Magic Nucleus ^{132}Sn and Its One-Neutron-Hole Neighbor ^{131}Sn

P. Bhattacharyya, P. J. Daly, C. T. Zhang, Z. W. Grabowski, and S. K. Saha*
Chemistry and Physics Departments, Purdue University, West Lafayette, Indiana 47907

R. Broda and B. Fornal
Chemistry Department, Purdue University, West Lafayette, Indiana 47907
and Niewodniczanski Institute of Nuclear Physics, PL-31342 Cracow, Poland

I. Ahmad, D. Seweryniak, I. Wiedenhöver, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, C. J. Lister, and P. Reiter
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

J. Blomqvist
Department of Physics Frescati, Royal Institute of Technology, S-10405 Stockholm, Sweden
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Prompt and delayed γ-ray cascades in doubly magic ^{132}Sn and its neighbor ^{131}Sn have been studied at Gammasphere using a ^{248}Cm fission source. Isotopic assignments of unknown γ rays were based on coincidences with known transitions in $A = 112-116$ Pd fission partners. The yrast level spectra of both tin nuclei are interpreted using empirical nucleon-nucleon interactions from the ^{132}Sn and ^{208}Pb regions. Results include identification of the $(\nu f_{7/2} h_{11/2}^{-1})9^+$ aligned state in ^{132}Sn and of extensive $(\nu f_{7/2} h_{11/2}^{-2})$, $(\nu f_{7/2} d_{3/2}^{-1} h_{11/2}^{-1})$ and $(\nu h_{11/2}^{-1} \times 3^-)$ multiplets in ^{131}Sn. The previously reported β^- decay of an unusual ^{131}In high-spin isomer to levels in ^{131}Sn is also elucidated.

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In the exploration of nuclear structure in regions of the nuclidic chart far from the N/Z stability valley, spectroscopic results for such doubly magic species as ^{48}Ni, ^{78}Ni, ^{100}Sn, and ^{132}Sn (and their few valence particle neighbors) provide important benchmarks. The neutron-rich doubly closed shell nucleus ^{132}Sn has no excited states below 4 MeV, and is thus marked as the most magic of all heavy nuclei. Our limited knowledge of the structure of ^{132}Sn and its immediate neighbors derives mainly from β-decay studies of fission product radionuclides, supplemented in a few cases by γ-ray decay data for yrast isomers. Most important is the work of Fogelberg *et al.* [1], who have investigated in detail the β^- decay of 0.21 s ^{132}In ($I^\pi = 7^-$), and have characterized as specific particle-hole excitations most of the ^{132}Sn levels populated in the decay. The ^{132}Sn states thus identified at excitation energies between 4 and 5 MeV consist of 2^+, 4^+, 5^+, 6^+, 7^+, and 8^+ $\nu f_{7/2} h_{11/2}^{-1}$ multiplet members, 4^- and 5^- $\nu f_{7/2} d_{3/2}^{-1}$ states, and a 3^- collective octupole at 4352 keV. The $(\nu f_{7/2} h_{11/2}^{-1})$ 8^+ state at 4848 keV is a long known isomer with $t_{1/2} = 2.0$ μs [2]. The neighboring one-neutron-hole nucleus ^{131}Sn has a $\nu d_{3/2}^{-1}$ ground state, with $\nu h_{11/2}^{-1}$ a low-lying β-decaying isomer. Essentially nothing was known up to now about yrast excitations in ^{131}Sn, with the notable exception of an old report [3] on β decay of an exotic $I \leq 23/2$ ^{131}In isomer to high-spin ^{131}Sn levels that deexcite finally through 4273 keV γ rays to the low-lying $\nu h_{11/2}^{-1}$ isomeric state.

Recent investigations using large detector arrays to study fission fragments have identified γ-ray cascades from individual product nuclei around ^{132}Sn [4–7]. The focus in the present work is on yrast states of the ^{132}Sn and ^{131}Sn isotopes populated following spontaneous fission of ^{248}Cm. The measurements were performed with the Gammasphere array at Argonne National Laboratory using a ^{248}Cm source consisting of about 5 mg of curium oxide embedded in a pellet of potassium chloride. This source delivered 6.3×10^4 fissions/sec. Fission fragments were stopped within the source in ~1 ps, with subsequent emission of deexcitation γ rays occurring from nuclei at rest. The γ-ray coincidence data were recorded over a 10 day period using Gammasphere, which consisted at that time of 99 escape-suppressed large volume Ge detectors. The event trigger required detection of at least four γ rays within a 0.8 μs interval, with storage of time and energy information for every γ ray registered. A total of about 1.8×10^9 events were collected, and they were sorted off-line into various $\gamma\gamma$ matrices and $\gamma\gamma\gamma$ cubes, both prompt and delayed, covering energy ranges to above 5 MeV.

The γ-ray spectra acquired in the Gammasphere measurements were extremely complex, but less so in the energy range above 4 MeV, where all the strong lines observed could be assigned to ^{132}Sn and its closest neighbors. The ungated γ-ray projection above 4 MeV and coincidence spectra gated on $2^+ \to 0^+$ transitions in ^{112}Pd, ^{114}Pd, and ^{116}Pd are displayed in Fig. 1 to illustrate how the isotopic assignments were made. Three prominent peaks in the ungated projection [Fig. 1(a)] were easily recognized as the known 4041 keV $2^+ \to 0^+$, 4352 keV $3^- \to 0^+$,

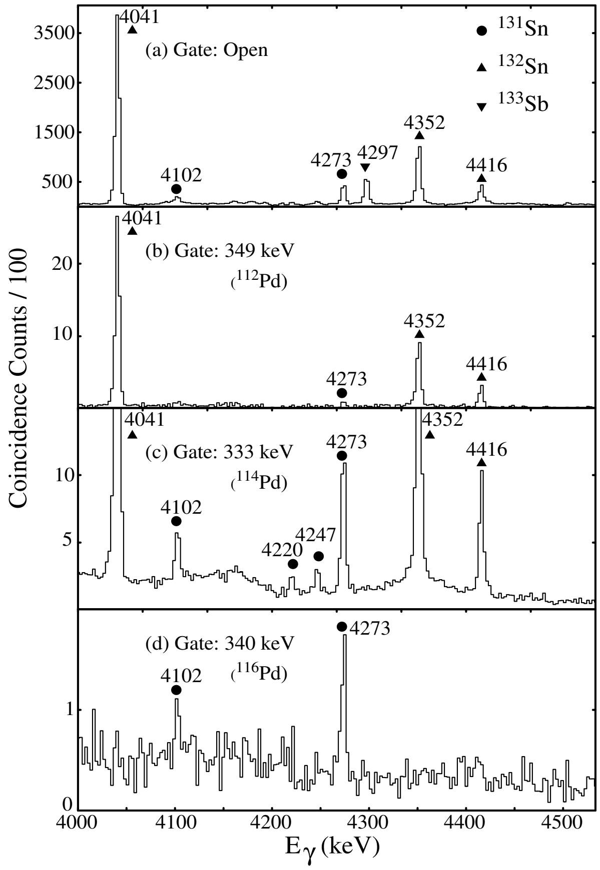

FIG. 1. (a)–(d) Gamma-ray spectra above 4 MeV recorded with the ^{248}Cm fission source using the specified gating conditions. Isotopic assignments for prominent peaks are indicated.

and 4416 keV $4^+ \rightarrow 0^+$ ground state transitions in ^{132}Sn. As shown in Fig. 1, these γ rays also appeared strongly in coincidence with γ rays of ^{114}Pd and ^{112}Pd, the $2n$ and $4n$ fission partners of ^{132}Sn, but they could not be seen in coincidence with ^{116}Pd γ rays (the zero neutron emission partner). The strong 4297 keV γ ray in Fig. 1(a) appeared in coincidence with Rh partner γ rays but not with Pd γ rays, and it has recently been identified [5] as a transition in one-valence-proton nucleus ^{133}Sb. The 4273 keV γ ray in Fig. 1(a) is almost certainly identical with the ^{131}Sn transition observed following β decay of 0.32 s ^{131}In; as would be expected, it is seen in Figs. 1(b)–1(d), but most strongly in coincidence with ^{114}Pd, its $3n$ fission partner. From the spectra shown in Fig. 1, it is obvious that the previously unknown 4102 keV transition also occurs in ^{131}Sn. Similar but more detailed analyses identified five other weaker ^{131}Sn γ rays with energies of 4220, 4247, 4423, 4447, and 4576 keV.

The Gammasphere γ-ray coincidence data for ^{132}Sn were of excellent quality, and they confirmed all the ^{132}Sn excited states below 5 MeV reported in Ref. [1] (see Fig. 2). It therefore came as a surprise when comprehensive analyses of all the prompt coincidence data failed to reveal any new γ rays that could be assigned to ^{132}Sn. Indeed, there was no trace of known transitions deexciting levels at 5399, 5479, and 5629 keV, populated in ^{132}In β decay and interpreted as 6^+, 8^+, and 7^+ states of $\pi g_{7/2} g_{9/2}^{-1}$ character [1]. In order to look for γ rays feeding the long-lived 8^+ yrast isomer in ^{132}Sn, a special delayed coincidence sort was performed selecting events in which at least two γ rays were delayed with respect to the prompt ones by more than 140 ns. The results clearly identified a new 431 keV transition in delayed coincidence with the 4041 keV γ ray and other transitions following the 2 μs isomer; it is placed feeding the 8^+ state from a new level at 5280 keV, which we interpret as the missing maximally aligned 9^+ member of the $\nu f_{7/2} h_{11/2}^{-1}$ multiplet. The counterpart of this state in the ^{208}Pb nucleus is the $(\nu g_{9/2} i_{13/2}^{-1})11^+$ state at 5235 keV, which deexcites by a single γ ray of 340 keV to the 10^+ multiplet member [8]. Scaling this energy by the usual $A^{-1/3}$ factor gives a prediction of 396 keV for the spacing between the 8^+ and 9^+ states of $\nu f_{7/2} h_{11/2}^{-1}$ type in ^{132}Sn, which agrees fairly well with the 431 keV transition energy reported here. No other transitions deexciting or feeding the new 5280 keV level in ^{132}Sn could be found.

The ^{131}Sn level scheme in nuclear data compilations shows the $\nu h_{11/2}^{-1}$ single particle state 241 keV above the $\nu d_{3/2}^{-1}$ ground state. However, this assignment seems far from secure since it is based entirely on the placement of a very weak 2192 keV γ ray observed in ^{131}In β decay [3], and indirect evidence from shell model calculations favors a lower $\nu h_{11/2}^{-1}$ energy of about 100 keV [9]. To avoid this complication in the present work, all ^{131}Sn level energies are expressed relative to zero for the $\nu h_{11/2}^{-1}$ state.

A gate on the strong ^{131}Sn 4273 keV transition showed in coincidence the 159, 173, and 285 keV γ rays previously observed in β decay of the ^{131}In high-spin isomer [3]. The 159 and 173 keV transitions occur in cascade deexciting a 0.30 μs isomer at 4605 keV, in accord with the β-decay findings [3]. (For the half-life of the 4605 keV isomer, the present analysis gave a result consistent with, but not as precise as, the $t_{1/2} = 300 \pm 20$ ns value obtained in Ref. [3].) Our excellent $\gamma\gamma\gamma$ coincidence data established the extensive ^{131}Sn level scheme displayed in Fig. 2. The placement of a moderately strong 258 keV γ ray posed a difficult problem since it appeared in coincidence with transitions deexciting both the 4447 and 4510 keV levels. One possibility is that there are two 258 keV transitions independently feeding these levels; alternatively, an unobserved 64 keV transition may connect the two levels, as represented in Fig. 2. The five weaker transitions with energies exceeding 4 MeV are also included in the ^{131}Sn scheme, with support from the coincidence data and from satisfactory energy sums.

One could anticipate that the lowest-lying yrast excitations in ^{131}Sn would be those arising from coupling of the known ^{132}Sn states with an additional $h_{11/2}$ neutron hole. Specifically, the ^{131}Sn yrast states expected below 5 MeV

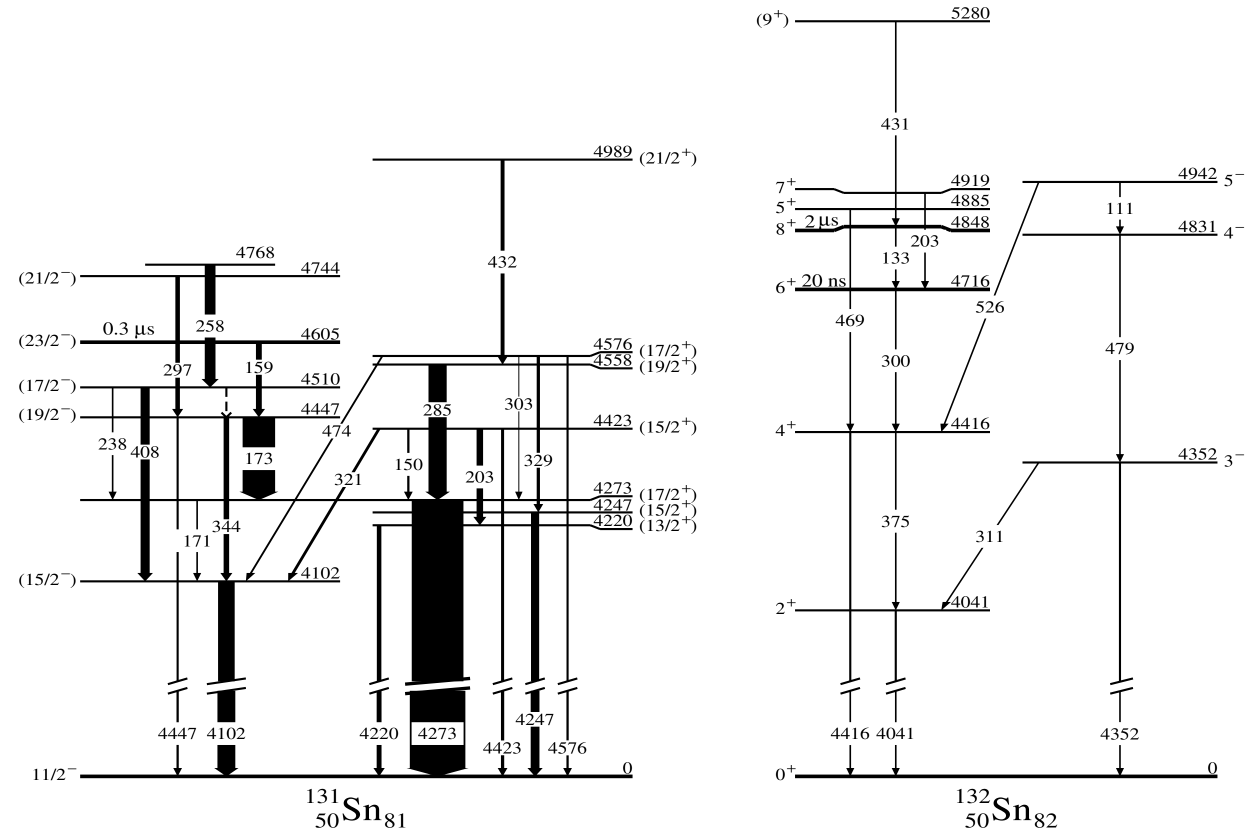

FIG. 2. Level schemes for ^{131}Sn and ^{132}Sn showing the yrast γ-ray cascades observed following fission of ^{248}Cm. For transitions in ^{131}Sn, widths of the arrows are proportional to the observed γ-ray intensities. The 4273, 4447, 4558, and 4605 keV levels of ^{131}Sn were already known from ^{131}In β decay [3], but in the ^{132}Sn level scheme only the 5280 keV level is new.

consist of $\nu f_{7/2} h_{11/2}^{-2}$ negative parity states together with positive parity states of $\nu f_{7/2} d_{3/2}^{-1} h_{11/2}^{-1}$ and $\nu h_{11/2}^{-1} \times 3^-$ character. A good case can be made for interpreting the sequence of levels shown to the left of the ^{131}Sn scheme (Fig. 2) as $15/2^-$, $19/2^-$, $17/2^-$, $23/2^-$, and $21/2^-$ members of the $\nu f_{7/2} h_{11/2}^{-2}$ multiplet. The energies of states of this type have been calculated using the Oxbash code, with empirical $\nu f_{7/2} h_{11/2}^{-1}$ interactions taken from ^{132}Sn, and $\nu h_{11/2}^{-2}$ interactions from the ^{130}Sn level spectrum. As seen in the lower part of Fig. 3, the agreement between experimental and calculated energies is rather good. In particular, the calculation reproduces nicely the energy staggering within the multiplet, which rules out the M1 decay possibility for the $19/2^-$ and $23/2^-$ levels. The $(15/2^-)$ 4102 keV and $(19/2^-)$ 4447 keV levels should mainly involve the coupling of the ^{132}Sn 2^+ and 4^+ states to the $h_{11/2}$ neutron hole. The 4447 keV transition to the $11/2^-$ state in ^{131}Sn is thus a counterpart of the 4416 keV E4 ground state transition in ^{132}Sn. In support of this viewpoint, the B(E2)/B(E4) ratios for the transitions deexciting the $(19/2^-)$ and 4^+ states in the two nuclei were found to be almost equal.

We should mention that some high-spin states involving proton particle-hole excitations can also be expected close to the ^{131}Sn yrast line. In ^{132}Sn, the second 8^+ state $\pi g_{7/2} g_{9/2}^{-1}$ comes 630 keV above $(\nu f_{7/2} h_{11/2}^{-1})\ 8^+$, but the strong proton-neutron attraction in $(\pi g_{9/2}^{-1} \nu h_{11/2}^{-1})\ 10^-$ will bring the $(\pi g_{7/2} g_{9/2}^{-1} \nu h_{11/2}^{-1}) 23/2^-$ excitation down several hundred keV; consequently, an admixture of this kind may well contribute to the composition of the ^{131}Sn $23/2^-$ isomer. However, the transition probability of the 159 keV transition deexciting this isomer is determined to be

$$\mathrm{B(E2; 159\ keV)} = 14.5\ e^2\mathrm{fm}^4 \quad \text{or} \quad 0.36\ \mathrm{W.u.}$$

This is essentially the same result as obtained for the $10^+ \rightarrow 8^+$ transition between $\nu h_{11/2}^{-2}$ states in ^{130}Sn [10], indicating that the $\nu f_{7/2} \nu h_{11/2}^{-2}$ contributions are dominant for the ^{131}Sn $19/2^-$ and $23/2^-$ states.

We interpret the 4423, 4558, 4576, and 4989 keV levels in ^{131}Sn as $15/2^+$, $19/2^+$, $17/2^+$, and $21/2^+$ states of $(\nu f_{7/2} h_{11/2}^{-1} d_{3/2}^{-1})$ character. The energies of these states were also calculated, with empirical interactions for $\nu f_{7/2} h_{11/2}^{-1}$ and $\nu f_{7/2} d_{3/2}^{-1}$ from ^{132}Sn, and those for $\nu h_{11/2}^{-1} d_{3/2}^{-1}$ from ^{130}Sn. The results match up excellently with the experimental energies as can be seen in the upper part of Fig. 3. Well below these levels occurs the $17/2^+$ level at 4273 keV, strongly populated following both the 0.32 s ^{131}In β decay and the fission of ^{248}Cm. It is

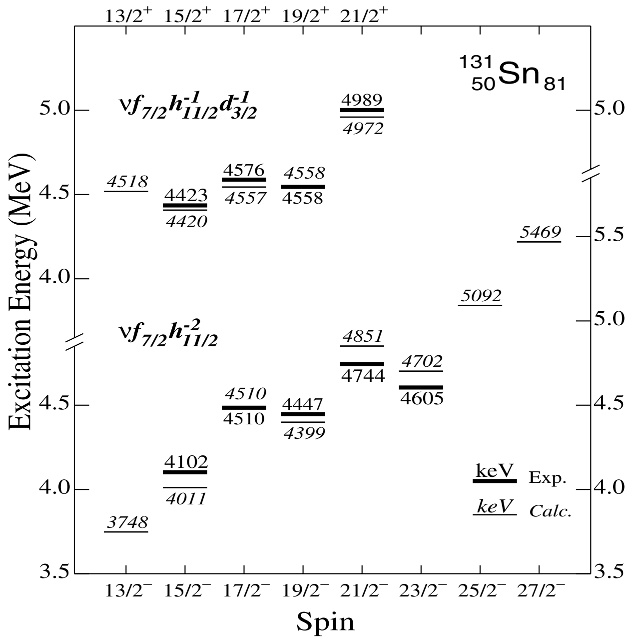

FIG. 3. Comparison of observed level energies in ^{131}Sn with those calculated for $\nu f_{7/2} h_{11/2}^{-2}$ and $\nu f_{7/2} h_{11/2}^{-1} d_{3/2}^{-1}$ yrast states using empirical nucleon-nucleon interactions. The calculated energies are normalized to match the experimental $(17/2^-)$ and $(19/2^+)$ energies in the two multiplets. Experimental and calculated levels are represented by thick and thin lines, respectively.

interpreted as the $\nu h_{11/2}^{-1} \times 3^-$ octupole state with maximum spin coupling. The E3 decay energy of 4273 keV is 78 keV less than the 3^- octupole energy in ^{132}Sn; for the corresponding $\nu i_{13/2}^{-1} \times 3^-$ state with $I^\pi = 19/2^-$ in ^{207}Pb, the E3 decay energy of 2485 keV is 129 keV less than the 3^- octupole energy in ^{208}Pb [11]. The less strongly populated ^{131}Sn levels at 4220 and 4247 keV are probably $\nu h_{11/2}^{-1} \times 3^-$ states also, with lower spins arising from nonstretched coupling of the neutron hole with the 3^- octupole vibration.

The present findings also serve to elucidate our understanding of the ^{131}In β-decay results reported many years ago [3]. We recall that the two strongest β-decay branches identified in decay of the ^{131}In 0.32 s high-spin isomer were a 70% branch with $\log ft = 4.4$ feeding a ^{131}Sn level at 6653 keV (relative to the $\nu h_{11/2}^{-1}$ state) and a 20% branch with $\log ft = 5.5$ feeding the 4605 keV isomeric level included in Fig. 2. The structure of the ^{131}In parent state is believed to be $(\pi g_{9/2}^{-1} \nu f_{7/2} h_{11/2}^{-1}) 23/2^+$, two spin units less than maximum alignment. This $23/2^+$ state can β decay in 3 main ways: by the Gamow-Teller $\pi g_{9/2}^{-1} \to \nu g_{7/2}^{-1}$ transition, or by the first forbidden transitions $\pi g_{9/2}^{-1} \to \nu h_{11/2}^{-1}$ and $\nu f_{7/2} \to \pi g_{7/2}$. The GT transition should be strongest, populating almost exclusively the $(\nu g_{7/2}^{-1} f_{7/2} h_{11/2}^{-1}) 21/2^+$ state because of the coupling scheme; accordingly, this configuration and spin may be assigned with confidence to the 6653 keV ^{131}Sn level. The second transition, $\pi g_{9/2}^{-1} \to \nu h_{11/2}^{-1}$, should also be fairly strong, although somewhat diminished in this case by Pauli blocking between the initial $\nu h_{11/2}^{-1}$ and the created $\nu h_{11/2}^{-1}$ hole. However, the remaining $(\pi g_{9/2}^{-1} \nu f_{7/2} h_{11/2}^{-1})\ 23/2^+ \to (\nu f_{7/2} h_{11/2}^{-2})\ I^-$ decay probability goes predominantly to the $I = 23/2$ member of the $(\nu f h^{-2})$ multiplet and only very weakly to the $21/2^-$ and $25/2^-$ members; the β-decay feeding of the 4605 keV $23/2^-$ isomer may thus be understood. In addition, the third β^- decay mode $\nu f_{7/2} \to \pi g_{7/2}$ should selectively feed the possible $(\pi g_{7/2} g_{9/2}^{-1} \nu h_{11/2}^{-1})\ 23/2^-$ admixture in the 4605 keV state. In summary, only two ^{131}Sn levels are strongly populated in the ^{131}In $23/2^+$ β decay, the 6653 keV level by an allowed Gamow-Teller transition, and the 4605 keV isomeric level in two possible ways by first forbidden transitions.

The present fission product study of prompt and delayed γ-ray cascades in doubly magic ^{132}Sn and its one-neutron-hole neighbor ^{131}Sn has identified yrast excitations in these nuclei up to about 5 MeV. The results have been interpreted in the shell model using empirical nucleon-nucleon interactions, and they should open prospects for broader exploration of the yrast spectroscopy of this important neutron-rich region. These findings should be of special interest in view of the current push to develop radioactive beams, including ^{132}Sn beams, for far-from-stability spectroscopic studies.

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*On leave from Radiochemistry Division, VECC, BARC, Calcutta, India.

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