First Low Temperature Measurement of the Giant Dipole Resonance Width in Sn


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Abstract. The width of the Giant Dipole Resonance in Sn was studied by means of inelastic scattering. This study allowed for the first measurement of the GDR width at a temperature of 1 MeV. The width was found to be $4 \pm 1$ MeV, and is consistent with the ground state measurement. This result is in disagreement with adiabatic thermal shape fluctuation calculations, indicating an overestimation of the influence of thermal shape fluctuations at low temperature.

INTRODUCTION

The Giant Dipole Resonance (GDR) has been the focus of numerous experimental studies. The experiments have predominantly measured the width of the GDR as a function of temperature [1, 2, 3]. The most extensive studies have been on Sn and Pb nuclei. Theoretical calculations predict that the width of the GDR in Sn and Pb should behave differently at low temperatures, due to the presence of shell effects in Pb [4, 5, 6].

At low temperatures, shell effects are very strong in Pb. This is quite different for Sn, where shell effects are weak. Theoretical calculations determine the width of the GDR by averaging the GDR strength function over a thermal ensemble of shapes [4, 5, 6]. The increase of the GDR width is then attributed with an increase in the shape fluctuations with temperature. In nuclei where shell effects are small, the shape fluctuations are expected to behave as determined from a rotating liquid drop. This is not the case for nuclei where shell effects are strong. In the case of nuclei with strong shell effects, shape fluctuations are small at low temperatures. This results in a suppression of the GDR width relative to the liquid drop predictions. As the temperature increases, shell effects begin to decrease, and the width increases. Eventually the nucleus gets sufficiently hot for shell effects to disappear, and the width approaches the liquid drop predictions. Data for both Sn and Pb are shown in Fig. 1 along with liquid drop and Nilsson-Strutinsky calculations. The initial suppression of the GDR width found in Pb should be absent in Sn.

In general, theoretical predictions describe the data for Sn and Pb well (See Fig. 1) [6]. However, the lowest temperature data point in Sn is on the order of 1–2 MeV lower than predicted. This discrepancy suggests a possibly significant deviation between theory and experiment. To investigate this discrepancy, an experiment was performed to measure the width of the GDR at low temperatures.
FIGURE 1. Data and theoretical calculations for Sn (left) and Pb (right) nuclei. Both plots are taken from Fig. 4 of Ref. [6]. In the case of Sn, four new data points [3] are shown as solid upside-down triangles. The solid curve in each panel shows liquid drop calculations, while the dashed curve shows Nilsson-Strutinsky calculations.

EXPERIMENTAL DETAILS

The width of the GDR has been studied by means of fusion-evaporation reactions and inelastic $\alpha$-scattering in Sn [3, 6]. In fusion-evaporation reactions, it is easy to determine the initial excitation energy of the nucleus. However, these reactions are limited to higher temperatures due to the Coulomb barrier in the entrance channel. Inelastic scattering does not have this limitation. Despite this, there is a disadvantage to inelastic scattering reactions. It is difficult to determine the initial excitation energy of the nucleus for large inelastic energy loss. This is due to the presence of knockout reactions and other processes that do not lead to full deposition and equilibration in the target of the energy loss of the projectile. To reduce these effects, heavy-ion scattering was used as opposed to $\alpha$-scattering [7].

The reaction employed in this experiment was $^{120}\text{Sn}(^{17}\text{O},^{17}\text{O})$. The $^{17}\text{O}$ projectiles were extracted from the K1200 cyclotron at the National Superconducting Cyclotron Laboratory at an energy of 80 MeV/nucleon. The target ($^{120}\text{Sn}$) had a thickness of 7.45 mg/cm$^2$. The inelastically scattered $^{17}\text{O}$ and other reaction products were measured in the S800 magnetic spectrometer. The S800 magnetic spectrometer served two purposes. It allowed for the determination of the projectile energy loss resulting from the scattering process. It was also used for particle identification.

High-energy $\gamma$ rays from the GDR decay were measured with the ORNL - Texas A&M - MSU BaF$_2$ detectors in coincidence with the S800. The detectors were arranged into two close packed arrays, each consisting of 68 detectors. The arrays were located at a distance of 31.8 cm from the target at angles of $\pm 90^\circ$ with respect to the beam axis.

$\gamma$-RAY SPECTRA

The $\gamma$-ray decay spectrum of the excited nucleus is essential in studying the GDR. High-energy neutron-induced events were of concern in this experiment. To eliminate these events, pulse shape discrimination using the two components of scintillation light emitted in BaF$_2$ was used. Final $\gamma$-ray selection was accomplished by using the excellent timing properties of BaF$_2$ [8]. In order to improve the response of the array, $\gamma$-ray events in neighboring detectors were added together.

The isolation of $\gamma$-ray events allowed for the decay spectrum to be extracted from the data. In fact, it was possible to extract several $\gamma$-ray decay spectra. Since all $\gamma$-ray events are in coincidence with inelastically scattered $^{17}\text{O}$ fragments, it was possible to correlate the detected $\gamma$ rays with the energy loss of the scattered $^{17}\text{O}$. This allowed for several spectra to be measured corresponding to various ranges of projectile energy loss. In this experiment, $\gamma$-ray decay spectra were extracted in 10 MeV energy loss bins. The energy losses considered in this work were in the range of 20–90 MeV.
FIGURE 2. Several extracted $\gamma$-ray spectra are shown. From left to right, these spectra are correlated with the range of energy losses given by 20–30, 30–40, 60–70, and 80–90 MeV, respectively.

The lowest and highest energy loss spectrum is shown, along with some representative spectra between these energy losses, in Fig. 2. The energy losses gated on are indicated in the figure caption. All spectra exhibit the enhancement at $E_\gamma \sim 14$ MeV characteristic of the $\gamma$-decay of the GDR. In Fig. 2 it is evident that as the projectile energy loss increases, so does the width.

ANALYSIS OF THE 20–30 MEV ENERGY LOSS SPECTRUM

The $\gamma$-ray spectrum gated on 20–30 MeV projectile energy loss is the lowest temperature measurement in Sn nuclei to date. To determine the parameters of the GDR from this spectrum, statistical model calculations were performed with the computer code CASCADE [9, 10]. In these calculations, the level density was parameterized with the method of Reisdorf [11]. At these low energies, it is very important to determine the level density accurately. To ensure that the correct level density was used at very low energies, the first several known discrete levels were input to the code for nuclei that the excited nucleus decayed through.

The results of the statistical calculations were then folded with the response of the BaF$_2$ detector arrays as simulated by GEANT [12]. A non-statistical bremsstrahlung component was also folded and added to the calculations. The bremsstrahlung component was assumed to have the form exp(-$E_\gamma$/E$_0$), where E$_0$ was set to 25 MeV [13, 14]. This value is smaller than that given in Ref. [13], because our collision is peripheral [14]. The folded CASCADE plus bremsstrahlung components were compared to the $\gamma$-ray spectrum by normalizing both components to the data.

The result of the calculations is shown in Fig. 3, along with the data. The GDR parameters were varied in the CASCADE calculations to minimize $\chi^2$. The parameters extracted were the GDR energy ($E_D$), width ($\Gamma$), and classical sum rule strength ($S$). These parameters were found to be $E_D = 16.5 \pm 0.7$ MeV, $\Gamma = 4 \pm 1$ MeV, and $S = 1.1 \pm 0.2$. For this spectrum, the mean excitation energy following the GDR decay with $E_\gamma = 15$ MeV is 9.7 MeV. This mean excitation energy was converted to a temperature (T) according to $T = (d\ln(\rho)/dE)^{-1}$ [3, 6]. This conversion yielded a temperature of 1.0 MeV.

The GDR width extracted at this temperature is shown with other existing data in Fig. 4. This new point is shown as the open square on this plot. Two curves are also shown on this plot. The dashed curve corresponds to liquid drop calculations. The solid curve is to guide the eye through the data. The width at $T = 0$ MeV was set to a value of 3.8 MeV [6]. It appears that the liquid drop calculations fail to describe the behavior of the data at low temperatures.
FIGURE 3. The $\gamma$-ray decay spectrum gated on 20–30 MeV projectile energy loss is shown by the solid circles. The solid curve shows the result of the statistical model calculations.

ANALYSIS OF THE HIGHER ENERGY LOSS DATA

This data was compared with previous measurements by analyzing the higher energy (temperature) $\gamma$-ray spectra. Rather than analyze the higher temperature data by fixing the width of the GDR over the entire decay, as done with the lowest energy spectrum, the width was varied continuously along the decay as shown by the solid curve in Fig. 4. In analyzing the higher temperature data, there was some difficulty. The initial excitation energy of the nucleus was difficult to determine. In past experiments, the initial excitation energy was equated directly with the energy loss of the projectiles [1, 2]. This technique has since been shown to be inaccurate [15, 16].

It has been determined in inelastic $\alpha$-scattering experiments that a significant range of energies are populated well below the energy losses considered [16]. To account for this, the initial excitation energy of the nucleus was not equated with the fragment energy loss. A distribution of excitation energy was used for each energy loss considered. The distributions are based on the work of Ref. [16]. The difference is that the low-energy rise in the distributions found in Ref. [16] was omitted. Since this rise is due to knockout reactions that are known to be much smaller in heavy-ion scattering [7], this is justified. As an example, the difference between the distribution used for the initial excitation

FIGURE 4. Liquid drop calculations from Ref. [6] are shown by the dashed curve. The solid curve is to guide the eye through the data. The open square is the low temperature data point from this work. All other data is as in the left panel of Fig. 1.
The energy of the nucleus and the energy loss of the fragments is shown in Fig. 5 for the energy losses of 60–70 MeV.

The calculations performed for the higher temperature spectra use distributions for the initial excitation energy as discussed earlier. The width of the GDR along the decay was determined by the solid curve in Fig. 4. Additionally, the sum rule strength and energy were set to values of 1.0 and 16.0 MeV, respectively. All parameters were fixed in the calculations. The only free parameter was the overall normalization. Hence, if this data is consistent with previous measurements, the spectral shapes of the calculations should be similar to the data.

The result of the calculations is shown in Fig. 6. The agreement between calculation and data confirms that this data is consistent with previous data. It is still important to investigate the effects of using a broad distribution for the initial
FIGURE 7. The $\gamma$-ray spectra (solid points) shown are for energy losses of 80–90 MeV, along with calculations (solid curves). In panel (a), the calculation was performed as described in the previous section. In panel (b), the calculation was performed assuming the initial excitation energy of the nucleus was equal to that of the fragment energy loss.

excitation energy as opposed to the fragment energy loss.

INFLUENCE OF INITIAL EXCITATION ENERGY DISTRIBUTIONS

The effects of using a broad distribution for the initial excitation energy of the nucleus can be investigated by considering the $\gamma$-ray spectrum extracted at the highest temperature. In this work, this corresponds to the spectrum obtained by gating on projectile energy losses of 80–90 MeV. The effects should be largest for this spectrum, as the calculations for this range of energies had the broadest distribution for the initial excitation energy.

A calculation was performed where the fragment energy loss was equated with the initial excitation energy of the nucleus for comparison. The result is shown in Fig. 7b. In Fig. 7a, the calculation was performed as described in the previous section. The calculations in each side of Fig. 7 describe the data very well. For each of the calculations, the width was adjusted as shown by the solid curve in Fig. 4 and the energy was set to 16 MeV. The only difference in the parameters used in the calculations was in the sum rule strength. In the case where the fragment energy loss was equated with the initial excitation energy (Fig. 6b), the strength had to be reduced from 100% to 36%.

This suggests that the choice of the initial excitation energy distribution influences the apparent GDR strength, but has only minor influences on the GDR width, at least up to the excitation energies of this experiment. This is consistent with the findings of Ref. [16]. The contribution of the lower part of the initial excitation energy predominantly adds to the lower statistical part of the spectrum, and this can be simulated by a reduction of the apparent GDR strength in the calculation where the energy loss is used.

COMPARISONS WITH OTHER NUCLEI

There are only a few nuclei where an extensive amount of experimental data and theoretical calculations exist. Some of these nuclei include Sn, Cu, and Pb. It is instructive to compare the GDR widths for these nuclei from both experiment and theory. In the case of Sn and Cu, shell effects are small. As this is the case, it is predicted that the liquid drop calculations should describe the experimental data for both Sn and Cu. In the case of Pb, shell effects are large, and consequently must be taken into account.
The data and theoretical predictions for the GDR width in Cu are shown in Fig. 8. The shape of the Cu data is similar to that of Sn (See Fig. 4). The data for both Sn and Cu suggest that the width is nearly constant at low temperatures (0 MeV < T < 1 MeV).

CONCLUSIONS

The width of the GDR in Sn has been studied by means of inelastic heavy-ion scattering. The data from this experiment is consistent with previous measurements of the GDR width at higher temperatures. A width of 4 ± 1 MeV was found at a temperature of 1 MeV. This value is significantly lower than theoretical predictions. Previous to this measurement, there was an indication that there may be a deviation between theory and experiment; however, this measurement shows conclusively that theoretical predictions fail to describe experimental data in Sn at low temperatures (See Fig. 4).

The behavior of the GDR width in Sn is similar to predictions for nuclei with strong shell effects, such as Pb. In Pb, the width of the GDR is predicted to be suppressed at low temperatures relative to the liquid drop predictions. This suppression is attributed to shell effects. While it is clear that shell effects limit shape fluctuations at low temperatures, it is not clear that these effects are entirely responsible for the suppression of the GDR width in Pb. In fact, the interpretation that shell effects are responsible for the suppression of the GDR width in Pb at low temperatures has to be questioned.

The suppression of the GDR width at low temperatures is evident in the experimental data for all nuclei discussed here (Sn, Cu, and Pb). In the case of Sn and Cu, shell effects are weak. Despite this fact, the behavior of the GDR width is as predicted for nuclei with strong shell effects. It appears that the GDR width is suppressed at low temperatures regardless of whether shell effects are present or not.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under grant number PHY95-28844 and the Department of Energy under grant number DE-FG03-97ER41020/A000. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.
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