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The structure of the excited 0_2^+ state in ^{150}Sm observed in double beta decay

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S. P. Bvumbi[*]
University of Johannesburg, Department of Physics, P. O. Box 524, Auckland Park 2006, South Africa
E-mail: `suzan@tlabs.ac.za`

Recent measurements of the double β decay to the first excited 0_2^+ states in $^{150}Sm_{88}$ [1] and $^{100}Ru_{56}$ [2] demand a full understanding of the exact microstructure and wave functions of the final states as well as the parent ground 0_1^+ states of ^{150}Nd and ^{100}Mo. It has been established [3, 4] that the first excited 0_2^+ states in $N = 88$ and 90 are not the traditional β-vibrations but 2p-2h states lowered into the pairing gap by configuration dependent pairing. They are classic examples of 'pairing isomers' [5] forming a 'second vacuum' [3] on which a complete set of excited deformed states are built that are congruent to those built on the 0_1^+ ground state. Evidence for this [6] has recently been found in ^{152}Sm where a repeating pattern of excitations built on the 0_2^+ state exist that are congruent to those built on the 0_1^+ ground state. We report here on the first observation of enhanced E1 transitions in the transitional nucleus ^{150}Sm from the levels in the first excited 0_2^+ band to the lowest negative parity band.

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[*] Speaker.

1. Introduction

The nucleus $^{150}_{62}Sm_{88}$ lies in a transitional region where nuclear collectivity rapidly changes from vibrational to rotational motion [7]. This is reflected in the rapid change in the experimental $\frac{(4^+)}{(2^+)}$ energy ratios between $N = 86$ and $N = 96$ nuclei for isotopes with $Z \sim 64$, as shown in Fig 1. The $\frac{(4^+)}{(2^+)}$ ratios of 2.00, 2.50 and 3.33 are expected for pure vibrational, γ-soft and rotational, respectively. The ratio $\frac{(4^+)}{(2^+)}$ for ^{150}Sm is ~ 2.32 approaching 2.50, the value expected for a γ-soft rotor [8], where vibrational modes of excitation couple to rotation [9]. The $N = 88$ nuclei have remarkable features; they are at a peak in the $|M(E3)|^2$ transition strength of $0_1^+ \rightarrow 3_1^-$ transitions for even-even nuclei as a function of neutron number; they also have very strong E0 transitions from the band built on the 0_2^+ states to the ground state bands. Generally, strong E3 transitions have been accounted for by the proximity of $\triangle I^\pi = 3^-$ shell model orbits near the Fermi surface. For $N = 88$ nuclei these are $i_{\frac{13}{2}} - f_{\frac{7}{2}}$ for neutrons and $h_{\frac{11}{2}} - d_{\frac{5}{2}}$ for protons. The nucleus ^{150}Sm has its first negative parity band at an unusually low excitation energy. Indeed, this negative parity band is actually yrast at spin 11^-. E1 transitions have been observed both ways between the positive parity yrast states, at 10^+ and above, and the negative parity band. Recent reflection-asymmetric relativistic mean-field [10] and folded Yukawa Strutinski with particle number projection [11] calculations indicate that ^{150,152}Sm and the isotone ^{152}Gd could have a permanent octupole $Y_{3,0}$ deformation, see Fig. 2.

2. Experimental details and Results

The lower spins of the nucleus ^{150}Sm were populated using the $^{148}Nd(\alpha,2n)^{150}Sm$ reaction at a beam energy of 25 MeV using the JUROGAM II spectrometer array equiped with 23 HPGe clover detectors and 15 segmented tapered detectors each in their individual BGO shields, in Jyväskyä, Finland (JYFL). The beam was supplied by the JYFL K=120 cyclotron and during the experiment we ensured that the beam was not contaminated by ^{12}C and ^{16}O beams of almost the same magnetic rigidity. A self-supporting target of ^{148}Nd ($\sim 94\%$ enriched) with a thickness of $\sim 4mg/cm^2$ was used. Two and a half days of running time gave ~ 1.5 Terabyte of data accumulated when at least three Compton-suppressed HPGe detectors fired in coincidence. This amount of data enabled us to unfold γ^3 events into a three-dimensional cube which we analyzed using Radware [12]. The partial decay scheme of ^{150}Sm is shown in Fig. 3, for the ground state yrast rotational band, the 0_2^+ band and the lowest lying negative parity band (octupole band).

The rotational band built on the 0_2^+ state has been extended in ^{150}Sm and additional intra-band E1 transitions between the ^{150}Sm band and octupole band have been observed. In order to assign spins and parities to the transitions in the 0_2^+ band in the decay scheme, γ-ray multipolarities were extracted by conducting an angular-correlation analysis using the method of Directional Correlation from Oriented states (DCO) [13] and Linear Polarization anisotropy (A_P) [14], these are listed in Table 1. Typical angular-intensity ratios extracted from this analysis were ~ 0.6 for the pure dipole ($\triangle I = 1$) new transitions. The polarization anisotropy for the E1 transitons were found to be positive indicating that they are stretched electric dipole transitions.

3. Discussion

The excited 0_2^+ states populated in the 2β decay are interesting as the excited states emit two characteristic γ-rays giving importatnt extra signature of the decay [1, 2]. To have these two γ-rays besides the two decay electrons is expected to lengthen a measurable 2β decay of partial lifetimes from the current $\sim 10^{20}$ years to the $\sim 10^{24}$ years estimated requirement for detecting any Majorana $2\beta 0\nu$ decay component [15]. The interleaving of the 0_2^+ band with the octupole band E1 transitions suggest that these bands are structurally related to each other in some way. It was suggested [16] that the relative E1 strengths and the behavior of the 0_2^+ band in ^{150}Sm argues for, but does not prove, the interpretation made by [17] of the ground state being quadrupole deformed whereas the 0_2^+ state has considerable octupole correlations. This argument was reached after comparing ^{150}Sm with the isotone ^{152}Gd and the well deformed nucleus ^{220}Ra. The 0_2^+ state in ^{150}Sm was observed to have similarity with those in ^{220}Ra using the 'Tidal wave' scenario painted by [18], that the interleaving of these states with the lowest negative parity states is formed by the condensation of rotation-aligned octupole phonons forming a heart-shaped nucleus. We therefore conclude that calculations along those of [17] are needed, particularly in nuclei in the rare earth region with $N = 88$ and $N = 90$ in order to have a clear understanding of the interaction of the 0_2^+ states with the low-lying neagtive parity states.

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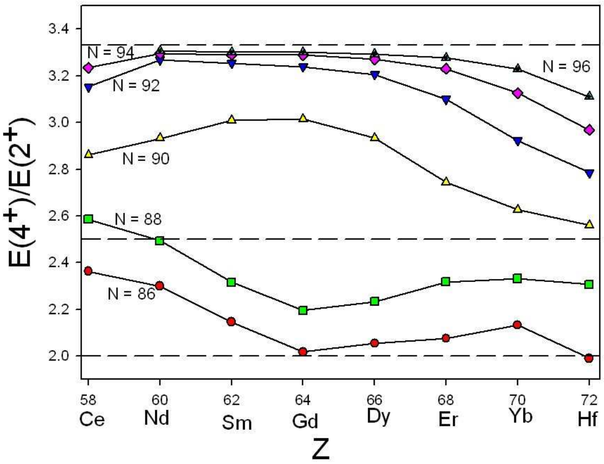

Figure 1: $\frac{E(4^+)}{E(2^+)}$ energy-ratio systematics for even-even nuclei as a function of atomic number Z. The horizontal dashed lines represent limits expected for pure vibrational (2.00), rotational (3.33), and γ-soft (2.50) behavior, respectively.

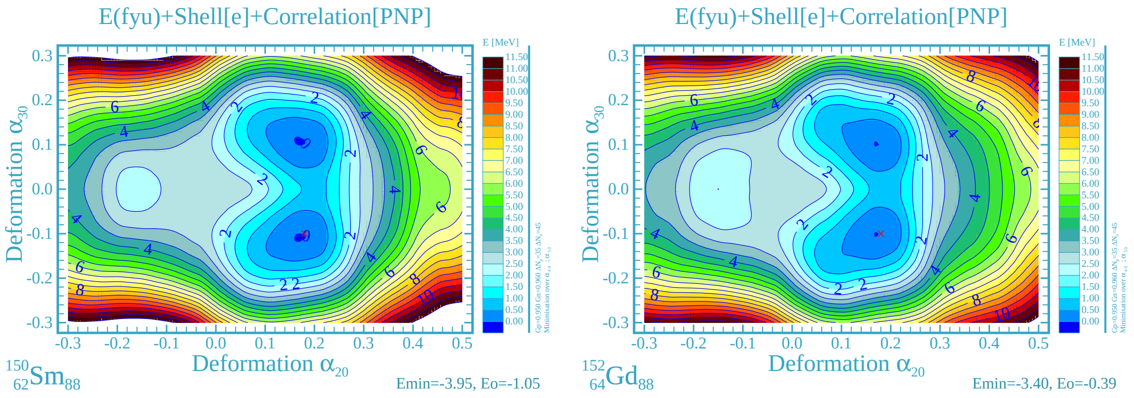

Figure 2: The contour plots of total energies for the even-even isotones ^{150}Sm and ^{152}Gd in (α_{20}, α_{30}) plane obtained in the Strutinsky with shell correlations and Yukawa approach. The main contours were calculated with $(Y_2, 0)$ and $(Y_3, 0)$ [11].

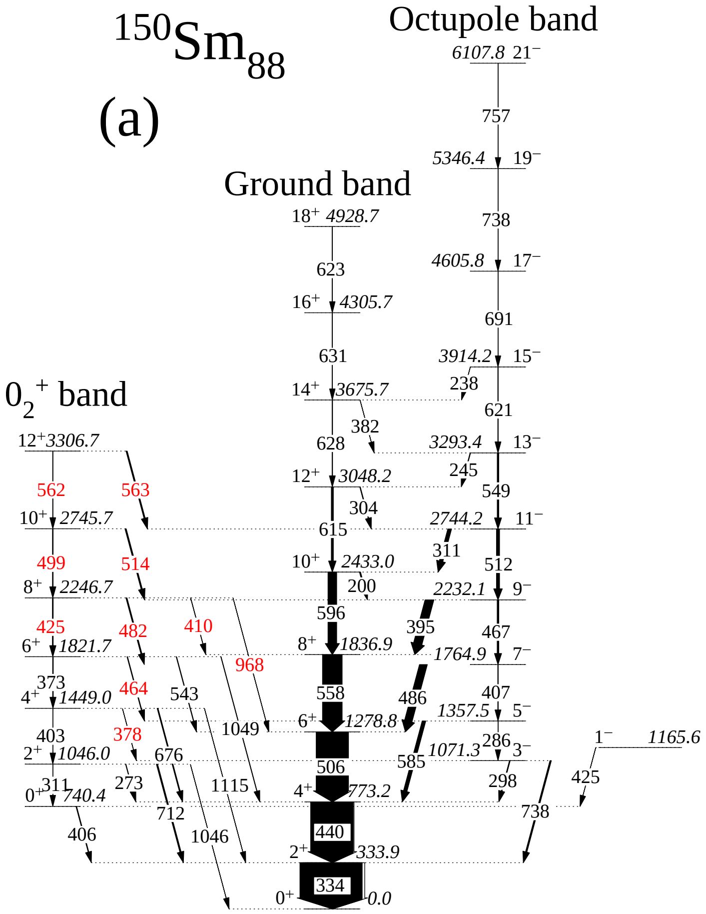

Figure 3: Partial level scheme of ^{150}Sm showing the ground state, band built on 0_2^+ and the octupole band. New transitions and E1 transitions from the 0_2^+ band to the octupole band are shown in red.

Table 1: Angular-intensity ratios , polarization anisotropy and apin and parity assignments for new transitions and E1 transitions in the 0_2^+ band. The $)^a$ sign represents that we did not have enough statistics to make the desired measurement.

$E_\gamma(keV)$	R_{DCO}	A_P	Assignment
378	0.639(62)	$)^a$	$4_2^+ \rightarrow 3^-$
464	0.601(29)	0.045(10)	$6_2^+ \rightarrow 5^-$
482	0.645(20)	0.046(7)	$8_2^+ \rightarrow 7^-$
514	$)^a$	$)^a$	$10_2^+ \rightarrow 9^-$
563	0.666(13)	$)^a$	$12_2^+ \rightarrow 11^-$
425	0.861(11)	0.105(31)	$8_2^+ \rightarrow 6^+$
499	1.557(33)	$)^a$	$10_2^+ \rightarrow 8^+$
562	$)^a$	$)^a$	$12_2^+ \rightarrow 10^+$