Giant Dipole Resonance Built on Highly Excited States of ^{120}Sn Nuclei Populated by Inelastic α Scattering

E. Ramakrishnan,* T. Baumann,† A. Azhari, R. A. Kryger,‡ R. Pfaff, M. Thoennessen, and S. Yokoyama
National Superconducting Cyclotron Laboratory and Department of Physics & Astronomy, Michigan State University,
East Lansing, Michigan 48824

J. R. Beene, M. L. Halbert, P. E. Mueller, D. W. Stracener, and R. L. Varner
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

R. J. Charity, J. F. Dempsey, D. G. Sarantites, and L. G. Sobotka
Department of Chemistry, Washington University, St. Louis, Missouri 63130

(Received 4 October 1995)

High energy γ rays from the decay of the giant resonance in hot ^{120}Sn nuclei were measured in the excitation energy range of 30–130 MeV. The excited nuclei were populated by inelastic scattering of α particles at 40 and 50 MeV/nucleon. The resonance width was observed to increase monotonically with increasing excitation energy, from 5 MeV at the ground state to ~12 MeV at the largest excitation energy. Inelastic scattering predominantly populates low angular momentum states, and the observed width increase is thus attributed to fluctuations in the nuclear shape induced by temperature.

PACS numbers: 24.30.Cz, 25.55.Ci, 25.70.Gh, 27.60.+j

The giant dipole resonance (GDR) is a collective mode of excitation of the nucleus that couples strongly to the nuclear shape degrees of freedom. The study of the resonance in highly excited nuclei conveys information on the properties of nuclei at high temperatures. The most systematic study of excited state GDR performed so far has been on Sn isotopes formed in heavy ion fusion reactions [1–3]. Fusion measurements have displayed a systematic increase of the GDR width with increasing excitation energy up to ~150 MeV. This increase could arise from changes in the nuclear shape induced by either temperature or angular momentum, or both.

For a better understanding of the resonance width, it is essential to decouple the effects of temperature and angular momentum. In a recent fusion-evaporation experiment on Sn isotopes, the GDR width was studied as a function of angular momentum, deduced from γ-ray multiplicity, at approximately constant temperature [3]. An increase of the width with increasing angular momentum was reported.

Inelastic scattering with light ions can be used as an alternative to fusion as the means of preparing the excited nuclear systems for study. In small angle inelastic scattering predominantly low angular momentum states are populated. Furthermore, the initial excitation energy of the target nuclei can be restricted to a narrow range by gating on the energy loss of the scattered projectile. The evolution of the GDR can thus be studied as a function of temperature, decoupled from angular momentum effects. Inelastic scattering in coincidence with decay products, primarily γ rays and light particles, has been employed to study collective excitations in heavy nuclei [4]. These measurements have focused on structures in the particle spectra below ~40 MeV that correspond to localized strengths of collective modes built on the ground state, and on multiphonon excitations. However, the continuum in the spectrum of inelastically scattered particles at higher energy losses has not been well studied. This continuum should correspond to high energy excitations in the target nucleus. Nucleon pickup and decay as well as nucleon knockout are expected to contribute only a small fraction of the total inelastic cross section. A measurement of the γ rays in coincidence with the inelastically scattered projectiles in this excitation energy region can thus be employed to study the GDR built on highly excited states of the nucleus [5].

In Fig. 1, the calculated angular momentum distribution populated in the inelastic scattering reaction $^{120}\mathrm{Sn}(\alpha, \alpha')$ at 50 MeV/nucleon (circles) is compared to the distribution of a typical fusion reaction, $^{18}\mathrm{O} + {}^{92}\mathrm{Mo} \rightarrow {}^{110}\mathrm{Sn}$ (diamonds), as a function of excitation energy. The angular momentum of the excited target nucleus following inelastic scattering was estimated from the momentum transfer and the assumption that the impact parameters contributing to inelastic scattering are strongly concentrated in the nuclear surface. The impact parameter was assumed to be in the range of the sum of the "matter half density" radii to the "nuclear interaction" radius [6]. For the fusion reactions, the angular momentum distributions were computed with a triangular distribution with a diffuseness of $2\hbar$. The mean angular momentum (top) is $\sim 15\hbar$ lower in the scattering reaction compared to the fusion reaction. In addition, the width σ (bottom) of the distribution is substantially smaller over the entire excitation energy range.

We report on a measurement of the GDR built on excited states of ^{120}Sn populated by inelastic scattering

0031-9007/96/76(12)/2025(4)$10.00

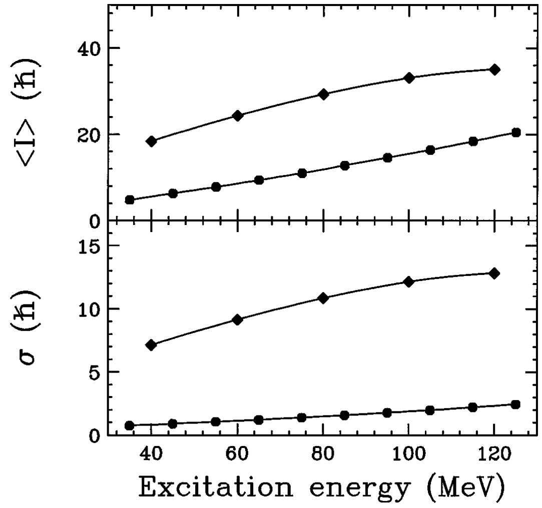

FIG. 1. Calculated mean ($\langle I \rangle$, top) and width (σ, bottom) of the angular momentum distributions populated in the inelastic scattering reaction ^{120}Sn(α, α') at 50 MeV/nucleon (circles) and in the fusion reaction ^{18}O + ^{92}Mo forming ^{110}Sn (diamonds).

of α particles. The experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL). A 16.8 mg/cm^2 target was bombarded by 40 and 50 MeV/nucleon α particles extracted from the K1200 cyclotron. The inelastically scattered projectile nuclei and other light charged reaction products were measured in the Dwarf Ball–Wall 4π CsI(Tl) array [7]. The Wall array consisted of 35 close-packed CsI(Tl) detectors arranged in four rings centered at laboratory angles of 14.78°, 22.39°, 23.18°, and 31.03° and covering the angular range of ~10° to ~36°. The main particle trigger in the experiment was formed by the detectors of the Wall array. The Ball array consisted of 64 close-packed CsI(Tl) detectors that covered laboratory angles of ~36° to ~155°.

High energy γ rays from the decay of the GDR in the target were measured using 95 BaF$_2$ detectors arranged in five close-packed arrays of 19 detectors each. The γ rays were measured in coincidence with particles in the Wall array. The detectors were 20 (25) cm in length with a face dimension corresponding to an inscribed circle 6.5 (6) cm in diameter. The five arrays were placed outside the Dwarf Ball scattering chamber at a distance of 50 cm from the target, at laboratory angles of 59° (2), 66° (1), and 118° (2). The solid angle coverage of the arrays together amounted to ~10% of 4π. Separation between neutrons and γ rays in the detectors was achieved by time of flight measurement. The detectors were calibrated at low energies using radioactive sources, and at an intermediate energy by measuring γ rays from the ground state decay of the 15.11 MeV state in ^{12}C populated by inelastic α-particle scattering. A calibration point at an energy of ~40 MeV was also obtained by measuring the energy loss of cosmic-ray muons in the detector volume. The response of the detector pack to γ rays was simulated using the Monte Carlo code GEANT3 [8].

Evidence for the formation of highly excited, equilibrated target nuclei was observed in the total yield of γ rays of energy $E_\gamma \geq 4$ MeV, as a function of scattered α-particle energy loss (i.e., target excitation energy) measured in the Wall array. These coincidence yields displayed structures that corresponded to the opening of successive neutron evaporation channels in the decay of the excited nucleus [5]. The emission of pre-equilibrium particles at the highest excitation energies cannot be ruled out, which would reduce the effective excitation energy.

Contributions to the inelastic cross section from background processes such as nucleon knockout and pickup decay were estimated by analyzing α-proton coincidence events in the Dwarf array. These events were predominantly localized at the kinematic limit where the total energy was shared by the proton and the α particle, with no appreciable excitation energy available for target excitation. Contamination of the coincidence γ-ray spectra was therefore negligible.

The γ-ray spectra in coincidence with α particles in the Wall array for a few typical projectile energy losses are displayed in Fig. 2. The left panel displays the γ-ray spectra in coincidence with α particles of the same energy, 120–130 MeV, for the two beam energies of 40 (open circles) and 50 (closed circles) MeV/nucleon. The corresponding target excitation energies are 30–40 and 70–80 MeV,

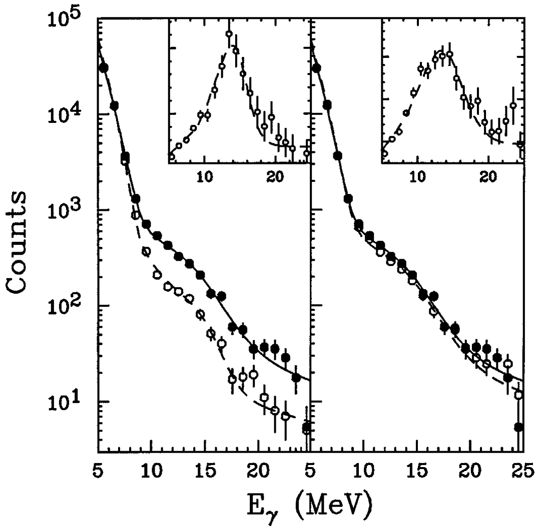

FIG. 2. γ-ray spectra in coincidence with α particles for the two beam energies of 50 (●) and 40 (○) MeV/nucleon. The spectra are gated by the same α energy range of 120–130 MeV (left) and the same excitation energy range of 70–80 MeV (right). The results of CASCADE calculations for the appropriate excitation energies are displayed as solid and dashed lines for the 50 and 40 MeV/nucleon reactions, respectively. The insets show the data and calculation for the lower beam energy on a linearized scale, obtained by dividing both by a second statistical calculation employing a constant $E1$ strength function.

respectively. The γ-ray spectra were normalized in the low energy region of 7–8 MeV. The spectra clearly show that the γ-ray multiplicity in the GDR energy region is enhanced for the data from the higher target excitation energy compared to the data from the lower excitation energy. The right panel of Fig. 2 displays the γ-ray spectra, in coincidence with α particles with the same energy loss of 70–80 MeV, corresponding to α-particle energies of 120–130 and 80–90 MeV for beam energies of 50 (closed circles) and 40 MeV/nucleon (open circles), respectively. The two spectra are in good agreement, thus confirming the estimation of target excitation energy from the energy loss of the projectile nucleus.

The analysis of the γ-ray spectra was performed within the standard statistical model, using a modified version of the evaporation code CASCADE [9]. The level density treatment in the standard code was modified to an energy-dependent parametrization [10–12]. In this description, the parameter a decreased from a value of $A/8$ at low excitation energies to $A/13$ at $T \sim 5$ MeV. The standard code was also modified to accept the initial population of excited nuclei as an input. This initial population was obtained, in 10 MeV wide binds, from the spectra of inelastically scattered α particles and was distributed over a range of angular momenta calculated using the assumptions discussed earlier.

The nonstatistical contributions to the experimental γ-ray spectra that arise from bremsstrahlung processes were assumed to have an energy dependence of the form $\exp(-E_\gamma/E_0)$, where the slope parameter E_0 was chosen to be 14 MeV from bremsstrahlung systematics [13]. This contribution was normalized to the experimental spectra in the energy range of 25–30 MeV and was added to the calculated γ-ray spectra from CASCADE after accounting for the detector response.

The calculated γ-ray spectra are in good agreement with the data for the appropriate target excitation energies for the 50 MeV/nucleon (solid) and 40 MeV/nucleon (dashed) reactions as shown in Fig. 2. The average nuclear temperature corresponding to each excitation energy range was computed using the expression $\langle T \rangle = \sqrt{E_{\text{eff}}/a(E_{\text{eff}})}$, where E_{eff} is the effective excitation energy, obtained from the mean energy of the input population after subtracting the mean rotational energy and the GDR energy. The quantity $a(E_{\text{eff}})$ is the energy-dependent level density parameter that was employed in the statistical model calculations. The sum rule strength extracted from the data was in the range of (90–110)%.

The extracted resonance energy decreased from a value of 16.0 to 14.5 MeV with increasing excitation energy. Keeping the resonance energy constant over the entire range of excitation energies did not yield good fits to the data. A systematic decrease of the GDR energy as a function of increasing excitation energy has been observed in deep-inelastic reactions [14] and has been predicted by some theoretical models [15]. However, previous fusion measurements in Sn nuclei [16] showed no temperature dependence of the mean GDR energy.

The GDR width increased monotonically with increasing excitation energy of the target. The resonance widths extracted from the spectra from the two beam energies were found to be in good agreement. The uncertainty of the extracted width was estimated to be ±1 MeV and includes the statistical error, the influence of the resonance energy variation, and the uncertainty of the bremsstrahlung contribution. It does not include any systematic dependence on the level density description. Figure 3 shows the GDR width from the 50 MeV/nucleon reaction (solid diamonds) as a function of temperature. In the top panel the data are compared with the widths extracted from fusion evaporation measurements from Refs. [1] (circles) and [2] (squares). The temperature for the fusion data was calculated with the same energy-dependent level density parametrization used for the inelastic scattering data.

The increase of the resonance width in excited nuclei can be attributed to the coupling of the resonance to shape variations of the nucleus induced by temperature and angular momentum [17]. At finite temperatures, the probability of assuming shapes far from the ground state configuration becomes appreciable. The probability is given by the Boltzmann factor $\exp(-F/T)$, where F is the deformation-dependent free energy and T is the nuclear temperature. The experimentally measured width is thus a weighted average over all possible deformations. On the other hand, large angular momenta also influence

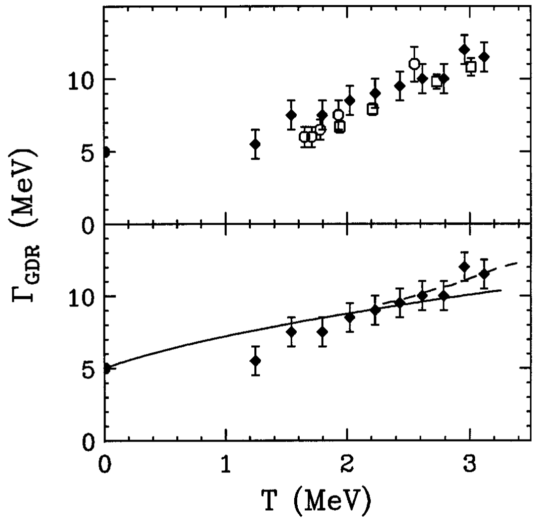

FIG. 3. The widths of the GDR from the 50 MeV/nucleon inelastic scattering reaction (diamonds) compared to previous inclusive fusion measurements in $^{108-112}$Sn nuclei (top) and adiabatic coupling calculations performed by Ormand *et al.* [18] (bottom). The fusion data were taken from Ref. [1] (○) and Ref. [2] (□).

the width evolution, since the nuclear potential surface evolves with angular momentum. The agreement between the scattering and the inclusive fusion data shown in Fig. 3 indicates that the temperature washes out the expected angular momentum effects.

Ormand *et al.* have performed adiabatic coupling calculations for the photoabsorption cross section as a function of temperature and angular momentum [18]. The bottom panel of Fig. 3 compares the results of these calculations (solid) with the present data. The calculation is in good agreement with our data. The dashed line depicts results including the effect of evaporation widths which increase rapidly with increasing excitation energy [19], and improves agreement between the calculation and the highest temperature data points [18]. The calculations were performed with a constant GDR energy, however, the peak of the resulting strength functions is found to decrease as a function of increasing temperature, in qualitative agreement with the experimentally observed reduction of the extracted GDR energy. In order to obtain a more stringent test of the model prediction, it will be necessary to incorporate the temperature-dependent strength functions into the statistical model. These calculations are currently in progress.

Our data suggest that the increase in observed GDR width in the Sn isotopes is driven primarily by temperature. This seems to contradict the interpretation of the γ-ray multiplicity-gated fusion data [3] that the width increase is due primarily to the effects of angular momentum. The theoretical calculations [18] show that this apparent disagreement results from the different regions of angular momentum explored by the two data sets. In the calculations, the influence of angular momentum on the resonance width becomes significant only at larger angular momenta. Whereas for a temperature of 2 MeV, the width increases by only 370 keV between 0 and $40\hbar$, the increase between $40\hbar$ and $60\hbar$ is 1.2 MeV [18]. In the present measurement, as well as in the inclusive fusion data [1,2], the angular momenta populated are predominantly below $\sim 40\hbar$ and thus the observed width increase can be attributed to large-scale thermal fluctuations in the nuclear shape. However, the exclusive multiplicity-gated fusion measurement by Bracco *et al.* was sensitive to angular momenta substantially beyond $40\hbar$ [3], where according to the calculations, the influence of angular momentum on the GDR width should be appreciable.

In summary, the excitation energy dependence of the GDR built on highly excited states of stable nuclei was measured for the first time by means of inelastic light ion scattering. Because the scattering process populates only low angular momentum states in the excited target, the evolution of the GDR can be studied as a function of temperature without the influence of angular momentum. Measurements in hot ^{120}Sn nuclei yielded a GDR width that increased with increasing temperature. This width increase is attributed to the broadening of the nuclear potential surface with increasing temperature. The measured data are in good agreement with the widths extracted from adiabatic coupling calculations for the resonance photoabsorption cross section performed as a function of temperature.

This work was partially supported by the U.S. National Science Foundation under Grant No. PHY-92-14992 and by the Department of Energy under Grants No. DE-FG01-88ER40406 and No. DE-FG02-87ER40316. Oak Ridge National Laboratory is managed by Lockheed Martin Energy Systems, under Contract No. DE-AC05-84OR21400 with the U.S. Department of Energy.

---

*Present address: Cyclotron Institute, Texas A&M University, College Station, TX 77843-3366.

†Present address: Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany.

‡Present address: Florida Flavors, Inc., 4330 Drane Field Road, Lakeland, FL 33811.

[1] J. J. Gaardhøje *et al.*, Phys. Rev. Lett. **53**, 148 (1984); **56**, 1783 (1986).

[2] D. R. Chakrabarty *et al.*, Phys. Rev. C **36**, 1886 (1987).

[3] A. Bracco *et al.*, Phys. Rev. Lett. **74**, 3748 (1995).

[4] *Proceedings of the Gull-Lake Nuclear Physics Conference on Giant Resonances* [Nucl. Phys. **A569** (1994)].

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

[6] W. W. Wilke *et al.*, At. Nucl. Data Tables **25**, 389 (1980).

[7] D. W. Stracener *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **294**, 485 (1990).

[8] R. Brun *et al.*, GEANT3 Users Guide, Data Handling Division DD/EE/84-1, CERN 1986.

[9] F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977).

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

[11] W. E. Ormand, P. F. Bortignon, A. Bracco, and R. A. Broglia, Phys. Rev. C **40**, 1510 (1989).

[12] S. Shlomo and J. B. Natowitz, Phys. Rev. C **44**, 2878 (1991).

[13] H. Nifenecker and J. A. Pinston, Annu. Rev. Nucl. Part. Sci. **40**, 113 (1990).

[14] J. E. Draper *et al.*, Phys. Rev. Lett. **49**, 434 (1982).

[15] C. Yanhuang and M. DiToro, Phys. Rev. C **39**, 105 (1989).

[16] J. J. Gaardhøje, Annu. Rev. Nucl. Part. Sci. **42**, 483 (1992).

[17] M. Gallardo *et al.*, Nucl. Phys. **A443**, 415 (1985). Y. Alhassid, B. Bush, and S. Levit, Phys. Rev. Lett. **61**, 1926 (1988); J. M. Pacheco, C. Yannouleas, and R. A. Broglia, Phys. Rev. Lett. **61**, 294 (1988); Y. Alhassid and B. Bush, Nucl. Phys. **A509**, 461 (1990).

[18] W. E. Ormand *et al.*, in Proceedings of the Groningen Conference on Giant Resonances, 28 June–1 July 1995 [Nucl. Phys. A (to be published)].

[19] Ph. Chomaz, Phys. Lett. B **347**, 1 (1995).