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Hot giant dipole resonance with thermal shape fluctuation corrections in the static path approximation

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The giant dipole resonances (GDR) of ^{120}Sn are calculated in linear response theory incorporating the thermal shape fluctuations within the static path approximation (SPA). This is the first application of such an approach to the GDR in a realistic nucleus at finite temperature and angular momentum using a model Hamiltonian with a quadrupole-quadrupole interaction. The results obtained show that thermal fluctuations of quadrupole shapes increase the GDR width only by about 15% at $T=4$ MeV compared to its value at $T=0$. The effect of angular momentum on the damping of the hot GDR of this nucleus increases the GDR width by $\sim$22% at $T=2$ MeV and $J\simeq 69\hbar$ compared to its value at $T=2$ MeV and $J=0$. A combined effect of temperature and angular momentum leads to a GDR energy that is nearly independent of the excitation energy.

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For about a decade there has been extensive experimental as well as theoretical studies of the decay properties of the giant dipole resonances (GDR) formed in heavy-ion fusion reactions at high excitation energies E^* (temperatures T and spins J) [1–5]. It has been concluded experimentally that the GDR width in tin isotopes increases sharply when increasing the excitation energy E^* up to $\sim$130 MeV and approaches a saturation at higher excitation energies. In the recent small-angle inelastic α-scattering experiments [6,7] only low angular-momentum states are populated. They show that the increase of the resonance width with the excitation energy for ^{120}Sn and ^{208}Pb is due mainly to the thermal effects. Recently it has been argued that there is no saturation of the width up to $T=3.2$ MeV beyond which the GDR width cannot be reliably extracted [8,9].

Theoretical studies of the behavior of the GDR describe the width's increase either as an effect of a direct adiabatic coupling of the GDR to thermal shape fluctuations (approach I), or due to coupling of the GDR to all possible incoherent ph, pp, and hh transitions at finite temperature (approach II). Approach I (see, e.g., Refs. [2,10–12]) proposes that the isovector dipole oscillation couples adiabatically with the quadrupole degrees of freedom with deformation parameters β and γ that are induced by thermal fluctuations and high spins. The adiabatic coupling model describes the increase of the GDR width up to $T\simeq 3$ MeV in ^{120}Sn and ^{208}Pb well [11], but the GDR shapes generated using the strength functions of this model differ significantly from the observed hot GDR shapes [13]. Recently, within approach II, the authors of Refs. [14,15] have proposed a phonon damping model (PDM) which is quite successful in reproducing the width [14] as well as the shapes of the hot GDR in ^{120}Sn and ^{208}Pb [15,16]. They also find that inclusion of pairing correlations for $T<1$ MeV is important for better agreement with experimental data for ^{120}Sn [16]. In the PDM, a model Hamiltonian including a coupling between the GDR phonon to all ph, pp, and hh configurations at $T\neq 0$ is used and the strength function is calculated directly in the laboratory frame without any need for an explicit inclusion of thermal fluctuations of shapes.

This situation requires further studies towards a consistent microscopic theory of thermal shape fluctuations in the hot GDR. We notice that, so far, the studies within approach I [4,10,11] usually incorporate the effects due to thermal fluctuation by averaging of the γ-absorption cross section $\sigma(E_\gamma)$ over all possible quadrupole shapes using a Boltzman weight factor, $e^{-F/T}$, where F is the free energy depending on the quadrupole deformation parameters β, γ and temperature T. In the calculations of Refs. [4,10,11], the dipole strength function is computed by a simple deformed harmonic oscillator (HO) model, whereas for the thermal averaging a free energy is used corresponding to the macroscopic-microscopic Strutinsky shell correction approach in combination with a parametrized expansion following the macroscopic Landau theory of phase transitions. Hence, a particular, specific Hamiltonian has not been employed for the calculation of every quantity.

On the other hand, the thermal averaging can be performed in a consistent manner following the static path approximation (SPA) for the grand canonical partition function where every quantity can be computed using the same Hamiltonian. The SPA allows one to include the angular momentum effects rather easily following the standard cranking approach. Thus, thermal averaged values $\langle\beta\rangle$ and $\langle\gamma\rangle$ can also be computed at a given temperature and spin. Such a scheme was proposed recently in Ref. [5], where only a model calculation was carried out using an HO model Hamiltonian for a doubly magic fictitious nucleus with $N=Z=70$.

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The aim of this Rapid Communication is to present an attempt to make a calculation of the hot GDR incorporating thermal shape fluctuation effects within the SPA for a realistic situation of ^{120}Sn with a standard effective quadrupole-quadrupole interaction Hamiltonian:

$$\hat{H}=\hat{H}_0-\frac{1}{2}\chi_Q\sum_{\mu}(-1)^{\mu}\hat{Q}_{-\mu}\hat{Q}_{\mu}, \qquad (1)$$

where $\hat{H}_0$ stands for the spherical part and the quadrupole operator $\hat{Q}_\mu$ is given as $\hat{Q}_\mu=(r^2/b^2)Y_{2\mu}$ with the usual HO length parameter $b^2=\hbar/m\omega_0$, and $\hbar\omega_0=41A^{-1/3}$ MeV. The interaction strength parameter χ_Q is taken as $\chi_Q=120A^{-5/3}f_c$ MeV [17], where f_c is a core polarization factor ($f_c\geqslant 1$) taken as unity if there is no assumption of an inert core. Effects of pairing correlations and higher multipolarities are not included at present. As is well known, corresponding to the Hamiltonian (1), a one-body mean field Hamiltonian is essentially a (β,γ)-dependent Nilsson-type Hamiltonian. The spherical single-particle energies are calculated using the spherical Nilsson potential with A-dependent Nilsson parameters [18]. Assuming $N=Z=28$ inert core, the space of the single-particle basis consists of 54 negative parity and 86 positive parity (total 140) orbitals extending the basis space up to $N=6$ major shells. With such a choice we have a large number of active particles (good for collectivity) in a quite reasonable basis space. The number of the basis states is more than six times the number of active protons, and it is more than three times for neutrons (42 particles), with important high-j orbitals like $0h_{11/2}$ and $0i_{13/2}$ included. The GDR cross section $\sigma(E_\gamma)$ within the SPA according to Ref. [5] [see Eq. (20) there] is

$$\sigma(E_\gamma,\omega,T)=\frac{\int dD(\beta,\gamma)e^{(-\alpha\beta^2/2T)}z(\beta,\gamma,\omega)\sigma(E_\gamma,\beta,\gamma,\omega,T)}{\int dD(\beta,\gamma)e^{(-\alpha\beta^2/2T)}z(\beta,\gamma,\omega)}, \qquad (2)$$

where the metric $dD(\beta,\gamma)$ is equal to $\beta^4 d\beta|\sin 3\gamma|d\gamma$; $z(\beta,\gamma,\omega)$ is the kernel of the partition function within the SPA that is given by Eq. (5) in Ref. [5]; $\alpha=(\hbar\omega_0)^2/\chi_Q$. The integration is carried over β from 0 to ∞, and over γ from $-\pi/3$ to $2\pi/3$ (if $\omega\neq 0$) or from 0 to $\pi/3$ (if $\omega=0$). More details of the formulation are given in Refs. [5,12].

Figure 1 shows our results for the GDR γ-absorption cross section σ (the peak value σ_0 normalized to unity) as a function of γ-ray energies E_γ at several temperatures T and angular momentum $J=0$ (i.e., cranking frequency $\omega=0$). The dipole interaction strength χ_D is reduced by 25% as compared to the value used in Ref. [19]. Then the GDR energy $E_{\rm GDR}$ becomes about 16 MeV roughly close to the experimental value $E_{\rm GDR}^{\rm exp}=15.5$ MeV. For the quadrupole interaction strength χ_Q, we have taken $f_c=1.75$ such that in a Hartree-Fock (HF) calculation we obtain $\beta\approx 0.1$ for a prolate ground state shape [20]. Here it is important to add that with a basis space larger than two major shells the $\hat{Q}\cdot\hat{Q}$ interaction is not quite realistic [21] and leads to a too large mean field deformation, β_0. In fact, even in a two major shell calculation Baranger and Kumar [21] had to reduce the quadrupole matrix elements of the upper shell by a factor $(N_0+3/2)/(N+3/2)$, where N_0 and N stand for the total principal quantum number of the lower and upper shells, respectively. In the present case without such a factor we obtain $\beta_0\sim 0.5$. However, after introducing such a factor with $N_0=3$ we find $\beta_0=0.104$ for the HF minimum at $T=0$, which is close to the experimental value of 0.112 [20].

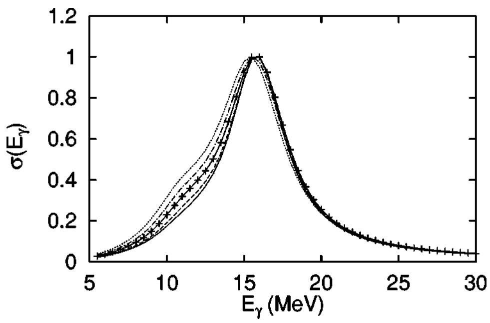

FIG. 1. γ-absorption cross section $\sigma(E_\gamma)$ of the GDR in ^{120}Sn at various temperatures T and angular momentum $J=0$. The solid, dashed, solid with crosses, dash-dotted, and dotted curves correspond to the results obtained at $T=0.5$, 1, 2, 3, and 4 MeV, respectively.

With the smearing parameter $\eta=2.0$ MeV in the linear response matrix (see Refs. [5,19]), the GDR width at $T=0.5$ MeV is about 5 MeV, close to the experimental value. The crosses on the curve for $T=2$ MeV indicate the exact values of E_γ at which numerical calculations are carried out from 5.5 MeV to 30 MeV in step $\Delta E=0.5$ MeV. The curves show some increase of the GDR width Γ as T increases. Fitting these curves to a single Lorentzian shape leads to the values of $\Gamma=4.85$, 5.00, 5.28, 5.49, and 5.57 MeV, respectively, for $T=0.5$–4 MeV. The increase of the width at $T=4$ MeV is only by about 14% compared to that at $T=0$, whereas it is found experimentally to become about twice as much at $T=3$ MeV. The value of the γ-ray energy $E_{\rm GDR}$ that corresponds to the maximum of the cross section shows a small shift towards lower values [6] with the increase of T. The thermal averaged values of quadrupole shape parameters are found to be $\langle\beta\rangle=0.143$, 0.188, 0.231, 0.244, 0.250, and $\langle\gamma\rangle=26°$, 25°, 25°, 26°, 27° for $T=0.5$–4 MeV, respectively. Thus, the average shape is a good triaxial one if $\omega=0$.

Displayed in Fig. 2 is the dependence of the resonance shape on spin J at a given value of temperature $T=2.0$ MeV. The J value is defined as the thermal average $\langle J_x\rangle=J$ at each value of the cranking frequency ω. The effect of orientation fluctuations is not included as it is expected to be negligible for the cross section σ [3–5]. However, we would like to check for this in future calculations as it has not been tested in SPA. At a given value of T the value of $E_{\rm GDR}$ shows a shift towards higher values of E_γ with the increase of angular momentum. The average value γ shows a

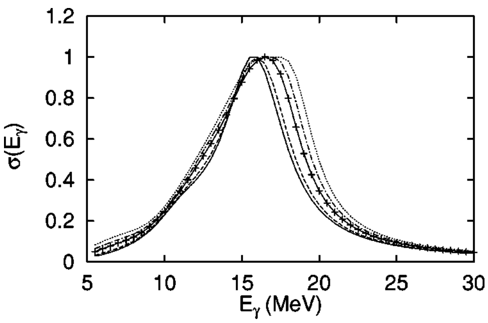

FIG. 2. γ-absorption cross section $\sigma(E_\gamma)$ of the GDR in ^{120}Sn at various angular momenta J and $T=2$ MeV. The solid, dashed, solid with crosses, dash-dotted, and dotted curves correspond to the results obtained at $J=0$, 26, 55, 69, and 83 $\hbar$, respectively.

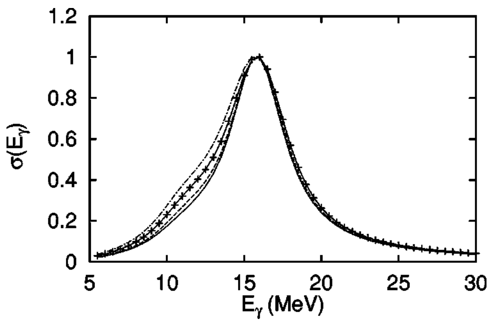

FIG. 3. γ-absorption cross section $\sigma(E_\gamma)$ of the GDR in ^{120}Sn at various angular momenta J and temperatures T. The solid, dashed, solid with crosses, and dash-dotted curves correspond to the results obtained at $(T,J)=(0.5$ MeV, $6\hbar)$, (1 MeV, $8\hbar$), (2 MeV, $16\hbar$), and (3 MeV, $20\hbar$), respectively.

strong angular momentum dependence. We find that $\langle\gamma\rangle=25°, 12°, -6°, -14°$, and $-21°$ for $J=0$, 26, 55, 69, and $83\hbar$, respectively, with $\langle\beta\rangle\approx0.23$ for all the J values. In the literature we do not find anyone reporting on the average value of γ as a function of T and J for Sn isotopes. Here it is to be noted that our convention of the sign of γ is opposite to that of the Lund group, as indicated above for the limit of the γ integration (see also Ref. [5]). In our case $\gamma=-\pi/3$ implies a noncollective rotation about the oblate symmetry axis. Thus, at very high spins $\langle\gamma\rangle$ goes in the right sector of 0° to $-60°$. The value of $\Gamma=5.28$, 5.55, 6.14, 6.49, and 6.96 MeV for $J=0$, 26, 55, 69, and $83\hbar$, respectively, shows a slow but almost linear increase with the increase of J. At $J=69\hbar$ the width increases by about 23% compared to the value at $J=0$. We note that the angular mometum leading to fusion in tin isotopes has been found experimentally to saturate at a value $\sim63\hbar$ [22]. This trend of the width increase as a function of J is quite consistent with the earlier results of Ref. [5] as well as with those of Ref. [11]. The averaged value $\langle\beta\rangle\sim0.23$ found in the present work is rather small compared to the one reported, e.g., in Ref. [10]. But our basic ingredients are very different, and, moreover, there is no mention of the averaged value $\langle\gamma\rangle$ in the above reference.

Shown in Fig. 3 is the combined effect of temperature and angular momentum on the GDR. The cranking frequencies are chosen such that the values of the angular momenta corresponding to the given values of temperatures are roughly equal to the values extracted in the inelastic α-scattering experiment [7]. It is seen that the downward shift of $E_{\rm GDR}$ due to temperature effect found in Fig. 1 and the upward shift due to angular momentum effect as in Fig. 2 almost cancel each other, yielding a nearly constant value of $E_{\rm GDR}\simeq16$ MeV at various excitation energies. The GDR shape becomes nearly a single Lorentzian centered at $E_{\rm GDR}$. This combined effect of T and J is a very interesting feature seen for the first time in a microscopic theoretical study. For $T=0.5$, 1.0, 2.0, 3.0 MeV with the corresponding values of $J=6$, 8, 16, and $20\hbar$ the values of Γ are 4.86, 5.03, 5.37, and 5.76 MeV, respectively.

As seen above, within the present model space the average value of β is not becoming large enough even at high temperature and spin. Taking the core polarization parameter $f_c=2.0$ instead of 1.75 for $T=3$ MeV and $J=20\hbar$ we obtain $\langle\beta\rangle=0.330$, an increase of about 35% compared to the previous value (0.243), but it leads to an increase of Γ only by about 6% to 6.08 MeV (compared to 5.76 MeV). Then at the same temperature and spin, keeping $f_c=1.75$, we have increased the value of the smearing parameter η to 2.2 MeV (10% increase compared to 2.0 MeV) and find Γ increasing to 6.18 MeV, again an increase of only about 6%. Thus, it is clear that in the present approach, at least to the extent that the numerical computations have been performed, the effect of thermal fluctuations of the shape parameters on the GDR width are turning out to be quite small.

In conclusion, we have studied the GDR properties of ^{120}Sn with thermal shape fluctuation corrections within the SPA theory. This is a microscopic approach that facilitates the investigation of the dependence of the resonance shape, width, and averaged shape parameters on temperature T and angular momentum J in a consistent manner, employing a standard many-body Hamiltonian. The presently obtained results show that the effects of thermal fluctuations of the quadrupole shapes lead only to a slow increase of the hot GDR width with increasing T up to 3–4 MeV. The width increases only by about 15% at $T=4$ MeV, i.e., much less than that experimentally observed. The effect of angular momentum on the hot GDR width is slightly stronger than the thermal effect. It increases the width at $T=2$ MeV and $J=69\hbar$ by about 22% compared to the value at the same temperature and $J=0$. On the other hand, it is the combined effect of temperature and angular momentum that yields the GDR's energy almost independent of excitation energy. However, this combined effect also shows only a small increase of the GDR width as a function of (T,J). This first application of the linear response theory in conjunction with the SPA to the calculation of the GDR in a realistic hot nucleus opens a scope of further improvements, which can be done employing more realistic interactions and including other effects such as thermal fluctuations of the pairing gap and of hexadecapole shapes, orientation fluctuation effects, etc.

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