Statistical analysis of the hot giant dipole resonance with the phonon damping model

N. Dinh Dang,[1,*] K. Eisenman,[2] J. Seitz,[2] and M. Thoennessen[2]
[1]RI-beam Factory Project Office, The Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako City, Saitama 351-01, Japan
[2]National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-1321

(Received 13 August 1999; published 6 January 2000)

The strength functions of the hot giant dipole resonance (GDR) in ^{120}Sn obtained within the phonon damping model (PDM) have been included in the complete statistical calculations and compared with their experimental divided spectra as a function of temperature *T*. The entire experimental shape of the hot GDR can be reproduced reasonably well using the PDM strength functions. The effect of superfluid pairing at $T<1$ MeV is important to obtain a better agreement between theory and data.

PACS number(s): 24.30.Cz, 21.10.Pc, 24.10.Pa, 21.60.−n

The evolution of the giant dipole resonance (GDR) built on highly excited nuclei has been a subject of considerable experimental and theoretical studies in recent years [1–4]. Most attention has been concentrated in the understanding of the hot GDR width, which increases sharply with increasing the excitation energy E^* up to ~130 MeV in tin isotopes and saturates at higher excitation energies. Several theoretical models [5–8] have been proposed to explain the behavior of the hot GDR width as a function of excitation energy (or temperature T). The adiabatic coupling model (ACM) [5] describes the temperature dependence of the hot GDR width as a result of thermal fluctuations of nuclear shapes in a macroscopic manner. Within the collisional damping model (CDM) [6], the width of the hot GDR arises due to collisional damping of nucleons. In the recently proposed phonon damping model (PDM) [7], it has been pointed out that the main mechanism that leads to the increase of the hot GDR width at low temperatures and its saturation at high temperatures is the coupling of the GDR phonon to the incoherent pp and hh configurations, which appear due to the distortion of the Fermi surface at finite temperature. The PDM provides a consistent and simultaneous microscopic description of the width, the energy, as well as integrated yields of γ-ray emission of the hot GDR as a function of temperature [8].

The comparison between the theory and the data of the hot GDR is not straightforward. Typically only the parameters of a Lorentzian strength function (resonance energy, width, and strength) were extracted from the data and compared to the theoretical values. In addition, the conversion of excitation energy which is measured in the experiments to temperature which is calculated in the models is difficult and sometimes misleading as has been discussed recently [9,10]. Although the importance of including the temperature dependence of the GDR parameters into the statistical model calculations was pointed out already a long time ago [11,12], it was not crucial as long as the data were not compared to detailed models but only fitted to extract a functional form of the width increase.

*On leave of absence from the Institute of Nuclear Science and Technique, Hanoi, Vietnam.

Recently a method has been proposed to incorporate the theoretical strength functions directly into full statistical decay calculations [10]. This way the entire shape of the GDR strength functions can be compared with the measured spectra and not just the GDR energy and width. This more complete procedure has been applied to test the ACM and the CDM [10].

In this Brief Report, we apply the same approach to the strength functions of the hot GDR obtained within the PDM [7]. These strength functions, which have been calculated at a given temperature, are known to reproduce reasonably well the inelastic α scattering divided spectra of the hot GDR folded with the contributions of the detector response and bremsstrahlung at the same (average) temperature [8].

The statistical decay calculations were performed using a modified version of the statistical model code CASCADE that includes high-energy γ-ray decay from GDR states [10]. The modified version includes a smooth and temperature-dependent level density over a large range of excitation energies. A level density parameter $A/9$ has been used in calculations. The results of calculations are presented in the form of the GDR cross section

$$f(E_\gamma)=\frac{4\pi^2e^2\hbar}{mc}\frac{NZ}{A}S_{\rm GDR}(E_\gamma). \qquad (1)$$

The experimental data are fitted in CASCADE making use of Eq. (1), where the (temperature-dependent) phenomenological Lorentzian strength function

$$S_{\rm GDR}^{\rm Lorentz}(E_\gamma)=\frac{1}{\pi}\frac{\Gamma_{\rm GDR}E_\gamma^2}{(E_\gamma^2-E_{\rm GDR}^2)^2+\Gamma_{\rm GDR}^2E_\gamma^2} \qquad (2)$$

has been employed for $S_{\rm GDR}(E_\gamma)$. The parameter $\Gamma_{\rm GDR}$ has been varied to achieve the best fit at each temperature. In order to compare these experimental spectra with theoretical predictions, one substitutes the phenomenological Lorentzian (2) with the corresponding strength functions from various theoretical models. Within the PDM, the strength function of the hot GDR has been derived as [8]

0556-2813/2000/61(2)/027302(3)/$15.00

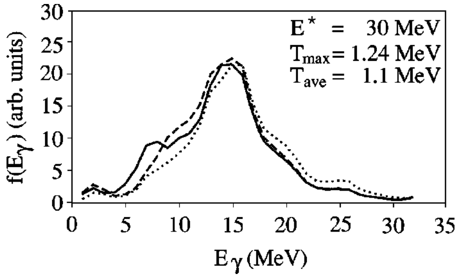

FIG. 1. Theoretical cross sections (divided spectra) of the GDR in ^{120}Sn at $E^* = 30$ MeV. The dotted curve is the cross section obtained from Eq. (1) using the PDM strength function (3). The dashed curve represents the results of CASCADE calculations using the strength function (3) at $T_{\mathrm{ave}} = 1.1$ MeV for all decay steps. The solid curve has been obtained using the PDM strength functions calculated at each corresponding temperature T_{max} of the daughter nuclei. Pairing is not included in the calculations.

$$S_{\mathrm{PDM}}(E_\gamma) = \frac{1}{\pi} \frac{\gamma(E_\gamma)}{(E_\gamma - E_{\mathrm{GDR}})^2 + \gamma^2(E_\gamma)}, \qquad (3)$$

where $\gamma(E_\gamma)$ is damping of the hot GDR, which has been calculated microscopically. It depends on temperature T and the γ-ray energy E_γ. For details, see Ref. [7]. At low temperatures $T < 1$ MeV, the effect of superfluid pairing must be taken into account. The role of this effect on the GDR within the finite-temperature random phase approximation has been studied in detail in Refs. [13]. We employ here the well-known approximated function for the pairing gap $\Delta(T)$, according to which

$$\Delta(T) = \Delta_0 \sqrt{1 - (T/T_{\mathrm{c}})^2} \qquad (4)$$

for $T < T_{\mathrm{c}}$, and $\Delta(T) = 0$ for $T \geqslant T_{\mathrm{c}}$. The critical temperature T_{c} is estimated as $0.567\Delta_0$ [14].

A value of $\Delta_0 = 1.4$ MeV was chosen for the neutron single-particle energies in ^{120}Sn, leading to $T_{\mathrm{c}} \sim 0.8$ MeV. PDM strength functions for ^{120}Sn were obtained within the PDM-1 [7] at temperatures ranging from 0.1 to 3.2 MeV in steps of 0.1 MeV. The γ-ray energy E_γ was calculated between 1 and 32 MeV in steps of 1 MeV. These strength functions were included in CASCADE. Calculations were performed at excitation energies of $E^* = 30$, 50, 70, 90, and 110 MeV, corresponding to compound nucleus temperatures of $T_{\mathrm{max}} = 1.24$, 1.54, 2.02, 2.43, and 2.79 MeV, respectively. The contribution to the spectra of daughter nuclei populated at lower temperatures leads to the average values $T_{\mathrm{ave}} = 1.1$, 1.5, 1.8, 2.2, and 2.4 MeV, respectively [15]. They have been obtained as the weighted average of the excitation energy E^* over all daughter nuclei in the modified CASCADE.

Figure 1 shows the differences between three calculations for the excitation energy $E^* = 30$ MeV, corresponding to $T_{\mathrm{max}} = 1.24$ MeV and $T_{\mathrm{ave}} = 1.1$ MeV. The dotted curve is the cross section directly calculated from Eq. (1) using the PDM strength function $S_{\mathrm{PDM}}(E_\gamma)$ (3) at $T = T_{\mathrm{max}}$. The dashed and solid curves were generated by including PDM strength functions into CASCADE and then dividing the resulting γ-ray spectra by a CASCADE calculation that did not include the GDR. The dashed curve has been obtained using the same PDM strength function (at $T = T_{\mathrm{ave}}$) incorporated in all the steps of CASCADE calculations starting from $E^* = 30$ MeV down to the ground state. The solid curve is the result of the full CASCADE calculation using the PDM strength functions calculated accordingly at each value of T that corresponds to each decay step in the daughter nuclei.

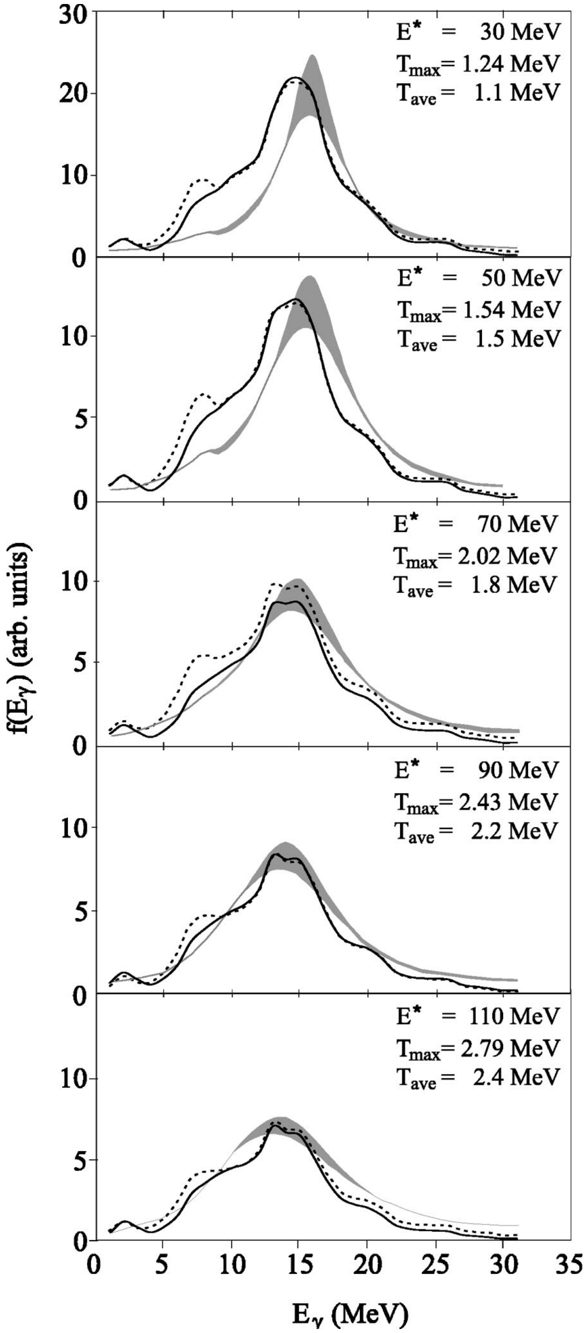

FIG. 2. Experimental (shaded areas) and theoretical divided spectra calculated within the CASCADE model without pairing (dashed curves) and including pairing (solid curves) at various excitation energies.

The comparison between the dotted and the dashed curve shows the difference between a calculated strength function and the ‘‘divided’’ spectra. It should be mentioned that the shape of the divided spectra depend critically on the choice of the constant $E1$ strength chosen for the calculation not including the GDR. The present no-GDR calculation was performed with a constant strength of 0.2 Weisskopf units [4]. The differences between the dashed and the solid curve demonstrate the importance of the full temperature dependent calculation compared to the average calculation. Except for the region $5 \leqslant E_\gamma \leqslant 12$ MeV where more strength is shifted towards lower energy in the full calculation, no major differences between the two calculations are present. The same feature has been obtained at the higher excitations energies E^* as well. The effect of pairing was not included in the calculations for Fig. 1.

In Fig. 2, the results of the full statistical calculations using the PDM strength functions are compared with the experimental cross sections of the hot GDR generated by CASCADE at various excitation energies. The shaded area corresponds to the uncertainty of the GDR width as extracted from the data [4]. The ''experimental'' spectra as well as the theoretical γ-ray spectra were divided by the same γ-ray spectrum from a calculation with a constant $E1$ strength equal to 0.2 Weisskopf units.

The full CASCADE results (dashed) using the PDM strength functions (3) reproduce the experimental spectra reasonably well, especially at high excitation energies. At low excitation energies the strength is overpredicted below ~ 12 MeV. Including the effect of superfluid pairing improves the fits substantially (solid). The extra strength at low γ-ray energies is significantly reduced for the low excitation energy and is in better agreement with the data.

In conclusion, full statistical model calculations have been carried out to compare the theoretical prediction of the PDM with the experimental data for the hot GDR in ^{120}Sn. The analysis has shown that the strength functions of the PDM are in overall reasonable agreement with the experimental spectra. It has also demonstrated that the effect of superfluid pairing at $T < 1$ MeV must be included in the theoretical calculations to obtain a better agreement between theory and data.

N.D.D. thanks the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University for the warm hospitality extended to him during his visit at NSCL where the main part of this work was done. K.E. thanks the High School Honors Science Program at Michigan State University.

[1] J. J. Gaardhøje *et al.*, Phys. Rev. Lett. **53**, 148 (1984); **56**, 1783 (1986); A. Bracco *et al.*, *ibid.* **74**, 3748 (1995).

[2] G. Enders *et al.*, Phys. Rev. Lett. **69**, 249 (1992); H. J. Hofmann, J.C. Bacelar, M.N. Harakeh, T.D. Poelhekken, and A. van der Woude, Nucl. Phys. **A571**, 301 (1994).

[3] P. Piattelli *et al.*, Nucl. Phys. **A599**, 63c (1996); T. Suomijärvi *et al.*, Phys. Rev. C **53**, 2258 (1996).

[4] E. Ramakrishnan *et al.*, Phys. Rev. Lett. **76**, 2025 (1996); Phys. Lett. B **383**, 252 (1996); T. Baumann *et al.*, Nucl. Phys. **A635**, 428 (1998).

[5] W. E. Ormand, P. F. Bortignon, and R. A. Broglia, Phys. Rev. Lett. **77**, 607 (1996); W.E. Ormand, P.F. Bortignon, R.A. Broglia, and A. Bracco, Nucl. Phys. **A614**, 217 (1997).

[6] P. Chomaz, M. Di Toro, and A. Smerzi, Nucl. Phys. **A563**, 509 (1993); A. Bonasera, M. Di Toro, A. Smerzi, and D. M. Brink, *ibid.* **A569**, 215c (1994); V. Baran, M. Colonna, M. Di Toro, A. Guarnera, V. N. Kondratyev, and A. Smerzi, *ibid.* **A599**, 29c (1996).

[7] N. Dinh Dang and A. Arima, Phys. Rev. Lett. **80**, 4145 (1998); Nucl. Phys. **A636**, 427 (1998).

[8] N. Dinh Dang, K. Tanabe, and A. Arima, Phys. Rev. C **58**, 3374 (1998); Phys. Lett. B **445**, 1 (1998); Nucl. Phys. **A645**, 536 (1999).

[9] M. P. Kelly, K. A. Snover, J. P. S. van Schagen, M. Kicinska-Habior, and Z. Trznadel, Phys. Rev. Lett. **82**, 3404 (1999).

[10] G. Gervais, M. Thoennessen, and W. E. Ormand, Phys. Rev. C **58**, R1377 (1998).

[11] D. R. Chakrabarty, S. Sen, M. Thoennessen, N. Alamanos, P. Paul, R. Schicker, J. Stachel, and J. J. Gaardhøje, Phys. Rev. C **36**, 1886 (1987).

[12] D. Pierroutsakou, F. Auger, N. Alamanos, P. R. S. Gomes, J. L. Sida, A. Gillibert, N. Frascaria, I. Lhenry, J. C. Roynette, and T. Suomijärvi, Nucl. Phys. **A600**, 131 (1996).

[13] N. Dinh Dang, J. Phys. G **11**, L125 (1985); N. Dinh Dang and N. Zuy Thang, **14**, 1471 (1988).

[14] L. D. Landau and E. M. Lifshitz, *Course of Theoretical Physics, Vol. 5: Statistical Physics* (Pergamon, Oxford, 1963).

[15] M. Thoennessen, *RIKEN Review No. 23: Proceedings of the RIKEN Symposium and Workshop on Selected Topics in Nuclear Collective Excitations*, edited by N. Dinh Dang, U. Garg, and S. Yamaji (Sanbi, Tokyo, 1999), p. 132.