $\rho(t)$ including the mean-field and the residual interactions in terms of a collision term. The equation of motion of the single particle density matrix determined by the first equation of the BBGKY hierarchy,

$$i\hbar \frac{\partial}{\partial t} \rho - [h(\rho), \rho] = K(\rho). \quad (1)$$

Here $h(\rho)$ is an effective mean-field Hamiltonian and the right hand side represents a non-Markovian collision term determined by the correlated part of the two-particle density matrix, $K(\rho) = \text{Tr}_2[v, C_{12}]$. The two-body correlations C_{12} is determined by the second equation of the BBGKY hierarchy which involves three-body correlations. In the extended TDHF, the hierarchy is truncated at the second level by neglecting three-body correlations, and two-body correlations are calculated in terms of effective residual interactions according to

$$i\hbar \frac{\partial}{\partial t} C_{12} - [h(\rho), C_{12}] = F_{12}(\rho) \quad (2)$$

where the source term is given by

$$F_{12}(\rho) = (1 - \rho_1)(1 - \rho_2)v\widehat{\rho_1\rho_2} - \widehat{\rho_1\rho_2}v(1 - \rho_1)(1 - \rho_2). \quad (3)$$

We obtain a description for small density fluctuations, $\delta\rho(t) = \rho(t) - \rho_0$, by linearizing the extended TDHF theory around a finite temperature equilibrium state ρ_0

$$i\hbar \frac{\partial}{\partial t} \delta\rho - [h_0, \delta\rho] - [\delta U + F, \rho_0] = \text{Tr}_2[v, \delta C_{12}] \quad (4)$$

where $\delta U = (\partial U / \partial \rho)_0 \cdot \delta \rho$ represents small deviations in the effective mean-field potential. The small deviation of two-body correlations $\delta C_{12}(t) = C_{12}(t) - C_{12}^0$ is specified by the second equation of the hierarchy,

$$i\hbar \frac{\partial}{\partial t} \delta C_{12} - [h_0, \delta C_{12}] - [\delta U + F, C_{12}^0] = \delta F_{12} \quad (5)$$

where δF_{12} is the small deviations of the source term and C_{12}^0 denotes the equilibrium correlation function. In order to study the collective response of the system, we include an external harmonic perturbation of the form, $F(\mathbf{r}, t) = F(\mathbf{r}) \exp(-i\omega t) + h.c.$ into the equation of motion. The two-body correlations can be determined by solving eq.(5) with the help of one-sided Fourier transform, and under a weak-damping approximation, the solution can be expressed as¹³⁾,

$$\delta C_{12}(t) = \int^t dt' \rho_1^0 \rho_2^0 e^{-i h_0(t-t')} [Q(t'), v] e^{+i h_0(t-t')} (1 - \rho_1^0)(1 - \rho_2^0) \quad (6)$$

where $Q(t)$ denotes the distortion function associated with the single particle density matrix, $\delta \rho(t) \approx [Q(t), \rho_0]$. Then, an expression for the linearized collision term can be obtained by substituting the correlation function to the right hand side of the transport eq.(4).

We analyze the linear response of the system to an external perturbation F by expanding the small deviation $\delta \rho(t)$ in terms of finite temperature RPA modes $O_\lambda^\dagger$ and O_λ ,

$$\delta \rho(t) = \sum_{\lambda > 0} z_\lambda(t) [O_\lambda^\dagger, \rho_0] - z_\lambda^*(t) [O_\lambda, \rho_0] \quad (7)$$

where $z_\lambda(t)$ and $z_\lambda^*(t)$ denote the amplitudes associated with the RPA modes, $O_\lambda^\dagger$ and O_λ , which are determined by the finite temperature RPA equation. In the Hartree-Fock basis the finite temperature RPA equation reads¹⁶⁾,

$$(\hbar\omega_\lambda - \epsilon_i + \epsilon_j) \langle i | O_\lambda^\dagger | j \rangle + \sum_{l \neq k} \langle ik | v | jl \rangle_A (n_l - n_k) \langle l | O_\lambda^\dagger | k \rangle = 0 \quad (8)$$

where $v = (\partial U / \partial \rho)_0$, the indices $i, j, \dots$ represent all single particle quantum numbers including spin-isospin, and $n_k = 1/[1 + \exp(\epsilon_k - \epsilon_F)/T]$ denotes the finite temperature Fermi-Dirac occupation numbers of the Hartree-Fock states. At zero temperature, occupation numbers are zero or one, so that the RPA functions $O_\lambda^\dagger, O_\lambda$ have only particle-hole and hole-particle matrix elements. At finite temperatures the RPA functions involve more configurations including particle-particle and hole-hole states. Substituting the expansion (7) into eq.(4) and projecting by O_λ , we find that the amplitudes of the RPA modes execute forced harmonic motion,

$$\frac{d}{dt} z_\lambda + i\omega_\lambda z_\lambda - \frac{i}{\hbar} \langle [O_\lambda, F] \rangle_0 \quad (9)$$

$$= -\frac{1}{2\hbar} \int^t dt' \bar{\Gamma}_\lambda(t-t') z_\lambda(t')$$

where the deriving term is determined by the external perturbation $\langle [O_\lambda, F] \rangle_0 = Tr[O_\lambda, F] \rho_0$ and the right hand side describe a non-Markovian damping term. Fourier transform of $\bar{\Gamma}_\lambda(t)$ is the collisional damping width due to mixing with the incoherent 2p-2h states. In the Hartree-Fock representation, it is given by¹³⁾,

$$\Gamma_\lambda(\omega) = \frac{1}{2} Im \sum \frac{|\langle ij | [O_\lambda, v] | kl \rangle_A|^2}{\omega - \Delta\epsilon - i\eta} [n_k n_l (1 - n_i)(1 - n_j) - n_i n_j (1 - n_k)(1 - n_l)] \quad (10)$$

where $\Delta\epsilon = \epsilon_i + \epsilon_j - \epsilon_k - \epsilon_l$, and η is a small positive number. In this expression, we neglect a small shift of the frequency ω_λ arising from the principle value part of the damping term.

Solving eq.(9) for the amplitudes by Fourier transform, the response of the system to the external perturbation F can be expressed as

$$\delta \rho(\omega) = R(\omega, T) \cdot F \quad (11)$$

where $R(\omega, T)$ denotes the finite temperature extended RPA response function including damping. The strength distribution of the RPA response is obtained by the imaginary part of the response function,

$$\begin{aligned} S(\omega, T) &= -\frac{1}{\pi} Tr\{F^\dagger Im R(\omega, T) F\} \\ &= \frac{1}{\pi} \sum_{\lambda > 0} |\langle [O_\lambda, F] \rangle_0|^2 D(\omega - \omega_\lambda) \\ &\quad - |\langle [O_\lambda^\dagger, F] \rangle_0|^2 D(\omega + \omega_\lambda) \end{aligned} \quad (12)$$

where the sum goes over the positive frequency modes and

$$D(\omega - \omega_\lambda) = \frac{\Gamma_\lambda/2}{(\hbar\omega - \hbar\omega_\lambda)^2 + (\Gamma_\lambda/2)^2} \quad (13)$$

In reference¹³⁾, neglecting the depletion of collective amplitudes in the collision term, the damping width of RPA modes are calculated in Thomas-Fermi approximation by substituting $\omega = \omega_\lambda$ in eq.(10). Here, we take into account for depletion of the collective amplitude in the collision term, and calculate the damping width by substituting $\omega = \omega_\lambda - \frac{i}{2}\Gamma_\lambda$. Then, the expression becomes a secular equation for the damping width.

Results and Conclusions

We calculate the isoscalar monopole, isoscalar quadrupole and isovector dipole excitations in ^{40}Ca at several temperatures. We use the Skyrme interaction SGII for the

Hartree-Fock and RPA calculations¹⁷⁾ and we neglect the temperature dependence of single particle energies and wave functions. We determine the hole states by solving the Hartree-Fock problem in coordinate representation. Then, the particle states are generated by diagonalizing the Hartree-Fock Hamiltonian in a large harmonic oscillator representation by including 12 major shells. The RPA strength distributions of the monopole $F_0(r) = r^2$, dipole $F_1(\mathbf{r}) = \tau_z r Y_{10}(\hat{\mathbf{r}})$ (in isospin symmetric systems $N = Z$), and quadrupole $F_2(\mathbf{r}) = r^2 Y_{20}(\hat{\mathbf{r}})$ excitation operators at temperatures $T = 0, 2, 4$ MeV are shown in figure 1. As seen from the top panel, the monopole strength at $T = 0$ MeV exhibit a large Landau spreading over a broad energy region $E = 16 - 28$ MeV with an average energy $E = 21.5$ MeV. The recent experimental data also show a broad resonance around a peak value of 17.5 MeV¹⁸⁾.

Fig. 1. RPA strength distributions in Ca^{40} as a function of the energy at temperatures $T = 0, 2, 4$ MeV for isoscalar monopole 0^+ (top), isovector dipole 1^- (middle) and isoscalar quadrupole 2^+ (bottom) excitations.

For increasing temperature, transition strength spread a broader range towards lower energies. As shown in the middle panel, the strength distribution of isovector dipole

shows a weaker temperature dependence than monopole. At $T = 0$, the dipole strength is concentrated at range $E = 16 - 23$ MeV. The Landau width is large and is spreading for increasing temperature. However, the average energy of the main peak remains nearly constant around $E = 16.5$ MeV. The experimental data shows a broad resonance at around 20 MeV¹⁹⁾ with a width close to 6 MeV. As illustrated at the bottom panel of figure 1, the RPA result at $T = 0$ MeV gives a very collective quadrupole mode peaked at $E = 17.5$ MeV, which agrees well the experimental finding of an average energy 17 MeV and the calculations of Sagawa and Bertsch²⁰⁾. At higher temperatures in addition to p-h excitations, p-p and h-h excitations become possible. The p-p and h-h configurations mainly change the strength distribution at low energy side at $E = 4$ MeV. As a result, the giant resonance has less transition strength.

Fig. 2. Collisional damping widths that are averaged over nearby states with more than 10% of the EWSR, for monopole, dipole and quadrupole modes as a function of temperature.

We obtain the collisional damping widths of the collective states by calculating the expression (10) and solving the associated secular equation by graphical method. We

perform the sums over single particle states explicitly using the projection of the total spin, m , as one of the explicit quantum numbers as done in ²¹⁾. Figure 2 shows the damping widths as a function of temperature, that are averaged over several nearby states with strengths more than 10% of the EWSR. The results for monopole, dipole and quadrupole are indicated in the top, middle and bottom panels, respectively. The incoherent damping widths at low temperatures are, in general, small and thus leaving room for a possible coherence effect of doorway states in the description of the damping properties. In particular in the case of dipole mode, since there is no odd parity 2p-2h states available in the vicinity of the collective energy, the collisional damping width vanishes at $T = 0$ MeV. This behavior is a particular quantum feature due to shell effects in the extended RPA calculation of double magic light nuclei, and it can not be described in the framework of semi-classical approaches. For increasing temperature the collisional damping becomes large and may even dominate the spreading width since the coherence effect is expected to diminish rather rapidly. Temperature dependence of the damping width in quantal calculations is a more complex than the simple quadratic increase predicted by the semi-classical calculations. An interesting property of the collisional damping is that it may saturate for increasing temperature. In fact, our calculations indicate that the damping width of giant quadrupole saturates around $T = 3 - 4$ MeV, however a saturation of the giant monopole and dipole modes is not visible at these temperatures.

Figure 3 shows the strength distributions including the collisional damping. The giant dipole strength at $T = 0$ MeV is smoothed by performing an averaging with a Lorentzian weight with a width of 0.5 MeV. The excitation strengths become broader for increasing temperature. The peak position of the monopole resonance does not change much, but the peak position of dipole slightly shifts down and quadrupole slightly shifts up in energy. This is a signature of the reduction of the collectivity of those states with temperature because the peak energy moves back towards the single particle expectations.

There are important quantal effects in the collective behavior of a hot nuclear system as illustrated in ²²⁾. Investigations presented here, also indicates that, the quantal effects has a large influence on the damping properties of collective excitations at low temperatures, which may even persist at relatively high excitations. The magnitude of the collisional damping is rather sensitive to the effective residual interactions, for which an accurate information is not available. The effective Skyrme force is well fitted to describe the nuclear mean-field properties, but not the in-medium cross-sections and damping properties. Therefore, a systematic study of the effective interactions in this context is clearly called for. However, our investigation, while remains semi-quantitative, gives a valuable insight on the quantal properties of collective excitations at finite temperature.

Fig. 3. The extended RPA strength distributions of the monopole, dipole and quadrupole excitations as a function of temperature.

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