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Letter

Blocking of coupling to the 0_2^+ excitation in ^{154}Gd by the [505]11/2$^-$ neutron in ^{155}Gd

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Abstract. The concept that the first excited 0^+ states in $N = 90$ nuclei are not a β-vibration but a second vacuum formed by the combination of the quadrupole pairing force and the low density of oblate orbitals near the Fermi surface is supported by the blocking of this collective mode in ^{154}Gd from coupling to the [505]11/2$^-$ single-particle quasi-neutron orbital in ^{155}Gd. The coupling of this orbital to the 2^+ γ-vibration in ^{154}Gd is observed since this coupling is not Pauli-blocked.

In the previous letter [1] it has been proposed that the low-lying first excited 0_2^+ states in the $N = 90$ transitional rare-earth nuclei are not one phonon β-vibrations but are a second vacuum state $|\mathbf{0}_2^+\rangle$ that mimics the ground-state vacuum $|\mathbf{0}_1^+\rangle$. The proposed cause of the second vacuum is the different configuration-dependent pairing strengths arising between deformed time-reversed neutron orbitals with different signs of their single-particle quadrupole moments. Thus, at neutron number $N = 90$, the prolate positive quadrupole moment [521]3/2$^-$, [651]3/2$^+$ Nilsson orbitals and the oblate negative quadrupole moment [505]11/2$^-$ orbital [2] are close to the Fermi surface. The pairing strength G_{pp} between prolate orbitals and that between oblate orbitals G_{oo} are taken to be equal, but the strength G_{op} between oblate and prolate orbitals is conjectured to be much weaker. Thus, $G_{pp} \approx G_{oo} \gg G_{op}$. This suggestion for the origin of $|\mathbf{0}_2^+\rangle$ is the same as the explanation [3–7] given for the existence of low-lying 0^+ states in deformed actinide nuclei that did not have the properties of a β-vibration or of a pairing vibration.

Evidence that the [505]11/2$^-$ oblate orbital is associated with reduced pairing was first presented by J.D. Garrett *et al.* [8,9]. But a direct test of the underlying microscopic structure of $|\mathbf{0}_2^+\rangle$ is required if we are to be completely confident in our interpretation of these states.

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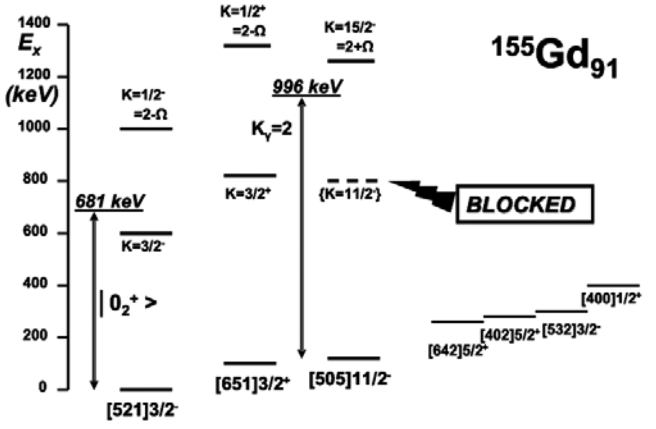

Fig. 1. Schematic showing the rotational bandheads arising from the coupling of the second vacuum $|\mathbf{0}_2^+\rangle$ and the first γ-vibration, at 681 keV and 996 keV, respectively, in ^{154}Gd to the Nilsson single-particle neutron orbits in ^{155}Gd with $K = \Omega$. The data for the $K \leq 5/2$ orbitals are taken from ref. [21] and the data for the [505]11/2$^-$ orbital are from the present experiment.

In many cases the single-particle orbitals dominating the configuration of a nuclear state can be ascertained from its population in direct reactions. However the $|\mathbf{0}_2^+\rangle$ levels in $N = 90$ nuclei are very weakly populated in

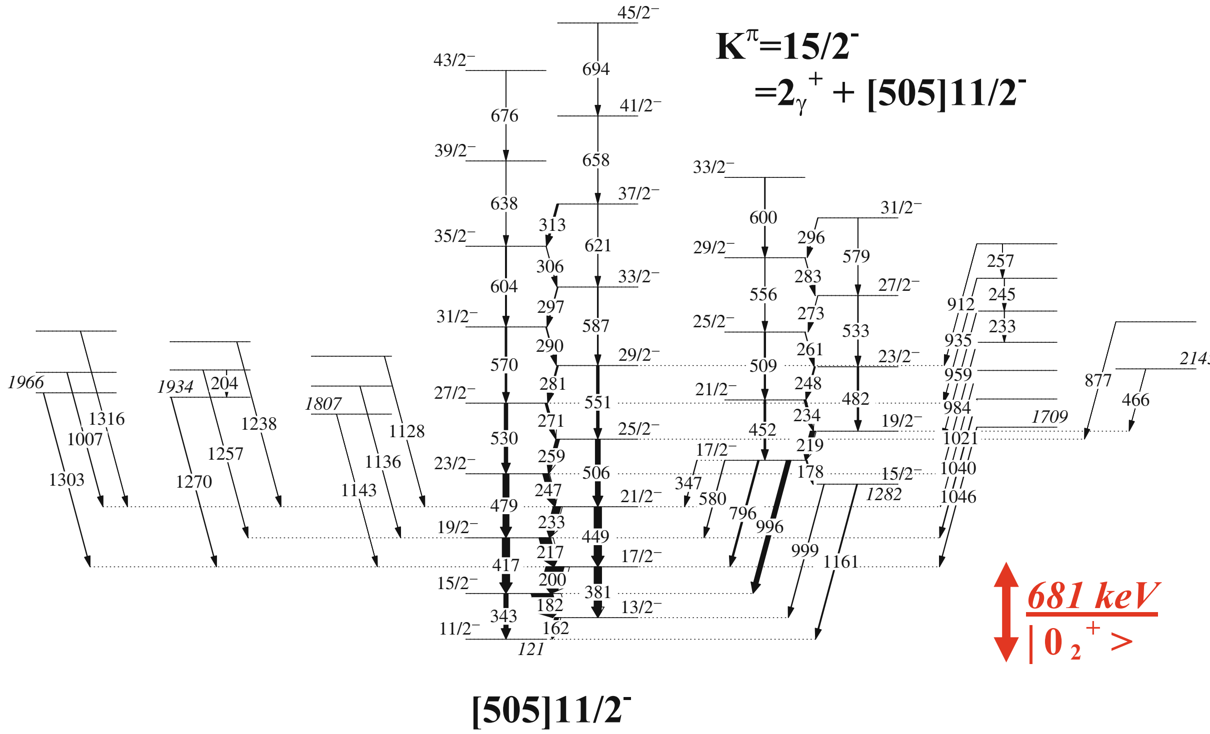

Fig. 2. Partial decay scheme for ^{155}Gd showing the [505]11/2$^-$ band at 121 keV and the high-K levels that decay to it. The levels above 1282 keV are conjectured to be formed by the [505]11/2$^-$ neutron coupled to the $K^\pi = 2^+$ γ-vibration of the ^{154}Gd core. Levels due to the coupling of the second vacuum $|\mathbf{0}_2^+\rangle$ at 681 keV in ^{154}Gd to the [505]11/2$^-$ quasi-neutron, to produce a $K = 11/2^-$ band, are conspicuous by their absence.

single-particle transfer [10–13] and electron scattering [14] experiments. They are also relatively weakly populated in (p,t) two-neutron pick-up reactions [15,16] but strongly in (t,p) two-neutron stripping reactions [17,18]. These latter data indicate that a considerable part of the $|\mathbf{0}_2^+\rangle$ configuration consists of two quasi-neutrons in time-reversed orbits. However, these $L = 0$ two-neutron transfer data give no information on which time-reversed orbits are involved.

In looking for an unambiguous test of the microscopic structure of $|\mathbf{0}_2^+\rangle$ we realise that the single-particle orbitals in odd nuclei, having an even-even $N = 90$ nucleus as a core, will couple to any collective excitations of that core. Thus classically the single-neutron orbitals in ^{155}Gd should couple to any β-, γ- and octupole vibrations of their ^{154}Gd core. Should any of these collective modes have the major part of their wave function composed of two quasi-neutrons in a particular time-reversed orbit, then the coupling of this particular quasi-neutron to that collective mode will be blocked in the odd neutron nucleus.

The coupling of the ground-state [521]3/2$^-$ neutron in the $N = 91$ nucleus ^{155}Gd to the $|\mathbf{0}_2^+\rangle$ core excitation at 681 keV in ^{154}Gd has been well established in transfer reactions [19,20]. In fig. 1 we show the results of Schmidt *et al.* [21] for ^{155}Gd. They carried out an extensive investigation of the low-spin levels using the (n,γ), (d,p) and (d,t) reactions. They identified the coupling of the lowest $K^\pi = 3/2^\pm$ orbitals, the ground state [521]3/2$^-$ and [651]3/2$^+$ at 105 keV, to the $|\mathbf{0}_2^+\rangle$ core excitation at 681 keV in ^{154}Gd, to have their bandhead energies at 592 keV and 815 keV, respectively. These bands also couple to the γ-vibration of the ^{154}Gd core, producing states with $K = |K_{\rm band} - 2|$ at 1003 keV ($K^\pi = 1/2^-$) and 1332 keV ($K^\pi = 1/2^+$), respectively. Only the lower-K band is seen when the bands couple to the γ-vibration because the $K = (K_{\rm band} + 2)$ coupling has higher spin and could not be reached by the low-angular-momentum reactions used by Schmidt *et al.* [21].

The state of highest spin seen in [21] is the 11/2$^-$ bandhead at 121 keV assigned to the [505]11/2$^-$ orbital. This state is seen in both the (d,p) and (d,t) reactions but not in the (n,γ) data. Reference [21] has no candidate for an 11/2$^-$ bandhead near 802 keV that might be associated with the [505]11/2$^-$ quasi-neutron coupling to the 681 keV collective excitation of the ^{154}Gd core.

We have used the AFRODITE spectrometer [22] of iThemba LABS to measure $\gamma\gamma$ coincidences in the ^{154}Sm(α, 3n)^{155}Gd reaction at a beam energy of 35 MeV. The target was 4 mg cm^{-2} of ^{154}Sm, sufficiently thick to stop the recoils. In total we obtained about $5 \cdot 10^8$ $\gamma\gamma$ coincidences. The data were analysed using *Radware* [23]. DCO ratios were measured together with γ-ray polarizations at 90° to the beam direction. The decay scheme divides itself into two [24]: one set of levels decaying to $K = 1/2$, 3/2 and 5/2 bands; the other set of levels decaying to the [505]11/2$^-$ band. This is because it would take at least a $\Delta K = 3$ transition to cross the gap between the $K \geq 11/2$ states and the $K \leq 5/2$ states. In fig. 2 we show the levels that decay to the [505]11/2$^-$ band.

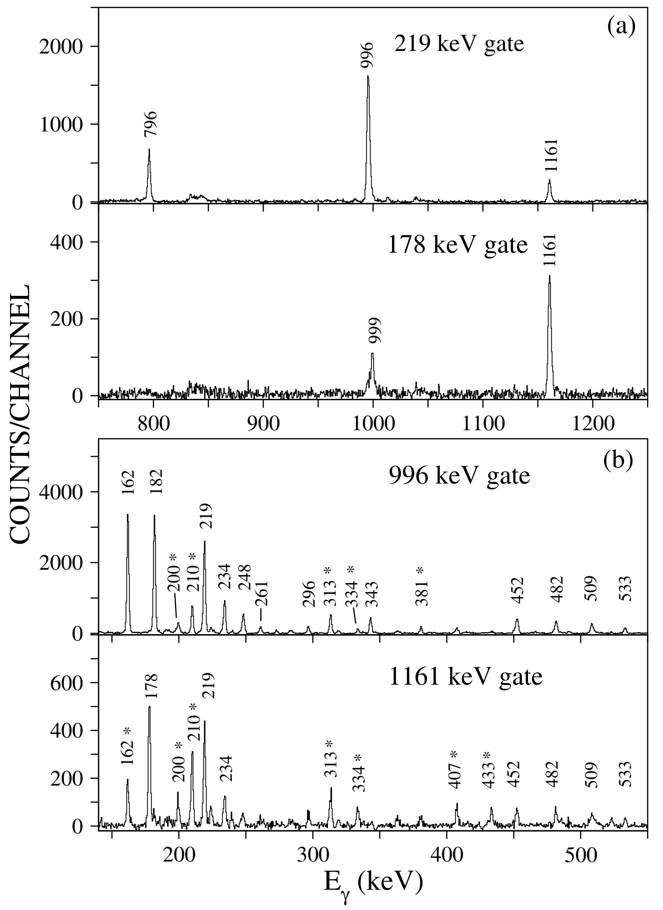

Fig. 3. Coincidence γ-ray spectra showing (a) the decays out of the lowest two levels of the conjectured $K^\pi = 15/2^-$ band and (b) the in-band γ-rays above the two main decays from the $K^\pi = 15/2^-$ band. The peaks marked with stars are contaminant lines mostly from break-through from peaks overlapping the gates that are in coincidence with the strongest γ-rays from the low-K levels in ^{155}Gd.

In our experiment we see no evidence whatsoever for γ decay to members of the [505]$11/2^-$ band, that could be associated with a $K^\pi = 11/2^-$ band formed by coupling the $|\mathbf{0}_2^+\rangle$ configuration to [505]$11/2^-$. The lowest-energy state we observe decaying to the [505]$11/2^-$ is 1161 keV above the [505]$11/2^-$ bandhead at an excitation energy of 1282 keV. This level is the lowest level attached to levels above it that are joined by strong $M1$ transitions. DCO data indicate that the 1282 keV level has spin-parity $15/2^-$. Levels above the 1282 keV level with $I \geq 17/2^-$ have also been observed by Hayakawa *et al.* [25]. In fig. 3 we show the spectrum of γ-rays in coincidence with the 178 keV $M1$ transition, feeding the new $15/2^-$ state from the $17/2^-$ level above it, and the spectra in coincidence with the 219, 996 and 1161 keV γ-rays.

The γ-vibrational band of the ^{154}Gd core has only very weak $\Delta I = 1$ intra-band transitions, which is a general feature of γ-bands [26] due to their essentially collective character. The strong $M1$ intra-band transitions seen in the levels above the $K^\pi = 15/2^-$ 1282 keV state arise from the [505]$11/2^-$ particle itself. Similarly, we would expect any $K^\pi = 11/2^-$ band from coupling the [505]$11/2^-$ orbital to the $|\mathbf{0}_2^+\rangle$ configuration to also contain similarly strong intra-band $M1$ transitions. We therefore conclude that, if it existed, it would be very hard to miss a band formed by the [505]$11/2^-$ to $|\mathbf{0}_2^+\rangle$ coupling.

If blocking of the coupling of $|\mathbf{0}_2^+\rangle$ to [505]$11/2^-$ occurs in ^{155}Gd, it follows that this blocking should occur in all odd neutron nuclei outside $N = 88$ and 90 even-even cores which possess low-lying 0_2^+ states that we identify as second vacua $|\mathbf{0}_2^+\rangle$. The systematics of the excitation energies of [505]$11/2^-$ bandheads have been presented in refs. [2, 27]. The odd neutron nuclei with [505]$11/2^-$ bandhead excitation energies below 300 keV are ^{151,3}Sm, ^{153,5}Gd and ^{155,7}Dy.

The nucleus ^{151}Sm has been studied extensively by both γ-ray spectroscopy [28, 29] and transfer reactions [30–33]. Again, as for ^{155}Gd and all the other $N = 89$ and 91 odd neutron nuclei, the decay scheme for ^{151}Sm is split in two [29] with levels feeding either states with $K \leq 5/2$ or feeding the [505]$11/2^-$ band. In ^{151}Sm three bands are found to feed the [505]$11/2^-$ band, all with spins $I \geq 17/2$. The most sensitive experiment [29] found no candidate for an $11/2^-$ band corresponding to [505]$11/2^-$ coupled to the core $|\mathbf{0}_2^+\rangle$ in ^{150}Sm at 740 keV or in ^{152}Sm at 685 keV. A similar situation is found in ^{153}Sm [34], ^{153}Gd [35], ^{155}Dy [36] and ^{157}Dy [37, 38]. We therefore deduce that the major component of all the $|\mathbf{0}_2^+\rangle$ states in $N = 88$ and 90 Sm, Gd and Dy nuclei is two time-reversed quasineutrons in the [505]$11/2^-$ Nilsson orbit.

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