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Triaxial superdeformed bands in ^{164}Lu and enhanced E1 decay-out strength

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Abstract

In a search for exotic structures in odd-odd ^{164}Lu, performed as one of the first Euroball experiments eight new, presumably triaxial, superdeformed bands were found. For the first time, evidence is presented for superdeformation in an odd-odd Lu isotope for which theory predicts large triaxiality. The data are compared to expectations from calculations with the code ''Ultimate Cranker''. Two of the bands are connected to normal-deformed structures and the E1 strength of the decay-out appears to be enhanced over single particle expectations, possibly due to octupole correlations. © 1999 Elsevier Science B.V. All rights reserved.

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Nuclei with N ∼ 94 and Z ∼ 71 constitute a new region of exotic shapes, coexisting with normal prolate deformation [1–4]. They provide a unique possibility of studying superdeformed (SD) shapes with a pronounced triaxiality. Two such cases have recently been found in ^{163,165}Lu [3,4]. Large Q_t values, corresponding to $\varepsilon_2 \sim 0.4$ (SD) with $\gamma \sim +18°$, were derived for the triaxial SD band in ^{163}Lu [4] from

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both Recoil Distance and Doppler Shift Attenuation Method measurements. This band was interpreted as most likely corresponding to the $\pi i_{13/2}[660]1/2^+$ configuration. In a later measurement, a band with transition energies, identical within 1-3 keV to those of the SD band in ^{163}Lu, was found in ^{165}Lu [3] and, based on the similarity, was also interpreted as a $\pi i_{13/2}[660]1/2^+$ band. Calculations [3] with the Ultimate Cranker (UC) code have revealed that large deformation minima are actually expected for all elements of the symmetry group (π,α) in ^{163,165}Lu. That is, the large deformation is due not only to the deformation-driving effect of the $\pi i_{13/2}$ intruder orbital, but also is the result of a re-arrangement of the core. The neutron number N $\sim$ 94 is crucial, as a gap in single particle energy appears at large values of γ ($\sim \pm 20°$). Therefore, large triaxial deformations are expected as a general phenomenon.

In an odd-odd nucleus, the possibility exists to exploit the various combinations of proton and neutron orbitals which are expected to sample the triaxial minima differently. Calculations [1] of the potential energy surfaces for the lowest expected configurations in ^{164}Lu with positive and negative parity are shown in Fig. 1. In addition to the minima at normal deformation the calculations show local minima with large deformation and $\gamma \sim \pm 20°$.

A search for triaxial SD structures in ^{164}Lu was performed as one of the first Euroball experiments using the reaction ^{139}La(^{29}Si,4n) with thin self-supporting targets at a beam energy of 145 MeV. The ^{29}Si beam was provided by the Legnaro XTU tandem accelerator and the γ-rays were detected with the Euroball array consisting, at the time of the experiment, of 13 clusters, 25 clovers and 28 single element tapered detectors. Altogether, $\sim 3.8 \cdot 10^9$ events requiring six or more coincident Ge signals before Compton suppression were collected. After presorting, $\sim 2.3 \cdot 10^9$ clean, three- or higher-fold events were sorted into gated matrices for DCO analysis, cubes and a 4D-hypercube.

The present Euroball data-set contains rotational bands in ^{163,164}Lu as the main exit channels, in addition to several Yb and Tm isotopes. The analysis has provided a major extension of the known [6,7] normal-deformed (ND) level scheme in addition to eight new, presumably triaxial SD, bands in ^{164}Lu. See Fig. 2. The SD bands have dynamic moments of inertia similar to those found in ^{163,165}Lu [3,4], and they may belong to both of the calculated minima with $\gamma \sim \pm 20°$. Two of the strongest populated bands, SD1 and SD3, have been connected to known [6,7], ND bands in ^{164}Lu. The band SD1, decays to several states of both positive and negative parity, which suggests the spin and parity assignments shown in Fig. 1. These assignments imply that the strongest transition of 1128 keV is of stretched dipole character, which agrees with the measured DCO ratio of 1.0(2). The theoretical values for the Euroball geometry using summed gating on all detector angles [8] are about 0.8 and 1.4 for stretched dipole and quadrupole transitions, respectively. A double gated γ-ray spectrum corresponding to this band is shown in Fig. 3a. For band SD3, the single decay of 1532 keV to the yrast ND 14^- state with a DCO ratio of 0.9(2) is assigned as a stretched dipole transition, which determines the spin of band SD3. Since a pure M1 transition of such high energy is very unlikely, we assume it is of E1 character, and SD3 is therefore assigned positive parity.

As can be seen from Fig. 3b, the new bands in ^{164}Lu have quite similar dynamic moments of inertia, $\mathscr{J}^{(2)}$, at low frequency, and a small variation in the moderate increase in $\mathscr{J}^{(2)}$ with increasing frequency. From the γ-ray energies, bands SD1 and SD2, and bands SD3 and SD4 could be signature partners, at least in a limited frequency range.

The excitation energies of the remaining SD bands, (SD2, and SD4-SD8), could not be established as the transitions linking them to the rest of the level scheme could not be found. In general, the relative population of states after heavy-ion induced fusion-evaporation reactions is strongly related to the excitation energy above the yrast line. In order to estimate the relative excitation energies of these bands, which all have dynamic moments of inertia $\mathscr{J}^{(2)}$ similar to SD1 and SD3, we have assumed that they also have similar alignments, i. Thereby the spin values $I \sim \mathscr{J}^{(2)}\omega + i$ can be estimated. A comparison of the γ-ray intensities at $I \sim 30\hbar$, and the assumption of the same dependence of population

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[1] Extensive use of the program ''NUSMA'' has been applied in the analysis of the UC calculations [5]

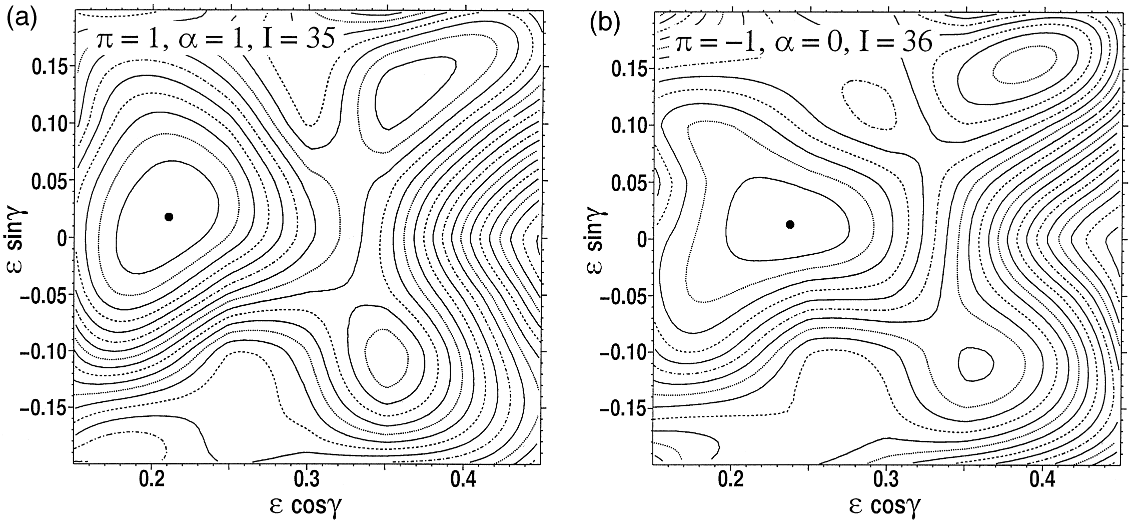

Fig. 1. Calculated (UC) potential energy surfaces at I = 35 and 36 for the lowest configuration with positive (left) and negative (right) parity in ^{164}Lu.

intensity on excitation energy as found for the ND band structures [10], for which the spin and excitation energy are known, can then be used to provide an estimate of the excitation energies of these bands. This assumption agrees with the measured relative intensities for bands SD1 and SD3. The results of this estimate are far from accurate, but give a rough idea of the relative placement of the bands. The population of band SD2 suggests that it is placed around 100 keV above SD1. A change in spin value of $1\hbar$ in the assumed spins of band SD2 would change the slope by 300 keV in the spin range $I = 20$–$40\ \hbar$. As can be seen from Fig. 4a, such a change would cause SD2 to have an unrealistic slope relative to SD1 and SD3 keeping the relative excitation at $I \sim 30\hbar$. For the bands SD4-SD8, the excitation energies are most likely within 200 keV above SD3. From this information it appears that all the new bands are found within an energy range of ~ 400 keV at $I\ \sim 30\hbar$.

The new bands may belong to both of the calculated minima with $\gamma \sim \pm 20°$, which have close to identical shapes but rotation around the smallest or intermediate axis. The calculated kinematic and dynamic moments of inertia, $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$, do not show a large difference between bands of positive and negative γ values, whereas an appreciable difference is found in the transition quadrupole moments for the two minima. At present, without measured transition quadrupole moments, only indirect evidence for the sign of γ can be given.

Experimental and calculated excitation energies are compared in Fig. 4. According to the calculation, the lowest excitation energies of the triaxial SD bands are expected for a deformation with positive γ values. The bands with negative γ deformation lie about 0.5 MeV higher than those for positive γ. The SD configuration with $(\pi,\alpha) = (-,0)$ corresponds to the lowest excitation with $\gamma \sim +20°$ which is in agreement with the parity and spin determined for the lowest-energy SD1 band. The lowest positive-parity SD band is expected about ~ 100 keV higher in energy. Bands SD1 and SD3 are therefore in qualitative agreement with the lowest calculated bands for $\gamma \sim +20°$ although the experimental alignments apparently are larger than calculated for the triaxial SD bands. This could be caused by a strong deformation dependence of the aligning $\nu i_{13/2}$ configurations in the calculations. In ^{163,165}Lu the identical triaxial SD bands were assigned to the lowest $\pi i_{13/2}$ orbital with a gradual alignment of the first pair (AB) of $i_{13/2}$ quasineutrons. In ^{164}Lu the lowest calculated configuration is obtained by coupling the $i_{13/2}$ quasiproton to the lowest negative parity $(h_{9/2})$ quasineutron. This is supported by an alignment increase of $\sim 2\hbar$ relative to the bands in ^{163,165}Lu,

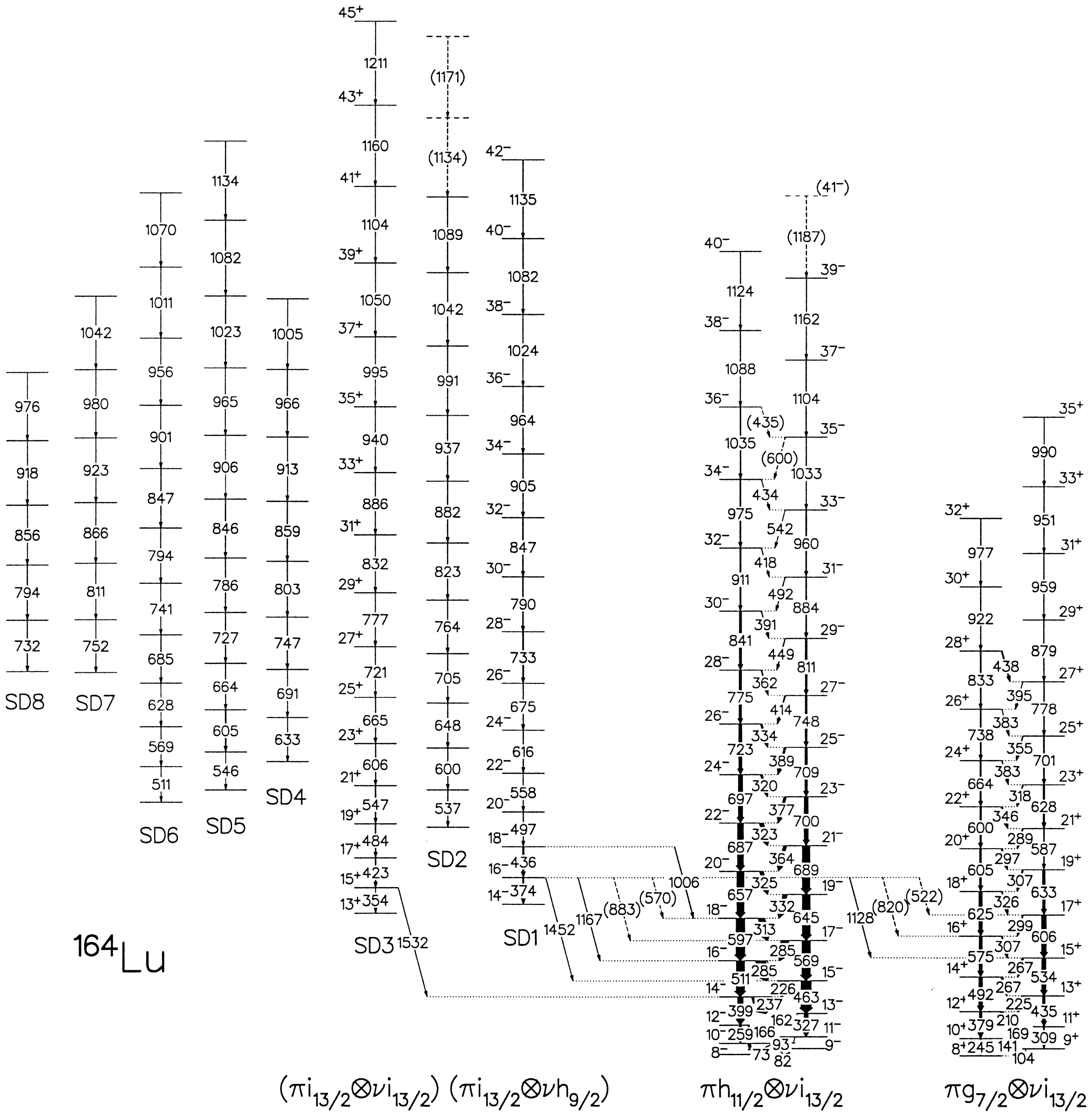

Fig. 2. Partial level scheme showing the new triaxial SD bands in ^{164}Lu. Only the lowest-energy positive and negative parity ND bands to which the new triaxial SD bands decay are included. For the 'hanging' bands the excitation energy is estimated from their intensities. See text.

which agrees with the expected alignment for the $h_{9/2}$ quasineutron in the observed frequency range. For SD3 with $(\pi,\alpha)=(+,1)$, the alignment increase relative to the SD bands in ^{163,165}Lu is $\sim 1.5\hbar$. This band could possibly be assigned to the configuration $\pi i_{13/2}\otimes\nu i_{13/2}$ with a gradual second (BC) $i_{13/2}$ quasineutron alignment. It should be noted that the configurations, $\pi i_{13/2}\otimes\nu h_{9/2}$ and $\pi i_{13/2}\otimes\nu i_{13/2}$, assigned to bands SD1 and SD3, both, in addition to the triaxial SD minima, have a normal deformed

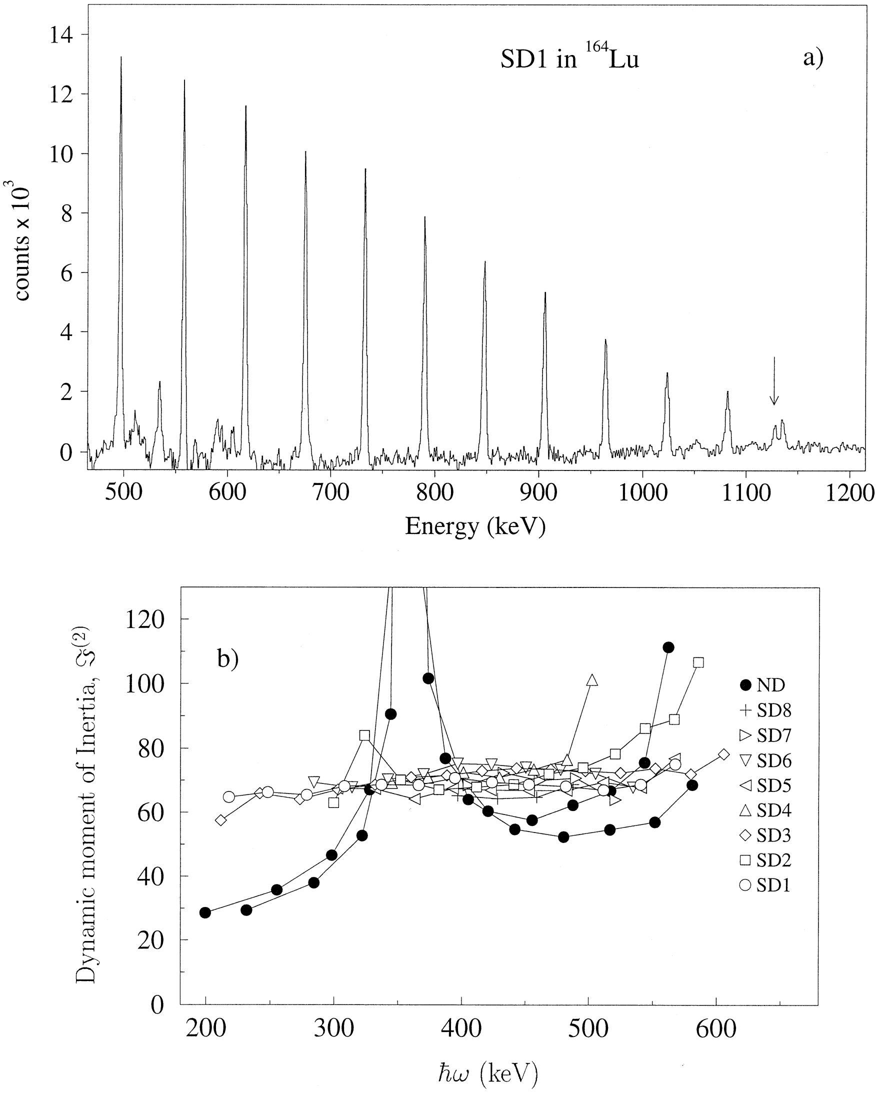

Fig. 3. (a) Sum of double gates on transitions in the triaxial SD band 1 connected to ND states in ^{164}Lu. The linking transition of 1128 keV is marked by an arrow. (b) Dynamic moments of inertia for the yrast ND band (full symbols) and all the new SD bands (open symbols) in ^{164}Lu.

minimum close to the minima at $\varepsilon_2 \sim 0.22$ shown in Fig. 1, but at considerably higher excitation energy.

With a detailed and complex decay-out of SD1 and a single decay of SD3, it is interesting to compare the E1 strength to statistical expectations. For SD1 the strongest E1 decay-out branch is the $I \rightarrow I - 1$ transition of 1128 keV. The 820 keV $I \rightarrow I$ and 522 keV $I \rightarrow I + 1$ E1 transitions are ≥ 5 and ≥ 10 times weaker, respectively, which may be partly explained by the E_γ^3 dependence. (See Fig. 3a) The strength of the E1 decay is estimated (assuming $Q_t(\mathrm{SD}) = 11\mathrm{b}$) from the out-of-band to in-band branching to be $B(E1) \sim 0.8 \cdot 10^{-4} e^2 \mathrm{fm}^2$ ($= 0.4 \cdot 10^{-4}$WU) for both bands, which is around 400 times faster than the E1-decay found for the (axially symmetric) SD to ND states in ^{194}Hg [12], and only ~ 6 times slower than octupole-enhanced E1 transitions between some of the ND bands in the same nucleus,

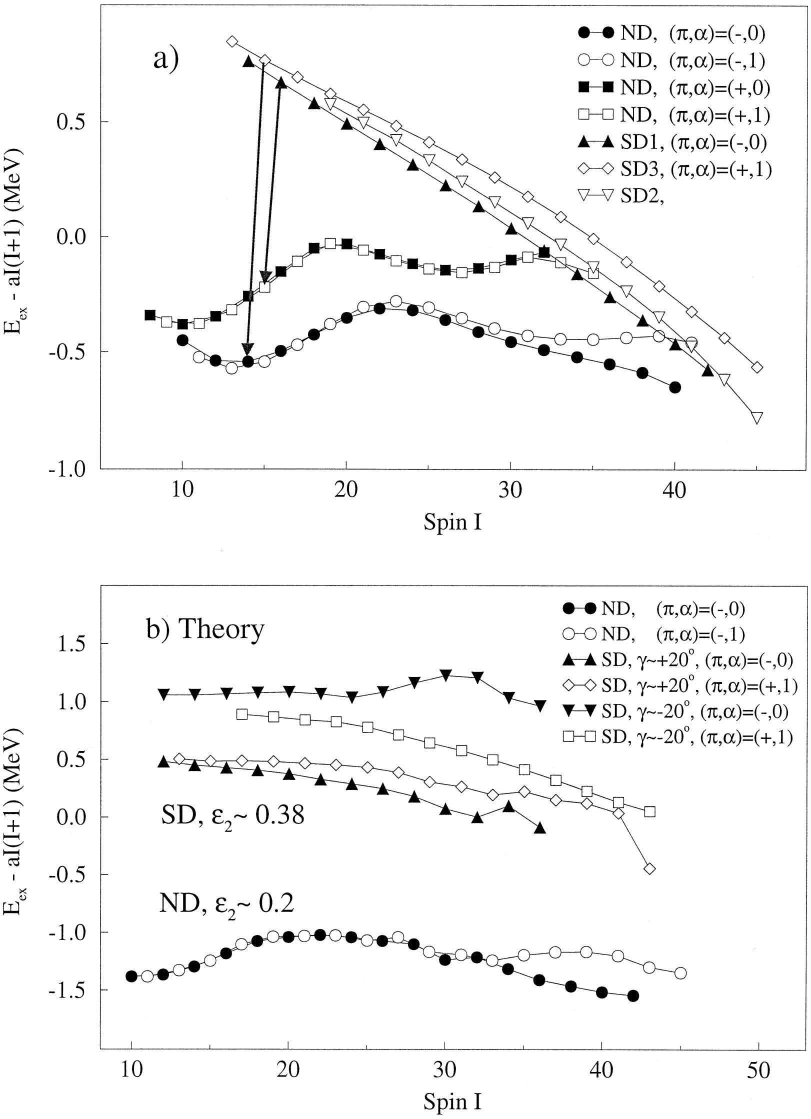

Fig. 4. (a) Excitation energy versus spin for three SD and selected ND bands in ^{164}Lu. The strongest E1 decay branches from SD to ND are indicated. The spin and excitation energy of SD2 are rough estimates based on alignments and population intensities. See text. (b) Calculated (UC) excitation energy for bands in ^{164}Lu corresponding to the ND and the triaxial SD local minima with $\gamma = \pm \sim 20°$ shown in Fig. 1.

^{164}Lu [10]. The E1 decay from SD1 is associated mainly with an $h_{9/2}$ SD to $i_{13/2}$ ND quasineutron transition, whereas the E1-decay from SD3 is associated with an $i_{13/2}$ SD to $h_{11/2}$ ND quasiproton transition. Octupole enhancement [11] is found between ND bands of similar structure in odd-N and odd-Z rare earth nuclei and may therefore be present in both of these different E1 transitions. The measured γ-ray branching ratio for the $16^- \rightarrow 15^-$, 1452 keV and $16^- \rightarrow 15^+$, 1128 keV transitions is ~ 0.3. From a similar estimate, (assuming negligible M1 contribution) the values of B(E2,SD $\rightarrow$ ND) are 10^3–10^4 times reduced compared to the SD in-band B(E2) values. This is quite different from the decay of the triaxial SD band in ^{163}Lu. In that nucleus the decay to the normal deformed structures takes place through an isolated mixing at $I = 21/2$ with an interaction strength of around 20 keV of the SD with the [411]$1/2^+$ configuration [9].

The measured difference in energy between the bands SD3 and SD1 in ^{164}Lu is ~ 200 keV, in agreement with the calculated energy difference for $\gamma \sim +20°$ at I $\sim 30\hbar$. In contrast, the measured excitation of the bands SD1 and SD3 relative to the ND yrast band shows that the triaxial SD minima in ^{164}Lu appear 0.5–1 MeV lower in excitation energy than calculated for $\gamma \sim +20°$, as shown in Fig. 4. For the $\pi i_{13/2}$ SD band in ^{163}Lu the calculated excitation energy relative to the yrast ND $\pi h_{11/2}$ band is also considerably higher than measured [9]. It should be noted that the UC calculations are based on generally accepted 'best' Nilsson parameters [13]. However, the most important deformation driving single-particle levels (such as $\pi i_{13/2}$) were not included in the fitting of the Nilsson parameters for nuclei in the deformed rare earth region. The position of those levels may therefore be incorrect, resulting in systematic deviations in the calculated excitation energies for rotational bands in the SD minimum. Alternatively, a more speculative explanation could possibly be found in a different rotational scheme. Inspecting Fig. 1, it is clear that the two SD minima are very similar in shape. The real minimum with the same shape might be found at a lower excitation energy rotating around an axis tilted away from the principal axes.

In summary, the present letter reports on eight, new presumably triaxial, SD bands in ^{164}Lu. The structure of the two lowest bands for which spin and parity have been determined correspond most likely to shapes with $\gamma \sim +20°$. Configurations have been assigned based on UC calculations and alignments. From the measured E1 and E2 decay out of the SD bands, relative to the in-band decay, the E1 decay strength from SD to ND states is found to be strongly enhanced over expectations from single particle estimates. Excitation energies of the new bands are lower than obtained from UC calculations which might imply problems with single particle intruder levels in the cranking calculations, or could be an indication for tilted rotation.

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