The structure of excited states seen in double beta decay

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Abstract. The are only two nuclei in which double beta decay to excited states in nuclei have been measured. Namely, ^{100}Mo $\rightarrow$ ^{100}Ru first excited 0_2^+ state and the ^{150}Nd $\rightarrow$ ^{150}Sm first excited 0_2^+ state. These are very useful in giving information about the nature of the neutrino (Dirac or Majorana) and the ordering of the masses. There is not enough knowledge on the microscopic structure of the 0_1^+ and 0_2^+ in ^{150}Sm. In transitional N = 88 nuclei strong E1 transitions have previously been observed at medium spins between the yrast and lowest negative parity bands. We have studied the detailed spectroscopy of ^{150}Sm and ^{152}Gd[1] isotones using the AFRODITE and JUROGAM spectrometer arrays following (α, xn) reactions. We observe very intense E1 transitions between the excited $K^\pi = 0_2^+$ bands and the lowest negative parity bands in both nuclei. With recent questioning of the nature of collective beta vibrations [2, 3, 4] in N = 88 and 90 nuclei, it is clear that understanding the microscopic detail of the structure of these states in nuclei in this range is most crucial. We think that exploring E1 transitions between bands could prove to be a very powerful tool in understanding the structure of negative-parity bands and their relationship to positive-parity bands. Directional Correlations from Oriented states (DCO) and Polarization Anisotropy for these new E1 transitions found are presented. A comparison with the actinide nucleus ^{220}Ra is made.

1. Introduction

The structure of the transitional nuclei near neutron numbers N = 88 and N = 90, where the nuclear shape is changing from spherical to quadrupole deformed, still pose a great challenge having many competing theoretical models with varying degrees of successs. A new perspective to the understanding of the structure of the N = 88 nucleus ^{150}Sm is brought by the proposition [2, 3, 4] that the low-lying first excited 0^+ states in nuclei in this mass region are not the traditional β-vibrations, postulated by Nobel prize winners Bohr and Mottelson [5], but constitute a second vacuum coexisting with the ground state vacuum. Other interpretations of pairing isomers have also been made [6], and have also been subsequently questioned [7]. We have shown [2, 3] that a large component of the microscopic configuration in nuclei in the region N = 88 and 90 is a pair of neutrons in the $[505]\frac{11}{2}^-$ orbit from the $h_{\frac{11}{2}}$ shell that is extruded to the fermi surface by the onset of deformation. This is the case for ^{150}Sm. The role of pairing is playing a very major role in the structure of these states, and it will be useful to measure the pairing component of the proton for these states and find out where the major part of the proton two particle-two hole (2p-2h) states lie. Previously the nucleus ^{150}Sm with two fewer protons than ^{152}Gd has been alleged to have a static octupole deformation in its ground state band above spin I = 8 [8]. A subsequent experiment [9] has a different decay scheme suggesting that the octupole deformation is destroyed at higher spins. A review [10] of experimental E3 strengths finds that these peak at proton number Z = 62 and number N = 88. Similarly it is known that the E0 strengths in ^{150}Sm are considerable [11, 12]. We discuss our observations based on the conjection [13] that the first excited 0^+ states in some nuclei have a static octupole deformation while the ground state remains with only a quadrupole deformation. We have made extensive spectroscopic measurements in the isotones ^{150}Sm and ^{152}Gd using modern spectrometers as mentioned before. We report here on the observation of E1 transitions in these nuclei from bands built on the first excited 0^+_2 states to the lowest negative parity bands ($K^\pi = 0^-$, octupole band)

2. EXPERIMENTAL DETAILS AND RESULTS

We have studied the nucleus ^{152}Gd using the ^{152}Sm(α, 4n)^{152}Gd reaction at 45 MeV at iThemba LABS employing the escape suppressed γ-ray spectrometer array AFRODITE [1]. The high spin states of ^{150}Sm were studied at iThemba LABS national laboratory, using the AFRODITE spectrometer array comprising 9 HpGe clover detectors 5 at 90° and 4 at 135° following the ^{136}Xe(^{18}O, 4n)^{150}Sm reaction at 75 MeV using a homogeneous cryogenic frozen ^{136}Xe target with a thickness of about 1.47 mg/cm^2, backed by a 1 mg/cm^2 layer of ^{197}Au, subjected to a vacuum of 10^{-5} mbar, is kept solid at a temperature of 55K cooled with a compact solid nitrogen sublimation system. A total of about 5×10^8 events were accumulated. The low spin states of ^{150}Sm were populated via ^{148}Nd(α, 2n)^{150}Sm reaction at 25 MeV, a self-supporting target of 5 mg/cm^2 and the escape suppressed spectrometer array comprising of 24 clover and 15 tapered HPGe detectors in Bismuth Germanate shields. An equivalent of 2×10^9 triple $\gamma\gamma\gamma$ coincidences were arranged into a cube. The data were analysed using the Radware package [14].

In order to firmly assign spins and parities to transitions in the decay scheme, we extracted gamma-ray multipolarities by using the method of Directional Correlation from Oriented states DCO [15] and Linear Polarisation Anisotropy (LPA) [16]. Results showing measurements for the new E1 transitions in the two isotones ^{150}Sm and ^{152}Gd are recorded in Table 1 and Table 2 respectively. From the ^{136}Xe(^{18}O, 4n)^{150}Sm reaction, the ground state band, band 1 is now known to $24\hbar$. The β-band 2 was only known up to $6\hbar$ and it has been extended to an impressive $12\hbar$ with three linking; two to the ground state and one to the octupole band 4. The positive parity band 3 has previously been known from the band-head at $14\hbar$, and now our results allowed us to get a lower band-head at $12\hbar$. A new transition has been observed in band 5 linking it to the octupole band. Band 6 has been previously known [17] but its spin and parity was uncertain, and our results allowed us to make a firm assignment of its spin and parity: Two new levels at $20\hbar$ (5920.1 keV) and $10\hbar$ (3120.7 keV) have been added to this band with a new transition linking it to the octupole band. The results are shown in Fig. 1 with new γ-rays in red. Partial

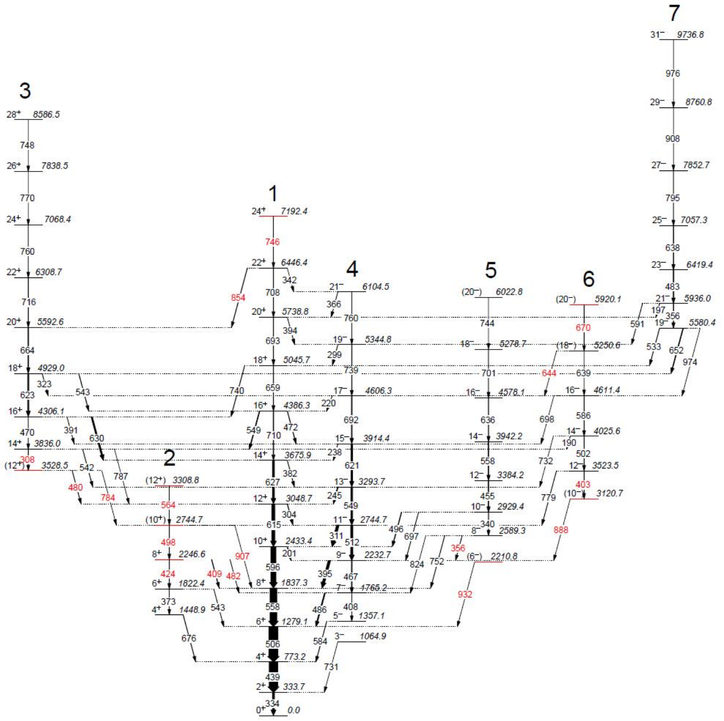

Figure 1. Level scheme of ^{150}Sm deduced from our ^{136}Xe(^{18}O, 4n)^{150}Sm data.

decay schemes for ^{152}Gd and ^{150}Sm are shown in Fig. 3 and Fig. 2 respectively for the ground, first excited 0_2^+ and the $K^\pi = 0^-$ band.

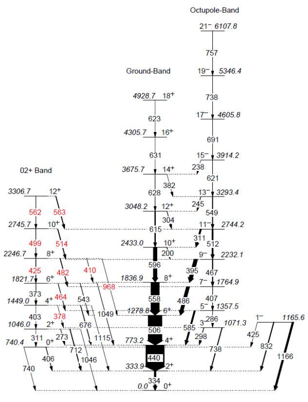

Figure 2. Partial level scheme of ^{150}Sm showing the new E1 transitions connecting the 0_2^+ and the octupole band from our ^{148}Nd(α, 2n)^{150}Sm data.

3. Discussion

The decay by E1 transitions in ^{150}Sm have been observed [8, 9] both ways between the positive parity yrast states, at 10^+ and above, and the negative parity band. It was conjectured that the yrast states were associated with a static octupole deformation at 10^+ and above. Recent measurements [18] of the double β decay of ^{150}Nd to the first excited 0_2^+ state in ^{150}Sm are a strong incentive to understand the exact structure of these 0_2^+ states and their ground 0_1^+ states. We discuss our findings in terms of the actinide nucleus ^{220}Ra [19] where it is assumed that the

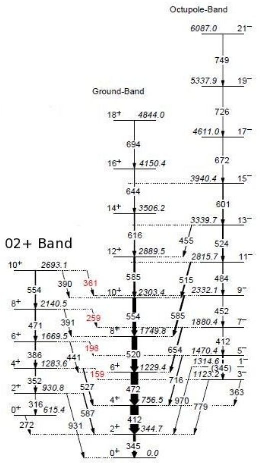

Figure 3. artial level scheme of ^{152}Gd showing the new E1 transitions connecting the 0_2^+ and the octupole band from our ^{152}Sm(α, 4n)^{152}Gd data.

Table 1. Angular-intensity ratios, polarization anisotropy, spin and parity assignments for E1 transitions between the 0_2^+ and octupole bands in ^{150}Sm. The $)^{a}$ represent that there was not enough statistics to do the desired measurement. The * on the γ-rays represent that their R_{DCO} ratio what measured gating on E1 transitions, and the rest were gated on E2 transitions.

Eγ (keV)	R_{DCO}	A_P	Assignment
377.7*	0.639±0.262	$)^{a}$	$4^+ \rightarrow 3^-$
464.2	1.662±0.029	0.0446±0.016	$6^+ \rightarrow 5^-$
481.8	1.55±0.02	0.0456±0.007	$8^+ \rightarrow 7^-$
513.6	$)^{a}$	$)^{a}$	$10^+ \rightarrow 9^-$
562.50*	1.101±0.075	$)^{a}$	$12^+ \rightarrow 11^-$

Table 2. Angular-intensity ratios, polarization anisotropy, spin and parity assignments for E1 transitions between the first excited 0^+ states and octupole bands in ^{152}Gd. The $)^{a}$ represent that there was not enough statistics to do the desired measurement. The * on the γ-rays represent that their R_{DCO} ratio what measured gating on E1 transitions.

Eγ (keV)	R_{DCO}	A_P	Assignment
160.4*	$)^{a}$	$)^{a}$	$4^+ \rightarrow 3^-$
199.1*	0.80±0.06	0.06±0.07	$6^+ \rightarrow 5^-$
260.1*	0.95±0.07	0.03±0.07	$8^+ \rightarrow 7^-$
361.1*	1.09±0.06	0.01±0.02	$10^+ \rightarrow 9^-$

quadrupole deformed nucleus is a rigid rotor with moment of inertia $\jmath$, and the octupole vibration is harmonic with frequency Ω, and there are no interactions between the octupole phonons and the quadrupole deformed potential of the nucleus. Fig. 4 shows the energy difference $\triangle$E(I) between the 0_2^+ band ($\pi = +$) and octupole ($\pi = -$) bands in ^{150}Sm, ^{152}Gd and ^{220}Ra. As it can be seen the two sequences do not merge but they cross. Fig. 5 and Fig. 6 display the aligned angular momentum I_x as a function of the rotational frequency ω, which is the slope of E(I). The $\pi = -$ sequence for both ^{150}Sm and ^{152}Gd starts at $\approx 5\hbar$ more angular momentum than the ground and first excited 0_2^+ $\pi = +$ bands. However at higher values of ω the $\pi = +$ ground band

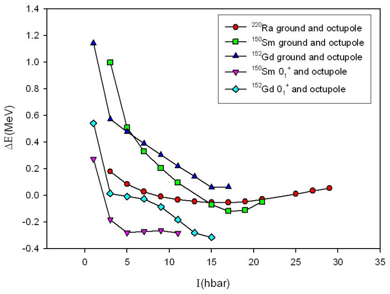

Figure 4. Energy difference $\triangle$E(I) = E_{-}(I) - (E_{+}(I+1) + E_{+}(I-1))/2) between the positive and negative parity states in ^{150}Sm, ^{152}Gd and ^{220}Ra.

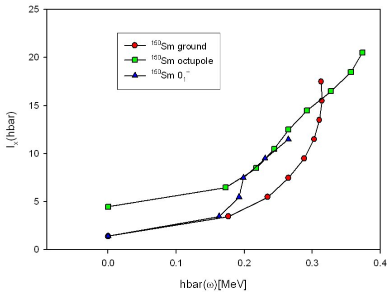

Figure 5. Angular momentum as a function of the angular frequency of the two band sequences in ^{150}Sm.

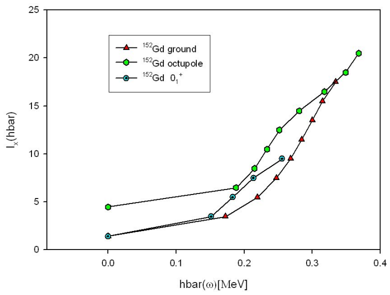

Figure 6. Angular momentum as a function of the angular frequency of the two band sequences in ^{152}Gd.

gains more alignment. Another indication of the condensation is the slow growth of ω above 0.25 MeV, specifically t for the $\pi = +$ zero phonon band. The strong octupole correlations of rotational bands observed in other mass regions can also be interpreted as phonon condensation [19]. We therefore propose the same for the nuclei in the rare earth regions with N = 88 and N = 90.

4. Conclusion

High-statics experiments with the AFRODITE and JUROGAM spectrometer arrays have unearthed new E1 structures in ^{150}Sm and ^{152}Gd at low and high spin regimes. A band built on the low-lying second excited 0^{+} state in ^{150}Sm has been established to an impressive 12^{+} with new E1 transitions decaying to the low-lying negative parity band ($K^{\pi} = 0^{-}$). In the isotone ^{152}Gd the same band has also been established to 10^{+} showing the same behaviour. Following [19] we conclude that the interaction between the 0^{+} and the 0^{-} states is the condensation of rotational-aligned octupole phonons as seen in the actinide nucleus ^{220}Ra.

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