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Quadrupole moment of superdeformed bands in ^{151}Tb

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Abstract. The quadrupole moments of the first two superdeformed (SD) bands in the nucleus ^{151}Tb have been measured with the Doppler Shift Attenuation Method (DSAM) using the EUROGAM γ-ray spectrometer. The first excited band (B2) is identical to the yrast SD band of ^{152}Dy in terms of dynamical moments of inertia and γ-ray energies. The measured relative quadrupole moments of the yrast band (B1) with respect to the band B2 are nicely reproduced by self-consitent Hartree-Fock calculations. The variation of the Q_0 value at the bottom of the yrast band suggests a large admixture between wave functions in the normal and the SD wells. This could explain the rather high deexcitation spin for the yrast band.

PACS. 21.10.Ky Electromagnetic moments – 21.10.Tg Lifetimes – 21.10.Re Collective levels

1 Introduction

The SD bands observed in the mass region $A \sim 150$ are based on an ellispoidal shape with a major axis to minor ratio around 2:1. These shapes are stabilized by the shell gaps in the single particle energy spectrum corresponding to the so-called high N intruder orbitals [1]. The dynamical moment of inertia of a band depends strongly on the occupation of these orbitals. One of the most puzzling phenomena in SD nuclei is the near identical moments of inertia belonging to nuclei which differ by up to four mass units [2]. The questions raised by the identical bands are still open and the underlying effects are not yet well-understood. So as to aid in our understanding of the properties of identical bands a measure of the quadrupole moment Q_0, of the bands is important. The Q_0 is deduced by lifetime measurements and provides an indication as to the elongation of the nucleus. Such studies have been performed mainly with array of small volume germanium spectrometers, and consequently only for the most intense SD bands (yrast bands). The relatively low efficiency of these arrays has not led to any conclusion about differences in Q_0 related to orbital occupation. With the new generation of spectrometers such as GAMMASPHERE or EUROGAM phase II, which consist of large volume germanium detectors and composite detectors, precise lifetime measurements using the Recoil Distance Method (RDM) or the Dopper Shift Attenuation Method (DSAM) have been carried out. The latter method has been widely used in the $A \sim 150$ mass region, namely for SD bands in $^{148-149}Gd$, ^{152}Dy [3], ^{150}Gd [5], ^{149}Tb [6], ^{151}Dy and for ^{151}Tb (yrast band) [7]. This letter reports on a DSAM experiment which was carried out to measured the Q_0 quadrupole moment of the yrast (B1) and the first excited (B2) SD bands in ^{151}Tb. This latter band has dynamical moments of inertia with γ-ray energies identical to the yrast band of ^{152}Dy [8]. It was assigned to a proton excitation from the level $\pi[301]_-$ into the intruder orbital $N = 6$ leading to the same intruder configuration ($\nu 7^2 \pi 6^4$) as ^{152}Dy. Recently, using a cranked Hartree-Fock model with Skyrme forces, Satula et al. [9] have calculated quadrupole moments of SD nuclei in the $A \sim 150$ mass region and have demonstrated the additivity of independent contributions from individual particle and hole orbitals to the doubly magic core ^{152}Dy.

2 Experiment

The experiment was performed at the Vivitron accelerator at the Institut de Recherches Subatomiques in Strasbourg. The EUROGAM phase II spectrometer consisted of 30 large volume hyperpure germanium (HPGe) detec-

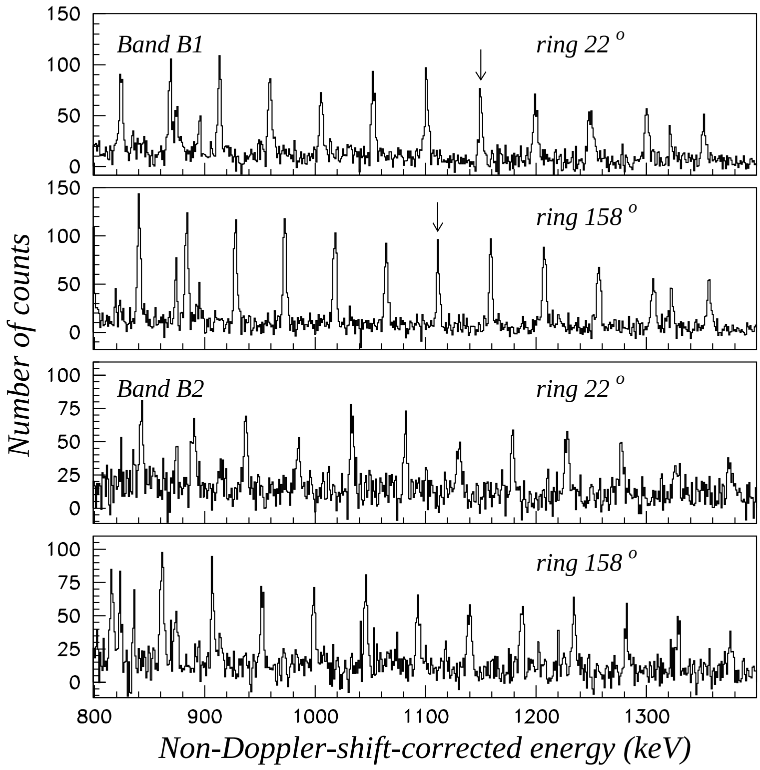

Fig. 1. Typical γ-ray spectra for SD bands collected at forward (22^o) and backward (158) symmetrical angles. As a visual indication of the Doppler Shift, the *arrows* mark the positions of the 1130 keV γ-ray transition for ^{151}Tb band B1. The difference in statistics at forward and backward angles is due to the slightly different set of gates selected to avoid non-shifted contaminating γ-ray lines

tors at backward and forward angles and 24 clover HPGe segmented detectors at angles around 90^o relative to the beam axis [10]. The spherical geometry of EUROGAM leads to the following ring occupations: 5 detectors at 22^o, 10 detectors at 46^o, 24 cristals at 71^o, 24 critals at 80^o, 24 cristals at 100^o, 24 cristals at 109^o, 10 detectors at 134^o and 5 detectors at 158^o. Superdeformed states in ^{151}Tb were populated via the $^{130}Te(^{27}Al, 6n)$ fusion-evaporation reaction at an incident beam energy of 152 MeV. The target consisted of $1mg/cm^2$ of ^{130}Te on a $15mg/cm^2$-thick gold backing. To prevent sublimation of the target material under beam bombardment, a thin gold layer ($60\mu g/cm^2$) was evaporated on the tellurium. Futhermore, to avoid migration of tellurium material into the gold backing, an aluminium layer ($36\mu g/cm^2$) was evaporated between the target and the backing. Gamma-ray events in coincidence were recorded whenever at least 7 detectors (Compton unsuppressed) fired. A total of 8×10^8 events (fold: $M_\gamma \geq 3$, Compton suppressed) were collected.

3 Results

The lifetimes of SD states in rare-earth nuclei are measured by DSAM because of the very rapid decay of these states (lifetime $< 200fs$). The γ-ray energies are affected by the Doppler shift due to the slowing down process of the recoiling nuclei in the target and in the backing material (see Fig. 1). The experimental fractional shift $F(\tau) =< \beta(t)/\beta(0) >$ is deduced from the equation:

$$< E_\gamma(\theta, t) >= E_{\gamma 0}[1 + F(\tau)\beta(0)cos(\theta)]$$

where $E_{\gamma 0}$ is the unshifted γ-ray energy and $\langle E_\gamma(\theta, t)\rangle$ the measured energy with a detector positionned at an angle θ with respect to the beam axis. $\beta(0)$ is the initial velocity of the residual nucleus. The resulting $F(\tau)$ factors versus the γ-ray energy for the first and second ^{151}Tb SD bands are presented in Fig. 2. The details about the method used in extracting the values of $F(\tau)$ are described in [3]. In this procedure, there are two free parameters: the intrinsic electric quadrupole moment Q_0 and the electric quadrupole moment Q_{sf} of the sidefeeding bands. Using a χ^2 minimisation procedure, the sensitivity of the fit has shown that only the intrinsic quadrupole moment Q_0 and the velocity profile that depend on stopping powers, are the most crucial parameters.

The deduced electric quadrupole moments for bands B1 and B2 are $Q_0 = 17.2 \pm 0.4\,eb$, $Q_{sf} = 14 \pm 3\,eb$ and $Q_0 = 18.4 \pm 0.6\,eb$, $Q_{sf} = 17 \pm 3\,eb$ respectively. The quoted errors include only the statistical uncertainties. If we assume that the stopping power is known with an accuracy of $\approx 12\,\%$ [4], this leads to a uncertainty in the intrinsic quadrupole moment of $\Delta^{sp}Q_0 = 0.2\,eb$. The dispersion in initial velocity $\beta(0)$ of the recoiling ions due to neutron evaporation, leads to a variation of $\Delta^{v}Q_0 = 0.4\,eb$. The uncertainty in the detector positions ($< 0.1^o$) has no significant effect on the Q_0 uncertainty. The systematic errors can then be estimated to be $\Delta^{st}Q_0 = 0.5\,eb$ (quadratically added). Therefore the final quadrupole moment values are $Q_0 = 17.2 \pm 0.7\,eb$ and $Q_0 = 18.4 \pm 0.8\,eb$ for band B1 and band B2 respectively.

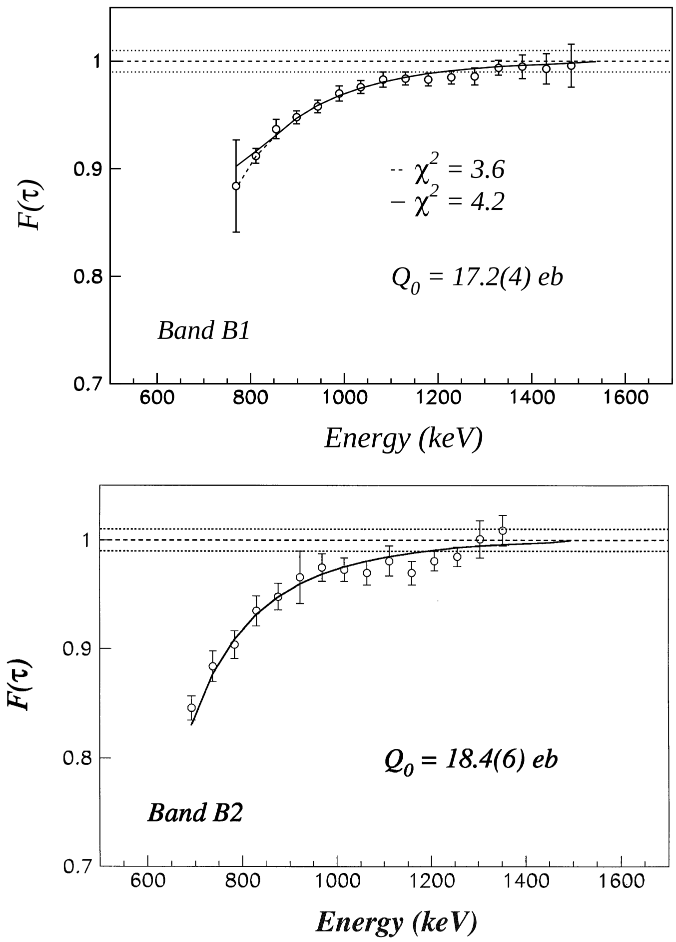

Fig. 2. Measured and calculated fractional shifts $F(\tau)$ for SD bands B1 and B2 of ^{151}Tb. The experimental $F(\tau)$ values were obtained from triple-gated spectra. The *dashed line* curve corresponds to Q_0 changes for the SD states involved in the deexcitation of band B1. Also indicated on the figure are the χ^2 obtained for the fits. The *dotted lines* indicate the error limits on the initial velocity $\beta(0)$ of the recoiling ions

4 Quadrupole moments

Calculations have been carried out in the mass region $A \sim 150$, using the cranked Hartree-Fock method with the Skyrme parametrisations SkM^* and SkP [9]. The electric quadrupole moments have been of the individual orbitals close to the N=86 and Z=66 shell gaps have been calculated, allowing the effect on the Q_0 of particle-hole excitations with respect to the ^{152}Dy core to be determined. Previous experimental results [3] have shown that the theoretical Q_0 values for SD bands in this mass region are greater than that measured experimentally. However, if the experimental and theoretical δQ_0 values are compared with respect to the ^{152}Dy core, then it is found that theory and experiment are in good agreement (see Table 1). One noticable deviation from this trend are the values of δQ_0 obtained in this work. The best agreement is obtained with the SkP parametrisation, so it seems that pairing does influence the polarization of the quadrupole moment even though pairing has always been assumed to be negligible in this mass region. The relative quadrupole moment $\delta Q_0^{exp}(B2)$ is $0.9 \pm 0.8\,eb$. This value is too large, since the polarization of the $\pi[301]_-$ orbital is estimated to be very weak ($0.18\,eb$ (SkP) and $0.16\,eb$ (SkM^*) [9]) and should not strongly affect the electric quadrupole moment. The quoted error includes statistical errors, stopping power uncertainties and the distribution width of the initial velocity of recoiling ions and have been quadratically added. One can also compare the experimental relative values for bands B1 and B2: $\delta Q_0^{exp} = Q_0^{exp}(B2) - Q_0^{exp}(B1) = 1.2 \pm 0.9\,eb$. In this case the errors due to uncertainties in the stopping power have not been taken into account since the nuclei were produced under the same experimental conditions. The relative value is well-reproduced by the Hartree-Fock calculations results $Q_0^{cal} = 1.13\,eb$ [9]. This indicates that the relative values of the measured quadrupole moments are reliable.

5 Decay out of SD band B1 and wave functions admixtures

At first we have assumed a constant value for Q_0 within the band B1. However, a better fit (χ^2) is obtained for band B1, if the Q_0 is kept as a free parameter during the fit for the states involved in the deexcitation. In this case the two last states of band B1 contributing to the decay-out have reduced experimental Q_0 values of $15 \pm 1\,eb$ and $12 \pm 2\,eb$ respectively. The sudden decay-out of SD bands is due to the admixture of ND states ($|ND>$) with SD states ($|SD>$). The total wave functions of the decaying SD state can be written in the following manner [11]:

$$|\Psi> = \alpha_{SD}|SD> + \alpha_{ND}|ND> \;\; with\ \alpha_{SD}^2 + \alpha_{ND}^2 = 1$$

The SD states has a given probability λ_{SD}^{E2} to decay onto the following SD states. And the partial decay-out probability λ_{out} for the deexcitation of a given SD level at spin I is given by:

$$\lambda_{out} = \alpha_{ND}^2(I)\lambda_{ND}^{E1}$$

where λ_{ND}^{E1} is the probability for E1 transitions, given in a statistical model by:

$$\lambda_{ND}^{E1} = \int_0^{U_i} \frac{\rho(U_f)}{\rho(U_i)} f_{GDR}(E_\gamma) E_\gamma^3 dE_\gamma = \frac{1}{\tau_{ND}}$$

The level density $\rho(U)$ is described using the formula [12]:

$$\rho(U) = \frac{1}{24} \cdot \frac{2I+1}{(U+U')^2} \cdot \left(\frac{\hbar^2}{2\Im^{(2)}}\right)^{3/2} \cdot \sqrt{a_N} . e^{2\sqrt{a_N U}}$$

The parameter U_i is the excitation energy of the SD state above the ND yrast line. The strength function of the giant dipole resonance $f_{GDR}(E_\gamma)$ is approximated by three Lorentzian shaped components. The level density parameter can be expressed as $a_N = A/a$, where A is the atomic mass number with parameter a varing from 7 to 12. The

Table 1. Comparison of experimental and theoretical Q_0 moments

Nucleus	$Q_0^{exp}(eb)$	reference	$\delta Q_0^{exp}(eb)^{(a)}$	configuration	$\delta Q_0(eb)$ SkP [9]	$\delta Q_0(eb)$ SkM^* [9]
^{152}Dy	$17.5(\pm 0.2)$	[3]		$\nu 7^2 \pi 6^4$		
^{151}Dy	$16.9(^{+0.2}_{-0.3})$	[7]	-0.6	$\nu[770]_-^{-1}$	-0.57	-0.48
$^{151}Tb(B1)$	$16.8(^{+0.7}_{-0.6})$	[7]	-0.7	$\pi[651]_+^{-1}$	-0.96	-0.96
$^{151}Tb(B1)$	$17.2(\pm 0.4)^{(b)}$	this work	-0.3	$\pi[651]_+^{-1}$	-0.96	-0.96
$^{151}Tb(B2)$	$18.4(\pm 0.6)^{(c)}$	this work	$+0.9$	$\pi[301]_-^{-1}$	$+0.18$	$+0.16$
^{149}Gd	$15.0(\pm 0.2)$	[3]	-2.5	$\nu[770]_-^{-1}\pi[651]^{-2}$	-2.42	-2.32
^{148}Gd	$14.6(\pm 0.3)$	[3]	-2.9	$\nu[770]_-^{-1}\nu[651]_+^{-1}\pi[651]^{-2}$	-2.85	-2.60

(a) $\delta Q_0^{exp} = Q_0^{exp}[^AZ] - Q_0^{exp}[^{152}Dy(yrast)]$ (errors less or equal to 0.1 eb)
(b) systematic errors will increase this value to $\pm 0.7eb$
(c) systematic errors will increase this value to $\pm 0.8eb$

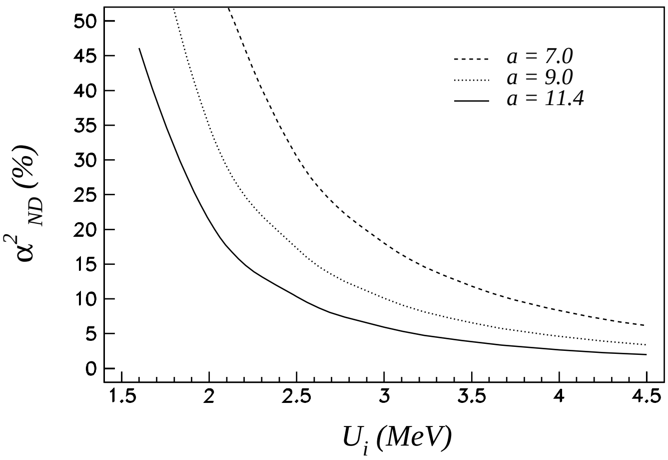

Fig. 3. Admixture coefficient α^2_{ND} versus the relative excitation energy U_i for different values of the a parameter in the level density estimation

partial decay-out probability λ_{out} could be experimentally deduced by:

$$\tau_{out} = \frac{1}{\lambda_{out}} = \tau(1 + \frac{N_{SD}}{N_{ND}})$$

where N_{SD} and N_{ND} correspond to the in-band and out-band intensities for a given spin I. The parameter τ is the experimental lifetime of the SD state. The mixing parameter α_{ND} between the wave functions in the first and second potential well could then be calculated using:

$$\alpha^2_{ND} = \frac{\tau_{ND}}{\tau_{out}}$$

Calculation of the admixture parameter has been performed for different excitation energies U_i and parameters a. Following results in reference [13] the spins of the two last SD states have been estimated to be $I = 69/2\hbar$ and $I = 65/2\hbar$ respectively. The value of the dynamical moment of inertia $\Im^{(2)} = 71\hbar^2/MeV$ has been extracted from a fit of the ND yrast line. The other parameters were taken from [12]. Dependence of the admixture parameter as a function of excitation energy U_i and on the level density parameters a is shown in Fig. 3. Similar values are obtained for α_{ND} using a slightly different level density formula of [14]. Assuming that the crossing of the ND yrast line with the SD band corresponds to the SD state with a 50% side feeding with respect to the plateau SD intensity ($I = 55\hbar$), one can fix the relative excitation energy U_i of the SD state at the bottom of the band to be $U_i = 2MeV$ above the ND yrast line. Following Pomorski's calculations [15] which evaluate the density parameter, a value $a = 11.4$ has been adopted for the level density in the first potential well of ^{151}Tb. With the above-mentioned set of parameters, the admixture of ND wave function in the SD wave function of the last SD state is $\alpha^2_{ND} = 18 \pm 6\,\%$. Only the errors on to the lifetimes of the SD states (τ_{SD}) have been included in this estimate. This large ND admixture compared to the one observed for the last SD states in the yrast SD band of ^{149}Gd ($\approx$ 5 %), could explain the deexcitation features of band B1 which occurs at higher spins than that in the neighbouring ^{149}Gd nucleus. Moreover band B1 has about the same average entry spin into the ND states as the ^{150}Gd SD yrast or ^{149}Gd first excited band. For those bands, neutron pairing $N = 7$ is predicted to be important [16] and seems to govern the decay-out process [17]. The barrier penetration probability between the two wells associated with different deformation depends strongly on pairing correlations [18]. Band B1 should then have a relatively strong pairing correlation that could lead to a large wave functions admixture. However, because of the weak strength of the last SD transition due to the decay-out, it is not possible to assign a more precise value to this admixture coefficient.

6 Conclusion

We have measured the electric quadrupole moments Q_0 for the first two SD bands in the ^{151}Tb nucleus. A study of statistical and systematic errors has been performed together with a test of sensitivity of the DSAM fractional shift fitting procedure. The relative quadrupole moments of the two bands are reproduced by Hartree-Fock calculations. The large amplitude of the ND component in the total wave function for the last SD states involved in the decay-out of band B1 could be related to stronger pairing correlation. And therefore explains the deexcitation that occurs at higher rotational frequency compared to neighbouring nuclei. Systematic and more precise measurements of quadrupole moments are likely to shed more light on such kind of investigations.

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