

Are the nuclei beyond ^{132}Sn very exotic?

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Abstract. The term exotic nucleus is used for nuclei that have different from normal behavior. However, it turns out that the term normal is valid only for nuclei close to stability and more particularly for regions close to double-shell closures. As long as one drives away in the neutron-rich nuclei, especially at intermediate mass number, interplay between normal single-particle and many collective particle-hole excitations compete. In some cases with the addition of neutrons, these may turn to evolve as a skin, acting against the core nucleus that may also influence its shell evolution. Knowledge of these nuclear ingredients is especially interesting beyond the doubly-magic ^{132}Sn , however a little is known on how the excitations modes develop with the addition of both protons and neutrons. Especially for the Sb nuclei, where one gradually increases these valence particles, the orbital evolution and its impact on exoticness is very intriguing. Experimental studies were conducted on several such isotopes using isomer and β -decay spectroscopy at RIBF within EURICA. In particular, new data on ^{140}Sb and ^{136}Sb are examined and investigated in the framework of shell model calculations.

1. Introduction

One particular region on nuclei receives a special attention from both experiment and theory since several decades. These are the chain of Sn nuclei, known to have superfluid characteristics, owing to the constant behavior of their 2^+ and 4^+ excitation energies all over the whole isotopic chain. Moreover, experimental data confirms the well developed $Z=50$ and $N=82$ magicity, contrary to some suggestions for a shell quenching in the neutron-rich Sn isotopes due to a neutron excess and a reduction in the spin-orbit force [1]. With increasing the proton particles or the neutron holes from the doubly-magic ^{132}Sn , a different behavior can be seen, particularly related to the $\pi g_{7/2}$ - $\pi d_{5/2}$ orbitals. For example, with increasing Z in the semi-magic $N=82$ isotones, the 2^+ , 4^+ excitation energies exhibit a hump at $Z=64$, indicating a sub-shell closure of the $\pi g_{7/2}$ - $\pi d_{5/2}$ orbitals [2].

Following the systematics of the low-lying states in the odd-even Sn isotopes below $N = 82$, compared to the even-odd $N=82$ isotones, one can trace that the difference in their spectra with respect to the even-even nuclei is rather large. Their evolution shows that the levels are compressed at $N, Z=64$, manifesting a clear decoupling of $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals with respect to the other three. It is therefore believed (as observed in the lowered energies of the $1/2^+$, $3/2^+$



and $11/2^-$ states in $^{142}_{65}\text{Tb}_{77}$) that the gap between the proton $d_{5/2}$, $g_{7/2}$ and the $d_{3/2}$, $s_{1/2}$ and $h_{11/2}$ orbitals is responsible for the rise of the 2^+ , 4^+ excitation energies in $^{146}_{64}\text{Gd}_{82}$ [2, 3, 4]. On the contrary for the Sn isotopes, the $1/2^+$, $3/2^+$ and $11/2^-$ decrease fast to mix up with the $5/2^+$, $7/2^+$ in $^{111}_{50}\text{Sn}_{61}$ [2, 3].

2. Physics motivation

The orbital evolution beyond ^{132}Sn is expected to be similar to the one below $N=82$ and $Z=50$. On one side, the interaction of the $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals with the $\nu h_{11/2}$ orbital shall persist due to the same parity of $\nu f_{7/2}$, resulting in repulsion of $\pi d_{5/2}$ and $\pi g_{7/2}$. However, experimental data manifest the opposite behavior with a fast drop for ^{133}Sb [5] and ^{135}Sb [6] in the observed position of the $5/2^+$ states with respect to the $7/2^+$ g.s. Interestingly, this effect was also detected for the I nuclei beyond ^{132}Sn where also drop was observed for the measured $5/2^+$ states. Several explanations were given in this context, from decrease of $\pi d_{5/2}$ and $\pi g_{7/2}$ spacing needed in shell model (SM) calculations in order to explain the experimental data in ^{135}Sb and ^{136}I [7, 8, 9], to an additional seniority mixing in the wave functions of these states [10]. According to some of the calculations, the distance between $\pi d_{5/2}$ and $\pi g_{7/2}$ decreases with both N and Z [11]. Thus, one may expect their crossing for the more exotic nuclei. The evolution of these particular proton orbitals was suggested to be related to the development of a neutron skin in the neutron-rich isotopes beyond ^{132}Sn [12]. For example, according to Mean field (MF) calculations, using SKX Skyrme interaction [13], a decreased spacing was predicted with the increase of Z . Suggestion about the same proton orbital evolution with N was given using HFB-D1S calculations [14], with a possible crossing at $N=90$. They indicated, that the radii of the systems and the spin-orbit interaction, known to be concentrated mainly at the nuclear surface, play an important role in such crossing, even though some additional $\pi\nu$ interactions also may give a contribution. It is challenging to find how such expectations would influence the excited schemes in these very exotic nuclei and could these be directly related to the formation of skin.

The evolution of the neutron orbitals beyond ^{132}Sn is also intriguing. With the increase of the neutrons, using empirical SM calculations [11], an opening of a sub-shell gap (of about 2 MeV) was suggested at $N=90$ between the $\nu p_{3/2}$ and $\nu f_{7/2}$ orbitals. At the end of the $\nu f_{7/2}$ shell (^{140}Sn) similar effect was independently proposed in the MF calculations using the Cooper-pair formalism [15]. Investigating the effect on the transition rates of $(f_{7/2}^n)_{6+}$ isomers, where n equals the number of valence neutrons in $^{134-138}\text{Sn}$, it was shown in [16] that one would expect apparent differences for these nuclei which were not seen. Therefore, the expected gap would be inconsistent with the isomer data [17], similarly to the purely theoretical conclusion of [18].

With the increase of both π and ν , anomalies were observed also in Te 2^+ excitation energies, dropping fast beyond $N=82$, similarly to the odd-proton Sb. In SM calculations [19], it was pointed out that increasing the neutron weight in the lowest collective 2^+ states, strong $p-n$ exchange asymmetry is developing with the addition of π between the Te and Xe isotopes. Along, strong polarisation effects were proposed also for the odd-proton I nuclei, as unexplained isomerism was observed in ^{138}I and exchange in g.s. spin/parity was detected between ^{138}I and ^{140}I [20]. Therefore, the interplay of several effects would influence the structure of the isotopes beyond ^{132}Sn and it is an experimental challenge to measure them and provide crucial ingredients to their understanding and the development of theory.

3. Experimental techniques

The experimental studies were performed using an isomer and β -decay measurement technique at the RIBF facility at RIKEN [21] in the framework of the EURICA project [22, 23]. The system represented one of the most powerful to date combinations of high-intensity uranium beams and a highly efficient γ -ray detector system. It enabled new and detailed spectroscopic studies from

light to heavy very-neutron rich nuclei carried out within several experimental campaigns. In this case, an in-flight $^{238}\text{U}^{86+}$ fission at 345 MeV/u was initiated on ^9Be target with a thickness of 2.9 mm. The beam intensity varied between 1-5 pA during the measurement time. The nuclei of interest were transported and selected by the BigRIPS and ZeroDegree spectrometers [24] and identified using the standard $\Delta E - ToF - B\rho$ method and a system of tracking and identification detectors at the focal planes [25]. The ions were further implanted in the wide-range active stopper for β and ion detection, WAS3ABi, comprising of a stack of five (1 mm thick) Double-Sided Silicon-Strip detectors (DSSSD) detectors with a segmentation of 60×40 strips (1-mm pitch) [22, 23].

For the nuclei produced in an isomeric state, with lifetime long enough to survive in-flight decay through the spectrometers (of the order of 600 ns), delayed γ rays were observed after their implantation. These were detected using the EURICA (4π) array surrounding the stopper (in a close-packed geometry), assembled from twelve Ge Cluster detectors (of seven HPGe crystals). Ion- γ coincidences (for isomeric or β -decay studies) were acquired for different time windows after the implantation using either a standard TDC for short- (μs) or DGF for a longer- (tens of μs) time ranges. Other experimental details can be found in [26, 27, 28, 29].

4. The Sb isotopes

In these studies we populated five exotic Sb isotopes between ^{136}Sb and ^{140}Sb [26], thus systematic studies could be performed. The data was in addition compared to earlier experiments on ^{134}Sb and ^{136}Sb at the beginning of the same $\nu f_{7/2}$ shell [2]. Low- and intermediate-energy states in these Sb nuclei were described in analogy with ^{210}Bi [30, 31, 8] and ^{212}Bi [32, 33], considered in the evolution of the equivalent $\pi g_{7/2}\nu f_{7/2}$ and $\pi h_{9/2}\nu g_{9/2}$ proton-neutron multiplets in the two different neutron-rich mass-regions. No data on the evolution of this resemblance for the more exotic species was, however, available up to date.

4.1. Earlier observations

A long-lived (10.07(5) s [34]) β -decaying isomer was reported in ^{134}Sb ($T_{1/2}(\text{g.s.}) = 0.75(7)$ s [35]), assigned as a 7^- level [36]. It was placed at 279 keV [8] together with other yrast states observed in an earlier fission fragment study [30]. The low-spin structure of ^{134}Sb was assigned from several β -decay studies: [37] suggested 0^- g.s. followed by a 1^- level 13 keV higher in energy, in contrast to the 1^- level proposed earlier at about 300 keV [35]. Spins 2^- , 3^- and 4^- were assigned to the other observed states below 1 MeV and reasonably explained with SM and Kuo-Herling (KH) interaction KH5082 [37]. However, according to some of the calculations (using scaled and unscaled KH208 and KH5082 for $p-n$) in [8] also 1^- g.s. should be considered, although they could describe the data of [35] using CD Bonn (for $n-n$). The long-lived state was attributed to the lowest member of the multiplet (0^- to 7^-), whose wave function was dominated (by 90% or more) with the $\pi g_{7/2}\nu f_{7/2}$ configuration, while the isomeric state was interpreted to the maximum-aligned configuration.

An isomer of the same $p-n$ excitation with suggested $\pi g_{7/2}\nu f_{7/2}^3$ configuration was observed also in ^{136}Sb [38, 39, 40]. A spin/parity (6^-) was suggested due to its appearance as an yrast trap, in contrast to the maximum-aligned configuration trap 7^- as in ^{134}Sb . For ^{136}Sb , in ^{238}U projectile fission at relativistic energies only one isomeric γ -ray of 173 keV was detected [38] with $T_{1/2}=565(50)$ ns. In a later work [39], the ^{136}Sb isomer was populated using (thermal) neutron-induced ^{241}Pu fission together with other $A=136$ isobars and detected using γ and conversion-electron spectroscopy with $T_{1/2}=480(100)$ ns. In that case, except the 173.0 keV transition, another low-energy γ -ray of 53.4(3) keV was identified to belong to the isomeric decay. The conversion electron (Si) spectrum in coincidence with 173.0 (Ge) line suggested another candidate, calculated to be a 51.4(5) keV γ transition, which was consistent with their

analysis of more than two transitions with $M1 - E2$ multipolarity. The unobserved transition was set as the isomeric (followed by the cascade of the other two transitions) in the level scheme, constructed in accordance to SM calculations [32, 39]. In a more recent ^{238}U fission run, however, no sign of this low-energy line was seen, reporting only the two γ rays of 53.9 keV and 173.1 keV and $T_{1/2}=570(5)$ ns [40].

The g.s. of ^{136}Sb was suggested to have a spin/parity of 1^- from β -decay data [41], mainly in analogy to ^{212}Bi (with g.s. of 1^-). It was questioned in some later theoretical works, supporting 2^- assignment, as such a scenario allowed them to better describe experimental data in the neighboring $^{134,135}\text{Sb}$, as well as the $N=84$ isotones [44, 9]. No spectroscopy results are currently known for the isotopes beyond ^{136}Sb with very few outcomes from first β -decay and g.s. lifetime measurement on ^{137}Sb , performed in [12, 42].

4.2. New experimental observations

In the current studies, for ^{136}Sb , we detected three (mutually-coincident) delayed γ -rays with $T_{1/2}=489(40)$ ns. Two of them, the 53.4 keV and the 172.5 keV transitions, were already observed and a third, unobserved, transition was placed in the level scheme [39]. In our case instead, we identified another low-energy line of 43.4 keV, to which we assigned $M1$ multipolarity using the intensity ratios between all observed transitions and theoretical conversion coefficients from [43]. With our data set, we suggested a different multipolarity for the 53.4 keV line of $E2$ type, while for the 172.5 keV γ -ray the known $E2$ multipolarity seemed consistent with our work. Further experimental details on these new observations are given elsewhere [27]. Taking into account all four studies available on this isomer [27, 38, 39, 40], the adopted $T_{1/2}$ amounts to 533(40) ns.

We rearranged the level scheme with the new information by placing the observed 53.4 keV as isomeric transition and by changing the energy of the first excited state to 43.4 keV. Comparing our results to SM calculations using the KH interaction [29], we confirmed the earlier suggestions for the isomer spin/parity of (6^-) . The level scheme is presented in comparison to ^{134}Sb in Fig.1.

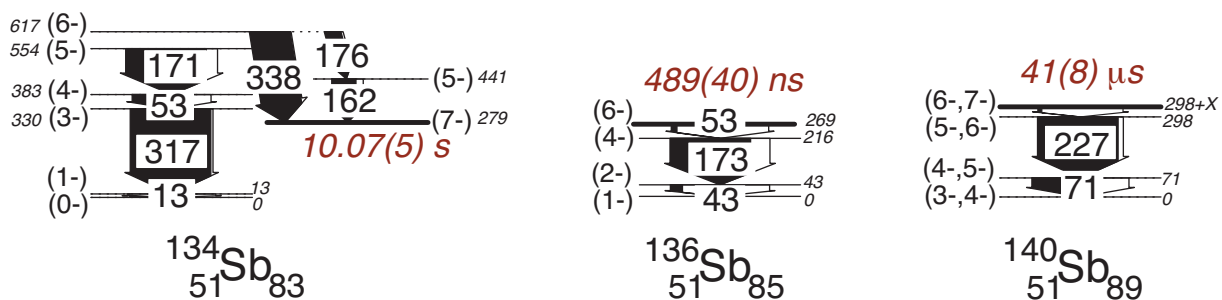


Figure 1. Isomeric level schemes in the neutron-rich Sb isotopes with $A=134-140$.

Furthermore, with these studies we were able to provide first spectroscopic data on ^{140}Sb [29]. We detected two (mutually-coincident) delayed γ transitions of 70.9(8) and 227.3(5) keV with $T_{1/2} = 41(8)$ μs . Using intensity analysis and conversion coefficients, we assigned their order in the level scheme as shown in Fig.1. However, according to our estimates another low-energy line shall be responsible for the isomeric lifetime, with an energy below our detection threshold. Both $M1$ and $E2$ multipolarity are possible for this transition [29]. In addition, according to our β -decay $^{140}\text{Sb} \rightarrow ^{140}\text{Te}$ analysis [45]), for the g.s. of ^{140}Sb both (3^-) and (4^-) options are probable. Thus, for the higher-lying states in the level scheme we proposed two respective possibilities, in

accordance to the available experimental information. As a consequence of that, for the isomeric state both (6^-) and (7^-) spin/parities are probable.

4.3. Interpretation and discussion

Despite the origin of its excited states, the level scheme of ^{136}Sb is certainly much different in comparison to the one in ^{134}Sb (see Fig.1) due to the extra neutrons. Their isomeric states are also suggested to be with $\pi g_{7/2}^1 \otimes \nu f_{7/2}^1$ in ^{134}Sb and $\pi g_{7/2}^1 \otimes \nu f_{7/2}^3$ in ^{136}Sb configurations.

As described in [27], we performed SM calculations using ^{132}Sn as a core nucleus and the whole valence space beyond. The yrast schemes for all of the three isotopes are shown in Fig.2 and compared to the experimental data. For these calculations the KH interaction was employed, shown already to be successful in the description of the ^{134}Sb nucleus [37], and the neutron-rich $N=82-84$ isotones near ^{132}Sn [44]. The results for ^{134}Sb (Fig.2(a)) are compared to the those for ^{136}Sb (Fig.2(b)) and ^{140}Sb (Fig.2(c)). A modification of the KH interaction [29] was employed for the better description of ^{140}Sb (Fig.2(d)). As it can be seen, the yrast spin traps for both $^{134,136}\text{Sb}$ are well reproduced with the original version of the KH interaction, however the ^{140}Sb seemed to be difficult as only traps for the g.s. could be expected with largely compressed levels in variance to the observed by the experiment. In order to tune the modified KH interaction, we used experimental information from the neighboring isotopes [45, 46], including [17]. We may note that the energy compression, especially for the 6^- and 7^- levels, may be further reduced, resulting in an increased spacing with respect to the lower-lying states. This is, however, at the expense of the g.s. information for the neighboring ^{139}Sb and ^{141}Sb nuclei. In this case it was set to the g.s. of ^{139}Sb according to our experimental information [46], in order to constrain the observable. In the modified version of the KH interaction, we inspected yrast (I excited) and yrare (II excited) states. As no spin-traps are expected (see Fig.2(d)), except for the (2^- and 4^-) candidates for the g.s., we suggested the possibility of occupying both yrast and yrare states in the isomeric decay. We note that such a scenario would be consistent with the observed isomeric ratios that we determined for $^{136,140}\text{Sb}$ [27, 29].

Concerning ^{136}Sb , theoretically, the 2^- state can be expected at less than a keV distance from the 1^- state, thus one may clearly have both possibilities for g.s. spin/parity. Although our data [27] would more be consistent with the 1^- assignment due to the order of the transitions and their multipolarity, a firm measurement would be extremely valuable for fixing one of them with a larger certitude. Concerning ^{140}Sb , theoretically, the 2^- state can be expected as a g.s. for this nucleus, closely followed by a 4^- state. Experimentally, such scenario would be in variance with the observed transitions and lifetimes of the populated states [29], therefore the 4^- suggestion would be more appropriate.

According to the calculations, the g.s. and the first excited states in ^{136}Sb are characterized by dominant $\nu f_{7/2}^3 \otimes \pi g_{7/2}^1$ component, which contributes to 66% of the wave function, in comparison to about 90% in ^{134}Sb . The $\nu f_{7/2}^{-1} \otimes \pi g_{7/2}^1$ component in ^{140}Sb amounts to about 60% for both the 6^- and 7^- states, according to the calculations. Therefore, one can conclude that the same isomeric structure is kept all over the whole $\nu f_{7/2}$ shell.

In order to search for isomeric candidates in ^{140}Sb we examined in detail the configurations of all excited states. We found, for example, that all of the low-lying states contained the strongly occupied $\pi d_{5/2}$ orbital, while the occupation of $\pi g_{7/2}$ was sizable only for the first 6^- and 7^- states. In contrast, the occupation of the $\pi d_{5/2}$ orbital was expected to be very weak in the lighter Sb isotopes as e.g. in ^{136}Sb . Based on detailed analysis of transition rates and orbital occupations [29], we interpreted the isomeric state to arise most probably due the change of the configuration. It shall result from the crossing of the $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals at this extreme neutron number and provides valuable information about their evolution in the very neutron-rich Sb isotopes. Our conclusion correlates also with the predictions for crossing between these

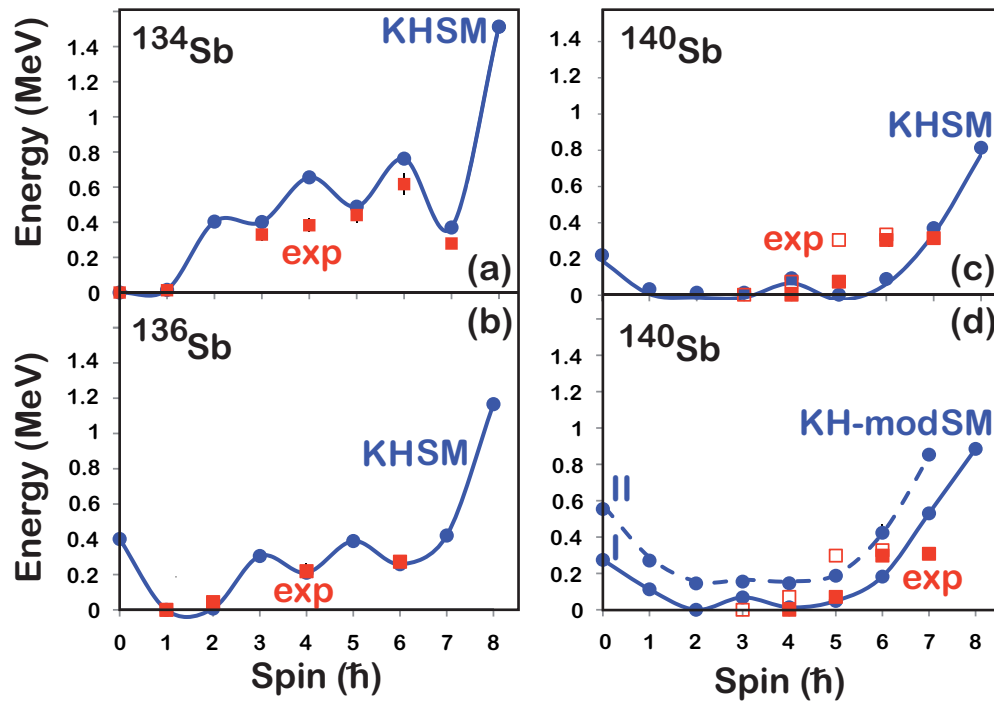


Figure 2. Yrast schemes in ^{134}Sb (a) and ^{136}Sb (b) compared to yrast (I excited) and yrare (II excited) states in ^{140}Sb (c,d) are shown by full and dashed lines, respectively. SM calculations using KH interaction (a,b,c) and modified KH interaction (d) are given for comparison with the experiment. The experimental data for ^{140}Sb , separating the two possible options for spin/parities (see text), are shown with empty and full squares.

π orbitals at $N=90$ [14], that we experimentally evidence at $N=89$. Thus, we may conclude, that the large amount of neutrons are strongly influencing the proton shell evolution beyond ^{132}Sn which may effect the development of a neutron skin [12, 47].

5. Summary and Outlook

Among the very neutron-rich isotopes beyond ^{132}Sn which we populated and analyzed (subject to several forthcoming articles), we observed five Sb isotopes, with ^{140}Sb being the most n-rich known up to date. Therefore, the study provides extension of the spectroscopy knowledge at extreme neutron number and probes the evolution of the excited states in these nuclei. The level scheme of the known (6^-) isomer in ^{136}Sb was revised with new experimental information and a new isomeric state was detected in ^{140}Sb with a most probable spin/parity of (6^-) . While for ^{136}Sb we confirmed the appearance of an yrast isomer, for ^{138}Sb , we did not detect an isomeric state in the μs lifetime range. The isomer we found again in ^{140}Sb was observed with a much longer μs lifetime, and both yrast and yrare states were suggested to be populated in its decay. Interpretation of the new information was performed in the SM framework using realistic interaction, suggesting that the configuration of the isomeric state in ^{140}Sb is similar to that in the lighter $^{134,136}\text{Sb}$ nuclei. It results from the coupling $\pi g_{7/2}^1 \nu f_{7/2}^{-1}$ and possibly appears due to the interchanging position of the $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals at $N=89$. The results from the coupling of two additional protons to the system is a subject to another forthcoming article, where interestingly we observe another isomeric state at the same $N=89$.

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