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INVESTIGATING CORE EXCITATIONS IN THE ^{131}Sn ONE-VALENCE-HOLE NUCLEUS*

S. Bottoni[a,b,†], Ł.W. Iskra[b,c,‡], S. Leoni[a,b], B. Fornal[c]
G. Colò[a,b], D. Bazzacco[d], L. Gatti[a], G. Benzoni[b], A. Blanc[e]
G. Bocchi[a,b], A. Bracco[a,b], N. Cieplicka-Oryńczak[c]
F.C.L. Crespi[a,b], M. Jentschel[e], U. Köster[e], C. Michelagnoli[e]
B. Million[b], P. Mutti[e], T. Soldner[e], C.A. Ur[f], W. Urban[g]

and the EXILL Collaboration

[a]Dipartimento di Fisica, Università degli Studi di Milano, 20133 Milano, Italy
[b]INFN Sezione di Milano, 20133, Milano, Italy
[c]Institute of Nuclear Physics Polish Academy of Sciences, 31-342 Kraków, Poland
[d]INFN Sezione di Padova, 35131 Padova, Italy
[e]Institut Laue-Langevin, 8042 Grenoble CEDEX 9, France
[f]ELI–NP, Măgurele-Bucharest, Romania
[g]Faculty of Physics, Warsaw University, 00-681 Warszawa, Poland

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The structure of the ^{131}Sn nucleus was studied at the Institut Laue-Langevin by prompt-delayed γ-ray spectroscopy across the 0.3 μs, $23/2^-$ isomeric state at 4670 keV, following cold-neutron-induced fission of ^{235}U and ^{241}Pu targets. New γ-ray transitions are observed and the results are compared with theoretical calculations performed with the Hybrid Configuration Mixing Model. The latter suggests that the majority of the states can be well-described in terms of couplings between single-hole degrees of freedom and ^{132}Sn core excitations, pointing to a robust neutron shell closure at $N = 82$.

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1. Introduction

The coexistence between single-particle/hole states and collective excitations is one of the most striking features of atomic nuclei, particularly enhanced in the vicinity of doubly-closed shell systems. The latter are typi-

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† Corresponding author: `simone.bottoni@mi.infn.it`
‡ Corresponding author: `lukasz.iskra@mi.infn.it`

cally considered spherical and their low-lying spectra are usually interpreted as coherent vibrations of the nuclear density, namely phonons. However, the microscopic configuration of these states is closely related to their shell structure and particle–hole (p–h) excitations across the energy gap may well compete with collective vibrations [1].

Among neutron-rich nuclei, the ^{132}Sn isotope ($Z = 50$ and $N = 82$) is considered one of the best examples of exotic, doubly-magic system [2–4]. Of particular interest are one-valence-particle/hole nuclei around this "core", the excitation spectra of which can provide valuable information on the interplay between fermionic and bosonic degrees of freedom in complex systems [5]. As a matter of fact, single particles and holes can couple to collective and non-collective core excitations, preserving or modifying the underlying structure according to the strength of the coupling and the robustness of the shell closure.

This phenomenon was recently investigated by the EXILL Collaboration in the ^{133}Sb nucleus [6] and, previously, in calcium isotopes [7–9]. In this work, we present recent experimental and theoretical studies on the structure of the ^{131}Sn nucleus, only one-neutron hole away from the ^{132}Sn core. The aim is to investigate the nature of its excited states, with particular attention to the couplings with ^{132}Sn core excitations.

2. The experiment

The experiment was performed at the PF1B facility of Institut Laue-Langevin, within the EXILL campaign [10], where the ^{131}Sn nucleus was populated by cold-neutron-induced fission of both ^{235}U and ^{241}Pu radioactive targets. The fission yields for the ^{131}Sn isotope were 0.88% and 1.10%, respectively. The γ-ray decay of the ^{131}Sn nucleus was measured by using an array comprising 46 HPGe detectors (8 EXOGAM clovers [11], 6 large coaxial GASP detectors [12] and 2 ILL clover detectors), for a total detection efficiency of $\approx 6.5\%$ at 1.3 MeV. A fully digital and trigger-less acquisition enabled the off-line reconstruction of fission events, exploiting the γ-ray multiplicity. This was done by scanning the stream of data with a 200-ns time window to identify clusters of γ rays with $M_\gamma \geq 3$, which were used to define the fission trigger. Prompt γ-ray coincidences were built within 200 ns from the fission event, followed by delayed transitions. The latter time window could be as wide as 20 μs, according to the time structure of each fission event. Preliminary results from prompt-delayed γ-ray spectroscopy studies in the ^{131}Sn nucleus are presented in Fig. 1. On the left, the prompt γ-ray spectrum gated on the delayed 4273.2 keV transition from the ^{241}Pu data is displayed. In this case, a 1.5 μs delayed time window was used. Three γ-ray transitions, feeding the 0.3 μs, $23/2^-$ isomeric state at 4670 keV, can be identified at 99.7 keV, 103.4 keV, and 270.2 keV, with the former two observed for the first time in this work. On the other hand, γ rays belonging to the ^{108}Ru fission partner are marked with triangles. Comparisons with ^{235}U data were also done in order to confirm the newly-observed γ rays and to rule out their origin from fission partners. The analysis is still ongoing and the full results, including other observed states and γ decays, will be presented in a future publication [13].

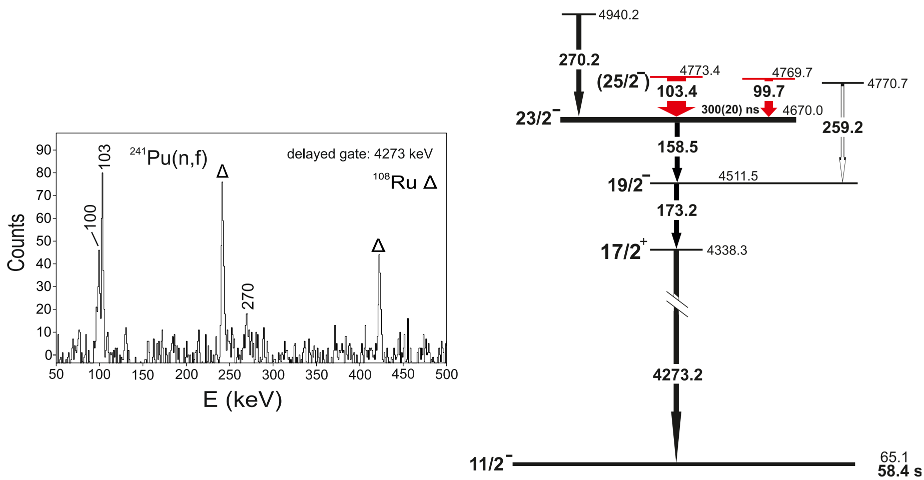

Fig. 1. Left: Prompt γ-ray spectrum from the ^{241}Pu data obtained from the prompt-delayed γ–γ matrix, by gating on the delayed 4273 keV transition. γ rays belonging to the ^{131}Sn nucleus are reported, as well as those coming from the ^{108}Ru fission partner, marked with triangles. Right: Partial level scheme of the ^{131}Sn nucleus showing in grey/red the newly-found γ rays (103.4 keV and 99.7 keV) populating the $23/2^-$ isomeric state at 4670 keV (with half-life of 0.3 μs).

On the right-hand side of Fig. 1, the partial level scheme of the ^{131}Sn nucleus, showing the relevant γ-rays discussed above, is presented. Since no γ-ray coincidence between the 99.7 keV and 103.4 keV transitions was observed, they are tentatively associated to the decay of two different levels at 4769.7 keV and 4773.4 keV, respectively. In particular, the latter is assumed to be the $25/2^-$ yrast state, based on the intensity of the 103.4 keV transition. The other states and γ-ray decays are in agreement with previous measurements [14, 15].

3. Theoretical interpretation

The excitation spectrum of the ^{131}Sn nucleus, including the new $(25/2^-)$ state, was compared with theoretical calculations performed with the revised version of the Hybrid Configuration Mixing Model, recently developed by the Milano theory group [16, 17]. In this context, we assume that the ^{131}Sn nucleus can be described in terms of a ^{132}Sn core coupled to single-hole degrees of freedom

$$\left|{}^{131}\mathrm{Sn}\right\rangle = \left|{}^{132}\mathrm{Sn}\otimes h^{-1}\right\rangle . \tag{1}$$

Calculations are performed self-consistently by using a Hamiltonian of Skyrme type

$$\begin{aligned} H &= H_0 + V\,, \\ H_0 &= \sum_{j_h m_h} \epsilon_{j_h} a_{j_h - m_h} a^\dagger_{j_h - m_h} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^\dagger_{JM} \Gamma_{JM}\,, \\ V &= \sum_{\substack{j_h m_h \\ j_{h_1} m_{h_1}}} \sum_{NJM} h(j_h - m_h; j_{h_1} - m_{h_1}, NJM) \\ &\quad \times (-)^{j_{h_1}+m_{h_1}} a^\dagger_{j_h - m_h} \left[a_{j_{h_1} - m_{h_1}} \otimes \Gamma^\dagger_{JM} \right]_{j_h - m_h}\,, \end{aligned} \tag{2}$$

where H_0 is the mean-field solution corresponding to the Hartee–Fock (HF) hole states and Random Phase Approximation (RPA) excitations of the ^{132}Sn core, with $a^\dagger$ and $\Gamma^\dagger$ being the usual fermion-creator and boson-creator operators, respectively, whereas V is the residual interaction between them [18]. It is important to note that in our model we include both collective phonons of the core and non-collective two-hole–one-particle ($2h$–$1p$) excitations. By solving the eigenvalue equation (2), the orthogonality and the completeness of the basis states is properly taken into account by eliminating the spurious configurations that violate the Pauli principle [19]. The results obtained with the SkX [20] Skyrme interaction, along with experimental data, are presented in Fig. 2. In the calculations, all single-particle states below the $h_{11/2}$ orbital were considered, as well as core excitations up to 5.5 MeV. The low-lying $11/2^-$, $1/2^+$, $17/2^+$, and $5/2^+$ are predicted to be almost pure single-hole states, corresponding to the $h^{-1}_{11/2}$, $s^{-1}_{1/2}$, $g^{-1}_{7/2}$, and $d^{-1}_{5/2}$ neutron vacancies, respectively. On the other hand, high-line, negative-parity states are suggested to arise from the coupling between a $h_{11/2}$ neutron hole and the 2^+_1, 4^+_1, and 6^+_1 phonons of the ^{132}Sn nucleus. Moreover, the model indicates that the new $(25/2^-)$ state found in this work has, most likely, a non-collective behavior and that it corresponds to a neutron, $2h$–$1p$ configuration $h^{-2}_{11/2}\, f_{7/2}$. On the contrary, the positive-parity $15/2^+$, $13/2^+$, and $17/2^+$ states are predicted to be members of the $h^{-1}_{11/2} \otimes 3^-$ multiplet, involving the 3^- octupole vibration of the ^{132}Sn core. Finally, the $19/2^+$ and $21/2^+$ states are calculated as different projections of the same $h^{-1}_{11/2}\, d^{-1}_{3/2}\, f_{7/2}$ non-collective configuration.

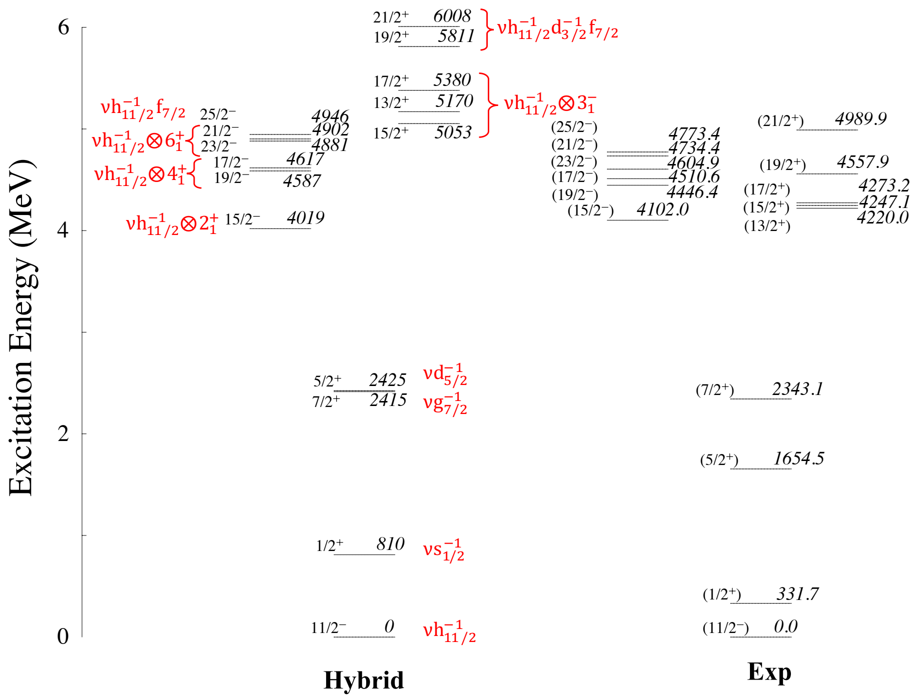

Fig. 2. Theoretical predictions (left) and experimental data (right) for the ^{131}Sn nucleus. Experimental data are taken from NNDC [21] and include the newly-found $25/2^-$. The whole spectrum is rescaled by 65 keV for comparison purposes. Calculations are performed with the Hybrid Configuration Mixing Model. The main components of the wave functions for each state are also reported.

Overall, our results are in good agreement with the experimental data. However, it must be noted that the positive-parity states are predicted higher in energy. This can be ascribed to the energy associated to the $\nu\, d_{3/2}^{-1} f_{7/2}$, p–h excitation, which is also one of the main components of the wave function of the 3^- state in the ^{132}Sn nucleus. As a matter of fact, the latter is calculated by RPA about 700 keV above the experimental value.

4. Conclusions and perspectives

The structure of the ^{131}Sn nucleus was studied by γ-ray spectroscopy during the EXILL experimental campaign. Prompt-delayed γ–γ coincidence relationships allowed us to observe, for the first time, two new γ-ray transitions and two new levels above the $23/2^-$ isomeric state at 4670 keV (with $T_{1/2} = 0.3\ \mu$s). The experimental data are interpreted by the Hybrid Configuration Mixing Model, assuming a $^{132}\mathrm{Sn} \otimes h^{-1}$ structure for the ^{131}Sn nucleus. The reasonable agreement between theoretical predictions and experimental results points to the validity of this assumption and suggests that a single neutron hole slightly affects the ^{132}Sn core excitations, which are still dominant in the ^{131}Sn spectrum, indicating a rather robust neutron shell closure at $N = 82$. In the future, lifetime measurements of excited states will be performed, with the aim of extracting reduced transition probabilities in order to pin down the microscopic composition of their wave functions.

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