Temperature Dependence of the Width of the Giant Dipole Resonance in ^{120}Sn and ^{208}Pb

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The giant-dipole resonance (GDR) in ^{120}Sn and ^{208}Pb is studied as a function of excitation energy, angular momentum, and intrinsic width. Theoretical evaluations of the full width at half maximum (FWHM) for the GDR strength function are compared with recent experimental data and are found to be in overall agreement. Differences observed between ^{120}Sn and ^{208}Pb are attributed to strong shell corrections in ^{208}Pb favoring spherical shapes at low temperatures. At high temperature, the FWHM in ^{120}Sn exhibits effects due to the evaporation width of the compound nucleus. [S0031-9007(96)00743-0]

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The study of the properties of the giant-dipole resonance (GDR) at finite excitation energy (or temperature) has been the objective of many experimental programs during the past decade (see the reviews in Ref. [1]). These experiments yield important information regarding theoretical models of the GDR; most importantly, the role played by quantal and thermal fluctuations in the damping of the giant vibration. Toward this end, the four important issues are (1) the temperature dependence of the intrinsic width [2], (2) the time scale for thermal fluctuations testing the validity of either the adiabatic picture [3,4] or the occurrence of motional narrowing [5,6], (3) the existence of a limiting temperature for the observation of collective motion in nuclei [7], and (4) the influence of the lifetime of the compound nucleus on the observed width of the GDR [8]. To address these issues a systematic comparison between experiment and theory over a range of temperatures for several nuclei is needed.

One of the principal experimental techniques for observing the GDR in hot nuclei has been compound-nuclear reactions induced in heavy-ion collisions [1]. For the most part, the wide range of experiments performed so far indicate that the full width at half maximum (FWHM) of the GDR strength function increases as a function of temperature, as is predicted by theories for the GDR in hot nuclei that account for adiabatic, large-amplitude thermal fluctuations of the nuclear shape [3]. Many of these experiments, however, involve slightly different compound systems and are often analyzed using different parameters. Also, because of the dynamics of heavy-ion collisions, the compound system is generally formed at high angular momentum, and it is difficult to separate the effects due to thermal fluctuations of the shape from those due to angular momentum.

Recently, two experimental methods for studying the effects of excitation energy and angular momentum separately on the GDR have been introduced. In experiments involving compound nuclear reactions, large arrays of gamma detectors have been used in order to identify GDR photons associated with a system at a definite angular momentum. With this configuration, the GDR may be studied within an angular momentum window that is usually of the order 10–15 units of angular momentum wide, and centered in the range $(30–50)\hbar$ [9]. An alternative technique is to excite a target nucleus from the inelastic scattering of a light particle [10], which yields an excited system with a fairly small angular momentum. Thus, it is now possible to analyze experimental data for the GDR in hot nuclei in terms of the effects due to thermal fluctuations and angular momentum individually.

In this work, we present a systematic study of the properties of the giant-dipole resonance (in particular, the FWHM) as a function of temperature, angular momentum, and intrinsic width for the nuclei ^{120}Sn and ^{208}Pb in comparison with recent experimental data from inelastic alpha scattering [10]. Because of the systematic analysis over a range of temperatures and the relatively low angular momentum of the emitting system, it is now possible to draw conclusions regarding the roles played by shell corrections, angular momentum, and the lifetime of the compound nucleus on the observed width of the GDR.

The description of the GDR in hot nuclei begins by noting that at a finite temperature, T, large-amplitude thermal fluctuations of the nuclear shape play an important role in the observation of nuclear properties. Under the assumption that the time scale associated with thermal fluctuations is slow compared to the shift in the dipole frequency caused by the fluctuations (adiabatic motion), the observed GDR strength function consists of a weighted average over all shapes and orientations. Projecting angular momentum, J, the GDR cross section is evaluated via [11,12]

$$\sigma(E) = Z_J^{-1} \int \frac{\mathcal{D}[\alpha]}{\mathcal{I}(\beta,\gamma,\theta,\psi)^{3/2}} \sigma(\vec{\alpha},\omega_J;E) \times e^{-F(T,\vec{\alpha},J)/T}, \quad (1)$$

where $\mathcal{D}[\alpha] = \beta^4 d\beta \sin(3\gamma) d\gamma \sin\theta d\theta d\phi d\psi$ is the volume element, E is the photon energy, $Z_J = \int \mathcal{D}[\alpha]/\mathcal{I}^{3/2} e^{-F/T}$, and $\mathcal{I}(\beta,\gamma,\theta,\psi)$ is given by

$$\mathcal{I}(\beta,\gamma,\theta,\psi) = I_1 \cos^2\psi \sin^2\theta + I_2 \sin^2\psi \sin^2\theta + I_3 \cos^2\theta, \quad (2)$$

where the I_k represent the deformation-dependent principal moments of inertia. The free energy is given by

$$F(T,\vec{\alpha},J) = F(T,\vec{\alpha},\omega_{\rm rot}=0) + (J+1/2)^2/2\mathcal{I}(\beta,\gamma,\theta,\psi), \quad (3)$$

where $F(T,\vec{\alpha},\omega_{\rm rot}=0)$ is the free energy evaluated in the cranking approximation with rotational frequency, $\omega_{\rm rot}$, equal to zero. We note that Eq. (1) has been used in the past to describe the GDR at very high spin [11], and a fixed rotational frequency framework has been used previously at lower spins [3–6]. We have performed calculations using both approaches, and have found that Eq. (1) yields FWHM that are approximately 100 keV smaller than the fixed rotational frequency approach.

Although Eq. (1) refers to a thermal averaging at constant angular momentum J, which includes fluctuations of the rotational frequency, it is not feasible to evaluate the GDR cross section at finite temperature and fixed J. As such, we proceed as in previous studies [3–6,11], and model the GDR with a rotating, three-dimensional harmonic oscillator. Within this context, the GDR is composed of three fundamental modes whose energies are deformation dependent and given by [13]

$$E_k = E_0 \exp[-\sqrt{5/4\pi}\,\beta\cos(\gamma + 2\pi k/3)], \quad (4)$$

where $E_0 \approx 80A^{-1/3}$ is the centroid energy for the spherical shape. Including the Coriolis term, the Hamiltonian for the GDR in the intrinsic frame may be written as [14]

$$H_D = \sum_k \frac{1}{2}(p_k^2 + E_k^2 d_k^2) - \vec{\omega}_{\rm rot}\cdot(\vec{d}\times\vec{p}), \quad (5)$$

where d_k and p_k are the coordinates and conjugate momenta associated with the dipole vibration and $\vec{\omega}_{\rm rot}$ is the rotational frequency, which is chosen along the z axis in the external reference frame. In addition, $\omega_{\rm rot}$ is taken to be $\omega_J = (J+1/2)/\mathcal{I}(\beta,\gamma,\theta,\psi)$, i.e., the saddle-point value that maximizes the exponential factor while projecting angular momentum onto the partition function (see Refs. [11,12]).

The GDR cross section evaluated in the intrinsic frame is evaluated with the three eigenstates $|\nu\rangle$ of H_D, and may be written as

$$\sigma^{\rm int}(\vec{\alpha},\omega_J;E) = \sigma_0 \sum_{\mu,\nu} |\langle\nu\,|\,d_\mu\,|\,0\rangle|^2 \times E[BW(E,E_\nu,\Gamma_\nu) - BW(E,-E_\nu,\Gamma_\nu)], \quad (6)$$

where $\sigma_0 = (4\pi^2 e^2\hbar/3mc)2ZN/A$, d_μ is the dipole coordinate written in terms of spherical components, $BW(E,E',\Gamma) = \Gamma/2\pi[(E-E')^2 + \Gamma^2/4]$, and Γ_ν is the intrinsic damping width for the resonance. In keeping with experimental findings [15], Γ_ν depends on the centroid energy E_ν via $\Gamma_\nu = \Gamma_0(E_\nu/E_0)^\delta$, where Γ_0 is the width for the spherical shape and $\delta \approx 1.8$. The laboratory cross section for each deformation and orientation used in Eq. (1) is evaluated by rotating the matrix elements $\langle\nu\,|\,d_\mu\,|\,0\rangle$ from the intrinsic frame to the fixed external reference frame and by shifting the dipole energies associated with the intrinsic μ components by $-\mu\omega_{\rm rot}$ [14]. Finally, the parameters E_0 and Γ_0 were taken from ground-state data and are $E_0 = 14.99$ MeV and $\Gamma_0 = 5.0$ MeV for ^{120}Sn and $E_0 = 13.65$ MeV and $\Gamma_0 = 4.0$ MeV for ^{208}Pb.

The free energies were computed using the Nilsson-Strutinsky [16] procedure extended to finite temperature [17] using the Nilsson and liquid-drop parameters of Refs. [18] and [19], respectively. The shell corrections in ^{120}Sn were found to be quite small, and effectively can be ignored. This is in sharp contrast to ^{208}Pb, where, at low temperatures, strong shell corrections ($\sim$14 MeV) were found that favor the spherical shape.

We have also found that effects due to pairing are significant only for temperatures below 0.75 MeV, which is lower than that for which experiments have been performed. In addition, Nilsson-Strutinsky calculations, including pairing, indicate that, for the most part, the effects on the free energy are negligible. This is because ^{208}Pb is a doubly closed-shell nucleus with pairing gaps equal to zero for the spherical shape, while the separate proton and neutron contributions tend to cancel in ^{120}Sn.

In Eq. (2), shell corrections obtained from cranked Nilsson-Strutinsky calculations were also applied to rigid-body moments of inertia with radius $R = 1.2A^{1/3}$ fm. We found that although the shell corrections to the moment of inertia can be quite large for the spherical shape in ^{208}Pb, in practice they have very little effect at low spin beyond that produced by the free energy. This is primarily because of the β^4 factor in $\mathcal{D}[\alpha]$ that suppresses the spherical shape and the fact that for $\beta \geq 0.1$ the moments of inertia are nearly equal to the rigid-body values. It should be noted, however, that the β^4 factor provides less suppression on the effects due to the shell corrections to the free energy because of the dependence on the exponential factor in Eq. (1). A detailed discussion on the effects of spin projection, moments of inertia, and the factor $\mathcal{D}[\alpha]/\mathcal{I}^{3/2}$ on the GDR is given in Ref. [12].

Shown in Fig. 1 are the results obtained for the FWHM of the GDR strength function for ^{120}Sn and ^{208}Pb as a function of temperature in comparison with experimental data [10]. The solid line represents the theoretical values obtained with zero angular momentum. The dependence of the FWHM for ^{120}Sn and ^{208}Pb on angular momentum

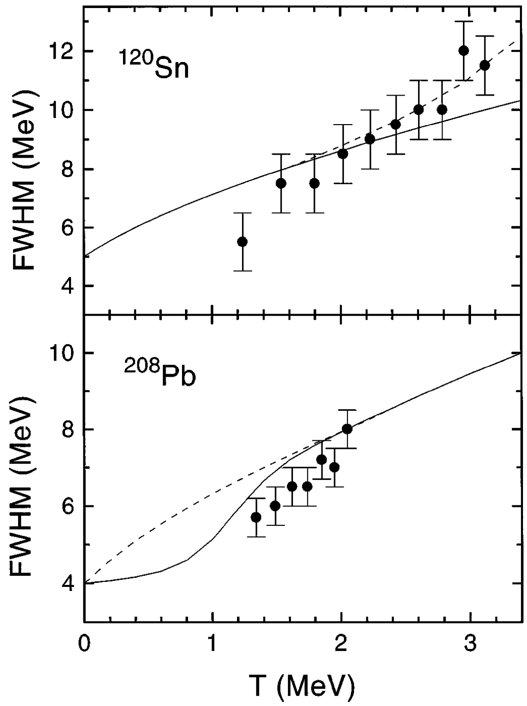

FIG. 1. The FWHM of the GDR strength function as a function of temperature for ^{120}Sn and ^{208}Pb. Experimental data are represented by the filled circles, while the solid line represents the theoretical results obtained for $J = 0\hbar$. For ^{208}Pb, the dashed line is the FWHM obtained assuming no shell corrections. For ^{120}Sn, the dashed line represents the FWHM obtained by including the increase to the intrinsic width, Γ_{cn}, due to the evaporation of particles from the compound system.

at $T = 1.6$ MeV is illustrated in Fig. 2, where it is seen that for $J \leq 25\hbar$ the FWHM is essentially unchanged from the $J = 0\hbar$ value. Given that the largest average angular momentum in the systems studied experimentally is of the order $20\hbar$ [10], the effects due to angular momentum are expected to be negligible.

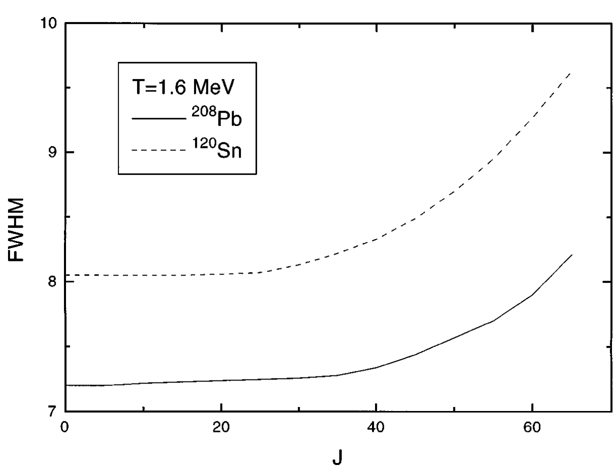

FIG. 2. The FWHM in ^{120}Sn (dashed line) and ^{208}Pb (solid line) at $T = 1.6$ MeV as a function of angular momentum.

To be noted in Fig. 1 is the overall agreement between the theory and experiment; in particular, the dependence in the FWHM on temperature is different between ^{120}Sn and ^{208}Pb. The FWHM in ^{208}Pb is suppressed at lower temperatures relative to ^{120}Sn. This is due to the strong shell corrections in ^{208}Pb that favor the spherical shape at low temperatures. The effect of such strong shell corrections is to limit the influence of thermal fluctuations at low temperatures, thereby reducing the FWHM. This is also illustrated in Fig. 1, where the dashed line for ^{208}Pb indicates the FWHM, assuming no shell corrections. We note that the shell correction effect and the angular momentum dependence were also observed for ^{140}Ce in Ref. [4]. The fact that the adiabatic model slightly overestimates the FWHM may be due to (1) uncertainties in the extracted temperature, (2) the shell corrections being more persistent at higher temperatures than expected, (3) the fact that the experimental cross sections were fit to a single Lorentzian, while theoretically they are a superposition of many Lorentzians, and/or (4) the presence of nonadiabatic effects that would lead to a motional narrowing of the FWHM [5]. Note that the temperatures inferred from experiment are sensitive to the choice of the level-density parameter, and, as a consequence, are uncertain at the level of $\approx 0.1-0.2$ MeV.

The FWHM shown in Fig. 1 are consistent with the adiabatic picture for the GDR, and do not present any evidence for the phenomenon known as motional narrowing [5,6], which tends to lessen the effects of thermal broadening, and, hence, reduce the FWHM. As is pointed out in Ref. [6], however, because of a lack of reliable theoretical estimates for the time scales associated with thermal fluctuations, the FWHM is not sufficient in of itself to exclude motional narrowing, in particular, when the time scales for the β and γ degrees of freedom are much faster than those associated with the orientation of the system. In this case, both the response function and the angular distribution a_2 coefficient are needed.

Finally, we note some slight discrepancies between the adiabatic model and experiment for ^{120}Sn. To begin with, the FWHM at $T = 1.24$ MeV is significantly lower than the theoretical prediction and is difficult to explain within the framework of the model. This datum seems to point to the existence of strong shell corrections that quickly disappear at $T = 1.5$ MeV, which is in disagreement with the expectations of the Nilsson-Strutinsky procedure. At temperatures above 2.8 MeV, experiment is somewhat larger than theory, and may indicate a systematic trend to be observed at still higher temperatures. Shown in Fig. 3 is the FWHM for ^{120}Sn at $T = 3.12$ MeV as a function of the intrinsic width Γ_0. At this temperature, the experimental FWHM is 11.5 ± 1.0 MeV, and we may infer from this datum a value of $\Gamma_0 = 7.7^{+1.8}_{-2.1}$ MeV, as indicated by the solid square and open circles in Fig. 3. We note, however, that this is consistent with the concept that the width observed for the GDR in hot

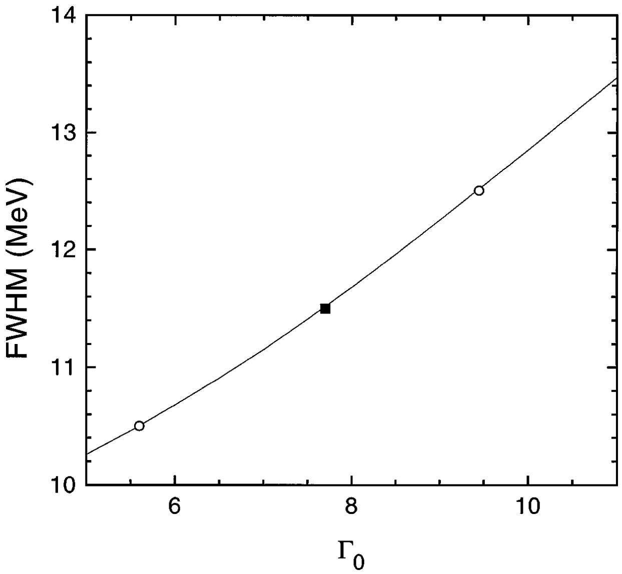

FIG. 3. The FWHM in ^{120}Sn at $T = 3.12$ MeV as a function of the intrinsic width Γ_0 (solid line). The experimental value of 11.5 ± 1.0 MeV is represented by the filled square (11.5 MeV) and the open circles (± 1 MeV).

nuclei should be affected by the evaporation of particles from the compound nucleus [8]. At higher excitation energies, the decay rate for particle evaporation increases, and, because of the uncertainty principle, the energy of an emitted GDR photon cannot be known with a precision better than $\Gamma_{cn} = \Gamma_{ev}^{\text{before}} + \Gamma_{ev}^{\text{after}}$, where $\Gamma_{ev}^{\text{before(after)}}$ is the width for particle evaporation before and after the emission of the GDR photon. To account for this effect in our calculations, Γ_{cn} was folded into the GDR response function by increasing the intrinsic widths via $\Gamma'_\nu \rightarrow \Gamma_\nu + \Gamma_{cn}$. We estimate Γ_{cn} for ^{120}Sn from Fig. 2 of Ref. [7], where Γ_{ev} is plotted as a function of excitation energy. At $T \approx 3.1$ MeV, we deduce $\Gamma_{cn} \approx 2.1$ MeV MeV, which is in good agreement with the experimental results (see Fig. 3). To further see the influence of the evaporation width, we have computed the FWHM for ^{120}Sn as a function of temperature including Γ_{cn}, which is shown in Fig. 1 by the dashed line. On the whole, the inclusion of Γ_{cn} leads to a better overall agreement with experiment.

We conclude that a systematic study of the FWHM of the GDR as a function of temperature for the nuclei ^{120}Sn and ^{208}Pb confirms the overall theoretical picture of the GDR in hot nuclei at low spin. In particular, the role played by adiabatic, large-amplitude thermal fluctuations of the nuclear shape. In fact, overall agreement between theory and experiment is observed over a range of temperatures for both ^{120}Sn and ^{208}Pb, which display quite different behaviors for the FWHM as a function of temperature. This difference can be attributed to the presence of strong shell corrections favoring spherical shapes in ^{208}Pb that are absent in ^{120}Sn. Finally, the increase in the FWHM over that expected from thermal averaging at temperatures of the order of 3.0 MeV is in accordance with the increase expected from the evaporation of particles from the compound system.

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