STUDY OF SHAPE COEXISTENCE IN SN ISOTOPES VIA MULTINUCLEON TRANSFER REACTIONS*

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Multinucleon transfer reactions were employed in a series of experiments at Legnaro National Laboratories of INFN and at the Tandem Laboratory of the Horia Hulubei National Institute in Bucharest. The main aim was to investigate the shape coexistence phenomenon in even–even Sn isotopes, with mass $A = 112$–118, through lifetime measurements of excited 0^+ states. Recent Monte Carlo Shell Model (MCSM) calculations predict, in fact, the appearance of well-separated secondary minima in the potential energy surfaces of these Sn isotopes, corresponding to deformed, prolate configurations. In this contribution, details on the analysis procedure and preliminary results are discussed.

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1. Introduction

The interplay between shell evolution and deformation is one of the most studied topics in recent nuclear physics [1]. In this context, 0^+ states are of particular importance, as they can be considered the ground states of deformed shapes residing in well-defined minima in the Potential Energy Surface (PES) of atomic nuclei. Consequently, they are strictly linked to the shape coexistence phenomenon [2, 3]. Recently, in Ni isotopes, the studies of Refs. [4, 5] provided evidence for coexisting spherical, oblate, and prolate 0^+ excitations in ^{64,66}Ni. A significant hindrance was found for the γ decay between the prolate 0^+_4 and the spherical 2^+_1 states, suggesting the existence of a sizable barrier between the prolate and spherical minima, *i.e.*, a shape-isomer-like scenario [6]. The experimental results were successfully reproduced by the Monte Carlo Shell Model (MCSM) calculations [7], which highlighted the importance of the monopole part of tensor force in stabilizing deep prolate minima in the PES. A similar situation is predicted to occur in $^{110-120}$Sn isotopes, where Hartree–Fock–Bogoliubov (HFB) calculations, with the A3DA-m interaction of Togashi *et al.* [8], predict the appearance of relatively deep and well-separated oblate and prolate secondary PES minima. Furthermore, while the prolate secondary minimum is well-defined in ^{112,114,116}Sn, it gradually disappears moving towards ^{110}Sn and ^{120}Sn, as shown by the PES reported in Fig. 1. Monte Carlo Shell Model calculations, based on the same Hamiltonian, provided information on the energy and wave function compositions of the three lowest 0^+ states, revealing that they all exhibit a spherical-oblate structure. This suggests that a prolate 0^+ excitation, expected on the basis of the PES minima from HFB, may exist at higher energies. It follows that a complete set of lifetime information along the $^{112-120}$Sn chain would provide a strong benchmark for theory predictions, in particular for MCSM calculations which give a microscopic interpretation of the state wave function in terms of proton and neutron contributions. Therefore, a series of experiments were performed by our collaboration at the Legnaro National Laboratories (LNL) and at the Tandem Laboratory of the Horia Hulubei National Institute (IFIN-HH) in Bucharest. The main aim was to characterize excited 0^+ states in Sn isotopes using different transfer reactions.

In this contribution, we focus on the preliminary analysis of the experiment performed at LNL, specifically, on the extraction of the transfer-reaction cross sections, and on the data from IFIN-HH on the population of excited 0^+ states in the Sn isotopic chain.

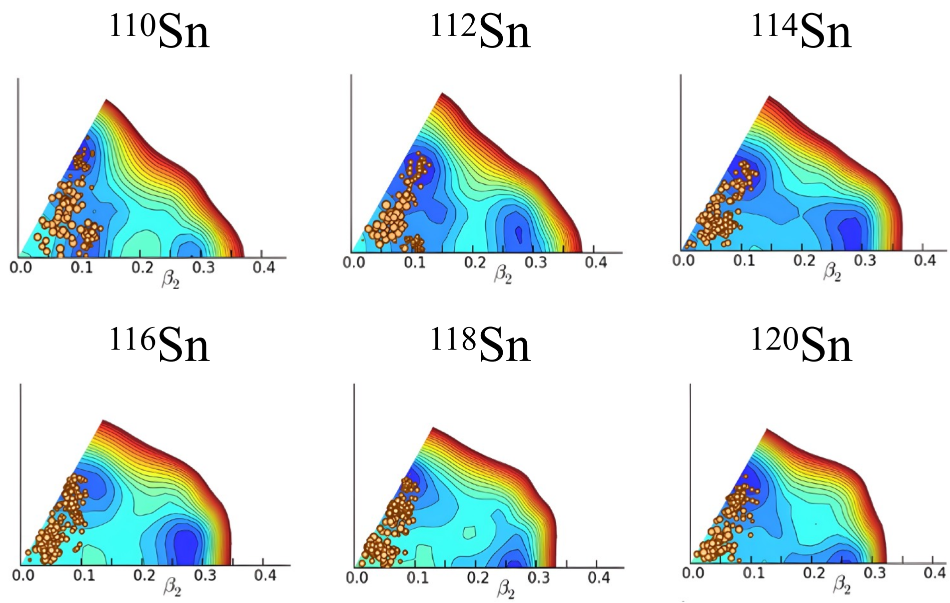

Fig. 1. Potential Energy Surfaces (PES) for $A = 110$–120 Sn isotopes obtained with the constrained Hartree–Fock–Bogoliubov method, using the A3DA-m interaction of Togashi *et al.* [8]. Circles on the PES represent the main components of the wavefunction of the 0_1^+ ground state, according to Monte Carlo Shell Model calculations.

2. The experiments

The first experiment was performed at the Legnaro National Laboratories of INFN (LNL) in July 2022. A ^{32}S beam was accelerated at 164 MeV by the TANDEM-XTU facility and impinged on a 1 mg/cm^2 target of ^{110}Cd with a 2 mg/cm^2 Ta backing. In the first configuration of the setup here discussed, the target was rotated at $\theta_\mathrm{t} = 47°$ with respect to the beam axis. A multinucleon transfer reaction was employed to populate nuclei from Cd to Te in proximity of the valley of stability. The beam-like products were detected and identified by the PRISMA magnetic spectrometer [9], which was placed at the grazing angle $\theta_{\text{lab}} = 67^\circ$. The emitted γ rays were measured by the Advanced Gamma Tracking Array (AGATA) [10], composed of 33 segmented HPGe detectors and placed at backward angles relative to the PRISMA spectrometer.

On the other hand, during the experimental campaign performed at IFIN-HH in 2023, several reactions at sub-barrier energies were employed in order to populate nuclei of interest in $1n$, $2p$, and α transfer processes. At first, a beam of ^{13}C was accelerated up to 43 MeV by the FN Pelletron Tandem accelerator and impinged on ^{117}Sn and ^{119}Sn targets, with thicknesses of $\sim$14 mg/cm^2. Finally, a ^{16}O beam was accelerated at 56 MeV toward a 10 mg/cm^2 ^{116}Cd target. The detection setup consisted of the ROSPHERE γ-ray spectrometer [11], with 20 Compton-suppressed HPGe detectors, coupled to the SORCERER charged particle detector [12], composed of 6 Si photodiodes.

3. Data analysis

In this section, analysis techniques and preliminary results of the different experiments are discussed.

3.1. Analysis and results of the AGATA-PRISMA experiment

Data acquired in the AGATA-PRISMA experiment allowed to perform the complete Z (charge), Q (charge state), and A (mass) identification of the beam-like products entering in PRISMA, through the reconstruction of the trajectories of the ions on an event-by-event basis [9, 13–15]. The procedure was the following. At first, the timing signal from the micro-channel plate entrance detector (MCP) was used as a start for the time-of-flight reconstruction of the incoming ions and for determining their point of interaction. Then, after a quadrupole and a dipole magnets, the MWPPAC focal plane detector was used to reconstruct the trajectories of the ions by providing the final x–y position and the stop timing signal. The atomic number Z could be identified with the help of the ionization chamber (IC) located at the end of the spectrometer, by correlating the energy loss ΔE in the first two sections with the total energy E deposited in the chamber.

After the trajectory reconstruction, the product of the radius of curvature R in the dipole magnet and the velocity β obtained from the time-of-flight information for each event was compared with the total energy E deposited in the IC to isolate the charge-state distributions. The final step involved the calibration of the A/Q spectra, gated on Z and Q, which gives the mass distribution of the detected ions. This is shown in panel (a) of Fig. 2, where the mass distributions corresponding to different Z gates are reported. An average resolution of $\Delta A/A \approx 230$ was achieved, allowing for a clean selection of the different channels. Such a result was obtained after optical aberration corrections, which account for fringe fields and higher-order effects of the magnetic fields.

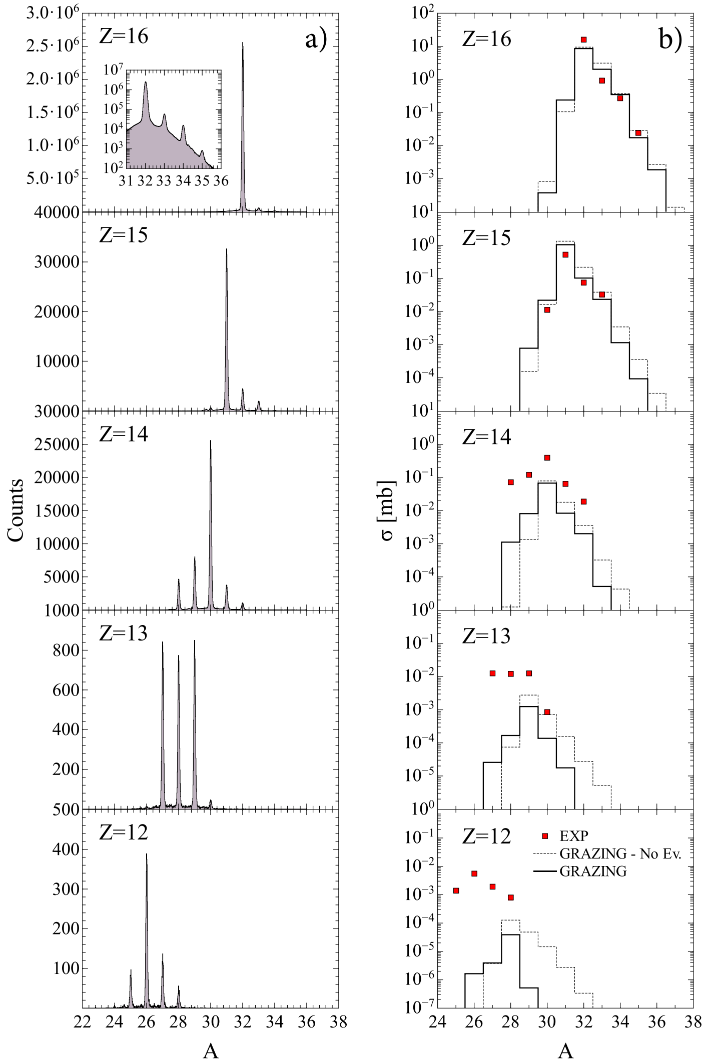

Fig. 2. (Color online) (a) Mass distributions gated on different atomic numbers Z. In the top spectrum, the neutron transfer peaks of the projectile-like S channel are also shown in the inset on a logarithmic scale. (b) Inclusive cross sections, integrated on total angle and Q-value, for the different reaction channels. The red/gray squares correspond to experimental values. The black lines indicate the cross sections calculated with the GRAZING code [16], with (solid) and without (dotted) the inclusion of the neutron evaporation channels.

The PRISMA spectrometer allows us to study inclusive cross sections of multinucleon transfer reactions on an absolute scale. First, the differential cross section of the ^{32}S quasi-elastic channel was extracted by measuring the counts within the $\Delta\Omega$ solid angles covered by the MCP detector for different θ angles. The experimental distribution was then normalized to the theoretical Rutherford scattering distribution, using a scaling factor extracted from the angular region where the Rutherford scattering dominates. Such a normalization factor converts *counts* to *mb*, providing the absolute scale of the inclusive cross section for each transfer channel. This is shown in panel (b) of Fig. 2, where the experimental data are compared with GRAZING calculations [16]. It can be observed that the $(0p)$ and $(-1p)$ channels are well reproduced by the calculations. The discrepancies increase gradually along the proton stripping side, where theoretical calculations underestimate the total cross section of the channels. Such deviations have been observed in several works [17–21] and are attributed to an incorrect treatment of the transfer process when many protons are involved, as well as to the complexity of describing the evaporation of neutrons.

The analysis and the results here obtained represent a solid starting point for the γ-ray spectroscopy and lifetime analysis of this dataset, which is currently ongoing.

3.2. Analysis and results of the ROSPHERE-SORCERER experiments

In a quest for the most effective mechanism to populate low-lying 0^+ excitations, we performed a spectroscopic study of the ^{116,118,120}Sn nuclei populated with $1n$, $2p$, and α transfer reactions. In the analysis, γ–γ coincidence techniques were employed for the data taken with the ROSPHERE array [11], with an additional gate on projectile-like particles detected at backward angles in the SORCERER solar-cells setup [12], to reduce the background coming from fusion–evaporation channels. Figure 3 shows the intensities of the γ-ray transitions depopulating the $0^+_{2,3,4}$ states of the different Sn isotopes, observed in coincidence with the $2^+ \rightarrow 0^+_1$ transition. Although all the tested reactions populate the states of interest, the one-neutron pick-up and stripping reactions appear to be the most effective, in particular in populating the 0^+_4 state. Moreover, the large differences in intensity population of 0^+ states within the same nucleus, observed in particular in ^{118}Sn and ^{120}Sn, may point to changes in the underlying structure of such states, with increasing excitation energy.

Based on these results, the $(\pm 1n)$ transfer reactions on odd-Sn targets were used in recent 2024 experiments at IFIN-HH, to measure the lifetime of these low-lying excited 0^+ states. The analysis is ongoing and the result will be compared with updated MCSM calculations to pin down the nature of such excitations.

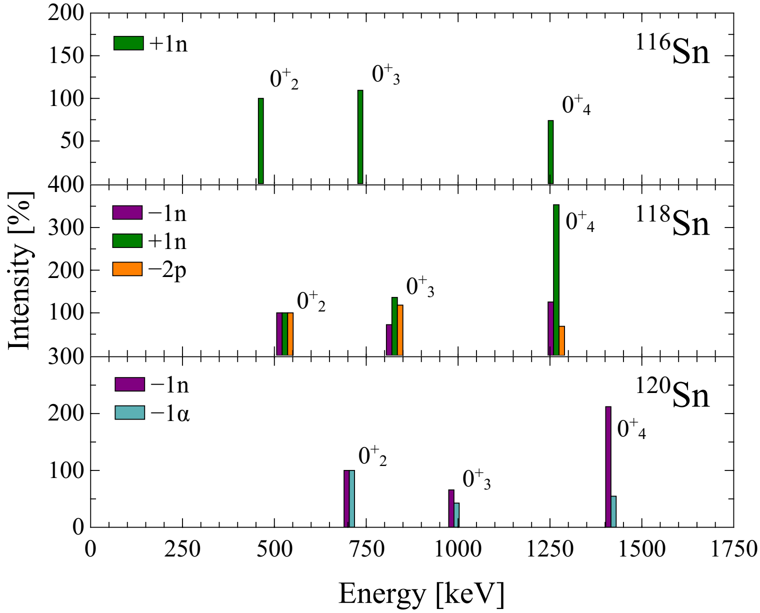

Fig. 3. (Color online) Relative intensities of the $0^+_{2,3,4} \rightarrow 2^+$ transitions of ^{116,118,120}Sn, observed in coincidence with the $2^+ \rightarrow 0^+_1$ transition and normalized to the intensity of the γ-ray depopulating the 0^+_2 state. The different colors indicate the reaction channel that corresponds to a specific population pattern.

4. Conclusions

A series of experiments was performed at the Legnaro National Laboratories of INFN, with AGATA-PRISMA, and at the Tandem Laboratory of the Horia Hulubei National Institute, in Bucharest, with the ROSPHERE array, to elucidate shape coexistence phenomena in even–even Sn isotopes with mass $A = 112$–118. A number of transfer reactions were employed. The preliminary analysis of the AGATA-PRISMA experiment led to a precise ion identification that will be used to obtain clean ion-gated γ-ray spectra for lifetime analysis. First results on the inclusive cross sections for all the identified channels were obtained. Good agreement was found with GRAZING calculations for the reaction channels involving the transfer of few nucleons, in particular for the $(0p)$ and $(-1p)$ channels. In Bucharest, the population of the excited $0^+_{2,3,4}$ states in ^{116,118,120}Sn was investigated employing different transfer reactions, and using γ spectroscopy techniques with the ROSPHERE-SORCERER setup. The $(\pm 1n)$ transfer proved to be the most effective mechanism to populate low-lying 0^+, in particular the 0^+_4 state, thus supporting the presence of a non-negligible neutron component in such excitations. Supported by these results, new lifetime measurements were performed at IFIN-HH using the one-neutron pick-up and stripping reactions. The analysis is currently ongoing, and the final results will be compared with MCSM calculations.

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