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Temperature dependence of the giant dipole resonance in ^{120}Sn

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Complete statistical model calculations including temperature- and spin-dependent theoretical strength functions of the giant dipole resonance (GDR) have been performed for the decay of excited ^{120}Sn for the first time. Previous analyses of GDR data with theoretical models compared the centroid and full width at half maximum of the theoretical strength functions with the extracted GDR parameters. In the new approach presented, the entire shape of the strength functions is considered and the theoretical spectra obtained can be directly compared with the experiment. This analysis does not rely on the accuracy of extracting the GDR parameters and/or the nuclear temperature of one data point. The nature of the temperature dependence of the GDR in the hot ^{120}Sn nucleus within the thermal fluctuation and collisional damping model is discussed in this new perspective. [S0556-2813(98)50209-9]

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The study of the properties of the giant dipole resonances (GDR) in hot nuclei is of major interest in nuclear structure (see Refs. [1,2] for reviews of the subject). The damping mechanism of the GDR as a function of spin and temperature has been highly debated and remains a central question in the field [3]. Two of the theoretical models aiming to explain the temperature dependence of the GDR are the thermal fluctuation model in the adiabatic coupling scheme [4–6] and the two-body collisional damping model [7,8]. Whether the temperature dependence of the GDR arises from thermal fluctuations of the nuclear potential landscape or collisional damping of nucleons is still unclear [9,10].

Experimentally, it has been shown that the GDR depends on the angular momentum of the states the vibration is built on [3,11,12] and the nuclear temperature [9,13,14]. In most previous analyses, the comparisons between experiment and theoretical models relied on the capability of extracting GDR parameters that assumed that the spectra could be well reproduced by statistical calculations including a Lorentzian strength function. These parameters, the resonance energy E_{GDR} and the full width at half maximum (FWHM) Γ_{GDR}, were then compared with the centroid and FWHM of theoretical GDR strength functions at the (average) nuclear temperature deduced from the experiment. The extraction of the nuclear temperature, crucial to obtain a meaningful comparison between the measured and calculated GDR parameters, includes an inherent uncertainty due to the level density parametrization and the contribution of daughter nuclei populated by the hot compound nucleus to the γ-ray spectra. It is often unclear if the calculations were compared with an experimental nuclear temperature derived from the compound nucleus in the first decay step or by a mean temperature averaged over all daughter nuclei populated, the latter being significantly lower at high excitation energies [15]. We report in this Rapid Communication on a new approach in which the theoretical models are directly incorporated into full statistical decay calculations and thus can be directly compared with the data. This analysis does not rely on the extraction of the GDR parameters and the nuclear temperature of one data point from the experiment.

The GDR built on highly excited states has been mainly studied via fusion-evaporation reactions, and more recently by inelastic α scattering in ^{120}Sn [13] and ^{208}Pb [14]. The experimental data on ^{120}Sn were used for the analysis of the present work. An interesting feature of the inelastic α-scattering technique is that it decouples the GDR from the influence of the effects of spins. The angular momentum transferred to the target by the α particles scattered at forward angles is relatively low ($\leq 20\hbar$) when compared to typical fusion-evaporation reactions ($\sim 40-50\hbar$). This decoupling from the angular-momentum degree of freedom is important to study the effects of temperature on the GDR discussed in this work. For the inelastic scattering reactions, the excitation energy of the target was determined from the energy loss of the detected α particles and by assuming that all of the energy loss was converted into target excitation. In the ^{120}Sn experiment, the excitation function of the GDR was determined for excitation energies ranging from ~ 30 to ~ 130 MeV. Recently, the energy deposition associated with inelastic α scattering in coincidence with evaporated light particles was measured [16,17] and it was shown that $\sim 80\%$ to $\sim 95\%$ of the α energy loss was converted into target excitation, indicating a $5-20$ % reduction of the excitation energy previously deduced [13,14].

The statistical decay calculations were performed with a modified version of the computer code CASCADE [18] including high-energy γ-ray decay from GDR states [19]. The original level density description of CASCADE has been modified [9,10] and the formalism of Reisdorf [20,21] was employed to achieve a smooth level density description over a large range of excitation energies. In addition, the temperature dependence of the level density was included based on the work of Shlomo and Natowitz [22,23] with a parametri-

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zation by Fineman *et al.* [24]. Following the notations and analyses of Refs. [9, 10], a level density parameter $da' = 9$ MeV was chosen. It should be noted that this level density description is based on a parametrization of the inverse level density parameter K_E and not K_{SE} which should be used in calculations such as in CASCADE (see [25] and references therein). At low temperature ($T \leqslant 3$ MeV), as it is encountered in the present work, there is only a small difference between the two parameters and in order to be consistent with the previous analysis the parametrization using K_E was retained.

The main modification of CASCADE was the substitution of the (temperature independent) phenomenological Lorentzian strength function for the theoretical strength functions from the thermal fluctuation and collisional damping model. In the first model, the spreading of the GDR strength function arises from the increasing shape fluctuations in the nuclear potential landscape with temperature. A complete adiabatic coupling is assumed, i.e., the time scale associated with thermal fluctuations is long compared to the shift in dipole frequency caused by the fluctuations. All possible shapes and orientations can be explored by the nucleus and the final result consists of a weighted average over both shape and orientation degrees of freedom. In the two-body collisional damping approach, the increase of the GDR width arises from a decrease of the relaxation time due to two-body collisions at higher temperature and the magnitude of the spreading width depends strongly on the nucleon-nucleon scattering cross section. It should be noted that the effect of nucleon-nucleon collisions on the GDR spreading width is still controversial [27,28].

The photo-absorption cross section for the GDR in the thermal fluctuation model (TF) was calculated as in Ref. [4]. The calculations were performed for temperatures ranging from 0.1 to 3.3 MeV in steps of 0.2 MeV, for angular momenta J from 0 to $30\hbar$ in steps of $3\hbar$, and for the isotopes $^{111-120}$Sn, $^{108-119}$In, and $^{106-116}$Cd corresponding to the predominant xn, pxn, and αxn evaporation channels of the initial excited ^{120}Sn. The GDR strength function was derived from the calculated cross-section $\sigma^{TF}(E_\gamma)$ by the relation

$$f^{TF}_{\rm GDR}(E_\gamma) = \frac{\sigma^{TF}(E_\gamma)}{E_\gamma}\,\frac{2}{3\pi\hbar^2c^2}S_{\rm GDR}, \qquad (1)$$

where $S_{\rm GDR}$ is the sum rule strength parameter and $f^{TF}_{\rm GDR}(E_\gamma)$ is in units of MeV^{-3}. Previous analyses of GDR data with this model [4,5,9,10] compared the FWHM of the calculated photo-absorption cross section with the extracted GDR width $\Gamma_{\rm GDR}$ from the experiment. However, the transformation of cross section into a strength function related by $\sigma_{\rm GDR}(E_\gamma) \propto f_{\rm GDR}(E_\gamma)\times E_\gamma$ does not conserve the FWHM whereas the GDR width $\Gamma_{\rm GDR}$ of a Lorentzian strength function is approximately the same under this transformation. The widths of the theoretical strength functions of the thermal fluctuation model shown in Fig. 1 are narrower than those extracted from the corresponding cross sections used in previous works. At temperature of 3 MeV, the FWHM of the strength function is $\sim$8.7 MeV while the cross section exhibits a larger value of $\sim$10.2 MeV. Therefore, the comparison depends on whether the extracted GDR parameters are compared with the calculated cross sections or strength functions.

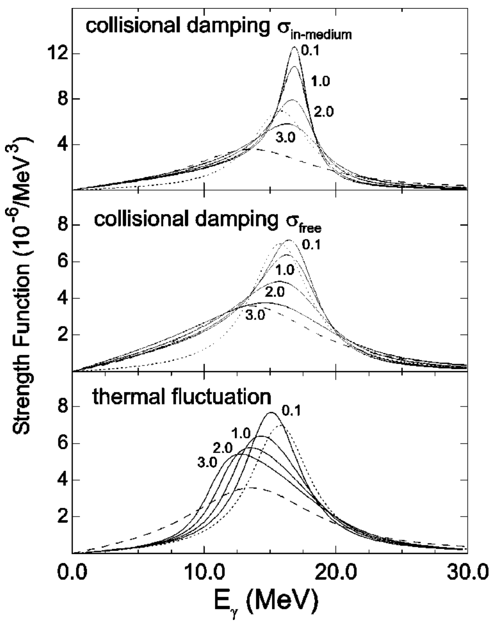

FIG. 1. Theoretical GDR strength functions (solid lines) of the ^{120}Sn isotope for the two-body collisional model (upper and mid panel) and the thermal fluctuation model (lower panel). They are shown for nuclear temperatures 0.1, 1, 2, and 3 MeV. The strength function in the collisional damping model was calculated with an in-medium (upper panel) and a free-space nucleon-nucleon scattering cross section (mid panel) [7]. A single-Lorentzian strength function with GDR parameters $E_{\rm GDR}=16.0$ MeV and $\Gamma_{\rm GDR}=5.5$ MeV (dotted line), and $E_{\rm GDR}=14.8$ MeV and $\Gamma_{\rm GDR}=12.0$ MeV (dashed line), used previously [9,10] to reproduce the experimental spectra at excitation energies 30−40 MeV and 110−120 MeV, respectively, is also plotted in the figure.

By contrast, a direct comparison of experimental data to a theoretical spectrum calculated from the γ-ray decay probabilities provides an unambiguous test of the relevant model.

For the collisional damping model (CD), the spin-independent strength function was calculated (only for the ^{120}Sn isotope) following the formalism described in Refs. [7, 26] for temperatures ranging from 0.1 to 3.3 MeV in steps of 0.1 MeV, for a free-space and an in-medium nucleon-nucleon scattering cross section. The GDR strength function was derived from the calculated strength function $f^{CD}_{\rm GDR}(E_\gamma)$ in units of MeV^{-1} fm^{-3} by use of the relation [26]

$$f^{CD}_{\rm GDR}(E_\gamma) = \frac{2\eta f^{CD}(E_\gamma)}{3\pi\hbar^2c^2}S_{\rm GDR}, \qquad (2)$$

where $\eta \simeq 1.91NZ/A^{1/3}$ (fm^5) with N, Z and A taken as neutron, proton, and mass number, respectively. In Fig. 1, the calculated strength functions are plotted for temperatures 0.1, 1, 2, and 3 MeV for both models (solid lines). For comparison, the phenomenological Lorentzian strength function of the GDR

$$f_{\rm GDR}(E_\gamma) = \frac{8}{3mc^2}\,\frac{e^2}{\hbar c}\,\frac{NZ}{A}\,\frac{E_\gamma\Gamma_{\rm GDR}S_{\rm GDR}}{(E^2_{\rm GDR}-E^2_\gamma)^2+E^2_\gamma\Gamma^2_{\rm GDR}} \qquad (3)$$

with $E_{\rm GDR}=16.0$ MeV and $\Gamma_{\rm GDR}=5.5$ MeV (dotted lines), and $E_{\rm GDR}=14.8$ MeV and $\Gamma_{\rm GDR}=12.0$ MeV (dashed lines) is shown. These values were used previously [9,10] to repro-

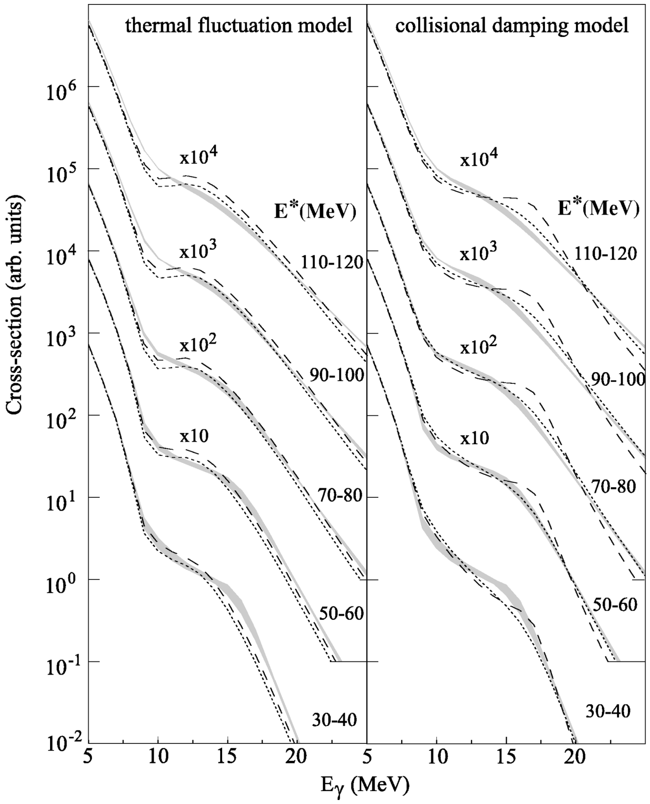

FIG. 2. High-energy γ-ray spectra for ^{120}Sn at several excitation energies. The thin lines (shaded area) correspond to CASCADE calculations (uncertainties of the width) that reproduced the experimental data of Refs. [9,10]. The right panel shows the theoretical spectra of the collisional damping model for a free (dotted line) and an in-medium (dashed lines) nucleon-nucleon scattering cross section. For both cross sections, S_{GDR} was chosen to be one. The left panel shows the theoretical spectra of the thermal fluctuation model for a sum rule strength parameter $S_{\mathrm{GDR}}=1$ (dashed lines) and $S_{\mathrm{GDR}}=0.8$ (dotted lines).

duce the experimental spectra at excitation energies 30−40 MeV and 110−120 MeV, respectively.

For each decay step in CASCADE, the nuclear temperature was calculated from the excitation energies with $T=\sqrt{E_{\mathrm{eff}}/a(E_{\mathrm{eff}})}$ where $E_{\mathrm{eff}}=E^{*}-E_{\mathrm{rot}}-E_{\mathrm{GDR}}$ is the excitation energy for which the collective rotational and vibrational energy has been subtracted and $a(E_{\mathrm{eff}})$ is the energy-dependent level density. The high-energy γ-ray decay probability was computed with the theoretical strength functions at the calculated temperature and a linear interpolation was applied for intermediate temperatures (both models) and spins (thermal fluctuation model only). For the collisional damping model, only the strength function for ^{120}Sn was used whereas in the thermal fluctuation model the strength functions corresponding to the daughter nuclei (xn, pxn, and αxn predominant evaporation channels) were employed. It should be noted that the transformation between the observable quantity E^{*} and the nuclear temperature T is still model dependent. However, in this case, the resulting spectra are an average over all decay steps of the the hot compound nucleus and the final result does not rely on the extraction of the temperature for one data point (e.g., Γ_{GDR}).

In Fig. 2, the results of the calculations for the thermal fluctuation (left panel) and collisional damping (right panel) model are shown. These theoretical spectra are compared with the results of CASCADE calculations (thin lines with shaded area) with parameters that fit the experimental data from Refs. [9,10] where the shaded area is the experimental uncertainty of the width. The spectra of Refs. [9,10] include contributions from bremsstrahlung and were folded with the detector response whereas Fig. 2 only shows the raw CASCADE calculations. Although both models reproduced the extracted widths [9,10] neither of them can reproduce the detailed shape of the γ-ray spectra in this refined description. The collisional damping model using a free-space cross section (dotted lines) and a fixed value of $S_{\mathrm{GDR}}=1$ shown in the right panel of Fig. 2 yields the best overall agreement with the experiment. However, a slight excess in the GDR region at higher excitation energies (90−100 MeV and 110−120 MeV) and a lack of strength at lower excitation energies shows that the temperature dependence of the GDR spreading width is larger than predicted by the model. The use of the in-medium nucleon-nucleon scattering cross section (dashed lines) exhibits a large excess in the GDR region relative to the experimental curves. This excess is caused by the narrower FWHM of the strength function with an in-medium scattering cross section, as it is seen in Fig. 1. The resonance energies are also overestimated by the model for both cross sections used.

For the thermal fluctuation model and $S_{\mathrm{GDR}}=1$ (dotted lines), a good agreement is achieved at low excitation energy, however, a discrepancy in the region $E_{\gamma}\sim 10$ MeV of the calculated spectra increases with the excitation energy. The use of a reduced value of 0.8 for the energy weighted sum rule improves the agreement with the experiment at higher energies in the spectra, however, discrepancies remain in the low-energy part. The strength functions were also recalculated by including the evaporation width [29,30] with the values taken from Ref. [4]. Although this yielded a better agreement with the extracted GDR width Γ_{GDR} of previous analyses [9,10], the overall spectra resulting from a complete CASCADE calculations, are essentially identical to those shown in Fig. 2, even for the higher excitation energies. The contribution to the total spectrum by the evaporation width, significant only for the first few decay steps ($T\sim 3$ MeV), is small relative to the total spectrum including all decay steps. We also compared the experimental spectra with calculations using lower energy bins to correct for the 15−20 % systematic reduction due to incomplete energy transfer [16,17]. This did not have a significant impact on the comparison with the data and the inherent problem in the $E_{\gamma}\sim 10$ MeV γ-ray region of the spectrum was still present. A variation of the level density parameter da' from 7 to 12 MeV did not improve the overall discrepancies between the data and the calculations. This is consistent with a previous study where the influence of the level density on the GDR parameters was studied [31]. It was found that for an increase of the level density parameter da' from 8 to 9 MeV, the resonance energy and width changed by not more than 5%.

In order to emphasize the GDR region of the spectra, the spectra of Fig. 2 at low (30–40 MeV) and high (110–120 MeV) excitation energy were divided by a statistical decay spectrum obtained by replacing the strength function of the GDR with a constant γ-decay strength of 0.2 Weisskopf units. The divided spectra are shown in Fig. 3 on a linear

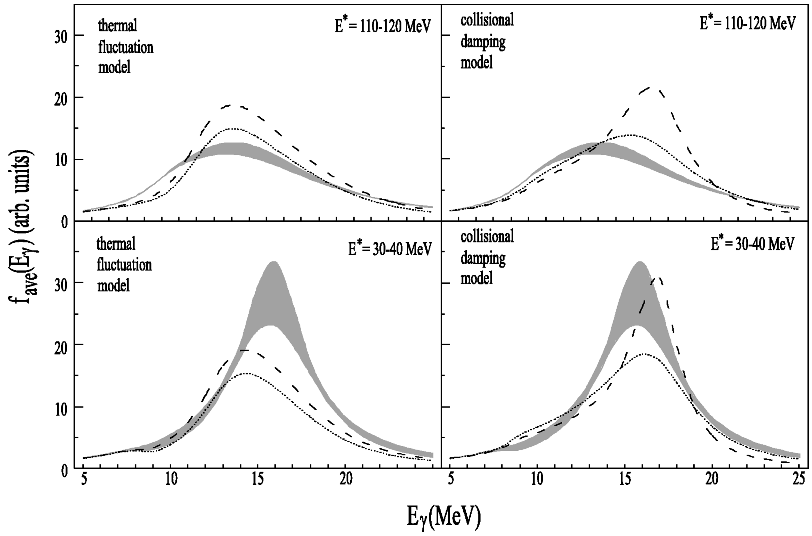

FIG. 3. Divided spectra at low (30−40) MeV and high (110−120) MeV excitation energy. In each panel, the thin lines with shaded area are the experimental divided spectra where the shaded area is the experimental uncertainty of the width. In the right panels, the divided spectra are plotted for the collisional damping model with a free (dotted) and an in-medium (dashed) nucleon-nucleon scattering cross section. In the left panels, the divided spectra for the thermal fluctuation model are plotted with an energy weighted sum rule exhausted of 1 (dashed) and 0.8 (dotted).

scale. The transformation favors the agreement of the high-energy part of the spectra while it attenuates the low-energy discrepancies between the data and calculations.

The lack of strength in the region $E_\gamma \sim 10$ for the theoretical spectra of the thermal fluctuation model can be seen in Fig. 1. For the higher temperatures, the strength function in this model rapidly drops at $E_\gamma \sim 10$ when compared to the Lorentzian strength function used to fit the data at 110–120 MeV excitation energy. This effect has also been observed in the previous comparison of the thermal fluctuation model with the GDR width at an average temperature [3]. While it is suggested by the experiment that the GDR strength functions remain Lorentzian in nature even at high excitation energies, the calculated strength function in the thermal fluctuation model does not keep its Lorentzian-like shape by contrast to the collisional damping model.

Although a better agreement with the experiment is found for the collisional damping model in the present analysis, it must be tested and verified in other systems and conditions. For example, the model predicts a spin-independent strength function inconsistent with the spin effects on the GDR observed by Bracco *et al.* [3,12]. If the effects of temperature discussed in this work can be explained within this theoretical framework, it would certainly be an incomplete theoretical picture of the evolution of the spreading width for both spins and temperature. The magnitude of the GDR width in this model is also highly dependent on the nucleon-nucleon scattering cross section introduced as a free parameter. By contrast to the analysis of Ref. [7] where a comparison of calculated and extracted GDR widths led to a better agreement of the model using an in-medium scattering cross section, it is found in this work that the use of the strength function calculated with the free-space nucleon-nucleon scattering cross section provides a theoretical spectra in better agreement with the experiment.

The thermal fluctuation approach with its spin-dependent strength function is potentially a more complete theoretical framework to explain both the temperature and spin dependence observed in the ^{120}Sn isotope. However, this model exhibits a discrepancy in the low-energy region of the spectra when analyzed with the present detailed calculations. To achieve a good agreement with the data at high-excitation energy, the model requires a reduced value of 0.8 for the energy weighted sum rule, while a better agreement with $S_{\mathrm{GDR}}=1$ is found at low-excitation energy. The loss in strength at high excitation energies could be due to processes like preequilibrium emission that do not result in high target excitations, but nevertheless contribute to the γ-ray spectra up to 8 MeV [10]. Finally, we emphasize the fact that the good agreement between the model and GDR data found by previous analyses was achieved by comparing the calculated FWHM with the experimental GDR widths at the nuclear temperature derived from the compound nucleus in the first decay step [4,9,10], thus neglecting the contribution to the spectra of daughter nuclei populated at lower temperature. The present analysis shows that only a comparison of the FWHM and resonance peak of the calculated quantities is not accurate but the complete shape of the GDR strength function should be considered and included into statistical model calculations to achieve a meaningful comparison between theory and experiment.

In conclusion, the analysis of GDR data with theoretical models has been improved by the inclusion of temperature- and spin-dependent theoretical strength functions into statistical model calculations. This new approach is a more complete test for GDR theoretical models since the entire shape of the strength function is now taken into account. Neither the thermal fluctuation model nor the collisional damping model could reproduce the data in this detailed analysis. It is not excluded that the increase of the GDR width can only be explained by including processes due to both model. With the availability of more detailed models it would also be desirable to reduce the systematic uncertainty of the data. Other nuclei, such as ^{208}Pb, should also be investigated in the same manner.

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