EFFECTIVE GDR WIDTH OF ^{132}Ce AT HIGH SPINS AND TEMPERATURES FROM THE LSD MODEL* **

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(Received December 7, 2006)

The Lublin–Strasbourg Drop (LSD) model, which reproduces quite satisfactorily the nuclear fission barriers, has been used as a basis for the thermal shape fluctuation method in order to compute effective GDR shapes of hot nuclei in particular at the regime of Jacobi shape transitions. In particular, the effective GDR width of ^{132}Ce evolution as a function of angular momentum and temperature was calculated and compared to the existing experimental results. The need of including the effect of compound nucleus lifetime for temperatures higher than 2 MeV is discussed.

PACS numbers: 21.60.–n

1. Introduction

Total giant dipole resonance (GDR) widths belong to those very few physical parameters that can be used to follow experimentally the nuclear shape evolution of compound nuclei at very high spins and temperatures [1].

* Presented at the Zakopane Conference on Nuclear Physics, September 4–10, 2006, Zakopane, Poland.

** This work was partially sponsored by the IN2P3 — Polish Laboratories Convention, Project No. 99-95, and by the Polish Ministry of Science and Higher Education (Grant 1 P03B 030 30).

In particular, by analysing theoretically the thermal shape fluctuations we can investigate the distribution of nuclear shapes for a given temperature and spin [2]. Moreover, from the Coriolis splitting of the giant resonance shape function for relatively light nuclei we can evaluate the evolution of the coupling of the dipole oscillations with the collective rotation [3].

2. The method

At high temperature limit the total nuclear energy can be well approximated by the macroscopic-model energies. One of the successful methods of this type is provided by the LSD approach [4] that takes into account the energy associated with the nuclear surface curvature. The corresponding energy expression reads

$$\begin{aligned} E_{\rm lsd}({\rm def}) \;=\; & ZM_H + NM_n - b_{\rm vol}\left(1-\kappa_{\rm vol}\left(\frac{N-Z}{A}\right)^2\right)A \\ & + b_{\rm surf}\left(1-\kappa_{\rm surf}\left(\frac{N-Z}{A}\right)^2\right)A^{2/3}B_{\rm surf}({\rm def}) \\ & + b_{\rm curv}\left(1-\kappa_{\rm curv}\left(\frac{N-Z}{A}\right)^2\right)A^{1/3}B_{\rm curv}({\rm def}) \\ & + \frac{3}{5}e^2\frac{Z^2}{r_0^{\rm ch}A^{1/3}}B_{\rm Coul}({\rm def}) - C_4\frac{Z^2}{A} + B_{\rm el.} \\ & - 10\,\exp\left(-42\left|\left(\frac{N-Z}{A}\right)\right|\Big/\,10\right). \end{aligned} \tag{1}$$

The parameters of this expression have been fitted to the binding energies of over 2700 experimental masses; the electronic binding correction is taken into account with the phenomenological term $B_{\rm el.} = -0.00001433Z^{2.39}$; all parameters in Eq. (1) are taken from the original article. The nuclear deformation is parametrized using the standard spherical harmonics expansion with the coefficient set, $\alpha \equiv \{\alpha_{\lambda\mu}\}$:

$$\mathcal{R}(\theta,\phi) = R_0\, c(\{\alpha_{\lambda\mu}\})\left[1+\sum_{\lambda=2}^{\lambda_{\rm max}}\sum_{\mu=-\lambda}^{\lambda}\alpha_{\lambda\mu}Y_{\lambda\mu}(\theta,\phi)\right]. \tag{2}$$

For rotating nuclei the total energy is described as a sum of the macroscopic energy (1) and rotational energy parametrized according to the rigid body expression employing the deformation dependent effective moment of inertia

$\mathcal{J} = \mathcal{J}(\alpha)$ as follows

$$E_{\rm macro}(\alpha; I) \equiv E_{\rm lsd}(\alpha) + \frac{\hbar^2 I(I+1)}{2\mathcal{J}(\alpha)}\,. \tag{3}$$

In the present study we have used the quadrupole deformations β, γ as well as α_{40}, α_{60} and α_{80}. In the final representation of the total nuclear energies we use the usual $\{\beta, \gamma\}$ plane; at each quadrupole deformation point the nuclear energy is minimized over the remaining multipole deformations.

In what follows we will need the probability of finding the excited nucleus at a given shape as given by

$$P[\alpha; I; T(\alpha)] = \exp\left\{-\frac{F[\alpha, T(\alpha)]}{kT(\alpha)}\right\}\,, \tag{4}$$

where $F[\alpha, T(\alpha)]$ is the free energy. The related formalism has been given in Ref. [5] and will not be repeated here.

The giant dipole resonance shape function was assumed to be the sum of 5 Lorentzians corresponding to deformation- and Coriolis-splitting effects

$$f_k[E_\gamma, ({\rm def})] = \frac{\sigma_k \Gamma_k E_\gamma^2}{(E_\gamma^2 - E_{{\rm GDR},k}^2)^2 + E_\gamma^2\,\Gamma_k^2}\,; \quad k = 1, 2, 3, 4, 5\,. \tag{5}$$

Above, σ_k denotes the strength of the $k^{\rm th}$-component of the GDR, Γ_k the corresponding width and $E_{\rm GDR,k} = \hbar\omega_k$ — the centroid. The symbol E_γ denotes the γ ray energy. In the following the GDR widths will be parametrized using the empirical expression taken from Ref. [6]

$$\Gamma_k = (E_{{\rm GDR},k}/E_{\rm GDR})^{1.9}\ \Gamma_0\,, \tag{6}$$

where the Γ_0 is the intrinsic GDR width, taken from the experimental data for the GDR built on the nuclear ground state. The centroid for spherical nucleus, $E_{\rm GDR} \equiv \hbar\omega_0$, was parametrized as

$$E_{\rm GDR} = 79 A^{-1/3}. \tag{7}$$

The *total* GDR spectrum (or strength function) is the sum over the (β, γ)-plane with the weight-factor of Eq. (4):

$$\sigma(E_\gamma, T, I) = \sum_{(x,y)} P({\rm def}; I; T) \sum_{k=1}^{5} f_k(E_\gamma, {\rm def})\,. \tag{8}$$

3. Results for ^{132}Ce

The calculation begins with minimizing the macroscopic (LSD) energy, Eq. (1), over deformations (α_{40}, α_{60}, α_{80}) at each (β,γ)-point. Figure 1 shows the corresponding LSD potential energy maps for ^{132}Ce in the spin region $I = 10-80\hbar$. As it can be seen from the Fig. 1, for spins higher than $I = 70\hbar$ the Jacobi transition brings the nucleus rapidly towards fission. The

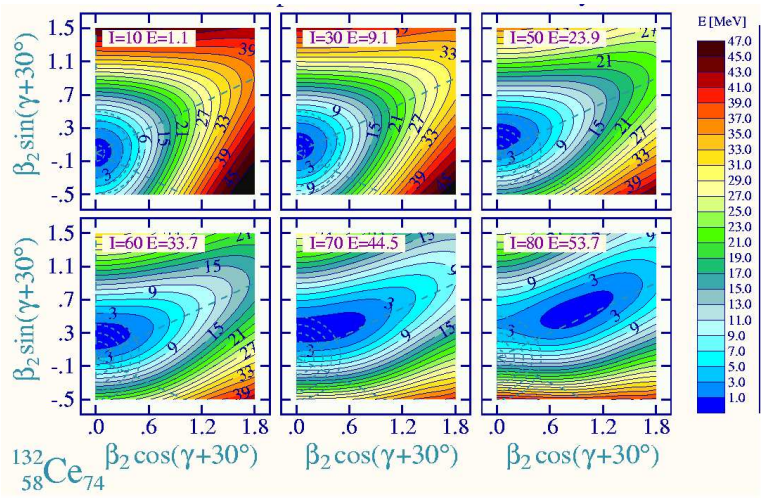

Fig. 1. Total macroscopic energies according to LSD method in the $\{\beta,\gamma\}$ plane. The energies are normalised to $E_{\rm lsd}(0)$. At each point and for each spin the energy has been minimized over $\alpha_{4,0}$, $\alpha_{6,0}$, $\alpha_{8,0}$.

next step is to introduce the thermal shape fluctuations and their influence on the total GDR shape. The shape probability distributions according to Eq. (4) in ^{132}Ce for temperature $T = 2$ MeV and for spins $I = 10-80\hbar$ are shown in Fig. 2. The total GDR spectra (8) for these spins are presented in Fig. 3. In the calculations we assumed that the intrinsic GDR width is equal to its ground state value $\Gamma_0 = 4.5$ MeV,

The calculated total GDR widths, defined as the full width at half of maximum (FWHM) of the calculated total GDR spectra, were compared to the experimental data [7] (Fig. 4). As one can see, the results reproduce the experimental data up to temperatures $T \approx 2$ MeV (solid line). However, for higher temperatures the experimental widths are becoming larger than those from LSD based thermal shape fluctuations. A possible explanation of this discrepancy can be related to the idea of Chomaz [8], in which it is proposed that the intrinsic GDR width can become larger at higher excitation energies due to shorter compound nucleus lifetime. Assuming that the contribution of the compound nucleus lifetime to the intrinsic GDR width is proportional

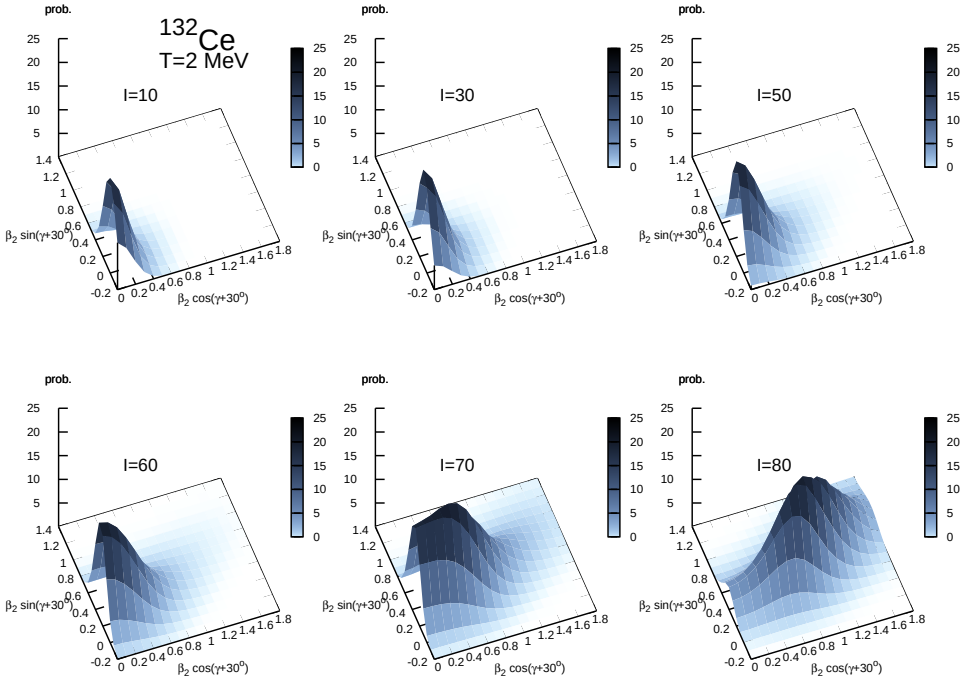

Fig. 2. The nuclear shape probability as a function of deformation parameters for ^{132}Ce for spins $I = 10 - 80\hbar$.

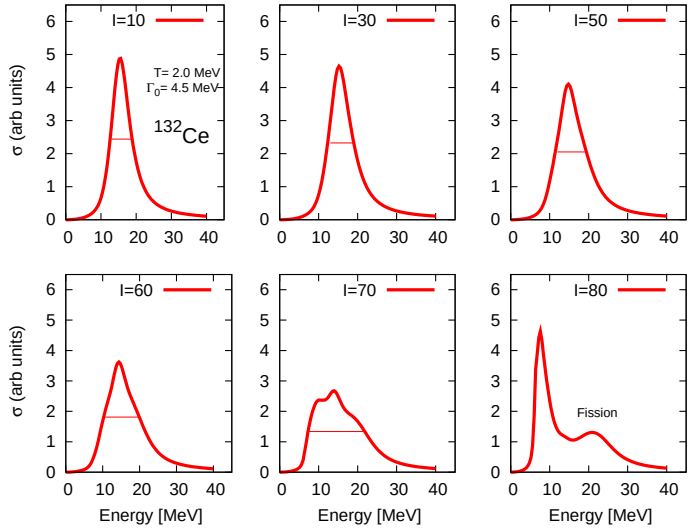

Fig. 3. The total GDR strenght for ^{132}Ce for spins $I = 10$–$80\hbar$.

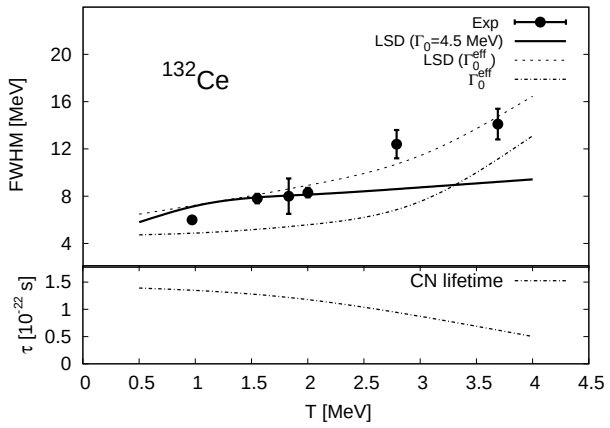

Fig. 4. Top: The experimental width of the GDR (dots) and theoretical predictions *versus* temperature for ^{132}Ce (see text for explanations). Dashed-dotted line shows the values of $\Gamma_0^{\rm eff}$. Bottom: Lifetime dependence of excited compound nucleus on its temperature.

to the density of states, *i.e.* proportional to the exponent of the temperature, we can replace Γ_0 in (6) by an *effective* GDR intrinsic width:

$$\Gamma_0^{\rm eff} = \Gamma_0 * (1. + a * \exp(b * T)) \,, \tag{9}$$

where a and b are free parameters, while for Γ_0 we can use its ground state value 4.5 MeV.

Using this effective intrinsic GDR width parametrization in the thermal shape fluctuations (6), and comparing in this way calculated total GDR width to the experimental data for each temperature, we obtained the best values for the parameters: $a = 0.03$ and $b = 1.037$.

The effective intrinsic GDR width with these parameters is plotted in Fig. 4 (top panel) as dashed-dotted line, while the dotted line shows the resulted total GDR width. Using this effective intrinsic GDR width, inferred from the experiment, one can deduce the lifetime of the compound nucleus via Heisenberg uncertainty relation, *cf.* bottom panel of Fig. 4.

4. Conclusions

It was shown that for temperatures $T < 2$ MeV the thermal shape fluctuation model combined with the LSD energies works satisfactorily. For $T > 2$ MeV, however, other effects have to be included. A possible explanation could be the influence of the shorter compound nucleus lifetime, but also the dependence of the Liquid-Drop Model parameters on temperature.

REFERENCES

[1] P.F. Bortignon, A. Bracco, R.A. Broglia, *Giant Resonances: Nuclear Structure at Finite Temperature*, Gordon Breach, New York 1998.

[2] W.E. Ormand, P.F. Bortignon, R.A. Broglia, *Nucl. Phys.* **A618**, 20 (1997).

[3] K. Neergård, *Phys. Lett.* **B110**, 7 (1982).

[4] K. Pomorski, J. Dudek, *Phys. Rev.* **C67**, 044316 (2003); J. Dudek, K. Pomorski, N. Schunck, N. Dubray, *Eur. Phys. J.* **A20**, 15 (2004).

[5] N. Dubray, J. Dudek, A. Maj, *Acta Phys. Pol. B* **36**, 1161 (2005).

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

[7] O. Wieland *et al.*, *Phys. Rev. Lett.* **97**, 012501 (2006); O. Wieland *et al.*, *Acta Phys. Pol. B* **38**, 1447 (2007), these proceedings.

[8] Ph. Chomaz, *Phys. Lett.* **B347**, 1 (1995).