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GIANT DIPOLE RESONANCE IN EXCITED ^{120}Sn AND ^{208}Pb NUCLEI POPULATED BY INELASTIC ALPHA SCATTERING* **

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The evolution of the giant dipole resonance in ^{120}Sn and ^{208}Pb nuclei at excitation energies in the range of 30–130 MeV was studied by comparing high energy γ ray measurements from the decay of the resonance at low angular momenta with theoretical model calculations. Both, a model of the adiabatic coupling of the GDR to the nuclear shape as well as a collisional model describe the increase of the width with temperature. However, while the collisional model is independent of angular momentum, the adiabatic model can describe the increase of the GDR width at high angular momenta.

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1. Introduction

The study of the giant dipole resonance (GDR) built on excited states reveals properties of nuclei at high temperatures. The GDR built on highly excited states has been studied since 1980 [1, 2] using fusion-evaporation reactions, and the most systematic data has been accumulated on Sn isotopes [3, 4]. In these measurements a broadening of the GDR width with increasing excitation energy was observed. In heavy-ion fusion reactions

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the compound nuclei are populated in high angular momentum states, due to the large angular momentum transfer in the entrance channel. High excitation energies are therefore inherently coupled with high spins, making an investigation of the temperature-related evolution of nuclear properties difficult. To decouple the effects of angular momentum and temperature is of high current interest [5].

This decoupling of temperature and spin effects in the study of excited state GDR is possible with small-angle light-ion scattering. Light-particle inelastic scattering has been used extensively in the study of collective modes built on the ground state [6]. High energy excitations in the target nucleus show their signature in the continuum of the scattered-particle spectra. Energy spectra of high energy γ rays measured in coincidence with the inelastically scattered projectiles show an enhancement in the GDR energy region, hence an examination of the GDR built on highly excited states is possible [7].

The angular momentum transferred to the target nuclei in light-ion inelastic scattering is very low compared to heavy-ion fusion reactions. Furthermore, a large range of excitation energies is populated, which offers the possibility to investigate the energy dependance of the evolution by gating on the energy loss of the scattered projectiles. A complementary approach to inelastic excitation is to employ fusion-evaporation reactions and gate on small ranges of the populated angular momenta via the measurement of γ-ray multiplicities with which the spin dependance of the GDR width at an approximately constant nuclear temperature is studied [8].

The measurements for the present analysis were performed with α-particle beams from the K1200 cyclotron at the National Superconducting Cyclotron Laboratory. 40 MeV/nucleon α-particles were scattered off ^{120}Sn and ^{208}Pb, and 50 MeV/nucleon off ^{120}Sn. The experimental details can be found elsewhere [9, 10] and in the present paper the details of the statistical model and the comparison with theoretical models will be presented.

2. Statistical model calculations

In order to extract the parameters of the GDR, the standard statistical model code CASCADE [11] was used. Two modifications have been made to customize the standard code: *(i)* Incorporating the initial population distribution which is spread over a range of excitation energies and angular momenta and *(ii)* the level density description which is especially important for the decay of ^{208}Pb.

The distribution of nuclei in the excitation versus angular momentum plane was obtained by taking 10-MeV-wide bins of the energy distribution measured in the inelastic α spectra, and by using a simple model to calculate the angular momentum transfer through inelastic scattering at each energy. The angular momentum imparted to the target was computed by taking into account the difference in the momenta of the incoming and outgoing α particles, measured through the energy loss, and by choosing an impact parameter in the range of the nuclear interaction radius [12] up to the sum of the half-matter radii of projectile and target [9].

The level density description is a crucial point in the calculation of the statistical decay. The parameterization in the standard version of CASCADE was changed to describe the level densities of nuclei near closed shells correctly. To achieve a smooth and uniform level density description over a large range of excitation energies, a formulation developed by Reisdorf *et al.* [13] was employed. In this parameterization the density parameter a depends on the excitation energy U via the expression

$$a = \tilde{a}\left[1 + \frac{\delta U}{U}\left(1 - e^{-\gamma U}\right)\right] \tag{1}$$

and takes the ground state shell correction δU into account. The quantity $\tilde{a}$ is defined as $\tilde{a} = A/da'$ with da' chosen to reproduce known level densities at low excitation energies. Figure 1 (right panel) shows the large differences of the parameter $da = A/a$ for neighboring Pb nuclei in Reisdorf's parameterization. At higher excitation energies and for nuclei farther away from the closed shell, these differences smoothen out and the da-parameter converges to a value of about 9, which is consistent with systematics.

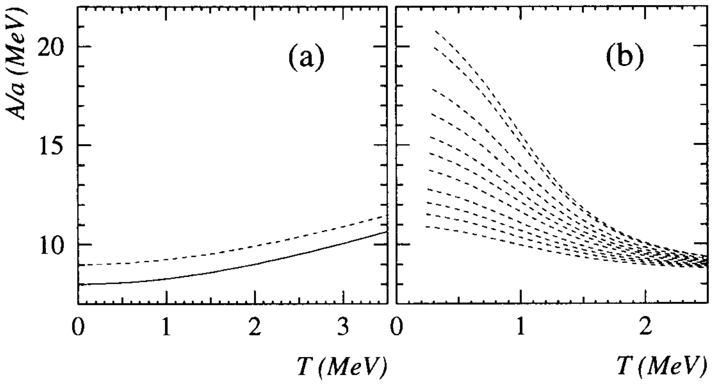

Fig. 1. Level density parameters A/a for ^{120}Sn (a) and Pb isotopes (b). The level density for ^{120}Sn is parameterized as $A/a = da + 2.3(U/A)$ with $da = 8$ (solid line) and $da = 9$ (dashed line). For the Pb isotopes the Reisdorf [13] approach for the level densities is used and $A/a = da$ is plotted sequentially for ^{208}Pb (top) to ^{198}Pb (bottom).

In case of the Sn target, the shell influence at low excitation energies is not significant. In our measurement, the Sn target nuclei were populated to higher excitation energies compared to the Pb target. A level density with the parameter $\tilde{a}$ was adopted according to Ref. [14], where $\tilde{a}$ is given by:

$$\tilde{a} = \frac{A}{da + 2.3\, U/A} . \tag{2}$$

This description leads to a decrease of $\tilde{a}$ from $A/8$ at low excitation to $\sim A/10$ at a nuclear temperature of 3 MeV (figure 1, left panel). In the analysis of the lead target data this parameterization was not used because the nuclear temperatures were lower and the effect is smaller for heavier masses.

To model the extracted γ-ray spectra, not only the statistically emitted γ rays, as calculated in the way described above, had to be taken into account, but also non-statistical contributions from nuclear bremsstrahlung processes. These were assumed to have an exponentially decreasing energy dependence of the form $\exp(-E_\gamma/E_0)$. The inverse slope parameter E_0 was chosen according to bremsstrahlungs measurements at different projectile energies from Ref. [15]. In the fits a value of 14 MeV was used for the beam energies of 40 and 50 MeV/nucleon. This value reproduced the observed slope in the γ-energy spectra at energies beyond the GDR.

The exponential description for the non-statistical contribution was folded with the detector response and then normalized to the measured spectra in the high energy range of 25–30 MeV. The statistical calculations were normalized to the measured data in an energy region below the GDR energy, where the non-statistical contribution is negligible, and then folded with the response of the BaF_2 detectors. The scaled non-statistical contribution was added before comparison to the full measured spectra. Non-statistical contributions amounted to about 10–15% in the GDR energy range.

By applying the statistical model calculation and comparing to the measured γ-ray spectra from all energy cuts, the GDR parameters for the Sn and the Pb target were extracted as a function of excitation energy. A systematic increase of the resonance width with excitation energy was observed in both targets. The nuclear temperature reflects the target excitation on which the dipole resonance is build on. The effective target excitation E_{eff} was calculated using the mean excitation of the input population of each energy cut and subtracting the mean value of rotational energy as well as the GDR energy.

To calculate the temperature with the effective target excitation the expression $T = \sqrt{E_{\text{eff}}/a(E_{\text{eff}})}$ was employed. Here $a(E_{\text{eff}})$ is the energy-dependent level density parameter used in the CASCADE calculation.

TABLE I

Results of the analysis of the ^{120}Sn and the ^{208}Pb data. The first column lists the excitation energy interval, and the following columns contain the nuclear temperature and the GDR width for both targets.

	^{120}Sn		^{208}Pb	
Energy range (MeV)	T (MeV)	$\Gamma_{\rm GDR}$ (MeV)	T (MeV)	$\Gamma_{\rm GDR}$ (MeV)
30–39	1.2	5.5	–	–
40–49	1.5	7.5	1.3	5.7
50–59	1.8	7.5	1.5	6.0
60–69	2.0	8.5	1.6	6.5
70–79	2.2	9.0	1.7	6.5
80–89	2.4	9.5	1.9	7.2
90–99	2.6	10.0	2.0	7.0
100–109	2.8	10.0	2.1	8.0
110–119	3.0	12.0	–	–
120–129	3.1	11.5	–	–

Table I lists the extracted GDR width for the calculated temperature for the two targets ^{120}Sn and ^{208}Pb. The uncertainty of the extracted widths for the Sn and the Pb target were estimated to be ±1 MeV and ±0.5 MeV, respectively. This estimation was obtained by a variation of the width input parameter of the CASCADE calculation and comparison to the measured data with its statistical errors. The errors include the statistical uncertainty, the effect of the variation of GDR energy, and the uncertainty of the non-statistical contribution. They do not reflect any systematic influence of the level density description.

3. Comparison with theoretical models

The increase of the GDR width with increasing excitation energy has been explained by the adiabatic coupling of the resonance to shape variations of the nucleus induced by temperature and angular momentum [16], or by a convolution of Landau damping (one-body) with the damping due to two-body collisions [17]. Simple estimates of the adiabatic coupling model predict approximately a $\sqrt{T}$ dependence of the width as a function of temperature [18], whereas the collisional model predicts a T^2 dependence [19], although this is still controversial because recently it was argued that the temperature dependence should bee extremely weak [20].

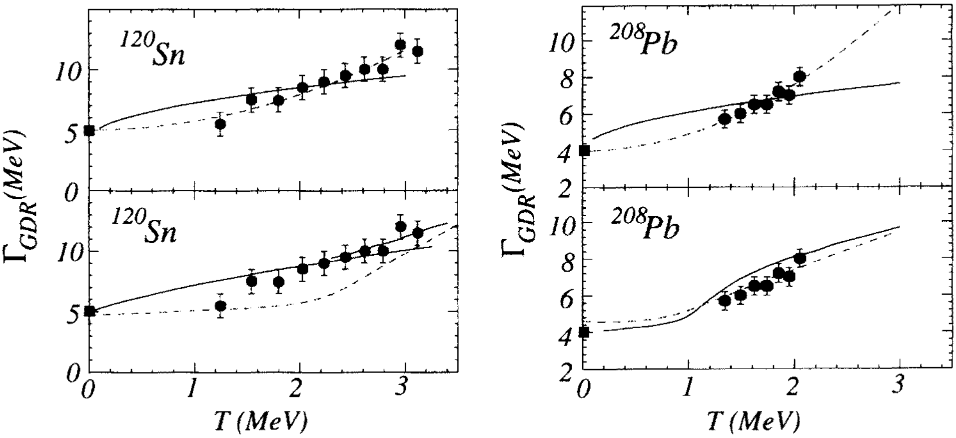

Fig. 2. The extracted GDR widths for ^{120}Sn (left) and ^{208}Pb (right) as a function of nuclear temperature. The ground state value is included at zero temperature. The upper panel includes fits with a $\sqrt{T}$ dependence (solid) and a T^2 dependence (dashed) and the lower panels compare the data with adiabatic coupling calculations (solid) and collisional damping calculations (dashed).

Figure 2 shows the measured width as a function of temperature for ^{120}Sn (left) and ^{208}Pb (right). As shown in the top panels the width increase is consistent with a quadratic dependence on temperature (dashed), which is expected from a two body collisional damping model. In contrast, a $\sqrt{T}$ dependence, corresponding to the adiabatic coupling and shown as the solid line in the two top panels of figure 2 describes only the ^{120}Sn data reasonably well whereas it fails to describe the observed increase in ^{208}Pb.

However, these are only simple estimates and the full calculations were performed for both models [5, 21]. The results of the collisional model are shown as dashed lines in the lower panels of figure 2. The calculated dependence is weaker than T^2 and although it can reproduce the ^{208}Pb data it fails to reproduce the ^{120}Sn data [17, 21]. The results of the adiabatic coupling model (solid lines in lower panels) are able to reproduce the trend of both data sets reasonable well. They both still show the general $\sqrt{T}$ dependence. The upper solid line in the ^{120}Sn calculation includes the effect of the evaporation widths which increases rapidly with increasing excitation energy [22], and improves the agreement between the calculation and the highest temperature data points [5]. The important difference between ^{120}Sn and ^{208}Pb is the strong shell effects present in the latter case, which shift the onset of the $\sqrt{T}$ behavior to approximately 1 MeV, at which the shell effects are washed out.

The direct comparison of these calculations with the data is however not straight forward. The determination of the temperature depends critically on the level density parameter. In order to get a more quantitative description of the data, it is necessary to incorporate the calculated GDR strength function in the statistical model code and compare the experimental spectra directly and not just the extracted GDR width.

In case of the measurement of the GDR in excited ^{120}Sn nuclei a comparison with other experimental results is possible, as data from various fusion-evaporation experiments performed with Sn isotopes are available [3, 4, 8].

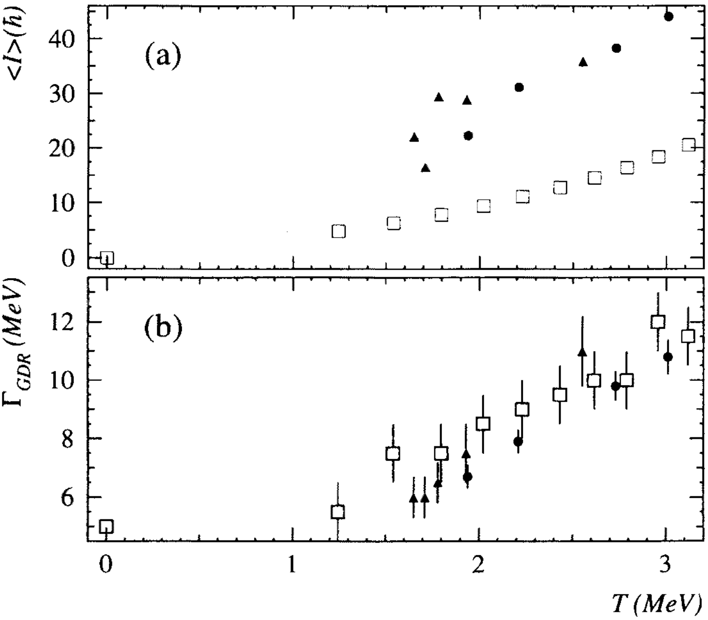

Fig. 3. Mean angular momentum (a) and GDR widths (b) from 50 MeV/nucleon scattering of ^{120}Sn □ in comparison to fusion-evaporation measurements of $^{108-112}$Sn nuclei from Ref. [3] (▲) and Ref. [4] (●).

In figure 3 the obtained results from the Sn measurement with beam energy of 50 MeV/nucleon [9] is compared to fusion-evaporation measurements of Sn isotopes. The top panel shows the calculated mean angular momentum of the compound nuclei of the fusion reactions (filled symbols) and the inelastic scattering reaction (open squares) versus the nuclear temperature. The temperature for the data from Refs. [3] (triangles) and [4] (circles) was calculated using the same energy-dependent level density parameterization as for the inelastic scattering data. The angular momentum is about 10 to 20 $\hbar$ lower in case of the inelastic scattering data. In the bottom panel the measured widths are plotted. In contrast to the angular momenta the values of the GDR width do not differ significantly in their evolution with nuclear temperature, indicating that the effect of the spin on the resonance width is not large.

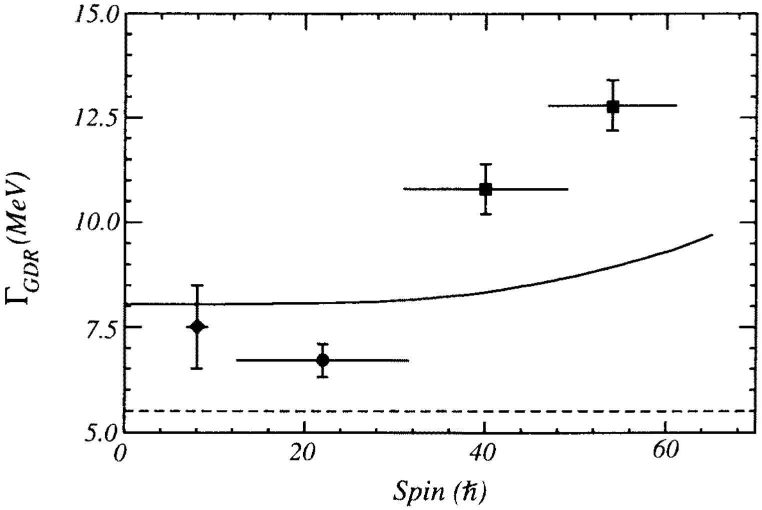

Fig. 4. The GDR width as a function of spin at a constant temperature of 1.8 MeV. The data include inelastic scattering (diamond), inclusive fusion (circle) and multiplicity gated fusion (squares) experiments. The results of an adiabatic coupling and a collisional damping calculation are shown as solid and dashed lines, respectively.

Thus it seems that the observed width increase of the GDR in highly excited Sn isotopes is mainly a temperature related effect which is in apparent contrast to the recent observation of the increase of the GDR width due to angular momentum at a constant temperature [8]. However, both effects can be qualitatively described within the adiabatic coupling model as shown in figure 4. The figure includes experimental values of the GDR width for a constant temperature of 1.8 MeV for inelastic scattering (diamond) [9], inclusive fusion (circle) [4] and multiplicity gated fusion (squares) [8] experiments. At spins below 30 $\hbar$ the width is constant for a given temperature, consistent with figure 3 whereas at larger spins the width increases. The collisional damping model does not include spin effects and thus is constant (dashed) and underpredicts the experimental values of the GDR width. The adiabatic coupling model (solid) predicts an increase at larger spins, although it underpredicts the magnitude.

4. Conclusions and outlook

The study of the GDR as a function of temperature independent of the influence of angular momenta is possible with small angle inelastic α-scattering. The increase of the GDR width with temperature was compared with an adiabatic coupling model and with a collisional model. The adiabatic coupling of the GDR to the nuclear surface could explain the data and showed the influence of shell effects up to a temperature of 1 MeV in ^{208}Pb. It also was able to predict the width increase for large angular momenta at a constant temperature. The collisional model agrees with the ^{208}Pb data, however, it underpredicts the width increase observed for ^{120}Sn and does not include any angular momentum effects.

For the detailed comparison between the data and the calculations it will be necessary to include the strength functions explicitly into the statistical model code. These calculations are currently in progress and will potentially be able to distinguish between the two descriptions of the broadening of the GDR as a function of temperature.

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