Eur. Phys. J. A **21**, 175–177 (2004)
DOI 10.1140/epja/i2003-10242-8

THE EUROPEAN PHYSICAL JOURNAL A

Letter

Experimental evidence for tunneling in the decay of superdeformed states

K. Lagergren[a] and B. Cederwall

Department of Physics, Royal Institute of Technology, SE-10691 Stockholm, Sweden

Received: 25 September 2003 / Revised version: 20 July 2004 /
Published online: 17 August 2004 –
Communicated by D. Schwalm

Abstract. A systematic study of the depopulation of superdeformed rotational bands in neutron-deficient $A \approx 80$–90 nuclei has been performed. We observed a correlation between the rotational frequency at which the decay out of the superdeformed bands takes place and the difference between the transition quadrupole moments of states in the superdeformed bands and high-lying states with "normal" deformation. The observation may constitute direct experimental evidence that the commonly adopted tunneling picture for the decay of superdeformed states is valid.

PACS. 21.10.Ky Electromagnetic moments – 21.60.Ev Collective models

Quantum-mechanical tunneling through a potential barrier is a process that is known to occur on the "microscopic" level in a wide range of physical phenomena. Well-known examples taken from the realm of nuclear physics are radioactive alpha-decay and solar fusion. In most cases the energy barrier originates from the electromagnetic interaction, and this is to a large extent also true for the above-mentioned examples. However, in nuclei the dominant interaction between the constituent nucleons is due to the strong nuclear force and we may expect energy barriers between states (or classes of states) that are due to the nuclear mean field. Corresponding examples are the decay of high-spin isomers and superdeformed (SD) states built on highly elongated nuclear shapes. This Letter is devoted to the latter case.

Nuclei with SD shapes have been identified in several regions of the nuclear chart. These are ellipsoidal-like nuclei with major-to-minor axis ratios around 2. At high spin, SD shapes may be energetically favored over more modest ("normal") deformations. The stability of the SD shapes has been attributed to large shell gaps opening up at these deformations, due to the presence of "intruder" orbitals with high single-particle angular momenta and deformation-driving properties.

The mechanisms behind the decay out of SD rotational bands in atomic nuclei has been an issue of large interest since the first observation of discrete gamma-ray transitions between SD states in ^{152}Dy [1]. When such a nucleus de-excites, thereby decreasing its rotational frequency, it eventually reaches a point where the SD shape is no longer energetically favored. The decay out of the band usually occurs after a near-constant intensity flow through a long series of transitions in the band. SD bands are usually fed (via heavy-ion reactions) over a very limited number of states, in contrast to lower-lying structures which may receive feeding over a large spin range. A notable feature of SD bands is also the sudden depopulation at the bottom of the bands, indicating a rather well-defined exit point for each band. In spite of this, discrete transitions linking the SD states to the low-lying states in the nucleus which are associated with lower deformations, have rarely been observed, and therefore the absolute excitation energies and spins of most SD bands remain unknown.

At the bottom of the SD band it suddenly decays to lower-lying normal-deformed (ND) states, a process which is generally viewed as tunneling through a potential barrier separating the SD and ND shapes. At the decay-out point the SD states are typically excited 3–5 MeV above the yrast line. The decay out of the SD bands seems to occur predominantly via a continuum of "hot", non-yrast, ND states since direct transitions linking the SD states with lower-lying states have been observed only in rare cases [2–5]. Even in such cases only a small fraction of the total intensity flowing through the SD states has been observed to be carried by direct linking transitions, further

[a] *Present address*: Department of Physics, Florida State University, Tallahassee, FL-32306, USA; e-mail: `karinl@nucmar.physics.fsu.edu`

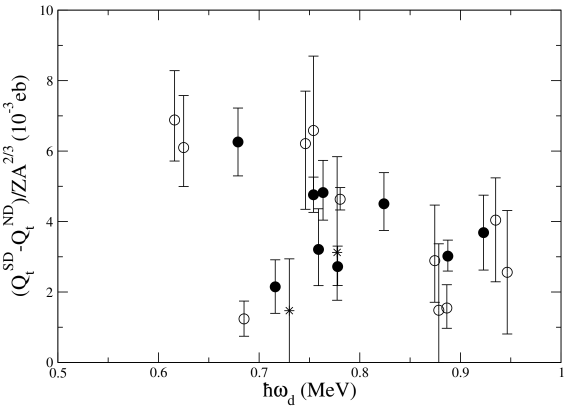

Fig. 1. Decay-out systematics for the superdeformed $A \approx$ 80–90 mass region. The rotational frequency ($\hbar\omega$) at which the feeding out of the bands (approximated by $E_\gamma/2\hbar$) takes place is plotted against differences in experimentally deduced transition quadrupole moments (Q_t) for the SD bands [10–13] and high-lying ND [14–23] states. SD bands assigned to even-even nuclei are indicated by solid symbols, those in odd-A nuclei by open symbols, and bands assigned to odd-odd nuclei are shown by stars. The error bars reflect the reported uncertainties for the states involved. Further details are given in the text.

supporting a statistical decay scenario involving an admixture of ND states [6]. The importance of the chaoticity of surrounding ND states for the strength of the first transition out of the SD band has been emphasized [7]. It deserves to be pointed out that although tunneling through a barrier in one dimension (deformation) is the generally adopted concept for the decay out of SD bands, little direct experimental evidence for such a scenario has been presented so far.

From a structural point of view we are interested in what factors determine the stability of the SD minimum, whether the sudden decay out at the bottom of SD bands reflects a tunneling through a distinct potential barrier or if rather a shallowing or disappearance of this minimum is at hand. Indeed, interesting evidence for the latter type of decay mechanism has been reported by Deleplanque *et al.* [8] for the nucleus ^{135}Nd. However, it is worthwhile to note that the ^{135}Nd case is rather atypical for SD nuclei in general since the band in question does not meet the commonly adopted criteria for SD bands (see above) with respect to the feeding pattern, relative excitation energy etc.

Here we address the issue of the decay-out mechanism of SD bands by means of a systematic study of the decay-out points for SD bands in mass $A \approx$ 80–90 nuclei in relation to the deformations of the SD and low-lying yrast states. This mass region features unique shape changes as a function of Z and A for both SD and ND states, enabling us to investigate whether the SD decay-out points are influenced systematically by the differences in quadrupole deformation between the SD and ND states. Since it has not been possible to experimentally establish the absolute spins and excitation energies for the states in the SD bands of this mass region, we choose to define the decay-out point by the corresponding rotational frequency $\hbar\omega$ at the bottom of each SD band. In order to avoid the complications from possible effects of pair correlations [9] which alter the level density of the ND states, we separate the experimental data into groups corresponding to even/odd Z and N. Naturally, the fact that the excitation energies and spins of the SD bands are unknown is a factor of uncertainty.

Table 1. Rotational decay-out frequencies and reported quadrupole moments for the SD bands, and differences between transition quadrupole moments of the SD bands [10–13] and high-lying normal-deformed states [14–23] for nuclei in the mass 80–90 region. The decay-out frequency was defined as an intensity-weighted average over the transitions to the states from which the bands are depopulated, divided by $2\hbar$. The transition quadrupole moment differences have been divided by $ZA^{2/3}$ in order to remove the macroscopic dependence on these parameters.

SD band	$\hbar\omega$ (MeV)	Q_t^{SD} (eb)	$\Delta Q_t/(ZA^{2/3})$ (10^{-3} eb)
80Sr(1)	0.778	$3.42^{+0.26}_{-0.23}$	$2.72^{+0.58}_{-0.54}$
80Sr(2)	0.889	$3.63^{+0.17}_{-0.15}$	$3.02^{+0.45}_{-0.43}$
80Sr(3)	0.923	$4.1^{+0.6}_{-0.6}$	$3.7^{+1.1}_{-1.1}$
80Sr(4)	10070	$4.9^{+0.6}_{-0.6}$	$4.8^{+1.1}_{-1.1}$
81Sr(1)	0.685	$3.08^{+0.16}_{-.15}$	$1.24^{+0.51}_{-0.49}$
81Sr(2)	0.887	$3.30^{+0.27}_{-.21}$	$1.54^{+0.66}_{-0.58}$
82Sr	0.716	$3.54^{+0.15}_{-0.14}$	$2.15^{+0.77}_{-0.75}$
83Sr	0.780	$3.60^{+0.20}_{-0.18}$	$4.63^{+0.33}_{-0.30}$
82Y	0.777	$4.3^{+1.8}_{-0.8}$	$3.1^{+2.7}_{-1.4}$
83Y(1)	0.947	$4.4^{+0.7}_{-0.7}$	$2.6^{+1.8}_{-1.8}$
83Y(2)	0.879	$3.6^{+0.8}_{-0.5}$	$1.5^{+1.9}_{-1.5}$
83Y(3)	0.935	$3.6^{+0.4}_{-0.3}$	$1.5^{+1.3}_{-1.2}$
84Y(1)	0.730	$3.6^{+0.5}_{-0.9}$	$1.5^{+1.5}_{-2.0}$
83Zr(1)	0.875	$5.8^{+0.8}_{-0.5}$	$2.9^{+1.6}_{-1.2}$
84Zr	0.763	$5.6^{+0.6}_{-0.5}$	$4.8^{+0.9}_{-0.8}$
86Zr(1)	0.759	$4.6^{+0.7}_{-0.6}$	$3.2^{+1.2}_{-1.0}$
86Zr(2)	0.754	$4.0^{+0.3}_{-0.3}$	$4.8^{+0.5}_{-0.5}$
86Zr(3)	0.933	$5.4^{+2.2}_{-1.1}$	$6.6^{+2.9}_{-1.5}$
86Zr(4)	0.824	$3.8^{+0.6}_{-0.5}$	$4.5^{+0.9}_{-0.8}$
87Nb(1)	0.625	$5.2^{+1.1}_{-0.8}$	$6.1^{+1.5}_{-1.1}$
87Nb(2)	0.746	$5.0^{+0.7}_{-1.0}$	$6.2^{+1.5}_{-1.9}$
87Nb(3)	0.754	$5.3^{+1.2}_{-1.0}$	$6.6^{+2.1}_{-1.9}$
88Mo(1)	0.679	$5.2^{+0.3}_{-0.3}$	$6.3^{+1.0}_{-1.1}$
89Tc	0.616	$5.9^{+0.7}_{-0.5}$	$6.9^{+1.4}_{-1.2}$
91Tc	0.716	$6.3^{+0.9}_{-0.6}$	$7.2^{+1.6}_{-1.3}$

If the SD bands have large variations in excitation energy one may expect corresponding differences in the decay-out points due to the associated differences in level density of the surrounding ND states. In fig. 1 are shown the rotational frequencies at the decay out of the SD bands plotted against the difference in transition quadrupole moments, Q_t, between the SD [10–13] and high-lying ND [14–23] states. The Q_t parameter has been divided by $ZA^{2/3}$ (where A is the nucleon number) in order to remove the macroscopic dependence on these parameters. The corresponding data are given in table 1. The rotational decay-out frequency was taken as an intensity-weighted average over the lowest-lying in-band transition energies, divided by $2\hbar$. Furthermore, a couple of the SD bands in the mass region were excluded due to large uncertainties in the experimentally deduced Q_t values and/or in their assignments as SD bands. The Q_t values of the ND states populated by the SD-ND decay were represented by an average over the ND states with known transition quadrupole moments having spins closest to those at which the SD bands are estimated to decay out (around $20\hbar$). As can be seen in fig. 1, a clear trend of increasing decay-out frequency with decreasing deduced difference between the Q_t values of ND and SD states is observed for the SD bands in the mass 80–90 nuclei. It is interesting to note that the observed correlation in fig. 1 is similar for the odd-A and even-even cases. We find it plausible that the observed correlation reflects the properties of the corresponding decay-out mechanism, although it should be pointed out that one cannot exclude other effects, *e.g.* a systematic variation in the excitation energies for the bands. The observed correlation between the SD decay-out points and the SD-ND deformation differences is not unexpected, and is in agreement with the statistical decay-out scenario outlined above. Indeed, in the tunneling picture a narrower potential barrier, which is reasonable to assume as a consequence of a smaller difference in deformation between the ND and SD states, will allow the SD states to be depopulated at a lower excitation energy relative to the ND yrast line, *i.e.* at an earlier decay-out point at a higher rotational frequency. A systematic increase in the decay-out frequency as a function of decreasing SD-ND deformation difference would hardly occur (other than accidentally) if the decay-out process takes place due to, *e.g.*, a shallowing or disappearance of the potential barrier rather than from tunneling through it. This is further supported by the suddenness of the decay out of the SD bands discussed in this work, and by the absence or extreme weakness of discrete linking transitions between the bands and states assigned to a lower deformation. In cases where a shallowing and disappearance of the second minimum (see, *e.g.*, [8]) have been established, the general properties of the bands are not typical of SD structures and the decay-out mechanism is more characteristic of a mixing with a limited number of low-lying yrast states.

In the simplest barrier penetration picture the decay-out rate can to first order be expected to behave like an exponentially decreasing function of the barrier thickness, *i.e.* the difference between the Q_t values of the SD and ND states. In order to quantify the observed correlation we have therefore performed a least-squares fit of an exponential function to the data points of fig. 1. The result confirms the decreasing trend as a function of increasing decay-out frequency with a negative exponential factor that differs from zero by more than three standard deviations. If the decay-out frequency and the difference in quadrupole moment are given in the same units as is fig. 1, the exponential factor is of the order of $-100\,\mathrm{eb}^{-1}$. The experimental uncertainties, however, preclude any detailed characterization of the observed correlation.

In summary, we have found in a systematic study of nuclei in the neutron-deficient mass 80–90 region a correlation between the exit points of superdeformed rotational bands and the difference between the deformations of superdeformed and normal-deformed states. This is in line with the statistical barrier penetration scenario commonly accepted for such decays.

References

1. P.J. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).
2. T.L. Khoo *et al.*, Phys. Rev. Lett **76**, 1583 (1996).
3. A. Lopez-Martens *et al.*, Phys. Lett. B **380**, 18 (1999).
4. A. Lopez-Martens *et al.*, Phys. Rev. Lett. **77**, 1707 (1996).
5. T. Lauritsen *et al.*, Phys. Rev. Lett. **88**, 042501 (2002).
6. T. Døssing, E. Vigezzi, R.A. Broglia, Phys. Lett. B **249**, 163 (1990).
7. S. Åberg, Phys. Rev. Lett. **82**, 299 (1999).
8. M.A. Deleplanque *et al.*, Phys. Rev. C **52**, R2302 (1995).
9. T. Døssing *et al.*, Phys. Rev. Lett. **75**, 1276 (1995).
10. F. Lerma *et al.*, Phys. Rev. C **67**, 044310 (2003).
11. D.G. Sarantites *et al.*, Phys. Rev. C **57**, R1 (1998).
12. D.R. LaFosse *et al.*, Phys. Rev. Lett. **78**, 614 (1997).
13. K. Lagergren *et al.*, Phys. Rev. C **68**, 064309 (2003).
14. R.F. Davie *et al.*, Nucl. Phys. A **463**, 683 (1987).
15. E.F. Moore *et al.*, Phys. Rev. C **38**, 696 (1988).
16. S.L. Tabor *et al.*, Phys. Rev. C **49**, 730 (1994).
17. D. Bucurescu *et al.*, J. Phys G **7**, 399 (1981).
18. S.D. Paul *et al.*, Phys. Rev. C **51**, 2959 (1995).
19. T.D. Johnson *et al.*, Phys. Rev. C **55**, 1108 (1997).
20. S. Chattopadhyay *et al.*, Phys. Rev. C **49**, 116 (1994).
21. W. Fieber *et al.*, Z. Phys. A **332**, 363 (1989).
22. S. Chattopadhyay, H.C. Jain, J.A. Sheikh, Phys. Rev. C **53**, 1001 (1996).
23. R.A. Kaye *et al.*, Phys. Rev. C **57**, 2189 (1998).