Saturation of the Width of the Giant Dipole Resonance at High Temperature

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The γ-ray spectrum in the giant dipole resonance (GDR) region associated with the reaction ^{40}Ar+^{70}Ge at 10 MeV/nucleon has been measured in coincidence with residues of the heavy composite systems whose excitation energy was $E^*=230$ MeV. From the statistical-model analysis, it is deduced that the GDR strength is consistent with 100% of the energy-weighted sum rule; the energy is 16 ± 1 MeV while the width is 13^{+1}_{-2} MeV. This value is not very different from the one measured at $E^*=130$ MeV, thus pointing to saturation effects in the damping of the GDR.

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Information on the properties of nuclei at high temperature can be obtained by measuring the high-energy γ rays which are emitted when they decay, in particular in the energy region of the giant dipole resonance (GDR) decay. In fact, studies of the energy, width, structure, and strength of the GDR as a function of excitation energy and spin provide direct information on the coupling of the GDR to fluctuations of the nuclear surface and on the size and strength of the average potential at finite temperature. Studies of this type have been carried out for a number of nuclei up to moderate excitation energies. The width of the GDR built on excited states in the Sn isotopes[1,2] has been found to increase nearly quadratically with the excitation energy of the compound nucleus up to $E^*\approx130$ MeV. Thermal fluctuations exploring the ensemble of nuclear shapes can account for only part of the observed increase. Indeed, the angular momentum transferred to the compound nucleus increases with bombarding energy and leads to a broadening of the GDR strength function due to deformation effects. This is supported by calculations[3] of the potential-energy surfaces of Sn nuclei as a function of nuclear temperature T and spin I, which predict that the Sn isotopes evolve from spherical shapes at low I to well deformed, predominantly oblate shapes at $I>40$. Assuming that the dipole vibration couples adiabatically to the nuclear surface vibrations, the width of the GDR increases.

In the present paper we report on a study of the structure of the GDR up to excitation energies $E^*\approx230$ MeV in ^{110}Sn nuclei. We find that the width of the GDR at this E^* does not deviate appreciably from the one measured at 130 MeV. This saturation opens up for new insights into the damping mechanism of the GDR at finite temperature.

A 1-mg/cm^2 ^{70}Ge target was bombarded by a 400-MeV ^{40}Ar beam from the coupled cyclotron SARA of the Institut des Sciences Nucleaires, Grenoble. The reaction products were detected in two position-sensitive parallel-plate avalance counters (PPAC's) with a sensitive area of 15×20 cm^2. The PPAC's were located symmetrically on both sides of the beam in the forward direction and subtended an angle of $\pm(3°-20°)$ in the laboratory system. The PPAC provided information on the time of flight from the target and the energy loss of projectilelike fragments and residues from fusion and incomplete fusion. The high-energy γ rays were measured in an array of five NaI detectors (12 cm diam$\times$17 cm) equipped with a 6-mm Pb absorber to reduce the count rate due to low-energy γ radiation and charged particles. The NaI detectors were placed at backward angle (160°) relative to the beam direction at a distance of 45 cm to allow for neutron discrimination by the measurement of the time of flight from the target determined relative to the beam pulse. The width of the beam burst was 1–2 nsec. Only γ rays with energy larger than 6 MeV, and in coincidence with a detected particle in either PPAC, were accepted. The NaI detectors were calibrated using a Pu ^{13}C source ($E_\gamma=6.13$ MeV) and cosmic rays for a high-energy γ-ray reference point.

Figure 1 displays the γ-ray spectrum measured in coincidence with heavy recoiling nuclei following complete fusion. At this bombarding energy the transfer of energy and mass is essentially complete.[4] As presented in our previous work,[5] the fusion reactions can be identified by selecting events corresponding to the largest energy loss and to a time of flight close to the center-of-mass velocity with the PPAC detectors. The γ-ray spectrum has been corrected for Doppler shift assuming emission from a source moving with the velocity of the

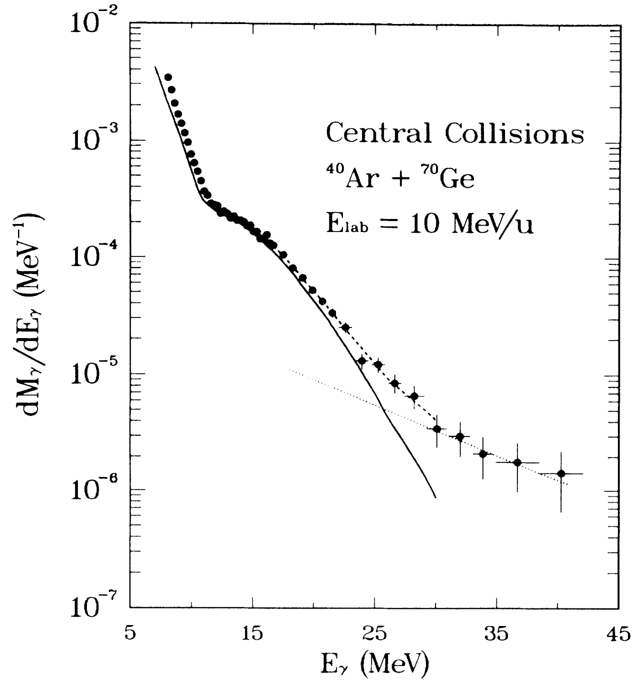

FIG. 1. γ-ray spectrum for the reaction $^{40}Ar + ^{70}Ge$ at 10 MeV/nucleon corresponding to central collisions (fusion). The spectrum has been corrected for Doppler shift assuming emission from a system moving with the center-of-mass velocity, and for the detector response function. The superimposed statistical-model calculation used $E_{GDR} = 16$ MeV, $\Gamma_{GDR} = 13$ MeV, and 100% of the energy-weighted sum-rule strength. The dotted line shows the estimated bremsstrahlung contribution. The dashed line is the sum of the dotted and solid curves.

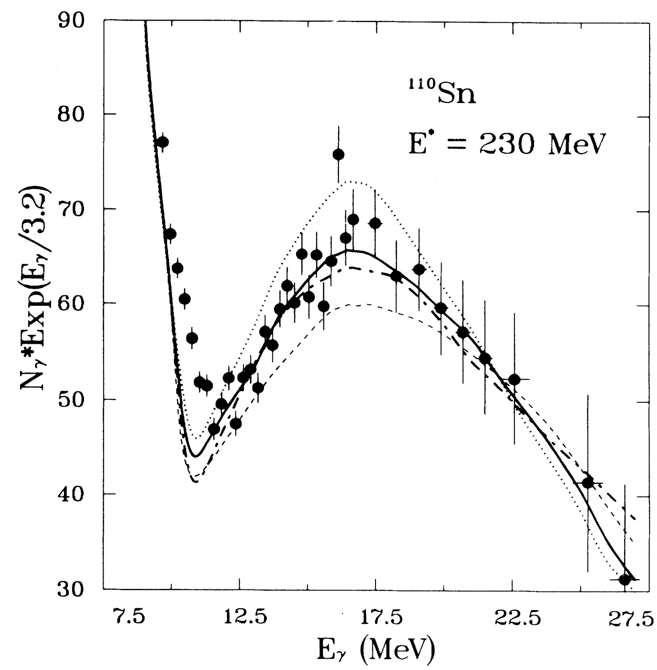

FIG. 2. γ-ray energy spectra of Fig. 1 from which the bremsstrahlung component has been subtracted. All spectra are multiplied by the function $\exp(E_\gamma/3.2)$. The shown statistical-model calculations assumed the following: $a = A/8$, $\Gamma_{GDR} = 13$ MeV, $E_{GDR} = 16$ MeV (solid line); $a = A/8$, $\Gamma_{GDR} = 11$ MeV, $E_{GDR} = 16$ MeV (dotted line); $a = A/8$, $\Gamma_{GDR} = 15$ MeV, $E_{GDR} = 16$ MeV (dashed line); $a = A/8$ up to $E^* = 130$ MeV and $a = A/12$ from $E^* = 130$–230 MeV, $\Gamma_{GDR} = 13$ MeV, $E_{GDR} = 16$ MeV (dot-dashed line).

center of mass and for the energy-dependent efficiency function of the detectors. The high-energy part of the spectrum contains contributions due to bremsstrahlung γ rays emitted in the initial stages of the reaction, which are thought to originate from first-chance nucleon-nucleon collisions.[6] Our estimate of this contribution is given by the dotted line in Fig. 1 as determined by a best fit of the spectrum at $E_\gamma \gtrsim 30$ MeV with an exponential function having slope and intensity as free parameters. The obtained inverse slope value of this exponential function is $E_0 = 8 \pm 2$ as determined in a frame of reference moving with the velocity of the nucleon-nucleon center of mass.

Also shown in Fig. 1 is a statistical-model calculation obtained by making use of an extended version of the CASCADE code.[7] In the calculation we assumed γ-ray emission from equilibrated Sn nuclei of excitation energies of 230 MeV. The dipole strength function was taken to have a Lorentzian shape with a centroid $E_{GDR} = 16$ MeV, width $\Gamma_{GDR} = 13$ MeV, and 100% of the energy-weighted sum-rule (EWSR) strength. In this calculation, E_{GDR} and Γ_{GDR} were assumed constant for all the nuclei in the deexcitation sequence. This is reasonable as the mass dependence of GDR properties is weak ($E_{GDR} \propto A^{-1/3}$). In addition, a constant level-density parameter $a = A/8$ was used. This is the same value used in previous analyses[1,2] up to $E^* = 130$ MeV and which, in general, gives a consistent description of GDR spectra at moderate excitation energies over a broad mass range. The absolute values of the GDR parameters determined by the statistical-model analysis depend, however, on the value of the level-density parameter used. The sum of the bremsstrahlung γ rays and the γ-ray spectrum calculated with the statistical model is presented by the dashed line in Fig. 1.

Recent analyses of the shapes of α spectra,[8] from the decay of heavy compound nuclei ($A \approx 160$), as a function of temperature suggest a reduction of the level-density parameter ($a \approx A/13$) for excitation energies above 230 MeV. This value is near that predicted for a hot Fermi gas ($a = A/15$). An isothermal scaling to the present mass region would imply a decrease of the level-density parameter for $E^* \gtrsim 150$ MeV.

In Fig. 2 we present a more detailed comparison between the experimental data and the statistical calculations in the GDR region. The assumed bremsstrahlung component has been subtracted from the experimental spectrum which has been then multiplied by the function $\exp(E_\gamma/3.2)$ to allow for a representation on a linear scale. The calculated spectra have been multiplied by the same function. The size of the error bars is due to both the uncertainty in the bremsstrahlung subtraction and the statistical uncertainty. Several calculations are shown all corresponding to 100% of the classical $E1$ EWSR strength. The calculation given by a full-drawn line is the same as shown in Fig. 1, i.e., $a=A/8$, $E_{\rm GDR}=16$ MeV, and $\Gamma_{\rm GDR}=13$ MeV. The dashed and dotted lines correspond to $\Gamma_{\rm GDR}=15$ MeV and $\Gamma_{\rm GDR}=11$ MeV, respectively. The dot-dashed line corresponds to a calculation in which the level-density parameter was decreased to $a=A/12$ above $E^*=150$ MeV. The latter case requires $E_{\rm GDR}=15$ MeV and $\Gamma_{\rm GDR}=11$ MeV in order to describe the data. By comparing on an absolute scale the calculations to the present data at $11\le E_\gamma\le 25$ MeV, we have deduced that the GDR strength function is consistent with a single Lorentzian whose energy is $E_{\rm GDR}=16\pm1$ MeV, intensity is 100% of the EWSR, and width is $\Gamma_{\rm GDR}=13^{+1}_{-2}$ MeV. The upper limit of $\Gamma_{\rm GDR}$ reflects the experimental error while the lower limit also takes into account that $a=A/12$ is a possible value for the level-density parameter.[8] The value of the GDR width extracted with the present analysis is comparable to those obtained at about half the excitation energy, suggesting a saturation of the effects leading to the observed increase of $\Gamma_{\rm GDR}$ with increasing E^*, at lower excitation energy. The extracted result from the present measurement is compared in Fig. 3 with the existing systematics for the Sn isotopes as a function of the maximum excitation energy of the compound nucleus E^*.

In general, $\Gamma_{\rm GDR}$ is expected to increase with excitation energy due to thermal fluctuations of the nuclear shape. This can be seen from the simplest arguments. For a Fermi gas, the entropy $S=2[a(E^*-V)]^{1/2}$ depends on the nuclear deformation via the potential energy V. For simplicity, we can assume $V=k\beta^2$, β being the deformation parameter. The probability of finding the system at a given deformation is $P(E,\beta)=\exp(S)$. The most probable deformation is the one which maximizes S. For a spherical nucleus this distribution peaks at $\beta=0$ but is broadened with increasing E^* (or T), as can be seen by expanding S as $S=2(aE)^{1/2}(1-V/2E)$. The deformation dependent part of the probability distribution is thus $P(\beta)=\exp(-k\beta^2/T)$, i.e., a Gaussian distribution of width $\Gamma=\frac{1}{2}(T/k)^{1/2}$. In the last derivation we have used the relation $T=(E^*/a)^{1/2}$. In the absence of other effects the width should then increase as $\sqrt{T}$. For the Sn isotopes, up to $E^*=130$ MeV, however, the experimentally observed[2] excitation energy dependence of the width is given by $\Gamma_{\rm GDR}=4.8+0.0026E^{1.6}$. This function is shown as a solid line in Fig. 3. It corresponds to an approximately cubic dependence on T, pointing to other mechanisms underlying the observed width increase.

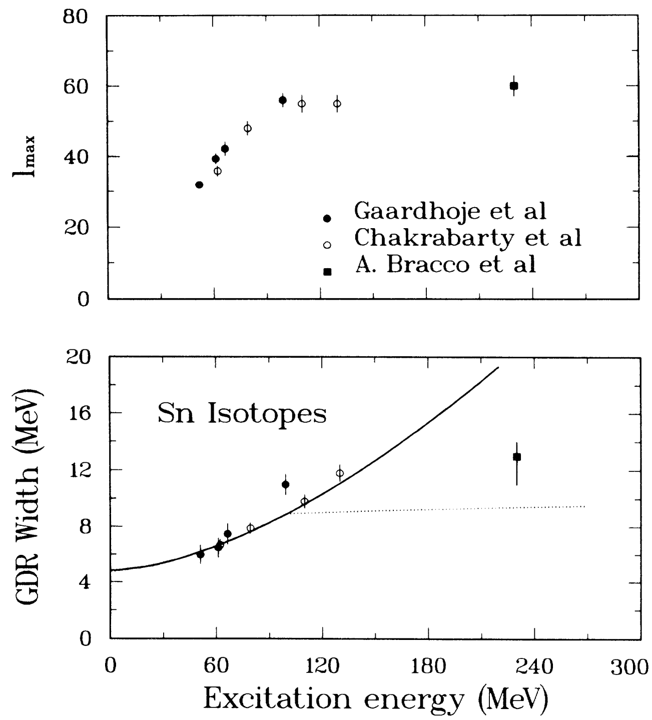

FIG. 3. Systematics of the width of the GDR in Sn isotopes as a function of excitation energy: filled circles (Ref. 1), open circles (Ref. 2), and filled squares (this work). The solid line is a phenomenological fit to the data (Ref. 2) up to $E^*=130$ MeV. The dotted line corresponds to an estimate of the contribution to $\Gamma_{\rm GDR}$ from thermal fluctuations of the nuclear shape (see text for details). Upper part: The maximum angular momentum of the compound nucleus based on the work of Refs. 9 and 10.

The previous discussion has entirely neglected angular momentum. Indeed, the angular momentum transferred to the compound nucleus in these inclusive reactions, grows with the excitation energy as a consequence of the increased bombarding energy. Calculations[3] support the premise that angular momentum effects are responsible for most of the observed increase of the GDR width at low T due to shape changes. Such effects, however, are expected to be limited by the maximum angular momentum which the compound nuclei can sustain without fissioning. This should make it possible to separate temperature effects from angular momentum effects allowing a more detailed investigation of the mechanisms responsible for the damping of collective excitations at finite T.

The maximum angular momenta $l_{\rm max}$ of the Sn isotope compounds studied in Refs. 1 and 2 and in the present work are plotted as a function of excitation energy in the upper part of Fig. 3. They are based on measurements of angular momenta of compound nuclei leading to evaporation residues. The maximum value of $l_{\rm max}$ that a compound nucleus with $A\approx110$ can sustain without fissioning is deduced to be $\approx 60\hbar$ from γ-ray multiplicity measurements in coincidence with the evaporation residues of the ^{37}Cl+^{74}Ge fusion reaction.[9] This value is lower than the prediction of the rotating-liquid-drop model but is in good agreement with γ-ray multiplicity studies of compound nuclei with $A=160-170$.[10] For these nuclei the limiting angular momentum occurs nearly independent of incident channel at $E^* \approx 80$ MeV.

The l_{max} of the Sn compound nuclei on which the GDR states are built saturates at $E^* \approx 100$ MeV suggesting that for $E^* \gtrsim 100$ MeV the GDR width should not depend on spin effects. The predicted evolution of the GDR width beyond $E^* \approx 100$ MeV, also shown in Fig. 3, is a result of the spread in the dipole frequencies due to thermal fluctuations as discussed above. A quantitative estimate of this spread assuming an adiabatic coupling of the GDR to the quadrupole degrees of freedom and using the liquid-drop model[11] yields $\Delta\omega \sim 1.3\sqrt{T}$. This result was found to be in reasonable agreement with detailed microscopic calculations using the Nilsson-Strutinsky method. In Fig. 3 the function $\Gamma_{GDR}=6.8+1.3(E^*/a)^{1/4}$ MeV with $a=A/8$ is plotted as the dotted line. A smaller level-density parameter (e.g., $a=A/12$) gives only a slightly more rapid increase as a function of excitation energy (~ 0.7 MeV from $E^*=100$ to 300 MeV). Within the framework of this simple model, the discrepancy (≈ 2 MeV) between the experimental data and the dotted line of Fig. 3 might reflect the presence of other temperature-dependent couplings, besides thermal fluctuations, which contribute to the GDR width. The size of this additional contribution to the GDR width may be important also in the understanding of the full width of GDR at lower E^*.

In conclusion, we find that the measured width of the GDR at increased temperature is consistent with the saturation of angular momentum effects. This will make more detailed studies of the effect of temperature on the damping of the GDR in hot nuclear matter accessible. Recent calculations[11] including a dynamical coupling of the GDR to oscillations of the nuclear surface predict, however, a decrease of the Γ_{GDR} already at a temperature of 1 MeV in the absence of spin effects. The observed saturation of the spin effects suggests that detailed tests of such theoretical models for the GDR damping can be made at higher excitation energy. As only few data[5] exist at higher energies, it appears promising to undertake such studies of the damping of collective excitations in nuclei as they approach the limits of their stability.

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