# Giant dipole resonance width as a probe for nuclear deformation at finite excitation

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(Received 26 February 2013; published 16 April 2013)

The first systematic study of the correlation between the experimental giant dipole resonance (GDR) width and the average deformation $\langle\beta\rangle$ of the nucleus at finite excitation is presented for the mass region $A \sim 59$ to 208. We show that the width of the GDR ($\Gamma$) and the quadrupole deformation of the nucleus do not follow a linear relation, as predicted earlier, owing to the GDR-induced quadrupole moment, and the correlation also depends on the mass of the nuclei. The different empirical values of $\langle\beta\rangle$ extracted from the experimental GDR width match exceptionally well with the thermal shape fluctuation model. As a result, this universal correlation between $\langle\beta\rangle$ and $\Gamma$ provides a direct experimental probe to determine the nuclear deformation at finite temperature and angular momentum over the entire mass region.

DOI: 10.1103/PhysRevC.87.044325 PACS number(s): 24.30.Cz, 24.60.Dr, 25.70.Gh

## I. INTRODUCTION

The atomic nucleus is a complex many-body quantum system which displays an unbelievably rich and intriguing variety of phenomena. While there are many excitations that are quite irregular and even considered to be the manifestation of chaotic motion, the nuclei, on the other hand, also show collective behavior that reflects the dynamical properties of the nuclear system. Giant resonances, the collective mode of excitation, are of particular interest because they currently provide the most reliable information about the bulk behavior of the nuclear many-body system. A typical example of this vibrational mode is isovector giant dipole resonance (GDR), in which the neutrons and protons oscillate out of phase against each other [1,2]. Interestingly, this is the only giant resonance experimentally studied extensively at finite temperature ($T$) and angular momentum ($J$). Consequently, it has become an indispensable tool in nuclear structure physics.

The GDR decay from excited nuclei occurs on a time scale that is sufficiently short and thus probes the conditions prevailing at that time [2]. The centroid energy of the resonance is inversely proportional to the nuclear radius and provides an idea about the nuclear size. Moreover, the centroid energy is strongly correlated with the nuclear symmetry energy, which is a fundamental quantity important for studying the structure of a neutron star [3]. On the other hand, the width of the resonance corresponds to the damping of this collective vibration owing to the viscosity of the neutron and proton fluids [4]. Recently, the precise experimental systematics of the GDR widths in hot nuclei have been applied to calculate the ratio of the shear viscosity $\eta$ to the entropy volume density $s$ [5]. It was concluded that the ratio $\eta/s$ in medium and heavy nuclei decreases with increasing temperature, to reach the value (1.3–4) $\times \hbar/(4\pi k_B)$ at $T = 5$ MeV, indicating that nucleons inside a hot nucleus at $T = 5$ MeV have nearly the same ratio $\eta/s$ as does quark gluon plasma. Microscopically, the total width of the GDR consists of the Landau width, the spreading width, and the escape width [1]. In medium and heavy nuclei, the Landau and the escape widths account for only a small fraction and the major contribution of the large resonance width comes from the spreading width [6,7]. Recently, an empirical formula has been derived for the spreading width with only one free parameter by separating the deformation-induced widening from the spreading effect [8]. It is now well known that the GDR strength function splits in the case of a deformed nucleus and the deformation can be estimated from the ratio of the two resonance energies [1]. However, for small deformations, the separation is not appreciable and the two resonance energies cannot be identified individually. As a result, the overall width of the GDR increases. Thus, the apparent GDR width ($\Gamma$) can provide us a direct experimental probe to measure the deformation of the atomic nuclei at a high temperature and angular momentum. However, this interesting aspect of the apparent GDR width has not been explored so far.

Several studies of the GDR $\gamma$ decay in hot nuclei have shown that while the GDR centroid energy remains more or less constant with the excitation energy, the apparent width of the resonance increases with both temperature and angular momentum [1]. The $J$ dependence of the GDR width is described very successfully within the thermal shape fluctuation model (TSFM) [9–11]. As the rotational frequency becomes higher, the nucleus undergoes an oblate flattening owing to centrifugal effects. The equilibrium deformation ($\beta_{eq}$) increases rapidly with $J$, and as a consequence, the total GDR strength function undergoes splitting, which increases the overall width of the resonance. The model has also been applied successfully to explain the Jacobi shape transition in atomic nuclei [12,13]. However, it should be mentioned that even though the equilibrium deformation of a nucleus increases with $J$, an increase in the GDR width is not evident experimentally until the equilibrium deformation increases sufficiently to affect the thermal average [14]. In particular, as long as $\beta_{eq}$ is less than the variance $\Delta\beta = [\langle\beta^2\rangle - \langle\beta\rangle^2]^{1/2}$, the increase in GDR width is not significant. Thus, the

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competition between $\beta_{\rm eq}$ and $\Delta\beta$ gives rise to the critical angular momentum, observed in all the experiments, below which the GDR width remains nearly constant at its ground-state values. In the case of $T$ dependence, it is observed that the experimental GDR widths remain more or less constant until $T \sim 1$ MeV and increase with $T$ thereafter. The increase in the GDR width above $T = 1.5$ MeV can be explained reasonably well within the TSFM. The model proposes that the nucleus does not posses a single well-defined shape but rather explores a broad ensemble of mostly quadrupole shapes because of thermal fluctuation around an equilibrium shape. Thus, in adiabatic assumption, i.e., when the shape fluctuations are slow compared to the frequency shift, the observed GDR width results from a weighted average over all frequencies associated with the possible shapes [9,15]. This gives rise to $T$-driven broadening of the width. However, the model fails to explain the experimental data below $T = 1.5$ MeV in different mass regions [16–20]. Recently, it has been shown that the GDR vibration itself produces a quadrupole moment causing the nuclear shape to fluctuate even at $T = 0$ MeV [20–22]. Therefore, when the giant dipole vibration, having its own intrinsic fluctuation, is used as a probe to view the thermal shape fluctuations, it is unlikely to feel the thermal fluctuations that are smaller than its own intrinsic fluctuation. The discrepancy between the experimental data and the TSFM predictions at low $T$ is attributed to the competition between the GDR-induced fluctuation ($\beta_{\rm GDR}$) and the variance of the deformation $\Delta\beta$ owing to thermal fluctuations. This gives rise to a critical temperature ($T_c$) in the increase in GDR width. A new phenomenological model has been proposed by invoking this idea and is called the critical temperature included fluctuation model (CTFM) [20]. The model gives an excellent description of the GDR width for both $T$ and $J$ over the entire mass range.

In this paper, we present a systematic study of a universal correlation between the GDR width and the average deformation of the nuclei. We show that the relationship between the GDR width and $\langle\beta\rangle$ is nonlinear because of the GDR-induced quadrupole moment. We also find good agreement between $\langle\beta\rangle$ extracted from the experimental GDR width and the TSFM calculation for both $T$ and $J$ in the mass region $A \sim 59$ to 208.

## II. THE FORMALISM AND THE UNIVERSAL CORRELATION

It is very interesting to note that the increase in the GDR width with both $J$ and $T$ can be explained by the spreading owing to the shift in the centroid energy of the GDR modes for each deformation. Moreover, simple scaling functions depending only on $J$, $T$, and $A$ represent the experimental data on the GDR width remarkably well. Hence, in principle, there should exist a correlation between the width of the GDR and the average deformation $\langle\beta\rangle$ of the nucleus at finite $T$ and $J$. The mass dependence of the mean value of $\beta$ and the FWHM of the GDR width was studied by Mattiuzzi *et al.* [23] and hinted at a correlation between $\langle\beta\rangle$ and GDR width. It was shown that the oblate flattening owing to the angular momentum would be small for heavier nuclei and thus the FWHM should

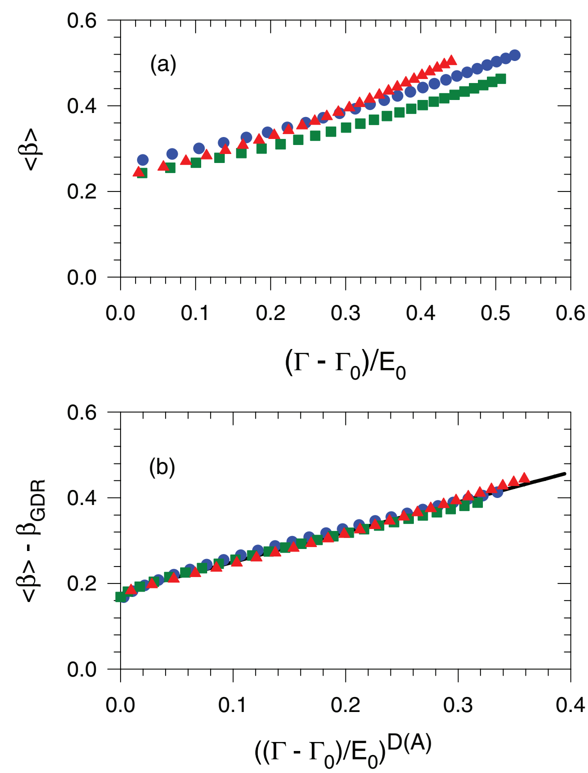


FIG. 1. (Color online) Average nuclear deformation vs GDR width for $^{63}$Cu (filled circles), $^{120}$Sn (filled squares), and $^{208}$Pb (filled triangles) for $T \leqslant 3.5$ MeV and $J = 15\hbar$. (a) The average deformation and the GDR width do not follow a linear relationship, as predicted earlier, when the actual $T$ dependence of the GDR width is considered. (b) A linear correlation is obtained when $\langle\beta\rangle - \beta_{\rm GDR}$ is plotted as a function of $((\Gamma - \Gamma_0)/E_0)^{D(A)}$. The solid line is the proposed correlation represented by Eq. (1).

exhibit less dependence on the angular momentum. A few years later, it was shown within the TSFM [24] that $\langle\beta\rangle$ is directly correlated with the quantity $(\Gamma(J,T,A) - \Gamma_0)/E_0$, where $\Gamma_0$ and $E_0$ represent the width and centroid energy of the GDR for a spherical nucleus, respectively. However, the comparison was made only for the Sn nucleus and the ansatz failed [24] to represent the temperature dependence of $\langle\beta\rangle$ deduced from experimental data with the TSFM calculation.

We remark here that the TSFM does not represent the proper $T$ dependence of the GDR width, as it does not take into account the fluctuations introduced by the GDR motion [20]. Hence, the linear relationship, proposed earlier, failed to explain the $T$ dependence of $\langle\beta\rangle$ derived from the experimental GDR width with the TSFM calculation [24]. In Fig. 1(a), we plot $\langle\beta\rangle$ as a function of $(\Gamma - \Gamma_0)/E_0$ for $^{63}$Cu, $^{120}$Sn, and $^{208}$Pb, as systematic data exist in this mass region over a wide range of $T$. In this case, the GDR width was derived from the CTFM, which represents the precise $T$ dependence of the GDR width, while $\langle\beta\rangle$ was calculated under the TSFM framework using the Boltzmann probability $e^{-F(\beta,\gamma)/T}$ with the volume element $\beta^4 \sin(3\gamma)d\beta d\gamma$ described in Ref. [13]. It is clearly shown in Fig. 1(a) that different nuclei have different slopes as well as different intercepts when the actual $T$ dependence of the GDR width is taken into account. We remark here that the width of the GDR and $\langle\beta\rangle$ of the nucleus cannot be directly compared, as GDR vibration itself produces a fluctuation and cannot probe variations that are smaller than its own intrinsic fluctuation [20]. In fact, $\langle\beta\rangle$ should be correlated with the width of the GDR along with the deformation induced by GDR motion ($\beta_{\rm GDR}$). Interestingly, a linear correlation is indeed obtained when $\langle\beta\rangle - \beta_{\rm GDR}$ is plotted as a function of $((\Gamma - \Gamma_0)/E_0)^{D(A)}$, where $D(A)$ has a small mass dependence [Fig. 1(b)]. We propose the correlation between the average deformation of the nucleus and the width of the GDR as

$$\beta_{\rm exp} = 0.18 + \beta_{\rm GDR} + 0.7\left(\frac{\Gamma(J,T,A) - \Gamma_0}{E_0}\right)^{D(A)}, \quad (1)$$

where

$$\beta_{\rm GDR} = 0.04 + 4.13/A,$$
$$D(A) = 2 - 0.0036A.$$

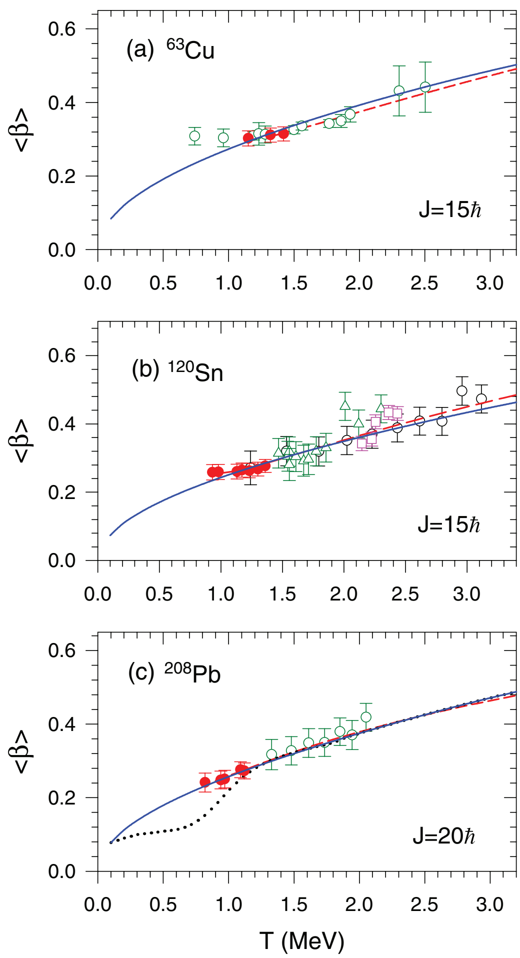


FIG. 2. (Color online) Average deformation as a function of $T$ for $^{63}$Cu, $^{120}$Sn, and $^{208}$Pb. (a) Filled circles are data from Ref. [20], while open circles are from Refs. [11,25] for $^{63}$Cu. (b) $^{120}$Sn data (open circles from [27], open squares from [26], triangles from [11]) are shown along with $^{119}$Sb data (filled circles from [16]). (c) $^{208}$Pb data (open circles from [27]) along with $^{201}$Tl data (filled circles from [20]). Solid lines correspond to TSFM calculations, while dashed lines represent the average deformations estimated using the GDR width from CTFM. The dotted line in (c) is the average deformation calculated for $^{208}$Pb including the shell effect.

## III. RESULTS AND DISCUSSIONS

It is interesting to note that the power coefficient $D(A)$ decreases with an increase in mass, as found previously for both $T_c$ and $\beta_{\rm GDR}$ [20]. In order to verify the correlation, the experimental data for $^{63}$Cu [11,20,25], $^{119}$Sb [16], $^{120}$Sn [11,26,27], $^{201}$Tl [20], and $^{208}$Pb [27] were used to extract the empirical deformation using Eq. (1). The values of $\langle\beta\rangle$ extracted from the experimental data are directly compared with the TSFM calculation (solid line) in Fig. 2. As can be seen, in all three mass regions, there is an excellent match between the experimental data and the TSFM calculation. The empirical deformations as a function of angular momenta for the nuclei $^{59}$Cu [28], $^{110}$Sn [29], $^{113}$Sb [30], $^{152}$Gd [31], and $^{176}$W [32] are also compared with the TSFM calculations in

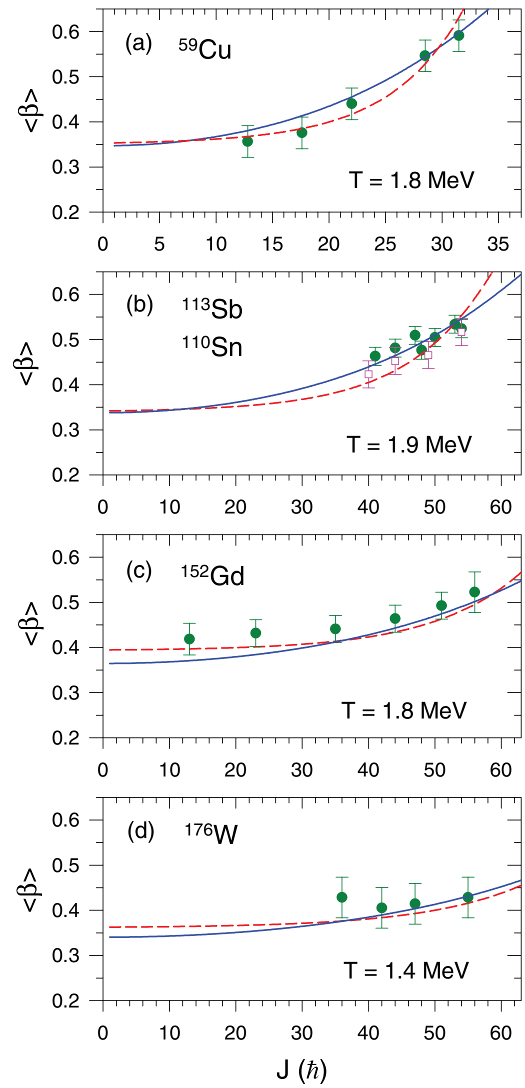


FIG. 3. (Color online) Average deformation as a function of $J$. (a) Filled circles represent the empirical deformation for $^{59}$Cu. (b) Filled circles correspond to $^{113}$Sb data, while open squares represent $^{110}$Sn data. (c) Filled circles represent data for $^{152}$Gd. (d) Filled circles represent data for $^{176}$W. Solid lines in (a)–(d) correspond to TSFM calculations, while dashed lines represent the average deformations estimated using the GDR width from the CTFM.

Fig. 3. Interestingly, in this case too the experimental data and TSFM calculations are in good agreement over the entire mass range. The average deformations estimated using the GDR widths predicted by the phenomenological CTFM have also been compared with the experimental data and found to match reasonably well (dashed lines in Figs. 2 and 3). For all the nuclei, the centroid energy of the GDR was calculated using the systematic $E_{\mathrm{GDR}} = 31.2A^{-1/3} + 20.6A^{-1/6}$ [1]. For calculation of the width of the spherical nucleus we used the relation $\Gamma_0 = 0.05E_{\mathrm{GDR}}^{1.6}$, which was derived recently by disentangling the effects of the spreading width and deformation-induced widening [8].

We mention here that the experimental GDR width can only be applied above the critical temperature ($T_c = 0.7 + 37.5/A$) to measure the nuclear deformation at finite excitation energy. Below $T_c$, the GDR vibration does not view the thermal fluctuations, as they are smaller than its own intrinsic GDR fluctuation [20]. Consequently, the experimental data and TSFM are not in good agreement below $T_c$ (Fig. 2). It is shown in Ref. [20] that shell effects indeed play an important role at low temperature with $A \sim 200$, as they increase the critical temperature from 0.5 to ~0.9 MeV. The value of $\langle\beta\rangle$ for $^{208}$Pb was also calculated including shell effects (dotted line in Fig. 2) and compared with the experimental data. It can be seen that the experimental data and the TSFM match very well above 0.9 MeV, as shell effects have already decreased by a factor of 10. Hence, the shell effects are directly included in the definition of the critical temperature. In general, Eq. (1) can be applied above $T_c$ as well as below the Jacobi transition point ($J_c \sim 1.2A^{5/6}$ [24]), as $\gamma_{\mathrm{min}}$ displays an abrupt change from $\gamma = \pi/3$ to $\gamma = 0$ and may not follow the simple correlation. Nevertheless, the empirical data and TSFM match exceptionally well above $T_c$ over the entire mass region for all values of $T$ and $J$. The GDR width, therefore, provides us a direct experimental probe to assess the nuclear deformation at finite temperature and angular momentum. Moreover, this novel idea of a universal correlation should provide new insights into the modification of the TSFM at low temperature by calculating the effective deformation probed by the GDR motion at finite excitation energy; i.e., the quadrupole moment induced by the GDR motion should be included in the TSFM.

## IV. SUMMARY AND CONCLUSION

In summary, we have presented a systematic study of the correlation between the width of the GDR and the quadrupole deformation of the nucleus at finite excitation. We have shown, by comparing $\langle\beta\rangle$ calculated within the TSFM and the GDR width $\Gamma$ estimated through the CTFM, that the correlation between $\langle\beta\rangle$ and $\Gamma$ is nonlinear owing to the GDR-induced quadrupole moment. The different experimental data, extracted using the proposed correlation, are in good agreement with the TSFM calculation over the entire mass range. Consequently, the apparent GDR width can be used as a direct experimental probe to measure the nuclear deformation as a function of $T$ and $J$, where the different GDR resonance energies owing to deformation cannot be separated.


[1] M. N. Harakeh and A. van der Woude, *Giant Resonances, Fundamental High-Frequency Modes of Nuclear Excitation* (Clarendon Press, Oxford, UK, 2001).
[2] J. J. Gaardhoje, Annu. Rev. Nucl. Part. Sci. **42**, 483 (1992).
[3] L. Trippa, G. Coló, and E. Vigezzi, Phys. Rev. C **77**, 061304(R) (2008).
[4] N. Auerbach and A. Yeverechyahu, Ann. Phys. **95**, 35 (1975).
[5] N. D. Dang, Phys. Rev. C **84**, 034309 (2011).
[6] P. F. Bortignon *et al.*, Nucl. Phys. A **460**, 149 (1986).
[7] P. Donati *et al.*, Phys. Lett. B **383**, 15 (1996).
[8] A. R. Junghans *et al.*, Phys. Lett. B **670**, 200 (2008).
[9] Y. Alhassid, B. Bush, and S. Levit, Phys. Rev. Lett. **61**, 1926 (1988).
[10] Y. Alhassid and N. Whelan, Nucl. Phys. A **565**, 427 (1993).
[11] D. Kusnezov, Y. Alhassid, and K. A. Snover, Phys. Rev. Lett. **81**, 542 (1998).
[12] A. Maj *et al.*, Nucl. Phys. A **731**, 319 (2004).
[13] D. Pandit *et al.*, Phys. Rev. C **81**, 061302(R) (2010).
[14] F. Camera *et al.*, Nucl. Phys. A **649**, 115 (1999).
[15] W. E. Ormand, P. F. Bortignon, and R. A. Broglia, Phys. Rev. Lett. **77**, 607 (1996).
[16] S. Mukhopadhayay *et al.*, Phys. Lett. B **709**, 9 (2012).
[17] P. Heckman *et al.*, Phys. Lett. B **555**, 43 (2003).
[18] F. Camera *et al.*, Phys. Lett. B **560**, 155 (2003).
[19] D. Pandit *et al.*, Phys. Lett. B **690**, 473 (2010).
[20] D. Pandit *et al.*, Phys. Lett. B **713**, 434 (2012).
[21] C. Simenel and P. Chomaz, Phys. Rev. C **68**, 024302 (2003).
[22] C. Simenel and P. Chomaz, Phys. Rev. C **80**, 064309 (2009).
[23] M. Mattiuzzi *et al.*, Nucl. Phys. A **612**, 262 (1997).
[24] D. Kusnezov and W. E. Ormand, Phys. Rev. Lett. **90**, 042501 (2003).
[25] M. Kicińska-Habior *et al.*, Phys. Rev. C **36**, 612 (1987).
[26] M. P. Kelly, K. A. Snover, J. P. S. van Schagen, M. Kicinska-Habior, and Z. Trznadel, Phys. Rev. Lett. **82**, 3404 (1999).
[27] T. Baumann *et al.*, Nucl. Phys. A **635**, 248 (1998).
[28] Z. M. Drebi, K. A. Snover, A. W. Charlop, M. S. Kaplan, D. P. Wells, D. Ye, and Y. Alhassid, Phys. Rev. C **52**, 578 (1995).
[29] A. Bracco *et al.*, Phys. Rev. Lett. **74**, 3748 (1995).
[30] S. Bhattacharya *et al.*, Phys. Rev. C **77**, 024318 (2008).
[31] D. R. Chakrabarty *et al.*, J. Phys. G **37**, 055105 (2010).
[32] M. Mattiuzzi *et al.*, Phys. Lett. B **364**, 13 (1995).