LABORATOIRE DE PHYSIQUE CORPUSCULAIRE

SCAN-0002074

CERN LIBRARIES, GENEVA

Collisional effects in the Finite temperature Dipole response of ^{120}Sn and ^{208}Pb .

D. Lacroix, Ph. Chomaz, S. Ayik

January 2000

LPCC 00-01

Submitted to Physics Letters B

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

INSTITUT NATIONAL
DE PHYSIQUE NUCLÉAIRE ET DE PHYSIQUE DES PARTICULES

INSTITUT DES SCIENCES DE LA MATIÈRE ET DU RAYONNEMENT

UNIVERSITÉ DE CAEN

- U.M.R. 6534 -

ISMRA - 6, Boulevard Maréchal Juin - 14050 CAEN CEDEX - FRANCE

Téléphone : 02 31 45 25 00 - Télécopie : 02 31 45 25 49

Internet : <http://caeinfo.in2p3.fr>

Collisional effects in the Finite temperature Dipole response of ^{120}Sn and ^{208}Pb .

Denis Lacroix^{a)}, Philippe Chomaz^{b)} and Sakir Ayik^{c)}

^{a)} *LPC/ISMRA, Blvd du Maréchal Juin, 14050 Caen, France,*

^{b)} *G.A.N.I.L., B.P. 5027, F-14076 Caen Cedex 5, France,*

^{c)} *Tennessee Technological University, Cookeville TN38505, USA*

We investigate for the first time the behavior of the GDR in ^{120}Sn and ^{208}Pb at zero and finite temperatures in the linearized version of the extended TDHF theory. It is shown that collisions between nucleons induce an increase of the GDR width together with a decrease of the collective energy with an increasing temperature. In ^{120}Sn , these effects are in global agreement with experimental data. A weaker dependence with temperature is found in ^{208}Pb . Influence of collisional coupling and of the range of the effective interaction on the presented results are discussed.

(January 5, 2000)

PACS: 24.30.Cz, 21.60.Jz, 25.70.Lm

Keywords: extended TDHF, linear response, one-body transport theory.

Nuclear many-body systems exhibit self-organized collective vibrations : the so-called giant resonances (GR) [1]. Damping of these collective vibrations at zero and finite temperature in nuclei have focussed the interest of the theoretical community since it gives the opportunity to understand how an ordered (collective) motion transforms in a disordered motion of intrinsic (single-particle) degrees of freedom in a many-body quantum systems.

The giant dipole resonance (GDR) at finite excitation has been studied in ^{120}Sn [2] and ^{208}Pb [3] nuclei during the past decade. New experiments based on alpha scattering are now available [4-6], reducing the mixing of thermal and angular momentum effects. The interpretation of the observed strength, and in particular of the apparent width, has been difficult due to different mechanisms involved in the damping of GR [7,8]. Indeed, a part of the damping is due to the coupling of the collective mode to external degrees of freedom giving rise to the escape width. On the other side, GR acquire an intrinsic width due to coupling with internal degrees of freedom. In the latter case, one can again distinguish (i) the Landau damping due to the spreading of the collective modes on non collective particle-hole (p-h) excitation (ii) a coherent mechanism due to coupling with low-lying surface modes which is particularly important at low temperatures [8,9], (iii) a damping due to the coupling with incoherent 2p-2h states usually referred to as the collisional damping [10].

In this work, we apply for the first time the ideas developed in ref. [11-13] based on the linearization of the extended Time-Dependent Hartree-Fock (extended TDHF) theory [15-17] to study the GDR response of ^{120}Sn and ^{208}Pb at zero and finite temperature. As it was shown in previous work, the linearized version of extended TDHF provides a suitable framework in order to include collisional effects on top of the mean-field dynamics. This correspond not only to a damping due to collisions between nucleons, but also to coupling between modes through their common decay channels, the so-called collisional coupling [13].

In the extended time dependent Hartree-Fock (TDHF) approach, evolution of the single particle density matrix $\rho(t)$ is determined by a transport equation [17],

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

where $h(\rho)$ is the mean-field Hamiltonian and the right hand side represents a collision term arising from the propagation of two-body correlations. The collision term can be written as,

$$I(\rho) = \int_{t_0}^t \left[v, U_{12}(t, s) F_{12}(s) U_{12}^\dagger(t, s) \right] ds \quad (2)$$

where the two-body propagator is expressed in terms of the extended mean-field propagator $U(t, s) = \exp \left(-i/\hbar \int_s^t h(\rho(t')) dt' \right)$ as $U_{12} = U_1 \otimes U_2$, whereas $F_{12} = \bar{\rho}_1 \bar{\rho}_2 \bar{v} \rho_1 \rho_2 - \rho_1 \rho_2 \bar{v} \bar{\rho}_1 \bar{\rho}_2$ with $\bar{\rho} = 1 - \rho$ and $\bar{v}$ is the antisymmetric residual interaction.

The linear response of the system is described by the deviation of the density matrix $\delta\rho(t) = \rho(t) - \rho_0$ from the finite temperature Hartree-Fock equilibrium ($[\rho_0, h_0] = 0$). This deviation follows the dynamical equation

$$i\hbar \frac{\partial}{\partial t} \delta\rho - [h_0, \delta\rho] - [\delta U + A, \rho_0] = \delta I \quad (3)$$

where $A(t) = A \exp(-i\bar{\omega}t) + \text{h.c.}$ is a one-body harmonic excitation operator containing a small imaginary part $\bar{\omega} = \omega + i\eta$ in order to adiabatically switch on the perturbation. The quantity δI represents the linearized form of the non-Markovian collision term $I(\rho)$. A general solution of equation 3, is obtained by using the development $\delta\rho(t) = [Q^+, \rho_0] \exp(-i\bar{\omega}t) + \text{h.c.}$ where $Q^+ = \sum_{\lambda>0} z_\lambda^+ O_\lambda^\dagger - z_\lambda^- O_\lambda$. In this expression, $O_\lambda^\dagger$ and O_λ are the creation and annihilation operators of the RPA state λ of energy $\hbar\omega_\lambda$. The linearized equation 3 can then be recast in terms of a set of coupled equations between the $(z_\lambda^+, z_\lambda^-)$ coefficients [13]

$$(\hbar\bar{\omega} - \Sigma(\bar{\omega})) \begin{pmatrix} z_{\lambda}^{+} \\ z_{\lambda}^{-} \end{pmatrix} = \begin{pmatrix} A_{\lambda} \\ -A_{\lambda}^{*} \end{pmatrix} \quad (4)$$

where $A_{\lambda} = \text{Tr}[O_{\lambda}, A]\rho_0$ and $\Sigma(\bar{\omega})$ denotes the self-energy matrix,

$$\Sigma(\bar{\omega}) = \begin{pmatrix} \hbar\omega_{\lambda}\delta_{\lambda\mu} + I_{\lambda\mu}^{++}(\bar{\omega}) & I_{\lambda\mu}^{+-}(\bar{\omega}) \\ -I_{\lambda\mu}^{*-}(-\bar{\omega}^{*}) & -\hbar\omega_{\lambda}\delta_{\lambda\mu} - I_{\lambda\mu}^{*-}(-\bar{\omega}^{*}) \end{pmatrix} \quad (5)$$

Introducing the Hartree-Fock basis $|i\rangle$ which diagonalize h_0 and ρ_0 with the corresponding eigen-energies ε_i and occupation numbers n_i , the elements of the collision matrix are given by

$$I_{\lambda\mu}^{++}(\bar{\omega}) = -\frac{1}{4} \sum_{ijkl} \frac{\langle k\ell|[O_{\lambda}, v]|ij\rangle \langle ij|[O_{\mu}^{\dagger}, v]|k\ell\rangle}{\hbar\bar{\omega} - \Delta\varepsilon_{ijkl}} \mathcal{N}_{ijkl} \quad (6)$$

$$I_{\lambda\mu}^{+-}(\bar{\omega}) = \frac{1}{4} \sum_{ijkl} \frac{\langle k\ell|[O_{\lambda}, v]|ij\rangle \langle ij|[O_{\mu}, v]|k\ell\rangle}{\hbar\bar{\omega} - \Delta\varepsilon_{ijkl}} \mathcal{N}_{ijkl} \quad (7)$$

with $\mathcal{N}_{ijkl} = \bar{n}_i \bar{n}_j n_k n_{\ell} - n_i n_j \bar{n}_k \bar{n}_{\ell}$ and $\Delta\varepsilon_{ijkl} = \varepsilon_i + \varepsilon_j - \varepsilon_k - \varepsilon_{\ell}$. The self energy is non diagonal and so it introduce a coupling between modes through their decay channels, so-called collisional coupling. When the non diagonal terms are neglected we only keep a damping (and a shift) of the collective modes. This part will be called the collisional damping. Calculating the expectation value of the observable A , $\langle A \rangle = \text{Tr} A \delta\rho(t)$, the associated response function can be expressed as,

$$S(\bar{\omega}) = -\frac{1}{\pi} \text{Im} (A_{\lambda}^{*}, A_{\lambda}) (\hbar\bar{\omega} - \Sigma(\bar{\omega}))^{-1} \begin{pmatrix} A_{\lambda} \\ -A_{\lambda}^{*} \end{pmatrix}$$

The above equations demonstrate that the collision term not only introduces a shift and a damping of the RPA frequencies but also induces a coupling between collective modes. Due to the numerical effort of calculation, the first application of the linearized version of extended TDHF was limited to ^{40}Ca .

In this paper, we estimate for the first time the strength distributions for isovector dipole excitations in ^{120}Sn and ^{108}Pb at several temperatures in the extended TDHF. Particle and hole states are obtained by diagonalizing the Hartree-Fock Hamiltonian in a large harmonic oscillator representation [18] which includes 15 major shells. We use a fixed imaginary part for the forcing frequency $\eta = 1$ MeV. The GDR strength distributions are calculated with the dipolar excitation operators $A(\mathbf{r}) = N/A \sum_p z_p - Z/A \sum_n z_n$. The Hartree-Fock and RPA calculations are performed using the effective Skyrme force SLy4 [19]. As discussed in our previous papers, for a quantitative description of the strength distributions, it is necessary to employ realistic effective residual interactions in the collision term. In this respect, the standard Skyrme force provides a poor approximation, since in the vicinity of nuclear surface, it does not match at all to the free nucleon-nucleon cross section [14].

The quadratic dependence of the relative momentum q strongly affect the real part of the collisional self-energy. On the other hand, the calculations with finite range effective interactions, are not yet feasible due to huge numerical effort. Therefore, in this work we estimate the collisional effects by employing a modified Skyrme force, which is obtained by introducing a Gaussian cut-off factor in the matrix elements of the Skyrme force v_S as in [12],

$$\langle ij|v|kl \rangle = \langle ij|v_S|kl \rangle \cdot \exp\left(-\frac{|\langle \beta^2 q^2 \rangle|}{\hbar^2}\right) \quad (8)$$

where β describes an effective range and the quantity $\langle q^2 \rangle$ provides a measure for the relative momentum which is defined by the relation $\langle ij|\delta(\mathbf{r})|kl \rangle \langle q^2 \rangle = \langle ij|q^2 \delta(\mathbf{r}) + \delta(\mathbf{r})q^2|kl \rangle$ with $\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$ and $\mathbf{q} = (\mathbf{p}_1 - \mathbf{p}_2)/2$.

FIG. 1. GDR strength in ^{120}Sn (Left) at $T = 2.6$ MeV for $\beta = 1$ (dashed line), 1.4 (thick line) and 2 fm (thin line).

The application of extended TDHF including collisional coupling between all RPA modes is actually intractable because it requires a large numerical effort. In the following, we first neglect the off-diagonal elements in the self-energy $\Sigma(\bar{\omega})$ in order to be able to compute the response function associated to a complete RPA basis [12]. Then, we discuss the effects of the coupling between modes on a selected example. Before presenting a detailed analysis of the GDR response, we discuss effect of the effective range of the force β on the presented result. In refs [12,13] a value $\beta = 1.4\text{fm}$ have been used since it is a reasonable range for a nuclear force. However, a fit of this effective parameter would be needed in order to fix its value using nuclear properties. In figure 1, we present the GDR response of ^{120}Sn at $T = 2.6$ MeV for different β values. We observe a sizable increase of the average energy with β . For $\beta > 2$ fm, the centroid of strength function does not change anymore. Considering the actual uncertainty on the parameter β , we can estimate the average energy within a typical error of 1 MeV. However, the global shape and width of the strength distribution seems to be more robust predictions since they do not depend much on the actual value of the β parameter. In the following we use a fixed value of $\beta = 1.4\text{fm}$.

Considering the response without non-diagonal terms in the collisional self-energy, it is possible to follow sys-

tematically the evolution of the strength as a function of temperature. Figure 2 presents the GDR strength in ^{120}Sn and ^{208}Pb at $T = 0, 2$ and 4 MeV obtained with the RPA (top) and Extended RPA (bottom). We observe a Landau width at the zero temperature RPA level leading to a Full Width at Half Maximum (FWHM) of 2.0 MeV for ^{120}Sn and 2.2 MeV for ^{208}Pb . However, the response of the system is almost not modified by the increase of temperature as it was already discussed in the literature [20,12]. If we now turn to the extended TDHF results at $T = 0$ MeV first, we can see that the width of the collective peak slightly increases by the collisional effects. We get a FWHM of 2.31 MeV for ^{120}Sn and 3.25 MeV for ^{208}Pb . However, in the dipole case, the width is mainly due to the Landau fragmentation while the collisional damping is small. The predicted widths are slightly below the experimental value of 5 MeV for ^{120}Sn and 4 MeV for ^{208}Pb . This underestimation may be partly due to the fact that we neglect the coherent coupling with low lying states.

Besides the small increase of the width, a systematic shift downward of 1 - 2 MeV for the resonance peak is observed. Indeed, at the RPA level the positions of the peak are 14.5 MeV for ^{120}Sn and 13.00 MeV for ^{208}Pb . They become 13.0 MeV for ^{120}Sn and 10.4 MeV for ^{208}Pb when the collisions are switch on. This is below the experimental energy of the GDR, 15.4 MeV for ^{120}Sn and 13.4 MeV for ^{208}Pb . This might be due to the problem of the adjustment of the effective forces discussed above. In the following, we therefore mainly focus on the relative evolution of the mean-energy shift ΔE and of the width $\Delta\Gamma$ compared to the ground state values.

In figure 3, ΔE and $\Delta\Gamma$ are plotted as a function of temperature. In ^{120}Sn , a strong increase of the FWHM accompanied by an increase of the shift towards low energy is observed in the extended RPA. For ^{208}Pb the increase of the width is found to be weaker while the modifications of the peak energy are almost negligible. Recent experiment [6] have reported a similar behavior. It was observed that the mean-energy of the response is almost constant for ^{208}Pb when T increase between 1.34 to 2.05 MeV while a decrease of 1.5 MeV is observed in ^{120}Sn when T goes from 1.24 to 3.12 MeV. Our calculation is able to reproduce qualitatively this behavior. Indeed, in the same temperature interval, we observe a shift of 1.4 MeV in ^{120}Sn whereas the mean energy is almost constant in ^{208}Pb . If we now turn to the FWHM, the large increase of width obtained in the extended RPA for ^{120}Sn reproduce the experimental increase of 4.5 MeV between $T=0$ MeV to $T=2.5$ MeV. For higher temperature, we slightly underestimate the increase. In ^{208}Pb , we are however not able to account for the strong increase of the width, and at intermediate temperature, we find narrowing of the response followed by an increase. This seems to indicate that other mechanisms besides the collisional damping are important in order to understand the collective strength.

FIG. 2. GDR strength in ^{120}Sn (Left) and ^{208}Pb (Right) at temperatures $T = 0$ MeV (thin line), 2 MeV (dashed line) and 4 MeV (thick line). Top: RPA results, Bottom: Extended RPA results.

FIG. 3. Increase of the width (top) and evolution of the centroid of energy (Bottom) compared to the calculated $T = 0$ MeV strength of the GDR in ^{120}Sn (circle) and ^{208}Pb (cross) as a function of temperature.

The qualitative difference between the collisional damping in the two nuclei comes directly from a different behavior of the self-energy as a function of the frequency (equation 5). In particular, the energy shift is related to the asymmetry of the imaginary part of the self-energy with respect to the collective energy. This asymmetry strongly depends on the density of 2 particles- 2 holes ($2p$ - $2h$) states around the collective energy and on the strength of their coupling with the collective state. Combination of these two effects yields an energy dependent distribution for coupling which may differ strongly from one nucleus to another giving rise to a different strength and temperature dependence of the internal mixing. In

the ^{120}Sn case, the distribution of 2p-2h coupling is rapidly increasing around the collective energy, hence it induces a strong downward shift. In the ^{208}Pb case the situation is different because this distribution is smoother leading to a weaker effect of the coupling on the GDR energy.

We also estimate the effects of the collisional coupling between RPA modes on the strength. Since the full calculation requires a large numerical effort, following [13], we introduce a truncation of the RPA modes by retaining only RPA states which exhaust more than 8 % of the energy weighted sum rule. This truncation do not affect the calculation of the collisional damping, but can reduce the magnitude of the coupling. Typical results (with $\beta = 1.4$ fm) of the calculation of the collective strength including the collisional coupling between the collective modes (thick line) are compared in figure 4 with the calculation including only the diagonal part of the self-energy (thin line). In heavy nuclei, effect of collisional coupling appears more important than in ^{40}Ca . Indeed, the off-diagonal collision term induces an increase of the FWHM of approximately 1 MeV in both cases. Besides the modification of the width, we also obtain an increase of the main peak energy in the Pb response by about 1 MeV, which bring the calculation closer to the experiment. The result demonstrate the fact that, in general, the collisional coupling between all the RPA modes may be important and should be taken into account.

FIG. 4. Example of Extended RPA GDR strength distributions in ^{120}Sn (top) and ^{208}Pb (bottom). The thick line corresponds to calculation including the off-diagonal collision terms while the thin line takes into account only the diagonal part.

In this paper, we estimate effects of collisions between nucleons on the dipole response of ^{120}Sn and ^{208}Pb at zero and finite temperature. These collisions correspond to an internal mixing with 2p-2h states, which leads to damping of collective motion together with a shift of the mean collective energy toward lower energies. In ^{120}Sn , collisional effects become more important when temperature increases, giving rise to a strong increase of the FWHM accompanied with a decrease of the mean collective energy. The variation with the temperature of the collisional damping is weaker in ^{208}Pb and seems less effective in damping collective motion. In that case, our calculation does not reproduce experimental data. We finally address the effect of the range of the interaction

and of the collisional coupling between modes. It appears that both are relatively important and should be carefully accounted for. In particular collisional coupling seems to be more important in heavy nuclei than in lighter nuclei.

Acknowledgments

One of us (S. A.) gratefully acknowledges GANIL Laboratory for a partial support and warm hospitality extended to him during his visit to Caen. This work is supported in part by the US DOE grant No. DE-FG05-89ER40530.

- [1] P. Ring and P. Schuck, *The nuclear many-body problem*, Springer-Verlag, New-York (1980).
- [2] J.J. Gaardhje, Ann. Rev. Nucl. Part. Sci. **42** (1992) 483.
- [3] H. J. Hofmann et al., Nucl. Phys. **A571** (1994) 301.
- [4] E. Ramakrishan et al., Phys. Rev. Lett. **76** (1996) 2025.
- [5] E. Ramakrishan et al., Phys. Lett. **B383** (1996) 252.
- [6] T. Baumann et al., Nucl. Phys. **A635** (1998) 428.
- [7] G.F. Bertsch and R.A. Broglia, *Oscillation in finite quantum systems*, Cambridge (1994).
- [8] G. F. Bertsch, P.F. Bortignon and R. A. Broglia, Rev. Mod. Phys. **55** (1983) 287.
- [9] W. E. Ormand, P. F. Bortignon and R. A. Broglia, Phys. Rev. Lett. **77** (1996) 607.
- [10] A. Smerzi, A. Bonasera and M. DiToro, Phys. Rev. **C44** (1991) 1713.
- [11] S. Ayik, O. Yilmaz, A. Gokalp and P. Schuck, Phys. Rev. **C58** (1998), 1594.
- [12] D. Lacroix, Ph. Chomaz and S. Ayik, Phys. Rev. **C 58** (1998) 2154; S. Ayik, D. Lacroix and Ph. Chomaz, Phys. Rev. **C** (in press).
- [13] Ph. Chomaz, D. Lacroix, S. Ayik and M. Colonna, Preprint GANIL 99-31.
- [14] O. Yilmaz, A. Gokalp, S. Yildirim and S. Ayik, Phys. Lett. **B** (in press).
- [15] C.Y. Wong and H.H.K. Tang, Phys. Rev. Lett. **40** (1978) 1070; Phys. Rev. **C20** (1979) 1419.
- [16] K. Goeke and P.-G. Reinhard, "Time-Dependent Hartree-Fock and Beyond", Proceedings, Bad Honnef, Germany (1982).
- [17] Y. Abe, S. Ayik, P. G. Reinhard and E. Suraud, Phys. Rep. **275** (1996) 49.
- [18] N. Van Giai and H. Sagawa, Nucl. Phys. **A371** (1981) 1.
- [19] E. Chabanat, P. Bonche, P. Haensel, J. Meyer and R. Schaeffer, Nucl. Phys. **A627** (1997) 710; Nucl. Phys. **A635** (1997) 231. Erratum: Nucl. Phys. **A643** (1998) 441.
- [20] H. Sagawa and G.F. Bertsch, Phys. Lett. **B146** (1984) 138.