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Evolution of the $N = 82$ shell gap below ^{132}Sn inferred from core excited states in ^{131}In

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The γ-ray decay of an excited state in ^{131}In, the one proton hole neighbor of the doubly magic ^{132}Sn has been measured. A high-spin, core-excited isomer with $T_{1/2} = 630(60)$ ns was identified following production by both relativistic fragmentation of a ^{136}Xe beam and fission of a ^{238}U beam. This state deexcites by a single γ-ray branch of 3782(2) keV from which direct evidence for the size of the $N = 82$ shell gap is inferred. The results are discussed in comparison to a shell-model calculation including configurations across the closed shells at $N = 82$ and $Z = 50$.

Shell evolution in nuclei has been an outstanding subject in nuclear structure physics of the last decade. Two main mechanisms are predicted to drive the possible shell evolution phenomena: the so-called monopole migration [1] acting for proton-rich nuclei as well as those with neutron excess, and the second, shell quenching due to a softening of the potential shape by excessive neutrons, especially pronounced in very neutron-rich nuclei [2]. These mech-

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anisms modify the known magic numbers as a consequence of shifting effective single-particle levels when going towards either the proton or the neutron drip lines. In medium-heavy nuclei the effort to establish shell evolution concentrates around the ^{100}Sn [3] and ^{132}Sn [4,5] doubly magic nuclei. The Sn isotopes form the longest isotopic chain in the nuclear chart accessible to current experimental study and thus provide a stringent testing ground for nuclear structure models. A remarkable similarity was found between the decay of 8^+ isomers in ^{98}Cd$_{50}$ [6] and ^{130}Cd$_{82}$ [5] which both have a pure $g_{9/2}^{-2}$ proton-hole configuration. However, the analogue of the known core excited isomer in ^{98}Cd [7] was not observed in ^{130}Cd within experimental sensitivity underlining the differences in the underlying neutron single particle structure. The understanding of analogies in the structure of both regions of nuclei and the evolution of the $N = 82$ shell gap below ^{132}Sn is of importance in predicting the path of the rapid-neutron capture r-process which partially drives the production of elements heavier than Fe in nature. Only in one $N = 82$ r-process waiting point nucleus, namely ^{130}Cd [5], have excited states been identified to date. In that case the persistence of the 8^+ isomer and the decay halflife suggested that no substantial shell gap reduction was present.

The expectation that magic numbers may be altered in nuclei far from the valley of stability has provided significant motivation for experiments with rare isotope beams coupled to the most efficient detector setups. At GSI Darmstadt the power of the FRagment Separator (FRS) spectrometer [8] in separating and selecting secondary radioactive beams has been combined with a highly efficient Ge array to form the RISING project [9,10]. The identification of a core excited state in ^{131}In (i.e., the single proton hole neighbour of ^{132}Sn) using the RISING setup, is presented in the current work. The excitation energy of this state provides a more direct measure of the size of the $N = 82$ shell energy gap than the qualitative conclusion drawn from ^{130}Cd isomerism [5]. To date only two β-emitting isomers have been identified above the $(9/2^+)$ ground state in ^{131}In with proposed spin-parity $(1/2^-)$ and $(21/2^+)$ and excitation energies inferred from Q_β measurements [11].

The experiment to identify the γ decay of excited states in ^{131}In was performed using primary beams of ^{136}Xe at 750 MeV/u and ^{238}U at 650 MeV/u to populate ^{131}In following projectile fragmentation and fission reactions on Be targets of 4 g/cm^2 and 1 g/cm^2 thickness, respectively. The secondary beams were separated and identified event-by-event with respect to their nuclear charge (Z) and mass (A) using the FRS [8], and implanted at the final focal plane in a passive stopper made of plastic to reduce the rate of electromagnetic atomic radiation produced during the implantation process. Gamma rays emitted in the isomeric decay process were measured in an array of 15 Cluster detectors [12] from the former Euroball spectrometer [13], which surrounded the stopper in a compact geometry, such that high detection efficiency could be achieved with high granularity. The photo-peak efficiency for the RISING array in the configuration used in the current work covered a range from 3.0(3)% at 45 keV, passing a maximum of 25(1)% at ∼ 65 keV and falling to 5.1(2)% for a 3.8 MeV gamma ray. More details on the Ge array are given in Ref. [10]. Directly after the ion implantion, γ rays were registered within a 50 µs time window.

An identification plot obtained from the fission experiment is shown in Fig. 1 where the A/Z distribution in a gate on implanted $Z = 49$ ions is indicated. A total sum of 175,000 ^{131}In ions were identified in the fission and fragmentation experiments. The γ-ray spectrum in delayed coincidence with fully stripped ^{131}In ions is shown in Fig. 2. Only one γ ray transition at 3782(2) keV energy is clearly visible. Additional counts of this γ ray were registered at 3271(2) keV from the single escape peak. The halflife of the

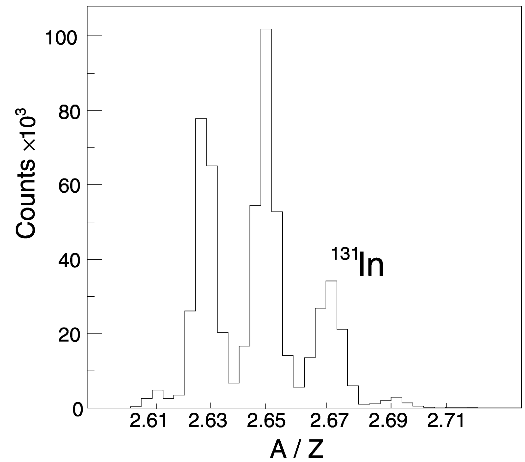

Fig. 1. The experimental spectrum of the A/Z value for In isotopes obtained in the fission experiment.

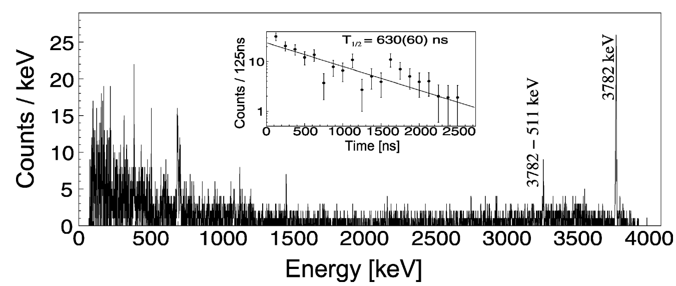

Fig. 2. Gamma ray energy spectrum of the isomeric decay in ^{131}In. Inset: Time distribution of the 3782 keV transition with a single component exponential fit.

isomeric state was extracted based on a least-squares fit of the time distribution of the 3782 keV transition to a single exponential decay curve, resulting in a value of $T_{1/2} = 630(60)$ ns as shown in the inset of Fig. 2. No other transitions associated with ^{131}In were observed within the sensitivity range i.e., from 55 keV to 6 MeV. For any transition with lower than the observed energy the efficiency would be significantly higher unless such transitions were highly converted. Low-energy transitions of different possible multipolarities are distinguished by their decay modes (conversion electron vs. γ-ray emission) and γ detection sensitivity. Assuming the same total intensity for a low-energy transition as for the 3782 keV line, the lower γ-ray observational limits of 52, 59, and 77 keV for E1, M1, and E2 transitions, respectively, were extracted based on the experimental data.

If the isomer decays by a 100% branch of a non-observed primary transition with an energy between the observational limit and the indium L-binding energy, the following limits for transition probabilities are derived from the measured half life: 1.3×10^{-6} W.u. $\leqslant B(\mathrm{E1}) \leqslant 3.0 \times 10^{-5}$ W.u., 1.5 W.u. $\leqslant B(\mathrm{E2}) \leqslant 9.2$ W.u., and 0.38×10^{-4} W.u. $\leqslant B(\mathrm{M1}) \leqslant 6.4 \times 10^{-4}$ W.u., respectively. The possibility of an $M1$ transition can be ruled out as values of 10^{-4} W.u. correspond to a retardation an order of magnitude larger than has been observed for M1 transitions between core excited states in ^{132}Sn [14]. The required E2 strength is rather large in comparison to the strengths of less than the 0.6 W.u. observed between core excited states in ^{132}Sn [14] but cannot be firmly excluded. Allowing E1 or E2 multipolarity for a possible non-observed transition in cascade with a $\Delta I = 0 - 3$ fast 3782 keV γ ray to the $(9/2^+)$ ground state would require a competing, high energy crossover transition of multipolarity E3, M3, E4 which would be well within the detection sensitivity. A lower multipolarity cross-over transition would destroy the isomerism while higher multipolarity transitions such as M4, M5, E5 would have too

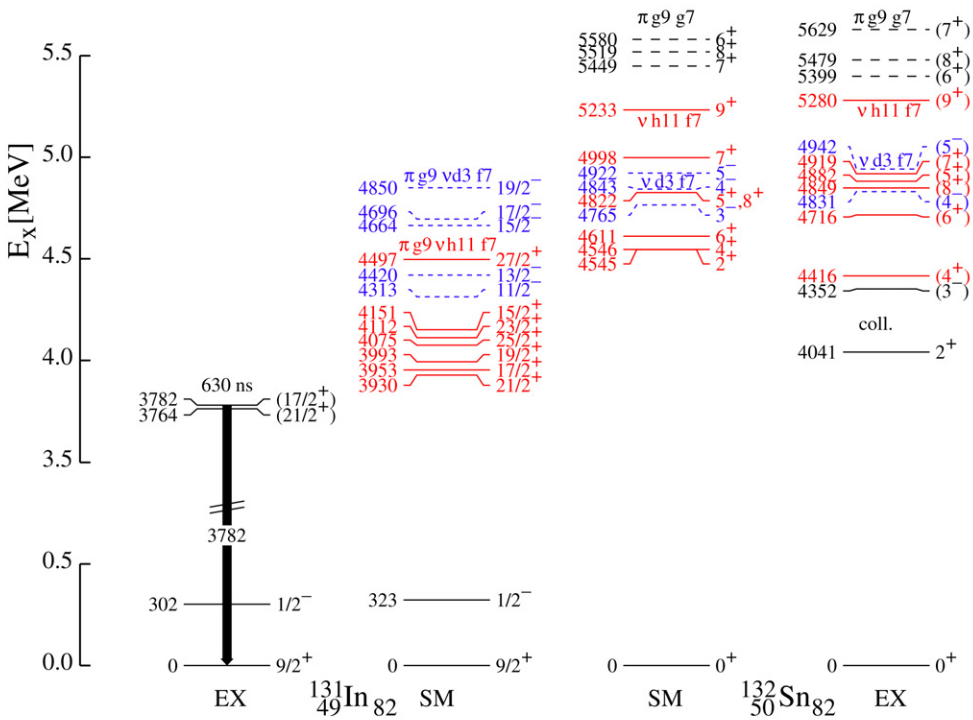

Fig. 3. Experimental level scheme in comparison to shell model calculation for [131]In and [132]Sn (colored in electronic version). The core excited states are labelled according to their leading configuration $\nu h_{11/2}^{-1} f_{7/2}$ (red—full line), $\nu d_{3/2}^{-1} f_{7/2}$ (blue—short-dashed) and $\pi g_{9/2}^{-1} g_{7/2}$ (black—long dashed). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

small partial width to compete. This leaves possible spin-parity assignments of $17/2^{\pm}$ and $19/2^{-}$for the isomer in this scenario as $19/2^{+}$ would allow an $M1$ to the $21/2^{+}$ isomer at variance with the observed half life (see above). Odd-parity assignments are unlikely as the corresponding odd-parity $(4,5)^{-}$ core states in ^{132}Sn needed to couple the proton $g_{9/2}$ hole to the required spin lie 400–500 keV above the 4^{+} state which can be coupled to $17/2^{+}$ (see Fig. 3).

A 3782 keV primary transition is compatible with E4 multipolarity, resulting in a $(17/2^{+})$ assignment for the isomer with decay strength of $B(\text{E4}) = 1.48(14)$ W.u., similar to those reported in ^{132}Sn [14] and ^{98}Cd [7]. Any single γ ray or cascade feeding the $(1/2^{-})$ isomer can be excluded due to fast competing branches from the isomer to the ground state or the $(1/2^{-})$ state. On this basis, we assigned the observed 3782 keV transition to the direct decay from a $I^{\pi} = (17/2^{+})$ isomer to the ground state.

The isomeric ratio, defined as the ratio of nuclei in excited states to the total number of nuclei amounts to 4.0(4)% averaged from fission and fragmentation data and is consistent with a relatively high spin and/or non yrast isomeric state [15,16], consistent with the proposed $(17/2^{+})$ assignment.

The ground state of ^{131}In is reported from beta decay measurements to be $(9/2^{+})$ [11] and is understood as one proton hole in the $g_{9/2}$ orbital. The first excited state at 302 keV energy [17] is the isomeric $(1/2^{-})$ state [11] formed when a proton from the $p_{1/2}$ orbit is excited, thereby filling the $g_{9/2}$ orbital. In the same work a high-spin beta-decaying isomer at 3764(88) keV excitation energy was also observed and interpreted as a $(21/2^{+})$ state based on its feeding to the $19/2^{+}$, $19/2^{-}$ and the $(23/2^{-})$ states in the daughter ^{131}Sn. In this earlier work [11] a neutron core excitation $\pi g_{9/2}^{-1} \nu h_{11/2}^{-1} f_{7/2}$ configuration was suggested for this isomer based on the fact that no proton-hole state configuration could explain the existence of that high-spin state. In the present work, due to the finite time correlation window, no beta decaying states were associated with γ rays and only the direct γ decay from isomeric states was registered. The proposed $(17/2^{+})$ state established at an excitation energy of 3782 keV must therefore lie above the $(21/2^{+})$ isomer at 3764(88) keV [11,14]. A possible highly converted, low energy E2 branch to this state makes the measured E4 strength an upper limit and explains the small isomeric ratio.

We have performed shell-model calculations in the proton $\pi(p_{1/2}, g_{9/2}, g_{7/2}, d_{5/2})$ and neutron $\nu(s_{1/2}, h_{11/2}, d_{3/2}, f_{7/2}, h_{9/2})$ model space using a ^{132}Sn core and experimental single-particle (hole) energies [14,18]. The two-body matrix elements (TBME) of the residual interaction were inferred from a realistic interaction for ^{208}Pb [19], one harmonic oscillator shell higher, replacing single-particle orbits (n, l, j) by $(n, l-1, j-1)$, which maintains the proper radial wave functions following the prescription given in Ref. [20]. The interaction strength was scaled up by $(208/132)^{1/3}$, and for intermediate spins in a multiplet interpolated according to their angular orbital overlap [21]. Calculations were performed using the code OXBASH [22]. Only $1p1h$ excitations were allowed for each valence orbit. The ph TBME for the 4^{+}, 6^{+} and 9^{+} states of the $\nu h_{11/2}^{-1} f_{7/2}$ configuration, and the 3^{-} state of the $\nu d_{3/2}^{-1} f_{7/2}$ were changed by −200, −200, +200, and −250 keV, respectively, to improve the relative level positions in the benchmark nucleus ^{132}Sn. In addition the monopoles for the $\nu h_{11/2}^{-1} f_{7/2}$, $\nu d_{3/2}^{-1} f_{7/2}$ and $\pi g_{9/2}^{-1} g_{7/2}$ multiplets were tuned to reproduce the corresponding unambiguously identified members of the multiplets in ^{132}Sn. These modifications compensate partly for the truncation which affects low-spin states in the multiplets stronger than the stretched coupled states. E2 and E4 transition strengths were calculated with effective charges of 1.5 e [5] and 0.7 e [23] for protons and neutrons, respectively. The results for levels in ^{132}Sn and ^{131}In are compared to experiment in Fig. 3. For ^{132}Sn a one-to-one correspondence between the experimental and shell model sequences of states is found with neutron core excitations being energetically favoured. The low-spin states $I^{\pi} = 2^{+}, (4^{+}), (3^{-})$ of collective character cannot be expected to be reproduced quantitatively in a $1p1h$ calculation. The high-spin states such as $I^{\pi} = 9^{+}$ agree well with experiment. Deviations are therefore ascribed to the truncation and the interaction is considered to be reliable. For ^{131}In the shell-model level sequence supports the spin-parity assignments of the isomers in the present and previous work. The predicted E4 strength of the $(17/2^+) \to (9/2^+)$ transition in ^{131}In is calculated to be 2.4 W.u., which compares well with the experimental upper limit of 1.6 W.u. which takes into account a possible non-observed E2 branch to the $(21/2^+)$ isomer. The reduction of the strength relative to the $4^+ \to 0^+$ transition in ^{132}Sn is due to the fact that the $17/2^+$ wave function besides the $g^{-1}_{9/2} \times 4^+$ components contains also couplings to the higher spin $(5\text{–}9)^+$ states which do not contribute to the E4 transition. With the shell model prediction of $B(\mathrm{E2}; 17/2^+) \to (21/2^+) = 0.29$ W.u. a total branch of $\leqslant 17\%$, which includes electron conversion and γ decay, is calculated for transition energies below the observational limit of 77 keV.

The extraction of a shell gap from the excitation energies of the $I^\pi = (21/2^+)$ and $(17/2^+)$ isomers in ^{131}In requires a careful assessment of the residual interaction. The standard procedure to extract a shell gap Δ for an even-even core nucleus involves the ground state binding energies (BE) of its odd–even neighbours according to $\Delta(Z,N) = 2\mathrm{BE}(Z,N) - \mathrm{BE}(Z,N+1) - \mathrm{BE}(Z,N-1)$ for neutrons and for protons accordingly [24]. This is equivalent within a few tens of keV to the spin-multiplicity weighted average of the excitation energies of a complete multiplet which can be verified for ^{132}Sn (Fig. 3) even if the low-spin $I^\pi = 2^+$ (collective) and 3^+ (not known) states are omitted. This method, however, is not applicable to an odd–even core nucleus like ^{131}In as the BE of the odd–odd neighbours is strongly determined by the residual interaction which is binding in the hole-hole neighbour ^{130}In while it is repulsive in the particle-hole case of ^{132}In. The $Z = 50$ shell gaps in the Sn isotopic chain provide a textbook example for this effect. The effect is evident in the SM results of Fig. 3, where the centroids of the $\nu h^{-1}_{11/2} f_{7/2}$ multiplet in ^{132}Sn and the respective $\pi g_{9/2} \nu h^{-1}_{11/2} f_{7/2}$ states in ^{131}In are shifted by about 910 keV which would indicate an apparently dramatic but erroneous shell gap reduction. The overall good agreement for core excited states in ^{132}Sn and ^{131}In in both sequence and maximum spin states, suggests that the interaction for the respective *ph* multiplets is well accounted for in the shell model calculation, which therefore can be used to infer consistently with ^{132}Sn a shell gap Δ for the even-even core ^{130}Cd from the calculated ground state binding energies of $^{129\text{–}131}$Cd. The result is a considerable decrease of the ^{132}Sn neutron gap of 4.89(8) MeV [14] by 610(100) keV which, however, is in the range of e.g. the reduction of the $Z = 50$ gap from $N = 82$ to 80 [25] of 680 keV. The uncertainty of the reduction due to interaction and truncation is estimated from the mean level deviation [21] within the $\nu h^{-1}_{11/2} f_{7/2}$ multiplet in ^{132}Sn and includes the experimental error in the $N = 82$ gap in the core nucleus. It is therefore concluded that the shell-gap reduction does not need any quenching mechanism due to excessive neutrons but can be explained by classical monopole-driven shell evolution. We note in passing that the interaction used does not predict a $1p1h$ isomer in ^{130}Cd.

In conclusion, a core-excited γ-decaying isomer has been identified in ^{131}In using the RISING-FRS setup. The data on energies and transition strengths are well reproduced by shell model calculations including $1p1h$ configurations. Based on the calculations, the shell gap in ^{130}Cd is inferred and interpreted as monopole driven.

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References

[1] T. Otsuka, et al., Phys. Rev. Lett. 95 (2005) 232502.
[2] J. Dobaczewski, I. Hamamoto, W. Nazarewicz, J.A. Sheik, Phys. Rev. Lett. 72 (1994) 981.
[3] H. Grawe, et al., Eur. Phys. J. 27 (2006) 257.
[4] A. Shergur, et al., Eur. Phys. J. A 25 (2005) 121.
[5] A. Jungclaus, et al., Phys. Rev. Lett. 99 (2007) 132501.
[6] M. Górska, et al., Phys. Rev. Lett. 79 (1997) 2415.
[7] A. Blazhev, et al., Phys. Rev. C 69 (2004) 064304.
[8] H. Geissel, et al., Nucl. Instrum. Methods Phys. Res. B 70 (1992) 286.
[9] H.-J. Wollersheim, et al., Nucl. Instrum. Methods Phys. Res. A 537 (2006) 637.
[10] S. Pietri, et al., Nucl. Instrum. Methods Phys. Res. B 261 (2007) 1079.
[11] B. Fogelberg, J. Blomqvist, Nucl. Phys. A 429 (1984) 205.
[12] J. Eberth, et al., Nucl. Instrum. Methods Phys. Res. A 369 (1996) 135.
[13] J. Simpson, Z. Phys. A 358 (1997) 139.
[14] ENSDF database, http://www.nndc.bnl.gov/ensdf/.
[15] M. Pfützner, et al., Phys. Rev. C 65 (2002) 064604.
[16] Zs. Podolyak, et al., Phys. Lett. B 632 (2006) 203.
[17] B. Fogelberg, et al., Phys. Rev. C 70 (2004) 034312.
[18] H. Grawe, K. Langanke, G. Martínez-Pinedo, Rep. Prog. Phys. 70 (2007) 1525.
[19] E.K. Warburton, Phys. Rev. C 44 (1991) 233.
[20] J. Blomqvist, CERN Report No. 81-09, CERN, Geneva, 1981, p. 535.
[21] H. Grawe, Springer Lect. Notes Phys. 651 (2004) 33.
[22] B.A. Brown et al., Oxbash for windows, MSU-NSCL report 1289, 2004.
[23] R. Lozeva, et al., Phys. Rev. C 77 (2008) 064313.
[24] B.A. Brown, Rep. Progr. Phys. 47 (2001) 517.
[25] A.H. Wapstra, G. Audi, C. Thibault, Nucl. Phys. A 729 (2003) 337.