Current status and future of hot giant dipole studies

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The study of the giant dipole resonance (GDR) built on highly excited states continues to be a useful tool to explore basic nuclear properties at finite temperatures and angular momenta. More and more exclusive measurements gating on, for example, evaporation residues, angular momenta or discrete low energy γ-ray transitions are able to study the behavior of the GDR in much more detail than previously possible. The dependence of the GDR width as a function of temperatures and angular momentum continues to be a topic of discussion. In the future, second generation rare isotope facilities together with high efficiency arrays should make the study of the GDR in hot exotic nuclei feasible.

1. INTRODUCTION

The giant dipole resonance (GDR) built on highly excited states was first identified in the high-energy γ-ray spectrum of spontaneous fission of 252Cf in the early seventies [1] and in heavy-ion fusion reactions in the early eighties [2]. For the last 20 years the field has expanded and resulted in significant nuclear structure and nuclear reaction information. Comprehensive reviews have been dedicated specifically to the GDR in hot nuclei [3–5], books about giant resonances included chapters about the hot GDR [6,7] and recently a dedicated book has been published [8]. In addition, the progress of the field can best be followed in the proceedings of the topical conferences on giant resonances [9–14].

Among the structure and reaction effects explored with the hot GDR were, for example, the determination of the nuclear shape, the coupling to low-lying states, motional narrowing, loss of collectivity at high temperatures, fission timescales, entrance channel effects and pre-equilibrium giant dipole vibrations.

The improvement of detection techniques, most notably the development of highly efficient scintillation detector arrays, allowed exclusive experiments and the study of reactions with smaller and smaller cross sections. Presently these experiments are concentrating on the search for the GDR built on exotic shapes [15,16]. However, most surprising is the fact that the temperature dependence of the GDR parameters themselves is not completely understood. The most widely accepted model for the hot GDR is the thermal fluctuation model (TFM) [17–19]. Although a phenomenological model [20] based on the TFM gives a reasonable description of the overall temperature dependence of the GDR width over a wide range set of data, recent experimental evidence demonstrated discrepancies which will be discussed in the following two sections.
2. GDR WIDTH AT LOW TEMPERATURES

At low temperatures (∼1 MeV) the GDR was believed to be a sensitive tool to explore the vanishing of shell effects with temperature. A comparison of the data in $^{120}$Sn and $^{208}$Pb [21,22] seemed to suggest that the temperature increase of the GDR width is delayed in $^{208}$Pb because of strong shell effects which first have to be dissolved before the width increases similar to nuclei without shell effects (∼$\sqrt{T}$). Although discrepancies in the $^{120}$Sn data at low temperatures were already noticed in the original reference [21] there was no conclusive experimental evidence. A recent experiment of $^{17}$O inelastic scattering was performed in order to measure the width of the GDR at very low temperatures in Sn [23].

Figure 1 shows the γ-ray spectrum for the excitation energy range of 20–30 MeV, corresponding to a temperature of ∼1 MeV. A narrow width of 4 MeV was required in order to fit the data (solid line). An energy dependent description of the width which follows the TFM fails to describe the data (dashed line). The temperature dependence of the GDR width in Sn including the new data point at 1 MeV is shown in Figure 2. The TFM (dashed line) clearly fails to describe the trend of the data. The solid line guides the eye to show the suppression of the increase of the GDR width similar to the trend in $^{208}$Pb.

Before a more general conclusion about this suppression can be drawn it is necessary to investigate other nuclei. An indication that this suppression occurs also in other nuclei can be found in the data of $^{59-63}$Cu [20]. Figure 3 shows the suppression of the data...
at low temperatures relative to the predictions of the phenomenological model which is based on the TFM. Another recent measurement explored the GDR width in a very cold fusion reaction to form \(^{179}\text{Au}\) [24]. Although only a single measurement was reported at a temperature of 0.7 MeV, comparisons with the data in \(^{208}\text{Pb}\) and predictions of the TFM including (solid line) and excluding (dashed line) shell effects, reveal the suppression of the width (see Figure 4).

The above examples show that the GDR width is suppressed relative to the predictions of the TFM in at least four different mass regions (Cu, Sn, Au, and Pb). With the exception of \(^{208}\text{Pb}\) the shell correction energies for these nuclei are small as can be seen in Figure 5. It shows the ground-state microscopic correction energies as a function of proton and neutron numbers and \(^{60-63}\text{Cu}, \ ^{120}\text{Sn}, \ ^{179}\text{Au}, \ \text{and} \ ^{208}\text{Pb}\) are indicated. The small correction energies for \(^{59-63}\text{Cu}, \ ^{120}\text{Sn} \ \text{and} \ ^{179}\text{Au}\) support the TFM calculations that the GDR width in these nuclei should not be suppressed at low temperatures. However, since the GDR width in these nuclei has been measured to be small at low temperatures, it indicates that the suppression is a general feature of all nuclei, independent of the presence of shell effects. Thus, the explanation of the width reduction in \(^{208}\text{Pb}\) cannot be substantiated.

### 3. Angular Momentum Dependence of the GDR Width

The angular momentum dependence of the GDR width has been non controversial up to recently. The data in two different mass regions (\(^{106}\text{Sn}\) and \(^{176}\text{W}\)) could be explained within the TFM [26]. However, a new measurement in \(^{86}\text{Mo}\) did not show a dependence of the GDR width over a wide range of angular momentum [27]. Figure 6 shows a constant width of \(~9\) MeV for angular momenta up to 30 \(\hbar\). This independence is inconsistent with the TFM. A comparison of this new data with the phenomenological model shows that a
Ground-state microscopic correction energies. The nuclei where GDR data are presented are indicated. With the exception of Pb they do not exhibit large shell correction energies and the GDR width should not be suppressed (adapted from [25]).

Figure 6. Angular momentum dependence of the GDR width in $^{86}$Mo (adapted from [27]).

Figure 7. Comparison of the angular momentum dependence of the (reduced) GDR width $L(\xi)$ in $^{108}$Sn and $^{86}$Mo with the phenomenological model (adapted from [28]).
significantly larger width is expected for the highest angular momenta in this mass region [28]. Figure 7 shows the $^{86}$Mo (triangles) and the $^{106}$Sn (circles) data in terms of the reduced width $L(\xi) = 1 + 1.8[1 + e^{(1.3-\xi)/0.2}]^{-1}$ as a function of the parameter $\xi = J/A^{5/6}$. Although the discrepancy does not seem large it corresponds to an increase of the width of up to 3 MeV.

4. FUTURE OF THE HOT GDR

The overall number of hot GDR experiments has decreased during the last few years. The general properties of the GDR as a function of temperature are understood, and it is very difficult to extract higher resolution data which could probe theory to a higher level of details.

The future of hot GDR studies, like many other subtopics of nuclear structure physics, is moving towards more exotic nuclei. Fusion evaporation reaction typically populate hot nuclei on the proton-rich side of the valley of stability, the neutron-rich side is difficult to reach with a combination of stable targets and stable beams. Although fusion evaporation reactions with rare very neutron-rich isotope beams will populate hot very neutron-rich compound nuclei, neutron evaporation will dominate the GDR $\gamma$-ray decay even more because of the lower neutron binding energy. This means that the increase of neutron numbers in the projectile will not directly translate to the same increase of neutron numbers in the evaporation residues.

The increased competition will reduce the GDR $\gamma$-ray emission and the GDR enhance-
ment in the spectra will be less pronounced. Figure 8 shows the calculated $\gamma$-ray spectra following the fusion reaction of carbon on tin isotopes with increasing neutron numbers. Despite this disadvantage relative to stable fusion reactions the figure shows that it still should be possible to extract the GDR parameters of hot neutron-rich nuclei. The typically small beam intensities of the rare isotope beams in addition to the reduced GDR strength makes highly efficient high-energy $\gamma$-ray detection arrays a necessity.

5. CONCLUSIONS

The study of the hot giant dipole resonance has been a very successful tool in nuclear structure physics for the last 20 years. While the main features are understood, data at low temperatures contradict the predictions of the thermal fluctuation model. The suppression of the width increase predicted by the model seems to be a general feature of all nuclei.

With the construction of second generation rare isotope facilities it will be possible to extend the GDR measurements also to hot neutron-rich nuclei.

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REFERENCES