Octupole Vibration in Superdeformed $^{152}_{66}\mathrm{Dy}_{86}$

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Nine transitions of dipole character have been identified linking an excited superdeformed (SD) band in ^{152}Dy to the yrast SD band. As a result, the excitation energy of the lowest level in the excited SD band has been measured to be 14 238 keV. This corresponds to a 1.3 MeV excitation above the SD ground state. The levels in this band have tentatively been determined to be of negative parity and odd spin. The measured properties are consistent with an interpretation in terms of a rotational band built on a collective octupole vibration.

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In a number of nuclei, strong deformed shell effects are responsible for an excited minimum associated with a large, prolate deformation (major to minor axis ratio of about 2:1). The physical properties of the excitations occurring in this superdeformed (SD) minimum continue to be a subject of much current interest. In SD nuclei of the mass $A \sim 150$ region, there is much evidence for single-particle behavior: observables such as the dynamic moments of inertia, $\Im^{(2)}$, the evolution of these moments with rotational frequency and the measured quadrupole moments, Q_0, can in most cases be understood in terms of the occupation of specific single-particle orbitals [1–5]. It was suggested in Ref. [3] that this behavior, which is observed not only in the lowest-energy SD rotational sequence (referred to hereafter as the yrast SD band) but also in most excited SD bands, is a consequence of "extreme shell-model" behavior in which the superdeformed nucleus is described by independent, noninteracting particles in a mean field. In contrast, most excited SD bands in even-even nuclei of the $A \sim 190$ region have been interpreted in terms of collective excitations. Specifically, evidence for octupole vibrations was first reported in the case of ^{190}Hg [6–10] where SD band 2 was found to deexcite into the yrast SD band via $E1$ transitions with rather low energy (~ 800 keV) and high transition rates. Similar evidence has also been reported for ^{194}Hg [11,12] and $^{196-198}$Pb [13–15]. The case of ^{194}Hg is particularly striking in that, in this nucleus, the absolute excitation energy as well as the quantum numbers of all the SD levels of interest have been established experimentally: this nucleus is one of only a handful where the transitions linking SD levels to states of normal deformation have been observed [11,16]. It is worth noting that octupole vibrational states built on the fission isomer in ^{240}Pu have recently been reported as well [17,18].

The SD minima in both the $A \sim 150$ and $A \sim 190$ regions are calculated [19–29] to be soft with respect to octupole deformation because of the presence of intruder orbitals ($j_{15/2}$ neutrons and $i_{13/2}$ protons) near the Fermi surface, where they are close to levels of opposite parity differing by three units ($\Delta l = 3$) in angular momentum ($g_{9/2}$ neutrons and $f_{7/2}$ protons). In fact, based on RPA calculations, Nakatsukasa *et al.* [30] proposed that most low excitations in $A \sim 190$ even-even SD nuclei are associated with octupole vibrations. Remarkably, while compelling evidence exists in the $A \sim 190$ region, the situation is quite different near $A \sim 150$. There is some evidence for interband transitions only for a single band in both ^{150}Gd and ^{152}Dy [31,32]. In the latter nucleus, the first one where superdeformation was reported [33], five excited bands are known [32], and it is one of the weakest of those (band 6) that has been proposed to decay into the yrast SD band; i.e., the transitions of the yrast SD band were observed to be in coincidence with the γ rays of SD band 6, but the transitions linking the two bands were not observed. Nevertheless, based on this fragmentary evidence an interpretation in terms of an octupole vibration was proposed in Ref. [34]. The other ^{152}Dy excited SD bands are understood in terms of proton and neutron excitations across the $Z = 66$ and $N = 86$ SD shell gaps [32,34].

In the present work, we report on the discovery of the transitions linking SD band 6 to the yrast SD band in ^{152}Dy and show that their properties are in line with an interpretation in terms of an octupole vibration. Furthermore, as in the ^{194}Hg case, the data also provide the absolute energy of the levels of band 6 with respect to the ^{152}Dy ground state, due to the fact that the yrast SD band has recently been linked to the states in the first well through a number of one-step linking transitions [35].

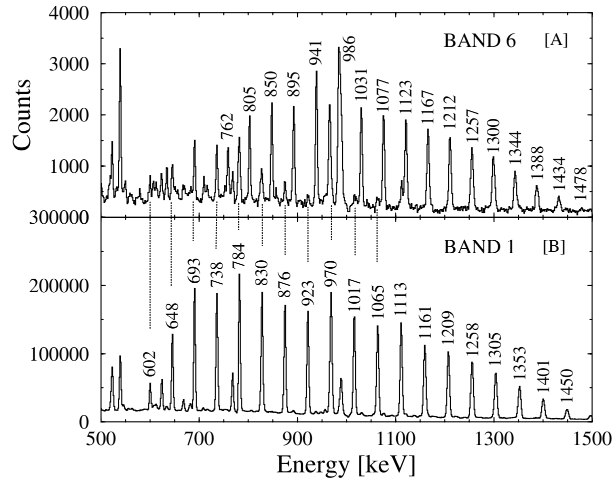

FIG. 1. (a) Spectrum from triple coincidence gates on lines in SD band 6 of ^{152}Dy. Clean combinations of the following SD transitions were used in the analysis: 762, 805, 850, 895, 941, 1031, 1077, 1123, 1167, 1212, 1257, 1300, 1344, and 1388 keV. (b) Spectrum obtained from setting pairwise gates on clean SD lines in band 1 of ^{152}Dy [35].

The large data set used to link the ^{152}Dy yrast SD band to the normal deformed levels [35] was also exploited to obtain the best possible spectrum of the very weakly populated SD band 6 ($\sim 5\%$ of the yrast SD band [32]) produced with the ^{108}Pd(^{48}Ca, $4n$) reaction using a 191 MeV (at midtarget) ^{48}Ca beam delivered by the 88 in. cyclotron facility at the Lawrence Berkeley National Laboratory. The target consisted of a stack of two 0.4 mg/cm^2 self-supporting ^{108}Pd foils. The Gammasphere array [36], with 100 Compton suppressed germanium detectors, measured the γ rays of interest. As described in Ref. [35], events associated with ^{152}Dy were selected by detecting with high efficiency the decay of a 86 ns, 17^+ yrast isomer (isomer tag). The result of summing triple coincidence spectra gated on clean SD lines in band 6 is shown in Fig. 1: the members of the yrast SD band (from 601 keV to $\sim$1113 keV) are clearly in coincidence with SD band 6, as was suggested in Ref. [32]. As a matter of fact, 53(8)% of the decay of band 6 proceeds through band 1.

Because of small differences in the moments of inertia of SD bands 1 and 6, any set of linking transitions between them will be characterized by specific energy spacings that depend on which levels are actually linked. Figure 2(a) presents the high energy part of the coincidence spectrum of Fig. 1(a). Nine weak transitions can be seen from 1645 to 1795 keV separated by one of the possible energy spacings ($\sim$ 20 keV). Coincidence gates were placed on the 1696 keV transition together with relevant lines in SD band 6, while also requiring the isomer tag: the resulting spectrum is given in Fig. 3. It clearly shows only transitions in SD band 6 with energies $E_\gamma \geq 850$ keV; i.e., the 805 and 762 keV γ rays of the

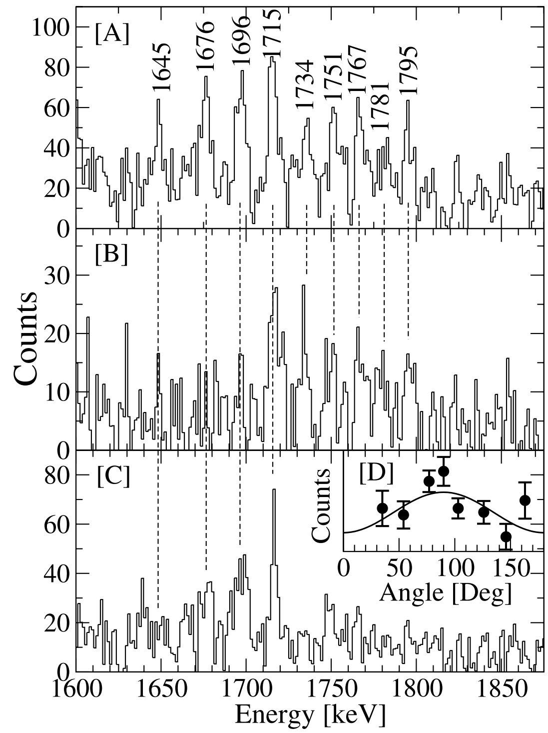

FIG. 2. (a) Summed coincidence spectrum obtained by placing gates on clean SD band 6 high energy transitions and SD band 1 low energy transitions. The nine transitions linking SD band 6 to band 1 are marked with their energies. (b) As (a), but requiring the 830 keV transition in band 1. (c) As (a), but requiring the 895 keV transition in band 6 and any SD band 1 transitions below 876 keV. (d) Angular distribution of the sum of the intensities in the 1676, 1696, and 1715 keV linking transitions vs the polar angle of the Gammasphere detectors.

sequence are clearly missing. Under the same coincidence conditions, only transitions of the yrast SD band with $E_\gamma \leq 784$ keV are observed. This unambiguously establishes the ordering proposed in the level scheme of Fig. 4. Additional supporting evidence is given in Fig. 2. In

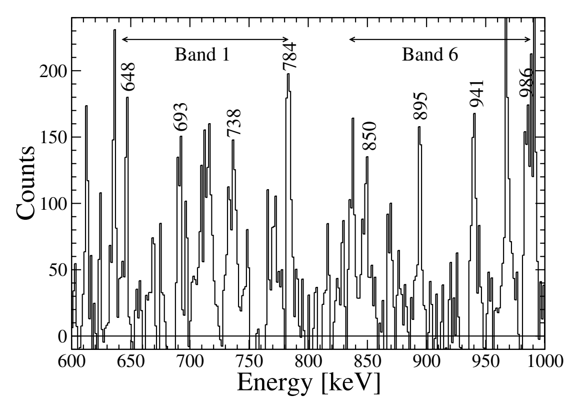

FIG. 3. Summed coincidence spectrum obtained by placing gates on the 1696 keV linking transition and clean lines in SD band 6.

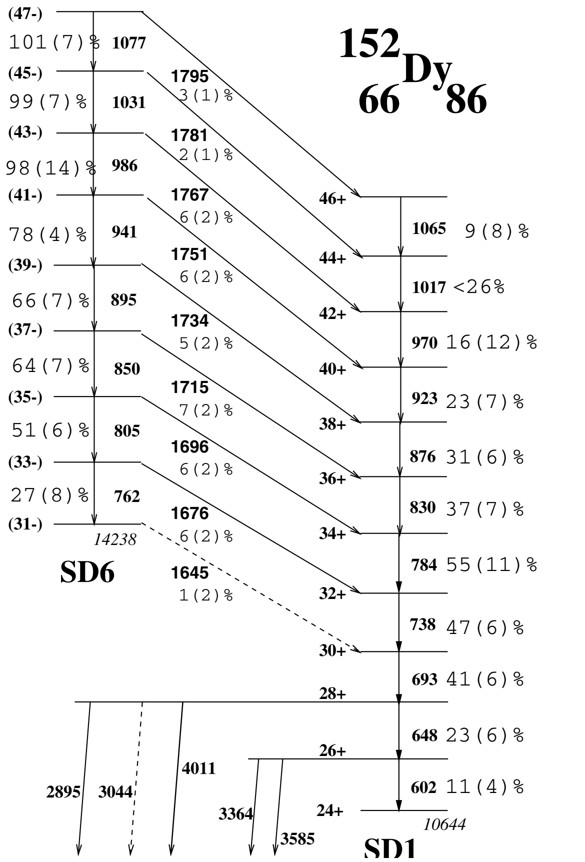

FIG. 4. Partial level scheme of ^{152}Dy showing the lowest part of SD band 6, the lowest part of the yrast SD band 1, and the transitions that link the yrast SD band 1 to the normal states [35]. The transition intensities, given in %, reflect the requirement of the isomer tag and are with respect to the strongest lines in SD band 6 (the 1031 and 1077 keV lines). The intensities shown for band 1 are from the feeding by band 6 only.

Fig. 2(b), the γ cascades are required to pass through SD band 6 *and* include the 830 keV band 1 transition: the decay-out transitions below 1715 keV are clearly absent. Conversely, in Fig. 2(c), the γ cascades are required to pass through the lower part of band 1 *and* include the 895 keV band 6 transition. Now the lower decay-out transitions are present, but the upper ones, from 1734 keV on, are missing. Thus, an excited SD band in the mass 150 region has for the first time been linked to an yrast SD band, which in turn is firmly connected to the normal states it decays into [35].

An angular distribution analysis of the three linking transitions at 1676, 1696, and 1715 keV finds negative A_2 coefficients in every case [$-0.9(4)$, $-0.3(3)$, and $-0.3(3)$, respectively]. If the yields of these three lines are added up and analyzed together, the combined A_2 coefficient is determined to be $-0.5(2)$; see Fig. 2(d). This value is consistent with those expected for stretched or antistretched $E1$ or $M1$ transitions (-0.24–-0.21), but inconsistent with transitions of $E2$ character or with $E1$ transitions without spin change (where large positive A_2 values of $\sim +0.34$ and $\sim +0.45$ are expected).

Assuming that SD band 6 has the same transition quadrupole moment of $17.5e$ b as the yrast SD band [37], it is possible to extract the partial half-lives of the interband transitions. Some of these are given in Table I, along with the transition strengths in Weisskopf units (W.u.) under the assumptions of $E1$ and $M1$ multipolarity. It is unlikely that $M1$ transitions between different quasiparticle configurations would occur with such short partial half-lives; the $B(M1)$ values in Table I are roughly 1 order of magnitude larger than those typically observed in deformed nuclei for interband γ rays [38]. On the other hand, while the $B(E1)$ values of Table I are stronger than typical $E1$ transitions in heavy nuclei [38], they are similar to those observed among actinide nuclei exhibiting strong octupole collectivity in the normally deformed well [39]. These $B(E1)$ values are also comparable to those reported recently for transitions in the SD wells of the $A \sim 190$ nuclei [9–11,14] that have been interpreted in terms of an octupole vibration. These considerations lead us to propose a negative parity for the levels of SD band 6, although it is recognized that, at this stage, this assignment remains tentative. Based on the measured angular distribution, two possible spin values could be assigned to these levels, making the nine interband γ rays either $J+1 \rightarrow J$ or $J-1 \rightarrow J$ transitions. While the former transitions could *a priori* be expected to dominate (because the larger energy is favored), it is sometimes the case for octupole vibrations that $J-1 \rightarrow J$ deexcitations gather more of the strength [40,41].

As stated above, the RPA calculations by Nakatsukasa *et al.* [34] interpret SD band 6 as an octupole excitation with signature $\alpha = 1$. At zero frequency, the band is characterized by $K = 0$, but K mixing is significant at the frequencies of interest here because of the Coriolis force. Experiment and calculations are compared in Fig. 5, where the Routhian of band 6 with respect to the yrast SD band is given as a function of the rotational frequency. The figure presents the lowest octupole excitation (dashed line), and the first $1p$-$1h$ configuration (solid line). The calculations reproduce the magnitude and evolution with frequency of the $\Im^{(2)}$ moment of

TABLE I. Branching ratios, partial half-lives, and Weisskopf estimates for most of the strongest linking transitions.

E_γ (keV)	Branching ratio	Partial half-life (fs)	$B(E1)$ (W.u. 10^{-4})	$B(M1)$ (W.u. 10^{-2})
1751	0.08(3)	130	4.9	4.6
1734	0.08(3)	169	3.9	3.7
1715	0.11(3)	152	4.5	4.2
1696	0.12(4)	185	3.8	3.6
1676	0.22(10)	331	2.2	2.1

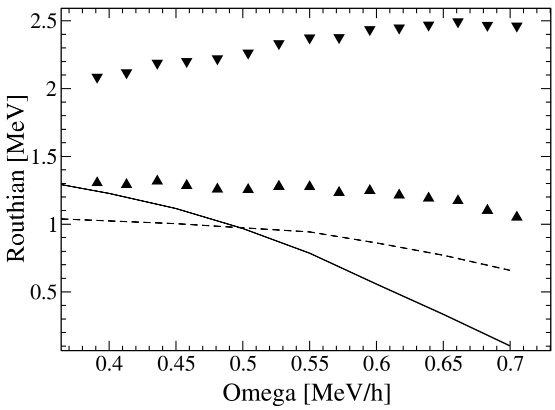

FIG. 5. Routhians of band 6 with respect to band 1 as a function of rotational frequency. The up (down) triangles are the data with the high (low) spin assignments to band 6. The lines are the result of the RPA calculations [34] for negative-parity states with signature $\alpha = 1$. The dashed line characterizes the lowest SD excitation associated with an octupole vibration. The solid line likewise shows the lowest $1p$–$1h$ excitation which, according to [34], corresponds to SD band 2.

inertia satisfactorily (see Fig. 3 in [34]). From Fig. 5, it is clear that the excitation energy and the evolution of the Routhian with frequency are well reproduced when the interband transitions are considered to be of the $J + 1 \rightarrow J$ type. This agreement argues for the spin assignment given in Fig. 4.

As stated above, SD bands 2–5 are interpreted in terms of single neutron or proton excitations across the $N = 86$ and $Z = 66$ shell gaps [32,34]. These bands are fed with intensities similar to that of band 6. Hence, their excitation energies with respect to the yrast SD band are likely of the same order as well in the frequency range where they are fed. Thus, the proton and neutron excitations of SD bands 2–5 are likely 1.6–1.8 MeV above the yrast SD band, and the present data also provide some measure of the SD shell gap at high frequencies. (Note that, as stated in Ref. [34], the octupole band is the lowest excitation in the SD well only at the low frequencies because of the evolution of its Routhian with frequency).

In summary, the decay of SD band 6 into the yrast SD band of ^{152}Dy has been confirmed and nine linking transitions have been identified. As a result, the excitation energy of the lowest level in band 6 has been measured to be 14 238 keV (or 1.3 MeV above the SD ground state). The states in this band have been tentatively determined to be of negative parity and odd spin. The measured properties are consistent with an interpretation in terms of a rotational band built on a collective octupole vibration.

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[1] T. Bengtsson, I. Ragnarsson, and S. Åberg, Phys. Lett. B **208**, 39 (1988).
[2] R. V. F. Janssens and T. L. Khoo, Annu. Rev. Nucl. Part. Sci. **41**, 321 (1991).
[3] W. Satula, J. Dobaczewski, J. Dudek, and W. Nazarewicz, Phys. Rev. Lett. **77**, 5182 (1996).
[4] L. B. Karlsson, I. Ragnarsson, and S. Åberg, Nucl. Phys. **A639**, 654 (1998).
[5] S. T. Clark *et al.*, Phys. Rev. Lett. **87**, 172503 (2001).
[6] B. Crowell *et al.*, Phys. Lett. B **333**, 320 (1994).
[7] B. Crowell *et al.*, Phys. Rev. C **51**, R1599 (1995).
[8] A. N. Wilson *et al.*, Phys. Rev. C **54**, 559 (1996).
[9] H. Amro *et al.*, Phys. Lett. B **413**, 15 (1997).
[10] A. Korichi *et al.*, Phys. Rev. Lett. **86**, 2746 (2001).
[11] G. Hackman *et al.*, Phys. Rev. Lett. **79**, 4100 (1997).
[12] P. Fallon *et al.*, Phys. Rev. C **55**, R999 (1997).
[13] S. Bouneau *et al.*, Z. Phys. A **358**, 179 (1997).
[14] D. Roßbach *et al.*, Phys. Lett. B **513**, 9 (2001).
[15] A. Prevost *et al.*, Eur. Phys. J. A **10**, 13 (2001).
[16] T. L. Khoo *et al.*, Phys. Rev. Lett. **76**, 1583 (1996).
[17] D. Pansegrau *et al.*, Phys. Lett. B **484**, 1 (2000).
[18] D. Gassmann *et al.*, Phys. Lett. B **497**, 181 (2001).
[19] J. Dudek, T. R. Werner, and Z. Szymanski, Phys. Lett. B **248**, 235 (1990).
[20] J. Skalski, Phys. Lett. B **274**, 1 (1992).
[21] J. Skalski *et al.*, Nucl. Phys. **A551**, 109 (1993).
[22] S. Mizutori, Y. R. Shimizu, and K. Matsuyanagi, Prog. Theor. Phys. **83**, 666 (1990).
[23] S. Mizutori, Y. R. Shimizu, and K. Matsuyanagi, Prog. Theor. Phys. **86**, 131 (1991).
[24] J. Höller and S. Åberg, Z. Phys. A **336**, 363 (1990).
[25] P. Bonche *et al.*, Phys. Rev. Lett. **66**, 876 (1991).
[26] X.-J. Li, J. Dudek, and P. Romain, Phys. Lett. B **271**, 281 (1991).
[27] T. Nakatsukasa, S. Mizutori, and K. Matsuyanagi, Prog. Theor. Phys. **87**, 607 (1992).
[28] R. Nazmitdinov and S. Åberg, Phys. Lett. B **289**, 238 (1992).
[29] J. Meyer *et al.*, Nucl. Phys. **A588**, 597 (1995).
[30] T. Nakatsukasa *et al.*, Phys. Rev. C **53**, 2213 (1996).
[31] P. Fallon *et al.*, Phys. Rev. Lett. **73**, 782 (1994).
[32] P. J. Dagnall *et al.*, Phys. Lett. B **335**, 313 (1994).
[33] P. J. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).
[34] T. Nakatsukasa, K. Matsuyanagi, S. Mizutori, and W. Nazarewicz, Phys. Lett. B **343**, 19 (1995).
[35] T. Lauritsen *et al.*, Phys. Rev. Lett. **88**, 042501 (2002).
[36] I.-Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[37] D. Nisius *et al.*, Phys. Lett. B **392**, 18 (1997).
[38] K. E. G. Loebner, Phys. Lett. **26B**, 369 (1968).
[39] I. Ahmad and P. A. Butler, Annu. Rev. Nucl. Part. Sci. **43**, 71 (1993).
[40] G. D. Dracoulis, C. Fahlander, and M. P. Fewell, Nucl. Phys. **A383**, 119 (1982).
[41] F. G. Kondev *et al.*, Phys. Rev. C **61**, 044323 (2000).