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To be published in Physics Letters B

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NSCL

Low-Temperature Measurement of the Giant Dipole Resonance Width

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Abstract

The width of the Giant Dipole Resonance (GDR) built on excited states was determined from a measurement of γ-decays in coincidence with ^{17}O particles scattered inelastically from ^{120}Sn. The bombarding energy was 80 MeV/u. A width of 4 ± 1 MeV, consistent with the width of the GDR built on the ground state, was found at a temperature T = 1 MeV. This result is in disagreement with adiabatic thermal shape fluctuation calculations, indicating an overestimation of the influence of thermal shape fluctuations at low temperature.

Key words: Heavy-ion scattering, Giant Dipole Resonance in ^{120}Sn, adiabatic thermal shape fluctuation model

The evolution of the Giant Dipole Resonance in hot nuclei has been the focus of many experimental studies. The increase of the GDR width with temperature and spin has been of particular interest. In general, adiabatic thermal shape fluctuation calculations provide a good description of existing GDR decay data [1–3]. However, in the Sn mass region, at low to moderate temperatures, measured GDR widths lie below the values calculated in the shape fluctuation model [3,4].

It is instructive to compare the GDR widths expected in different nuclei such as Sn and Pb. Shape fluctuation calculations of the evolution of the GDR width with temperature predict differences between Sn and Pb due to shell effects. In Sn and nearby nuclides, where shell effects are small, the GDR width is expected to increase with temperature in a manner consistent with the properties of a rotating liquid drop. In Pb and nearby nuclides, the GDR width in the liquid drop regime, $T > \sim 1.5$ MeV, should behave similarly to the width in Sn, while at lower temperatures the increase of the GDR width with temperature should be suppressed relative to the liquid drop prediction, due to shell effects.

Fusion-evaporation and inelastic scattering reactions have been used to extract the GDR width in Sn and Pb at various temperatures [5,6,4] and spins [3]. The existing width data for Pb are in reasonable agreement with shape fluctuation calculations [1–3]. However, no data exists for temperatures below ~ 1.2 MeV, where shell effects should be large. In Sn, data in the range $T > \sim 1.9$ MeV are in agreement with adiabatic thermal shape fluctuation calculations, while measured widths at lower $T \sim 1.3$–1.8 MeV lie 1–2 MeV below the calculations [4]. These differences suggest a possibly significant deviation between *theory and experiment*.

In order to investigate these differences in the case of Sn decays, we have measured the GDR width at $T = 1$ MeV in the decay of the ^{120}Sn nucleus produced by the inelastic scattering of ^{17}O projectiles. This measurement is the lowest finite-temperature GDR width measurement in such heavy nuclei [3].

In contrast to fusion-evaporation experiments that are limited to higher temperatures due to the Coulomb barrier in the entrance channel, inelastic scattering may be used to populate nuclei at low excitation energies (temperatures).

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Inelastic α-scattering has been used to measure the width of the GDR as a function of temperature; however, for such a light projectile, it is difficult to determine the initial excitation energy of the residual nucleus for large inelastic energy loss [7,8]. This is due to the presence of knockout reactions and other processes which do not lead to full deposition and equilibration in the target of the energy loss of the scattered particle. The latter effect, which grows with increasing energy loss, should not be significant at low excitation energies. The contributions due to knockout reactions can also be reduced by heavy-ion scattering as compared to α-scattering [9].

Our experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL). A 7.45 mg/cm^2 target of ^{120}Sn was bombarded by ^{17}O particles at an energy of 80 MeV/u. The inelastically scattered ^{17}O and other reaction products were detected at scattering angles between 0° and 10° in the S800 spectrometer. The focal plane detectors [10] allowed for particle identification. In order to make an accurate determination of the projectile energy loss, the trajectory of the projectile was reconstructed using the code Cosy Infinity [11].

High-energy γ rays from the GDR decay were detected with the ORNL - Texas A&M - MSU BaF$_2$ array in coincidence with the S800. The detectors were arranged in two close-packed arrays of 68 detectors each, placed at a distance of 31.8 cm from the target at angles of ±90° with respect to the beam axis. High-energy neutron-induced events were separated from γ-ray events by pulse-shape discrimination using the two components of scintillation light emitted by BaF$_2$. Final γ-ray selection was accomplished by using the excellent timing properties of BaF$_2$ [12]. In order to improve the response of the array, γ-ray events in neighboring detectors were added together.

In inelastic-scattering experiments, it is possible to measure the entire excitation function within one spectrometer setting by gating on different energy losses of the projectiles. This relies on the assumption that the lost energy is completely equilibrated as excitation energy in the target nucleus [5,6]. The successive opening of neutron evaporation channels [9], visible in the spectrum of inelastic scattered ^{17}O gated by γ rays (Fig. 1), indicates a correlation between energy loss and excitation energy. The peaks can clearly be identified up to 35 MeV corresponding to the 4n channel. Additionally, in the study of inelastic α-scattering on ^{209}Bi [7], the average initial excitation energy of the nucleus was found to be equal to the energy loss of the projectile for values up to 55 MeV. Thus, the energy loss can be equated directly with the excitation energy up to at least 35 MeV.

The high energy γ-ray spectrum gated on excitation energies between 20 and 30 MeV is shown in Fig. 2. It exhibits the enhancement at $E_\gamma \sim 14$ MeV characteristic of the γ-decay of the GDR. The parameters of the GDR extracted

were the GDR energy (E_D), width (Γ), and strength (S). The parameters E_D, Γ and S (in units of the TRK sum rule) were deduced by comparing the data to CASCADE statistical model calculations [13,14]. In these calculations a mean excitation energy, following the γ-decay, was computed and converted to a temperature according to $T = (dln(\rho)/dE)^{-1}$ [3,4], where ρ is the level density. The level density was parameterized with the method of Reisdorf [15]. The effective radius, pairing energy, and damping parameters in the level density calculation were set to 1.16 fm, 8.5 MeV, and 18.5 MeV respectively. These values are within the uncertainties given in Ref. [15].

The results of the statistical calculations were folded with the response of the detector arrays as simulated by GEANT [16]. 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 [17,18]. This value is smaller than that given in Ref. [17], because our collision is peripheral [18]. The folded CASCADE plus bremsstrahlung components were compared to the corresponding γ-ray spectrum by normalizing both components to the data.

The γ-ray spectrum shown in Fig. 2 was fit with CASCADE by varying the GDR parameters and minimizing χ^2, resulting in $E_D = 16.5 \pm 0.7$ MeV, $\Gamma = 4 \pm 1$ MeV and $S = 1.1 \pm 0.2$. The results of the fit are shown by the solid line in Fig. 2. For this case, the mean excitation energy following GDR decay with $E_\gamma = 15$ MeV is 9.7 MeV, corresponding to a mean (final-state) temperature $T = 1.0$ MeV. The fitted width agrees with the ground-state GDR width of 4.9 ± 0.1 MeV [19]. The fitted resonance energy E_D is somewhat higher than the ground state value of 15.5 MeV [19]; however, a resonance energy higher than the ground state value was also measured at low excitation energies in Refs. [5,6].

Our low-temperature width (solid circle) is shown in Fig. 3 with other existing data points taken from Refs. [3,4]. The value of the width at $T = 0$ MeV was set to the value of 3.8 MeV [20], as done in Ref. [3]. The GDR ground-state width varies from 4.2–5.1 MeV [19] for Sn isotopes with masses of 116–120. This range of widths is indicated by the solid rectangle at $T = 0$ MeV in Fig. 3. The temperature of all data points in Fig. 3 was determined using the Reisdorf level density formalism [3,4]. There is a systematic uncertainty in the temperature of ~ 0.1 MeV. The dashed curve shows the adiabatic thermal shape fluctuation width calculated by Ref. [3] at low spin. The dashed curve is generally consistent with the data at higher temperatures, but fails to describe the data at low temperatures, as noted earlier. We also incorporated the energy-dependent width shown by the dashed curve into CASCADE, and calculated the expected γ-ray spectrum shape for the 20–30 MeV bin assuming $E_D = 16.5$ MeV and $S = 1.1$ as determined from the constant-width fit. The result, shown as the dashed curve in Fig. 2, does not describe the data well.

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The width of the calculated spectrum shape is clearly too large, distributing the strength over a larger energy range than the data.

The present experiment provides information on the GDR width at higher temperatures as well as at T = 1 MeV. Instead of extracting the width at higher temperatures by fitting the individual γ-spectra for different inelasticities, we calculated the expected γ-ray spectral shapes with CASCADE using the energy dependent width shown by the solid curve in Fig. 3, and compared to the data. The uncertainty of the width given by the solid curve in Fig. 3 is ∼ 1 MeV, as indicated by the shaded region. The technique of using an energy-dependent width may be contrasted with most previous experimental analyses, which were performed assuming an energy-independent width during the de-excitation cascade. In addition, at inelasticities higher than 30 MeV, a distribution of initial excitation energies was estimated for a given inelasticity. The distributions used were similar to those estimated in Ref. [7] for inelastic α-scattering. The difference is that we omitted the low energy rise in the distributions of Ref. [7] (see insert of Fig. 5a), which are due to knockout processes that are known to be much smaller for ^{17}O scattering [9]. The γ-spectra calculated with this procedure for energy loss gates of 30–40 MeV, 50–60 MeV and 80–90 MeV, and with E_D = 16 MeV and S = 1 are shown as the solid curves in Fig. 4 along with our data. It should be mentioned that the GDR parameters were not free parameters in these calculations. The only free parameter was the overall normalization. The agreement between data and calculation provides an important consistency check with previous experimental work. A second dashed curve is also shown in each panel of Fig. 4. This curve was calculated in the same manner as the solid curve in the figure, except that the width in the calculation was given by the dashed curve in Fig. 3. The agreement between this calculation and data improves as higher energy losses are considered, as expected since the dashed curve in Fig. 3 approaches the data at higher temperatures.

In order to better understand the effect of the assumed initial excitation energy distribution, we computed the γ-ray spectrum shape for the 80–90 MeV bin by setting the initial excitation energy equal to the inelastic energy loss (see insert of Fig. 5b). Here, as before, an energy-dependent Γ was assumed in the de-excitation cascade, as given by the solid curve in Fig. 3. The result, computed with E_D = 16 MeV and S = 0.36, is shown in Fig. 5b. Fig. 5a is identical to Fig. 4c. The calculations shown in Fig. 5a,b describe the data equally well, and hence 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 the present experiment. This is consistent with the findings of Ref. [7]. The contribution of lower initial excitation energy predominantly adds to the lower statistical part of the spectrum, and this effect can be simulated by a reduction of the apparent GDR strength in the calculation with a sharp initial excitation energy distribution.

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The temperature dependence of the GDR width determined from experiment (solid line in Fig. 3) differs significantly at low temperatures from adiabatic thermal shape fluctuation calculations [3] (dashed line in Fig. 3), indicating that the calculations overestimate the influence of shape fluctuations at low temperature. A similar deviation between adiabatic thermal shape fluctuation calculations and data can also be observed in Cu [3]. The calculations determine the GDR width by averaging the GDR strength function over a thermal ensemble of shapes. The increase of the width with temperature is due to an increase in the shape fluctuations with temperature. For nuclei without a strong shell effect, such as Sn isotopes and nearby nuclides, the shape fluctuations are expected to be determined by the properties of a rotating liquid drop. This is consistent with Ref. [3], who showed that the expected GDR width at low temperatures in Sn is the same in both liquid-drop and shell-corrected calculations. In contrast, the experimental width dependence at low temperature in Sn (and nearby nuclides) is similar to that expected for nuclei with strong shell effects such as ^{208}Pb and nearby nuclides (Fig. 4 of Ref. [3]).

It can be speculated that pairing effects may account for the difference between theory and experiment at low temperatures, as both the shape fluctuation calculations and the CASCADE spectrum-shape calculations presented here neglect pairing. However, pairing effects should not be important at the present temperatures (see e.g. [15]). Deviations from the adiabatic approximation, which assumes that the time scale for shape fluctuations is long compared to the inverse frequency spread associated with the deformation broadening of the GDR, would result in a smaller GDR width; however, it seems peculiar that such deviations, if present, would be apparent only at low temperatures. Attempts to explain the observed GDR widths by mechanisms other than deformation broadening also do not agree with the data [21,6]. We conclude that the narrow GDR widths observed in Sn and nearby nuclides at low temperature are not understood.

References

[1] W. E. Ormand, P. F. Bortignon, and R. A. Broglia, Phys. Rev. Lett. **77**, 607 (1996).

[2] W. E. Ormand *et al.*, Nucl. Phys. A **614**, 217 (1997).

[3] D. Kusnezov, Y. Alhassid, and K. A. Snover, Phys. Rev. Lett. **81**, 542 (1998), and references therein.

[4] M. P. Kelly *et al.*, Phys. Rev. Lett. **82**, 3404 (1999).

[5] E. Ramakrishnan *et al.*, Phys. Rev. Lett. **76**, 2025 (1996).

[6] T. Baumann *et al.*, Nucl. Phys. A **635**, 428 (1998).

[7] G. Viesti *et al.*, Nucl. Phys. A **652**, 17 (1999).

[8] D. Fabris *et al.*, J. Phys. G **23**, 1377 (1997).

[9] M. Thoennessen *et al.*, Phys. Rev. C **43**, R12 (1991).

[10] J. Yurkon *et al.*, Nucl. Instrum. Methods A **422**, 291 (1999).

[11] M. Berz *et al.*, Phys. Rev. C **47**, 537 (1993).

[12] M. Laval *et al.*, Nucl. Instrum. Methods **206**, 169 (1983).

[13] F. Pühlhofer, Nucl. Phys. A **280**, 267 (1977).

[14] R. Butsch *et al.*, Phys. Rev. C **41**, 1530 (1990).

[15] W. Reisdorf, Z. Phys. A **300**, 227 (1981).

[16] Detector Description and Simulation Tool GEANT, Version 3.21, CERN Program Library, Geneva.

[17] H. Nifenecker and J. A. Pinston, Ann. Rev. Nuc. Part. Sci. **40**, 113 (1990).

[18] G. Martínez *et al.*, Phys. Lett. B **349**, 23 (1995).

[19] S. S. Dietrich and B. L. Berman, At. Data Nucl. Data Tables **38**, 199 (1988).

[20] Y. Alhassid and B. Bush, Nucl. Phys. A **509**, 461 (1990).
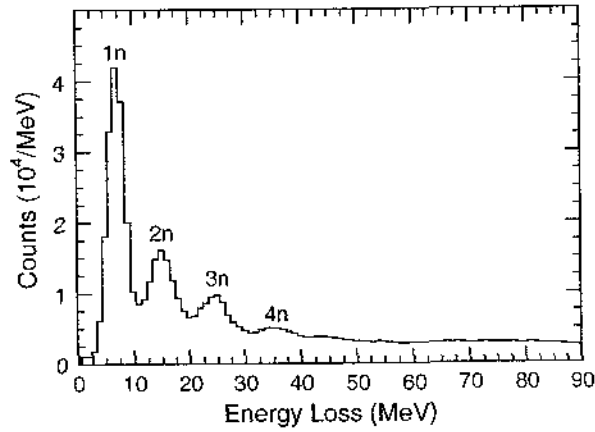
[21] V. Baran *et al.*, Nucl. Phys. A **599**, 29c (1996).

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Fig. 1. Spectrum of ^{17}O particles scattered inelastically from ^{120}Sn, in coincidence with γ rays with $E_\gamma \geq 4$ MeV.

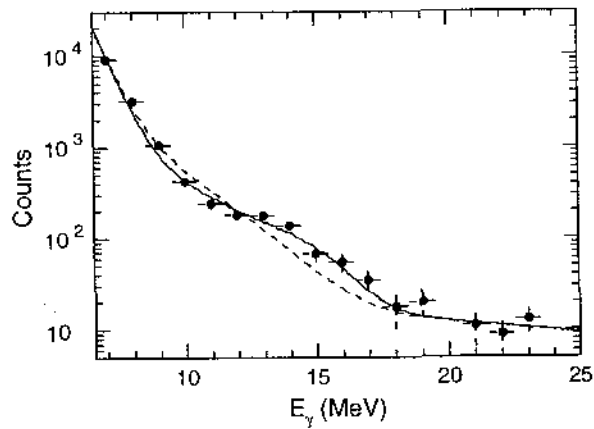Fig. 2. Solid points – γ-ray spectrum measured in coincidence with ^{17}O particles for energy losses of 20–30 MeV. Solid line – CASCADE calculation with $\Gamma = 4$ MeV. Dashed line – CASCADE calculation with energy-dependent Γ as shown by the dashed curve in Fig. 3.
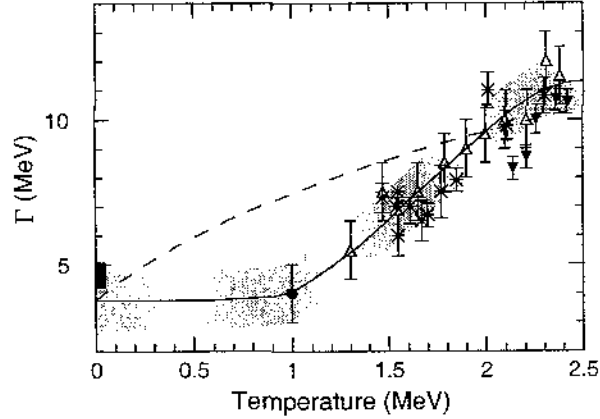
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Fig. 3. GDR width Γ vs. final-state temperature T, for decays of Sn compound nuclei. Solid circle – low temperature data point from this work. Crosses and triangles – data from Fig. 4 of Ref. [3]. Solid upside-down triangles – data from Ref. [4]. Solid rectangle – range of GDR ground-state widths in Sn isotopes considered. Solid curve – line to guide the eye. The shaded region around this curve shows the uncertainty. Dashed curve – adiabatic thermal shape fluctuation calculation for low spin, taken from Fig. 4 of Ref. [3]
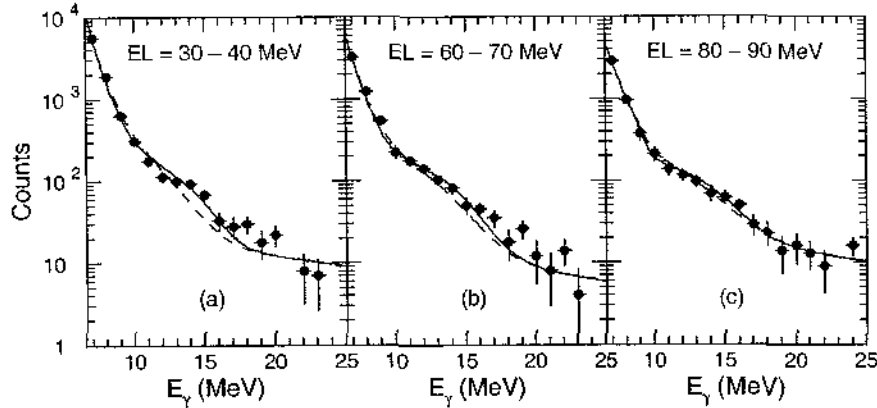

Fig. 4. Solid points – γ-ray spectra measured in coincidence with [17]O particles scattered inelastically with energy loss (EL) 30–40 MeV in panel (a), 60–70 MeV in panel (b), and 80–90 MeV in panel (c). Solid curves – CASCADE calculations with Γ given by the solid curve in Fig. 3. Dashed curves – CASCADE calculations with Γ given by the dashed curve in Fig. 3. Both curves were calculated with $E_D = 16$ MeV and S = 1
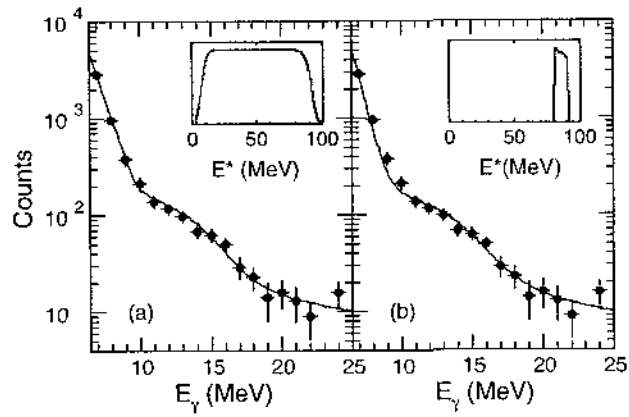
Fig. 5. Solid points – γ-ray spectrum in coincidence with ^{17}O particles with energy losses 80–90 MeV. Panel (a) – CASCADE calculation assuming a distribution of initial excitation energies as shown in the insert. Panel (b) – CASCADE calculation assuming the initial excitation energy was equal to the energy loss of the scattered fragment as shown in the insert. The GDR strength is fit to the data in panel (b). The GDR width in both calculations is given by the solid curve in Fig. 3.