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Letter

Congruent band structures in ^{154}Gd: Configuration-dependent pairing, a double vacuum and lack of β-vibrations

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Abstract. We have used the $(\alpha, 2n)$ and $(\alpha, 4n)$ reactions and the AFRODITE γ-ray spectrometer to make a comprehensive study of the nucleus ^{154}Gd below $20\hbar$. While the first excited 0_2^+ state at 681 keV is usually considered to be the head of a $K^\pi = 0^+$ β-vibrational band, we propose that the data are best described as two separate vacuum states, the ground state and the 681 keV level, each with its own γ and octupole vibrations, pairing and alignments. The implications of this finding, for understanding the structure of transitional rare-earth nuclei, are discussed.

It has been a natural assumption since the early days of the collective model [1,2], that the first excited 0_2^+ state in deformed even-even nuclei is a β-vibration along the symmetry axis. Doubts about this assumption have been expressed [3–12] over the years and, more recently, a comprehensive review of the characteristic properties of such states was made by Garrett [13]. He found that the properties of most 0_2^+ states were not those of β-vibrations, *e.g.* in ^{166}Er [14], and he stressed the role pairing must play in the existence of the observed states.

The rare-earth nuclei with neutron numbers $N = 88$ and 90 have particularly low-lying first excited 0_2^+ levels with excitation energies between 600 and 800 keV, well within the pairing gap of about 2.1 MeV. It has usually been assumed that these 0_2^+ levels are collective β-vibrations based on the ground state $|\mathbf{0}_1^+\rangle$ vacuum in spite of the observation that they are very weakly excited in inelastic electron scattering [15,16], which is unusual for states with a collective nature. The $N = 88$ 0_2^+ levels are strongly populated in (p,t) two-neutron pick-up reactions [17–21] but are weakly populated in (t,p) two-neutron stripping reactions [22,23]. In contrast the $N = 90$ 0_2^+ levels are weakly populated in the (p,t) reactions and strongly populated in the (t,p) reactions. If one assumes that the 0_2^+ levels correspond to collective β-vibrations it remains unclear why there would be a substantial difference in the population patterns of these states. For nuclei with $N \geq 92$ most of the two-neutron transfer strength is concentrated in the ground states [17–22,24], which is expected [25] for superfluid nuclei with a ground-state vacuum $|\mathbf{0}_1^+\rangle$ well described by the BCS or Hartree-Fock-Bogolyubov theories [26].

One should keep in mind that for the $N = 88$ and 90 nuclei even the most sophisticated models [2,4,27] fail to predict a β-vibration below about 1.5 MeV, adding further doubts about the interpretation of these states as β-vibrations. A totally different approach has been adopted by the Yale group [28] in which the 0_2^+ levels become $s = 2$ boson excitations [29–31] at a critical point $X(5)$ symmetry.

An alternative interpretation to β-vibrations for 0_2^+ states was suggested for the actinide isotopes, where several 0_2^+ states that could not be described as a pairing or β-vibration had been observed by Maher *et al.* [7] in the (p,t) reaction. The suggestion of Griffin *et al.* [8] that these states could arise from the weakness of the oblate-prolate pairing force was taken up by van Rij and Kahana [9] and studied in detail by Ragnarsson and Broglia [12] in the framework of BCS and RPA. The core idea is that the oblate-prolate pairing force G_{op} is significantly weaker than the oblate-oblate G_{oo} and prolate-prolate G_{pp} pairing forces. Here oblate refers to single-particle Nilsson states that have a polar orbit (negative quadrupole moment, usually high-K) and prolate to equatorial orbitals

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(positive quadrupole moment, usually low-K). Central to this model [8] is the paucity of oblate Nilsson levels near the Fermi surface in the actinides (fig. 1 of ref. [11]). This decoupling of the polar and equatorial orbitals leads to the oblate pairing energy Δ_o, and hence the oblate quasiparticle energy, being reduced and permitting the existence of low-lying 0^+ states. Also the two-neutron transfer cross-section to these states is no longer reduced by the normal pairing effects. Reference [12] coined the term "Pairing Isomers" for such 0^+ levels. A similar situation occurs in the transitional nuclei with $N \sim 90$ at the start of the rare earths (fig. 1 of ref. [10]), where the oblate orbital nearest the Fermi surface is $[505]11/2^-$. This letter reports on new experimental data on low-spin states in ^{154}Gd, which indicate that the 0_2^+ level is not a β-phonon excitation, but rather has a two-particle–two-hole (2p-2h) configuration relative to the ground state.

We have made a comprehensive study of the transitional Gd nuclei using $(\alpha, x\mathrm{n})$ reactions and the iThemba LABS escape-suppressed γ-ray spectrometer array AFRODITE [32] consisting of 8 HPGe clover detectors in BGO shields. Using $4\,\mathrm{mg\,cm^{-2}}$ targets of ^{152}Sm and ^{154}Sm we obtained about 5.10^8 $\gamma\gamma$ coincidences each for the reactions $^{152}\mathrm{Sm}(\alpha, 2\mathrm{n})^{154}\mathrm{Gd}$ at 25 MeV and $^{154}\mathrm{Sm}(\alpha, 4\mathrm{n})^{154}\mathrm{Gd}$ at 45 MeV. DCO ratios and linear polarizations at 90° were measured to establish spins and parities. The level scheme we have constructed using *Radware* [33] builds on the comprehensive β-decay work of Kulp *et al.* [34] and the work of Morrison *et al.* [35], who observed levels up to spin 26 using the $^{150}\mathrm{Nd}(^9\mathrm{Be}, 5\mathrm{n})$ reaction. The decay scheme we obtain is very complex [36]. We report here partial results related to the study of the 0_2^+ level.

1) The previously known γ-band was extended from the 7^+ to the 17^+ level and is shown in the partial level scheme in fig. 1. A spectrum of γ-rays in coincidence with the $13^+_{\gamma 1}$ level to the 12^+_{gnd} transition is shown in fig. 2(a).
2) Levels up to spin 18^+ have been found that are connected to the sequence of rotational levels based on the 0_2^+ state at 681 keV. These are also shown in fig. 1 and coincidence γ-ray spectra are shown in fig. 2(b)–(d). We propose that these levels are candidates for members of a $K^\pi = 2^+$ γ-vibrational band based on the 0_2^+ state.
3) The continuity of the lowest-lying negative-parity band, the octupole vibrational band, has been established (as we reported in ref. [37]) from 1^- to 21^- for the odd spins and from 2^- to 16^- for the even spins (fig. 4(a)).
4) The $K^\pi = 4^+$ band at 1646 keV has been extended from the 9^+ to the 13^+ level. This band is seen strongly in proton stripping reactions [38], which confirms its two-proton nature. Therefore this band is undoubtedly mainly $\pi[413]5/2^+ \otimes \pi[411]3/2^+$ [38] and not a multiple γ-phonon excitation [39]. However, the $K^\pi = 4^+$, $\boldsymbol{n_\gamma = 0}$ bandhead energy is predicted [40] to be at $\boldsymbol{E_\gamma = 2(\hbar\omega_\gamma + \hbar^2/\mathscr{I})} = 1990\,\mathrm{keV}$. These two $K^\pi = 4^+$ bands could mix and decay strongly to the $K^\pi = 2^+$ γ-band. The lower band will be pushed down into the pairing gap by the mixing rather than by a g-boson component as suggested in [38].
5) A new band based on the $K^\pi = 7^-$ isomer was established up to spin 17^-. The isomer has a neutron configuration of $\nu[505]11/2^- \otimes \nu[651]3/2^+$ [41,42]. The levels of the octupole band, the proton $K^\pi = 4^+$ and the neutron $K^\pi = 7^-$ particle-hole bands are shown in fig. 4.
6) We do not observe the new levels at 1353 and 1498 keV proposed [21] as 0^+ levels from (p,t) data that is only statistically significant at the scattering angle of 5°. These levels have not previously been observed either in β-decay studies [34] or in the (n, γ) reaction [41, 42], nor are equivalent states found [43] in the lighter $N = 90$ nucleus ^{152}Sm. Neither do we find any higher-spin members of $K^\pi = 0^+$ rotational bands that might be based on these 0^+ states.
7) We find no candidates for a double β-vibration below 1.5 MeV.

In order to study the behaviour of the observed rotational bands we show in fig. 3 the excitation energies, minus a fixed rotational energy, for various structures in ^{154}Gd. Figure 3(a) shows that the γ-band tracks the ground-state band almost exactly showing no evidence of a sharp band crossing up to $\hbar\omega = 0.31\,\mathrm{MeV}$. Similarly the proton $K^\pi = 4^+$ and neutron $K^\pi = 7^-$ particle-hole bands track the ground-state band with no sign of a sharp band crossing. In contrast the known $K^\pi = 0_2^+$ band has an early alignment [44] at spin 12^+ where it is crossed by the $\nu(i_{13/2})^2$ aligned band based on $|\mathbf{0}_1^+\rangle$. The series of levels that decay predominantly to the $K^\pi = 0_2^+$ band, starting with the known [34] 2^+ and 3^+ levels at 1531 and 1661 keV respectively, are in parallel with the 0_2^+ band at lower spins and appear to track this band round the start of its back-bend, fig. 3(b). Such behaviour suggests that these levels might form a $K^\pi = 2^+$ γ-vibrational band based on the 0_2^+ level which is then crossed by the γ-vibration built on the aligned band.

A simple interpretation of the data is of two different vacua; one based on the ground state which we will denote by $|\mathbf{0}_1^+\rangle$, and the other based on the state at 681 keV which we will denote by $|\mathbf{0}_2^+\rangle$. In fig. 4(a), (b) we show the structures that we identify as belonging to the two distinct vacua in $^{154}\mathrm{Gd}_{90}$. In fig. 4(c), (d) we show the published [34,43,45–47] data for $^{152}\mathrm{Sm}_{90}$ presented in a similar manner. Each of these vacua has γ- and octupole vibrations built upon them in both ^{154}Gd and in ^{152}Sm. The congruence of $|\mathbf{0}_1^+\rangle$ and $|\mathbf{0}_2^+\rangle$ in both these $N = 90$ nuclei is remarkable.

It is of interest to discover any differences in the properties of these two vacua. Lifetime measurements [48] for the states of the rotational bands built on $|\mathbf{0}_1^+\rangle$ and $|\mathbf{0}_2^+\rangle$ show that $|\mathbf{0}_2^+\rangle$ is about 25% less deformed than $|\mathbf{0}_1^+\rangle$. The moments of inertia at the bottom of the bands are greater for $|\mathbf{0}_2^+\rangle$ than for $|\mathbf{0}_1^+\rangle$, suggesting that the rotation is more rigid and hence the pairing is reduced for $|\mathbf{0}_2^+\rangle$. Possible differences in the microscopic configurations of the $|\mathbf{0}_1^+\rangle$ and $|\mathbf{0}_2^+\rangle$ vacua should be reflected in the population

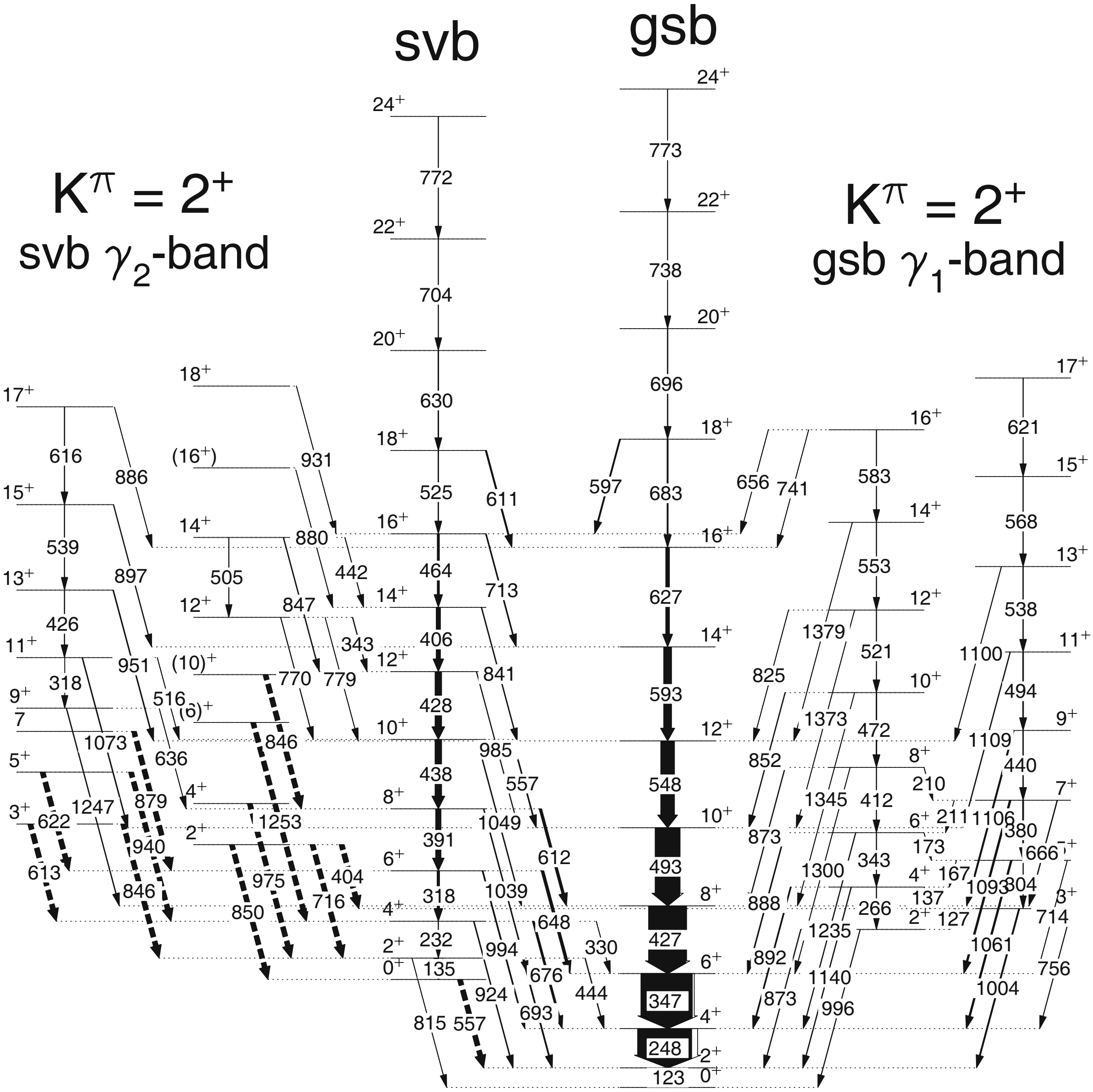

Fig. 1. Partial decay scheme for ^{154}Gd showing the observed positive-parity bands. The widths of the γ-rays are proportional to the intensities found in the $(\alpha, 4n)$ experiment. The γ-rays shown as dashed arrows were only observed in the $(\alpha, 2n)$ experiment. The ground-state band $|\mathbf{0}_1^+\rangle$ is labeled "gsb", the second vacuum band $|\mathbf{0}_2^+\rangle$ is labeled "svb". Each has its own $K^{\pi} = 2^+$ γ-band.

patterns of these states obtained in transfer reactions. The excited 0^+ levels are not as strongly populated in the (p,t) reaction as the ground 0^+ state, showing that some differences in the microscopic structure do exist. The 0_1^+ and 0_2^+ levels are both strongly populated in the (t,p) reaction [23] as is the 0_3^+ level at 1182 keV which has been identified as a "pairing isomer" by Kulp *et al.* [49], showing that these levels are well populated when two extra neutrons are added. The $|\mathbf{0}_1^+\rangle$ band and the γ-band are populated in one-proton stripping reactions [38] but there is almost no cross-section to the $|\mathbf{0}_2^+\rangle$ band. This indicates that the ground state of ^{153}Eu can be represented as a coupling of a core very similar to $|\mathbf{0}_1^+\rangle$, but different from $|\mathbf{0}_2^+\rangle$, and a proton in the $\pi[413]5/2^+$ orbital. Furthermore it makes it unlikely for $|\mathbf{0}_2^+\rangle$ to be a β-vibration, because in this case it remains unclear how to explain the observation that the collective γ-band is well populated, while the collective β-band is not. In the neutron pick-up (d,t) reaction [50] $|\mathbf{0}_2^+\rangle$ is again very weakly populated, 25 times less than $|\mathbf{0}_1^+\rangle$, again pointing at differences in the microscopic configurations of $|\mathbf{0}_1^+\rangle$ and $|\mathbf{0}_2^+\rangle$.

As the structures of the $N = 90$ nuclei ^{154}Gd and ^{152}Sm are very similar (see fig. 4), the proton pick-up [51] and neutron stripping [52] to ^{152}Sm should give relevant information on the structure of the equivalent states in ^{154}Gd. Again in these reactions $|\mathbf{0}_2^+\rangle$ is very weakly populated compared to $|\mathbf{0}_1^+\rangle$, reflecting important differences in their structure.

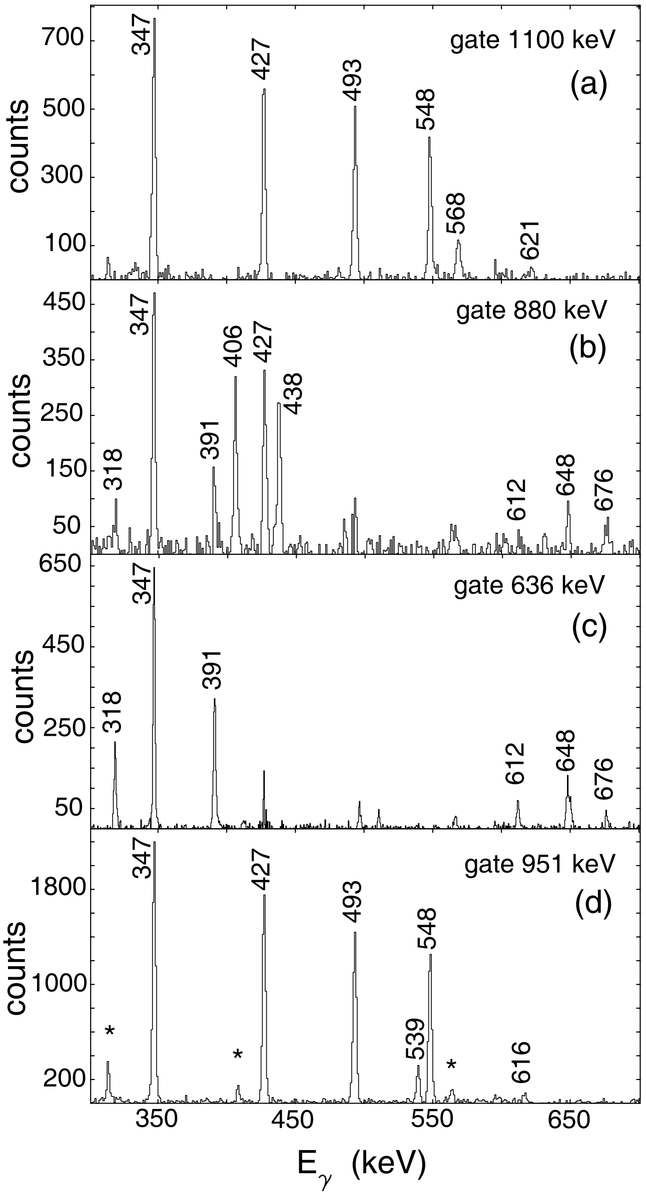

Fig. 2. Partial spectrum of γ-rays in coincidence with (a) the 1100 keV transition from the $13^+_{\gamma 1}$ level to the $12^+_{\rm gnd}$ level. (b) The 880 keV transition from the $(16^+_{\gamma 2})$ level to the $14^+_{\rm svb}$ level. (c) The 636 keV transition from the $9^+_{\gamma 2}$ level to the $8^+_{\rm svb}$ level. (d) The 951 keV transition from the $13^+_{\gamma 2}$ level to the $12^+_{\rm gsb}$ level. Contaminant peaks marked * are yrast γ-rays in ^{155}Gd from the $(\alpha, 3n)$ reaction in coincidence with a 952 keV γ-ray.

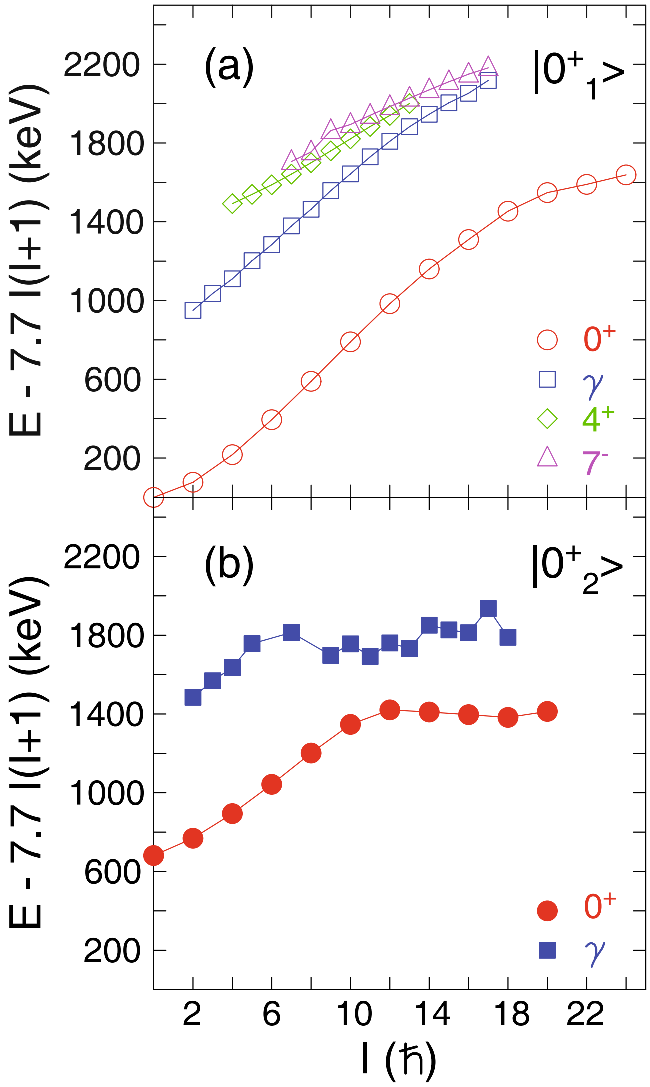

Fig. 3. Excitation energies, minus a rigid rotational reference, for bands in ^{154}Gd. (a) The ground-state band $|\mathbf{0}^+_1\rangle$, the $K^\pi = 2^+$ γ_1-band, $K^\pi = 4^+$ proton p-h band and the new $K^\pi = 7^-$ band based on the 68 ns isomer. (b) The second vacuum band $|\mathbf{0}^+_2\rangle$ and the proposed $K^\pi = 2^+$ γ_2-band based on $|\mathbf{0}^+_2\rangle$.

Thus, the results from the transfer reaction data suggest that $|\mathbf{0}^+_1\rangle$ and $|\mathbf{0}^+_2\rangle$ differ in their microscopic configuration. Furthermore they indicate that $|\mathbf{0}^+_2\rangle$ is not a single β-phonon excitation but has a 2p-2h neutron configuration relative to $|\mathbf{0}^+_1\rangle$.

In summary, the data available on both ^{154}Gd and ^{152}Sm suggest the following:

1) There are γ- and octupole vibrations built on both $|\mathbf{0}^+_1\rangle$ and $|\mathbf{0}^+_2\rangle$, consistent with these 0^+ states acting as two different vacua.
2) There is no sign of a $\beta\beta$ or double phonon $K^\pi = 0^+$ level and associated rotational band at approximately twice the excitation energy of $|\mathbf{0}^+_2\rangle$, indicating that $|\mathbf{0}^+_2\rangle$ is unlikely to be a β-vibration.
3) $|\mathbf{0}^+_2\rangle$ is well within the pairing gap, has an intrinsic configuration different from $|\mathbf{0}^+_1\rangle$ and reduced pairing. For the moments of inertia $\mathscr{I}_2 > \mathscr{I}_1$, whereas for the quadrupole moments $Q_2 < Q_1$ which is consistent with reduced pairing and hence more rigid rotation for $|\mathbf{0}^+_2\rangle$.
4) $|\mathbf{0}^+_2\rangle$ is not seen in one-nucleon stripping or pick-up reactions but is strong in two-neutron stripping. This implies that $|\mathbf{0}^+_2\rangle$ has a two–quasi-neutron configuration. In the following letter [53] it is shown that the odd neutron occupying the $[505]11/2^-$ orbital in ^{155}Gd, blocks the coupling of this orbital to $|\mathbf{0}^+_2\rangle$. This determines the nature of the quasi-neutron configuration

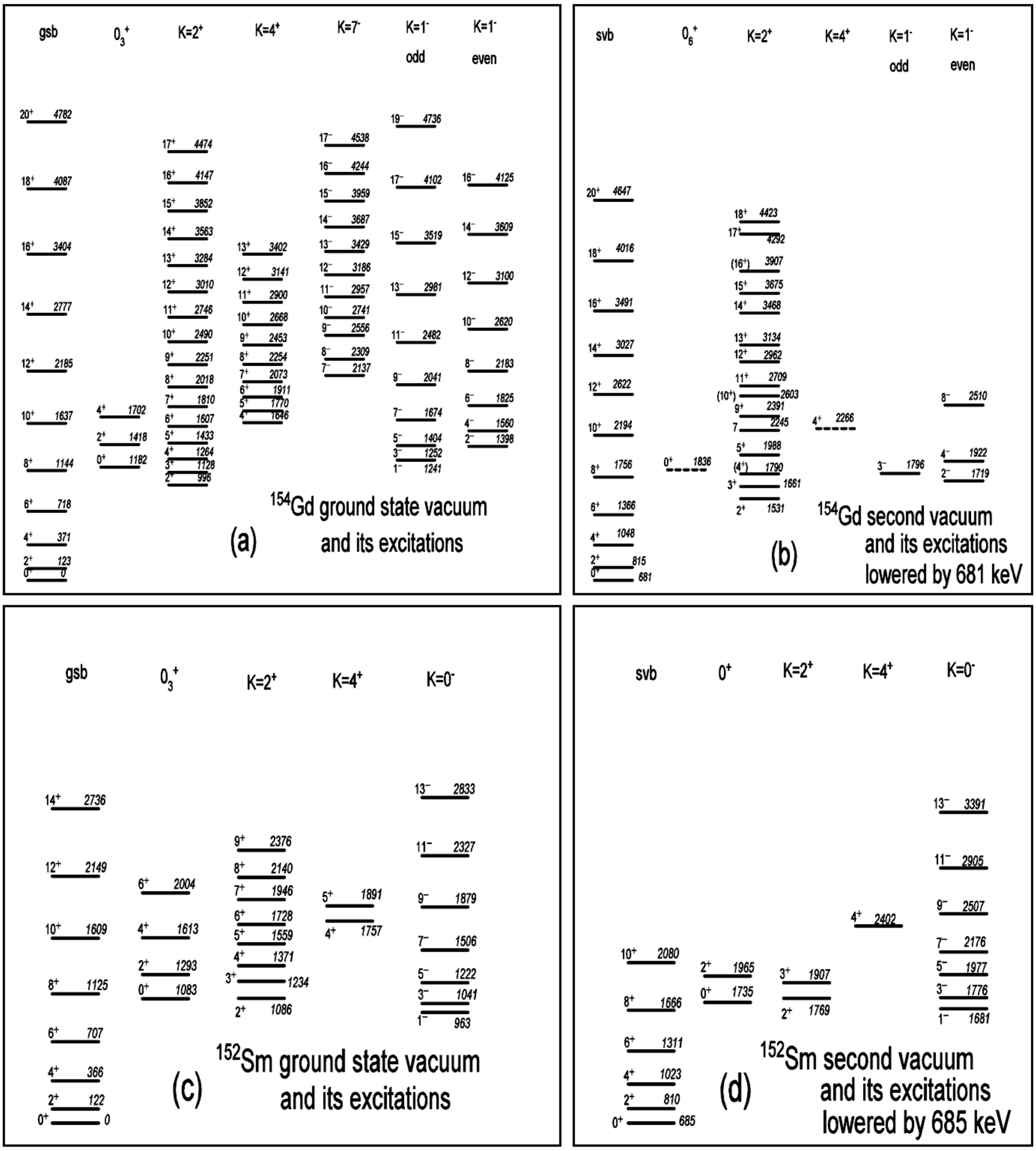

Fig. 4. Rotational bands in ^{154}Gd and ^{152}Sm, allocated to their respective vacua, to demonstrate their congruence. Bands allocated to: (a) the ground-state vacuum $|\mathbf{0}_1^+\rangle$ in ^{154}Gd (b) the second vacuum $|\mathbf{0}_2^+\rangle$ in ^{154}Gd. These states have been lowered by 681 keV so that 0_1^+ and 0_2^+ are at the same height in the figure. (c) and (d) the same for ^{152}Sm taken from refs. [34,43, 45–47].

of $|\mathbf{0}_2^+\rangle$ showing that it has a dominant component of two quasi-neutrons in the $[505]11/2^-$ orbital.

5) $|\mathbf{0}_2^+\rangle$ is a "pairing isomer", in the terms of [12], or we would prefer the term "second vacuum" as these states are in no way "isomeric" and they mimic all the properties of the ground state. Clearly, the two vacua mix at least weakly as the oblate-prolate pairing force G_{op} will not vanish exactly.

6) $|\mathbf{0}_3^+\rangle$ is probably a pairing isomer as well, as proposed by [49], being similar to the 0_3^+ state calculated for ^{234}U in [12].

These results and conclusions raise several more general comments and suggestions, for instance:

1) We still need to find convincing proof of the existence of β-vibrational bands [13].

2) It seems that transitional nuclei in general are not as soft to β-vibrations as it is assumed in [28–31], even though the deformation is changing rapidly with nucleon number. If β-vibrations exist, they are near the top or above the pairing gap and are inextricably mixed with all the possible particle-hole excitations that couple to $I^\pi = 0^+$.
3) It is remarkable that the only excitations well within the pair gaps of the $N = 90$ nuclei are the γ-band and the negative-parity "octupole" states. The γ-band is not a band containing a quantum in the γ-direction [40] but has $K^\pi = 2^+$, $\boldsymbol{n}_\gamma = \mathbf{0}$ and a bandhead energy given by $\boldsymbol{E}_\gamma = \boldsymbol{\hbar\omega}_\gamma + \boldsymbol{\hbar}^2/\mathscr{I}$. In the rotation-vibration model there is a strong coupling between rotations and γ-vibrations, physically expressing the fact that rotations with non-vanishing K become possible only in the presence of dynamical triaxiality [40]. However, no $\boldsymbol{n}_\gamma = \mathbf{1}$ ($K^\pi = 0^+$ or $K^\pi = 2^+$) gamma-vibrational bands have been unambiguously identified.
4) Even the most formidable calculations [54] that do not include 2p-2h configurations will not correctly predict the experimental properties of 0_2^+ states in transitional rare-earth nuclei.

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