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First evidence for linking transitions between the superdeformed yrast band and the normal deformed states in ^{149}Gd

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Abstract

Double step resolved γ -ray transitions linking the yrast superdeformed (SD) band of ^{149}Gd to the normal deformed (ND) level scheme have been observed using the EURO GAM phase II spectrometer. The excitation energy of the $47/2^-$ SD state above the $7/2^-$ ground state has thus been determined to be 10.625 MeV. The most likely multipolarity of the linking transitions is deduced, which permits the assignment of the most probable spins for this SD band. This measurement represents the first observation of discrete γ -ray transitions linking SD and ND states in the $A \sim 150$ mass region of the nuclear chart. © 1999 Elsevier Science B.V. All rights reserved.

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The study of superdeformed (SD) bands in different mass regions, $A \sim 150$ [1], $A \sim 190$ [2] and more recently $A \sim 80$ [3] and $A \sim 60$ [4], has led to an extensive set of data. However since the discovery of the first SD band, it has been an experimental chal-

lenge to observe the discrete line γ -ray linking transitions between the SD and normal deformed (ND) states, allowing an unambiguous determination of the excitation energy, spins and parities of the SD states. In addition to the previously measured observables

such as the dynamical moment of inertia, alignment and lifetimes of the SD bands, the determination of the excitation energy, spin and parity of the SD states are critical to a complete understanding of the structure and properties of the SD nuclear states (e.g. orbital occupation, collective motion, identical band phenomenon). Moreover, they put new constraints on the existing theoretical models and lead to crucial test for the predictions. Despite the vast quantity of experimental data collected on SD nuclei, only a few discrete linking transitions have ever been observed directly, namely for the ^{194}Hg nucleus band (1) [5] and band (3) [6] and ^{194}Pb nucleus band (1) [7,8]. For these two nuclei, the deduced excitation energy (relative to ND yrast states with the same spin), spin and parity (E_x , J_π) of the SD state, from which the band decays, were found to be: ^{194}Hg band (1) (4.2 MeV, 10^+), ^{194}Hg band (3) (5.1 MeV, 9^-) and ^{194}Pb (2.7 MeV, 6^+). The decay of the SD nucleus reflects mostly a statistical process. Isolated by the barrier between the two potential wells, ND and SD, the SD nucleus cascades to low excitation energy states in the second minimum of deformation (low density of “cold” SD levels). However, with respect to normally deformed yrast states with same spins, the SD states are rather high in excitation energy. With the decrease of angular momentum, transmission coefficients through the barrier become more important. The sudden decay from the low SD states can then be explained by an abrupt tunneling through the barrier [9–11] and the coupling of the cold SD state with the hot compound ND states. A small admixture of the ND wave function in the total SD wave function drives the depopulation of the SD band through this ND component [12,13]. The high ND level density in the energy region to where the SD band decays to, offers numerous paths to the ND yrast line, resulting mainly in a quasi-continuum of decay paths. The excitation energy of the yrast SD band of ^{192}Hg has been determined from an analysis of this quasi-continuum [14].

Candidates for discrete linking transitions have also been reported in the SD nuclei ^{193}Pb [15] and ^{143}Eu [16,17]. It is worth mentioning the particular case of the $A \sim 130$ mass region [18]. Here the so-called highly deformed states ($\beta_2 \sim 0.45$) lie only about 1 MeV above the ND yrast line and this leads to a reduced number of discrete pathways in the

decay. It has then been possible to find the major part of the linking transitions available for the decay-out process (see for example Ref. [19]). One should also mention the particular case of ^{58}Cu nucleus where the SD band also decays via emission of a prompt proton [20].

The present work, in the $A \sim 150$ mass region, is devoted to the study of the deexcitation of the SD yrast band in ^{149}Gd and to the search for high energy discrete γ -rays connecting the SD band to ND states. The nucleus ^{149}Gd is one of the most widely investigated nuclei in this mass region in both potential wells [21–23]. The experiment was performed at the Vivitron accelerator at IReS in Strasbourg. The nucleus ^{149}Gd was populated through the fusion-evaporation reaction $^{124}\text{Sn}(^{30}\text{Si}, n)$ at a bombarding energy of 158 MeV. The target consisted of a stack of two ^{124}Sn foils of $\approx 470 \mu\text{g}/\text{cm}^2$ thickness each, allowing the nuclei to recoil into vacuum. The γ -ray energies were measured with the EURO GAM II γ -ray spectrometer [24] consisting of an array of 30 large germanium detectors (coaxial) at backward and forward angles and of 24 composite detectors (clover) at angles about 90° relative to the beam axis. Coincidence events were recorded to magnetic tape whenever a minimum of 7 detectors (Compton unsuppressed) fired. A total of 4.0×10^9 events were collected. After time filtering, the number of remaining clean events was reduced to 3.4×10^9 (for events having a suppressed fold $M_\gamma \geq 4$). The Doppler shift corrected γ -ray events were stored on disk using the software package of Ref. [25]. The background-subtracted spectra were obtained using a modified version [26] of the method described in Ref. [27].

A high energy part of the spectrum corresponding to sets of three gates on the SD yrast band transitions is presented in Fig. 1a. This spectrum shows the presence of three high energy transitions, 1802, 2188 and a doublet (1995–2001) keV at a $(4\text{--}8)\sigma$ level. A weaker 2585 keV transition at a 3σ level is also observed. The 1802 keV line is a new ND transition (also observed in coincidence spectra with gates set only on ND transitions) and has been placed in the level scheme. The 1995, 2001, 2188 and 2585 keV lines, in coincidence with the SD band transition members, are candidates for linking transitions. Their relative intensities with respect to the plateau of the SD band are 0.6(3)%, 0.5(3)%, 2.4(6)% and 0.5(2)%

Fig. 1. Panel (a): high energy part of the triple gated spectrum of the ^{149}Gd yrast SD band showing the linking transitions. The low energy part is shown in panel (d). Panel (b): double gated spectrum on the SD transitions combined with one gate on the 186 keV ND line. Panel (c): double gated spectrum on the SD transitions combined with one gate on the 2188 keV linking transition.

respectively. Combined coincidences procedures were used with the 186 keV ND line ($49/2^+$ to $45/2^+$) in conjunction with the SD transitions: to increment an event in the spectrum, the γ ray must be in coincidence with the 186 keV transition and at least two transitions of the SD band. With this method, one can select the decay-out pathway through the 186 keV line. Fig. 1b shows the resulting coincidence spectrum. The observed 2001 keV transition clearly indicates that this line is exclusively in coincidence with the 186 keV ND transition, the 1995, 2188 and 2585 keV lines being absent. Further, as illustrated in Fig. 1c, the 186 keV transition is not observed in the spectrum obtained with combined coincidence with the 2188 keV linking transition. However the 371 keV ($45/2^+$ to $41/2^+$), fed by the 186 keV, is present. For comparison the triple gated spectrum (low energy part) of the SD band is

also shown (Fig. 1d), where the 186 keV line is present. Consequently, comparing these spectra, the 2188 and 2585 keV lines connect to the ND level scheme at spin $45/2^+$ where the 186 keV ND transition decays to. The same arguments hold true for the 1995 keV line. To check whether these candidates are single step links, combined coincidence spectra with one of the candidates and a minimum of two transitions of the SD band (gate-combined procedure) have been built. In Fig. 2a one observes the 2585 keV transition in the spectrum obtained with the 2188 keV link (the most intense one) in combined coincidence with the SD band. Compared to the three SD gates coincidence spectrum of Fig. 1a where the 2585 keV line is embedded in highly fluctuating background, this gate-combined selection of the decay-out pathway is more restrictive and reduces the background and fluctuations, allowing a better observation of this γ -ray line in Fig. 2a. A spectrum in coincidence with this 2585 keV transition and at least two γ -rays of the SD band was also built, the result is presented in Fig. 2b where the 2188 keV line can be observed. We

Fig. 2. Double gated spectrum on the SD energy transitions (except the 617 keV transition) combined with one gate on the 2188 keV, panel (a), and combined with one gate on the 2585 keV, panel (b).

therefore establish that the 2188 keV line is in coincidence with the 2585 keV line and both in coincidence with the SD band. The ordering of the 2188 and 2585 keV transitions has been deduced looking at the intensity of the 371 keV ($45/2^+$ to $41/2^+$) transition, obtained in combined coincidences with the SD transitions and the 2188 respectively 2585 keV transition. The intensity loss indicates that the 2188 keV transition decays at least by another branch in parallel with the 2585 keV which bypasses the 371 keV ND transition. Combined coincidences procedures were used alternately with the 664 and the 617 keV γ -ray and the remaining SD transitions. Based on the coincidence relationships of these obtained spectra, we could establish that the 1995–2001 keV and 2188 keV transitions decay out of the SD state just below the 664 keV γ -ray transition. With all the coincidence relationships, the decay pathway of the SD states below the 664 keV γ -ray transition into the ND states $45/2^+$ have been assigned. High energy lines 2778(2) keV and 2785(2) keV have also been found in coincidence with the SD band transitions in the 20 MeV range spectrum. However due to their low intensity (together 0.5(3)% of the SD band intensity), they were placed in the level scheme based only on energy difference arguments and are displayed as dashed lines in the SD decay-out level scheme proposed Fig. 3.

Information on the multipolarity of linking transitions was obtained by measuring angle-dependent intensity $I_\gamma(\theta)$ ratios using a method derived from directional correlations of decays from oriented nuclear states (DCO ratio). An asymmetry ratio is defined as

$$R_{\text{asym}} = \frac{I_\gamma(\text{coaxial})}{I_\gamma(\text{clover})} = \frac{I_\gamma(\text{forward} + \text{backward})}{I_\gamma(90^\circ)},$$

where I_γ is the efficiency corrected intensity of the γ -ray detected with the coaxial and the clover detectors, respectively. For comparison R_{asym} values of known stretched E1 (or M1) transitions of the ND level scheme and E2 transition from the SD yrast band of the ^{149}Gd nucleus have also been extracted: the mean values obtained are 1.2(2) and 2.0(2) for E1 (or M1) and E2 multipolarities respectively. The values measured for the 2188 keV transition and the 1995–2001 keV doublet are respectively 1.2(2) and

Fig. 3. The decay-out level scheme for the SD yrast band in ^{149}Gd . The percentages of the SD band intensity feeding the ND states are indicated together with the percentages of the intensities leaking out the SD band.

1.3(2). The 1802 keV ND line has also a similar asymmetry 1.1(2) value. This indicates a dipole character for these transitions. Without a linear polarization, it is not possible to distinguish between a magnetic or electric radiation. Based on similarities between the SD band decay and the primary γ -decay from resonant thermal neutron capture [5] and also on E1–M1 probability ratios, we have assumed an E1 character for those transitions. For lower intensity lines, in particular the 2585 keV transition, it has not been possible to extract a valid DCO ratio, and we therefore make assumptions concerning the multipolarity of these transitions. The yrast SD band has been assigned negative parity [22]. This transition could thus be of M1 or of E2 nature. If we take the M1 or the E2 hypothesis, the last observed SD state would have a spin of $45/2\hbar$ or $47/2\hbar$ respec-

tively. Theoretical calculations predict a spin of $47/2 \hbar$ modulo $2 \hbar$ for the last SD state (see for instance Ref. [28]). A difference of one unit of spin between the experimental spin and the calculated one is unlikely. We therefore adopt a spin assignment of $47/2^-$ for the last SD state which implies an E2 multipolarity for the 2585 keV transition. This fixes the average decay-out spin of the band to $50.7/2 \hbar$. With the measured average entry spin value of $45.6/2 \hbar$ on ND states, the relative spin difference between the SD decay-out region and the feeding into the ND states is then $\sim 2.5 \hbar$.

The measured quadrupole moment of the SD states $51/2^-$ has a lower value of 8 eb compared to 15 eb for the other SD states in the band [29]. From the lifetime value and the intensities of the decays from this state (in and out of the SD band), one can deduce the partial probability λ_{out} for decay-out of the band. If the decay-out process is assumed to be mostly statistical, emitting E1 transitions with a probability $\lambda_{\text{ND}}^{\text{E1}}$, then following the method outlined in Ref. [30], the squared normal mixing amplitude $\alpha_{\text{ND}}^2 = \lambda_{\text{out}} / \lambda_{\text{ND}}^{\text{E1}}$ between the ND and SD wave functions can be extracted. Assuming for the E1 statistical γ -ray transitions that the dipole strength associated with each state follows a Lorentzian distribution [31] with shape parameters similar to the GDR built on the ground state [32], and for simplicity a Fermi gas model for the level density $\rho_n = 1/D_n$ with a level density parameter $a = A/a_0 = 11.4 \text{ MeV}^{-1}$ calculated according to Ref. [33], the statistical E_1 transition probability $\lambda_{\text{ND}}^{\text{E1}} = 389 \text{ ps}^{-1}$ has been estimated. This results in a $\alpha_{\text{ND}}^2 = 2.4\%$ value for the $51/2^-$ SD state. This mixing value represents a lower limit. If instead of $a_0 = 8$ for the level density, then its value increases to $\alpha_{\text{ND}}^2 = 7.4\%$.

Following the discussion about the nearest neighbor ND level mixing approach [30], an upper limit for the mean interaction strength $\langle v^2 \rangle$ between SD and ND states can be obtained:

$$\langle v^2 \rangle_{\text{max}} = \frac{1}{8} D_{\text{ND}}^2 \alpha_{\text{ND}}^2,$$

where D_{ND} is the average spacing between two states in the ND well at the excitation energy above the yrast line corresponding to the excitation energy of the SD state (4.2 MeV at spin $51/2 \hbar$ in the ^{149}Gd (1) case). Only slightly sensitive to the level

density parameter used in the calculation, the square root ratio

$$\sqrt{\frac{\langle v^2 \rangle_{\text{max}}}{D_n^2}} \approx \sqrt{\frac{\alpha_{\text{ND}}^2}{8}},$$

which compares the maximum average interaction $\sqrt{\langle v^2 \rangle_{\text{max}}}$ and the average level spacing, is small, moving from 0.05 for $a_0 = 13$ up to 0.10 for $a_0 = 8$. This low value may indicate, like in the $A \approx 190$ mass region, that only mixing with the closest ND levels accounts for the admixture of ND wave function in the total wave function [34].

The lowest observed state for the ^{149}Gd yrast SD band corresponds to a spin of $47/2^-$ and an excitation energy of 4.121(1) MeV with respect to the $47/2^-$ ND state, i.e. to an absolute excitation energy of 10.625(2) MeV above the $7/2^-$ ground state. The 4.121 MeV value is comparable to the relative excitation energy observed for ^{192}Hg and ^{194}Hg , 4.3 MeV and 4.2 MeV (at spin 10^+), respectively, but its value is much higher than for ^{194}Pb and for the odd-even nucleus ^{193}Pb , respectively 2.7 MeV (at spin 6^+) and 2.2 MeV (at spin $27/2^-$) [15]. Theoretical calculations using the Hartree-Fock method with a Skyrme force (SkM*) predict a 5 MeV excitation energy for the last $47/2^-$ SD states above the yrast ND line of ^{149}Gd [35]. This theoretical value is slightly too high compared to the experimental one deduced in this work, a situation similar to the one in the $A \sim 190$ mass region.

One can wonder why, a one-step decay has not been found in the ^{149}Gd nucleus instead of a two step process. In the SD yrast coincident spectrum, only few discrete transitions are observed in the 2–3 MeV γ -energy range and the high energy part above 3 MeV is bare of resolved lines. This situation is similar to the ^{192}Hg SD nucleus where no single step decay and only a few primary lines (below 3.4 MeV) are observed, as opposed to the ^{194}Hg nucleus which might be considered a “lucky” case [36].

In summary, we have measured the excitation energy for the yrast SD band in ^{149}Gd . This is the first case for which the excitation energy has been measured for a SD band in the $A \sim 150$ mass region. Suggestions about the most probable spin assignment has also been made. The admixture parameter between the SD and ND wave functions deduced in

this work has a small value which indicates that the SD states mix only with the nearest ND states.

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