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LIFETIME MEASUREMENTS IN ^{105}Sn: THE PUZZLE OF B(E2) STRENGTHS IN Sn ISOTOPES*

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Information on the doubly-magic nature of the $N = Z = 50$ ^{100}Sn nucleus can be extracted from systematic studies of the tin isotopic chain. In this context, the lifetimes of the neutron deficient ^{105}Sn have been investigated with the coincidence Recoil Distance Doppler Shift (RDDS) technique through the reaction ^{50}C(^{58}Ni, $2pn$)^{105}Sn. The experimental technique has been validated by comparing the preliminary results with known lifetimes in ^{105}In.

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1. Introduction

The study of the structure of atomic nuclei far from the beta-stability valley is one of the challenges in modern nuclear physics. The nuclear Shell Model is able to approximate very well the behaviour of the atomic nucleus describing it as an ensemble of independent particles in an average central potential created by all of them. From this picture, a shell structure naturally arises, where protons and neutrons arrange themselves in various ways in order to form all possible nuclear states. A "magic number" of nucleons is required to completely fill a major shell, and nuclei with a magic number of protons and/or neutrons present particular characteristics of stability against excitation. However, the energies of the shell-model orbitals are not fixed, but change with the number of nucleons in the system, implying a variation of the main energy gaps between them. To study the evolution of

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shell closures and the development of collectivity throughout the Segrè chart, the exploration of the nuclear properties of magic nuclei situated far from the stability line is essential. Key quantities in this regard are the reduced transition probabilities $B(\sigma L)$. In particular, the study of the quadrupole strengths $B(\mathrm{E2};\, 2^+ \rightarrow 0^+)$ as a function of the neutron (proton) number along an isotopic (isotonic) chain when approaching a closed shell can provide significant information.

2. Physics case

The chain of even–even tin isotopes represents a perfect laboratory for a systematic study of the $B(\mathrm{E2};\, 2^+ \rightarrow 0^+)$ evolution, since it extends between doubly-magic nuclei, the self-conjugated $Z = N = 50$ ^{100}Sn and the $Z = 50$, $N = 82$ ^{132}Sn, crossing the line of beta stability in the middle. While the doubly-magic nature of ^{132}Sn is well-established, for the ^{100}Sn nucleus only indirect indications from decay spectroscopy show that the $Z = 50$ shell closure is present [1]. This makes it meaningful to test the robustness of this proton shell closure approaching $N = 50$ and to extract information on the ^{100}Sn nuclear structure via spectroscopic studies of the Sn isotopic chain [2–4].

The generalized seniority scheme is a symmetry of the Hamiltonian that well describes low-lying excited states in semi-magic systems in terms of excitation energy and transition probabilities. For the even–even Sn isotopes, the experimental $B(\mathrm{E2};\, 2^+ \rightarrow 0^+)$ values on the neutron-rich side follow the predicted parabolic behaviour but for lighter Sn isotopes, an unexpected enhancement in the E2 strengths is present. However, the experimental data for lighter Sn isotopes are affected by large uncertainties which, so far, have hindered precise theoretical interpretations. In fact, the study of the reduced transition probabilities in a direct way via fusion–evaporation reactions is hampered by the presence of low-lying isomers in even–even Sn isotopes. Therefore, $B(\mathrm{E2};\, 2^+ \rightarrow 0^+)$ values have been extracted from measurements of the Coulomb excitation, yet the results suffer from substantial experimental errors. Recently, a direct measurement of the lifetime of the 2^+_1 and the 4^+_1 excited states in ^{106,108}Sn was performed in GANIL via a multi-nucleon transfer reaction for the very first time [5].

2.1. Odd–even Sn isotopes

Shell-model calculations with the CD-Bonn interaction in the full *gds* valence space show that the quadrupole strengths between the core-coupled states in odd–even nuclei closely follow the general trend of the corresponding even–even isotopes for the 2^+_1 states. In this context, the neutron-deficient odd–even ^{105}Sn isotope provides the opportunity for direct lifetime measurements of low-lying levels in odd Sn isotopes close to ^{100}Sn.

Another indication of the decreasing collectivity going towards ^{100}Sn comes from the study of the M1 transition strength for the decay of the first excited states in odd–even tin isotopes. Shell-model calculations predict a dominant M1 character for this transition, which is highly suppressed in the case of a single-particle nature of the excited state, being an ℓ-forbidden M1. This leads to a lifetime of several ns for this state, which is in complete disagreement with the value of only several hundreds ps measured for ^{105}Sn. Actually, this lifetime was measured only once and has only been published in a short annual report [6]. A precise re-measurement of the lifetime of the $7/2^+$ first excited state in ^{105}Sn was therefore performed.

3. Experimental details

The Coincidence Recoil Distance Doppler Shift (RDDS) technique was applied since lifetimes of the order of ps are expected [7]. The plunger device [8] allows performing lifetime measurements of nuclear excited states with the RDDS technique. This method is based on the distinction, for a detected γ-ray transition, of a Doppler shifted component, emitted by nuclei in-flight between the target and a second layer of material (stopper), and an unshifted component, emitted by nuclei at rest in the stopper. Depending on the distance between the target and the stopper, a different ratio between the intensities of the in-flight peak and the stopped peak is observed, from which lifetimes can be obtained.

^{105}Sn was populated via a fusion–evaporation reaction using a 180 MeV ^{50}Cr beam and a ^{58}Ni target of 1 mg/cm^2 thickness. Based on a previous spectroscopy investigation of this nucleus [9], such a reaction was chosen to maximize the production cross section of the channel of interest. The 16 mg/cm^2 ^{197}Au stopper was mounted in the plunger device behind the target and placed at the center of the reaction chamber.

The experiment was performed at Legnaro National Laboratories using the GALILEO array [10] coupled to the EUCLIDES detector [11]. GALILEO is a γ-ray spectrometer composed of 25 Compton-suppressed HPGe detectors. The position of the GALILEO detectors in five "rings", at different angles with respect to the beam direction (152°, 129°, 119°, 61° and 51°), allows obtaining excited-state lifetimes for each ring independently, as the energy shift of the γ ray emitted in-flight depends on the direction of emission. Subsequently, the average lifetime can be extracted, leading to a more precise measurement. The ΔE–E silicon array EUCLIDES was used to detect evaporated light charged particles and then select the reaction channel of interest. The array can be placed only at forward angles in the plunger configuration.

A total of 12 target–stopper distances in the range between 10 μm and 8000 μm were chosen to obtain sensitivity to the very short lifetimes in the high-spin magnetic band of ^{105}Sn as well as its long-lived $7/2^+$ first excited state.

4. Analysis and preliminary results

The selection of the channel of interest from among all the possible fusion–evaporation and Coulomb-excitation events is possible requesting γ-ray coincidences with light charged particles. As an example, Fig. 1 shows how the Coulomb-excitation events, due to the interaction between the beam and the stopper, can be significantly reduced in the spectrum requesting a 2-proton coincidence.

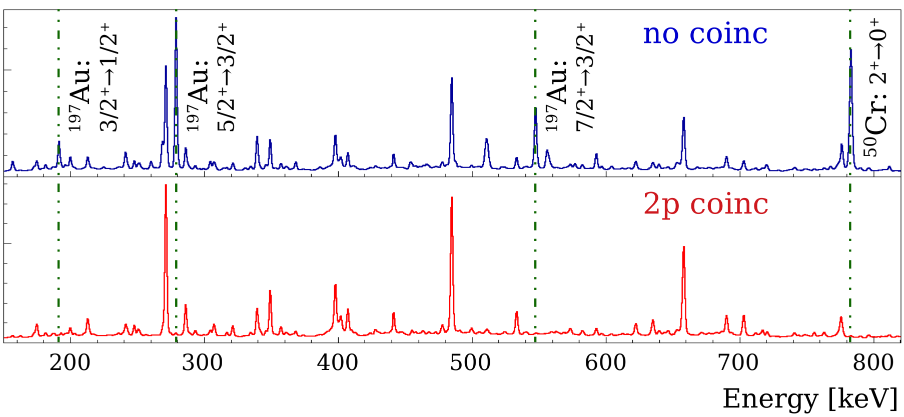

Fig. 1. Comparison between the spectra in coincidence with two protons (bottom) and the total γ-ray spectrum (top) detected at 152° with a target–stopper distance of 10 μm. The suppression of the ^{50}Cr and ^{197}Au Coulomb-excitation events is shown by vertical lines.

The lifetime of an excited state can be estimated with the coincidence Differential Decay-Curve Method (DDCM) [7]. The coincidence condition reduces systematic errors, usually introduced in single-γ measurements by the unknown feeding history of the state. The γ-ray spectra are constructed for each GALILEO ring by gating on the shifted component of the direct-feeding transition of the state of interest. The lifetime τ is calculated at each target–stopper distance x using the equation

$$\tau(x) = \frac{I_{\mathrm{us}}(x)}{\frac{\mathrm{d}}{\mathrm{d}t} I_{\mathrm{sh}}(x)}\,, \tag{1}$$

where $I_{\rm us}$ is the intensity of the unshifted component and $\frac{\rm d}{{\rm d}t}I_{\rm sh}(x)$ is the derivative of the function fitting the shifted values as a function of the distance. A detailed description of this relation and the DDCM analysis are presented in Ref. [7].

The experimental technique and the analysis method have been validated by measuring the lifetime of the $19/2^+$ excited state of ^{105}In, which is known in the literature [12]. Panels (a) and (b) of Fig. 2 show the $I_{\rm sh}(x)$ and $I_{\rm us}(x)$ values together with a piece-wise second-order polynomial function fitting the data with a χ^2 minimization procedure performed with the Napatau software [13]. To take into account a different acquisition time for each distance, the intensities $I_{\rm sh}(x)$ and $I_{\rm us}(x)$ have been normalized to the total number of events collected during the measurement at each distance. Panel (c) of Fig. 2 shows the weighted average of the $\tau(x)$ values, calculated with Eq. (1) in the sensitive region, which includes distances where the derivative of the fitting function is largest.

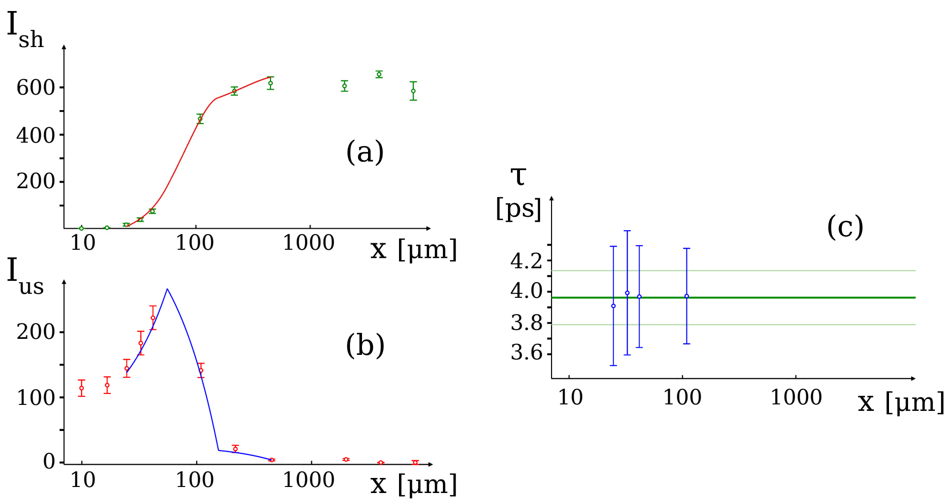

Fig. 2. (a) Normalized intensity curve for the shifted component $I_{\rm sh}(x)$. (b) Normalized intensity curve for the unshifted component $I_{\rm us}$, which is proportional to the derivative of the fitting function in (a) according to Eq. (1). (c) Lifetime values calculated at each distance x in the sensitive region for the 272-keV, $21/2^+ \rightarrow 19/2^+$ transition in ^{105}In, measured with GALILEO detector at 152°. The thick solid line shows the weighted average. The associated uncertainties are represented by the thin lines.

The presented lifetime is obtained using coincident γ rays detected with GALILEO detectors at 152° and 51°, where the energy difference between the shifted and unshifted components is largest. The preliminary results for the lifetime of the $19/2^+$ state in ^{105}In are $\tau = 3.96(17)$ ps and $\tau = 4.13(17)$ ps for the GALILEO rings at 152° and 51°, respectively, which are in good agreement with the adopted value $\tau = 3.76(18)$ ps.

The analysis of the lifetime for other excited states in ^{105}In is on-going, with the aim to confirm the reliability of the presented experimental technique. A further and detailed study is also in progress to evaluate the influence of the background subtraction in the gated spectra on the resulting lifetime.

5. Summary and perspectives

The fusion–evaporation reaction ^{50}Cr + ^{58}Ni was used to populate the neutron-deficient ^{105}Sn isotope. Gamma rays emitted by the excited states of the populated nucleus were detected with the γ-ray array GALILEO in coincidence with the Si detector EUCLIDES. The RDDS technique using a plunger device was applied to determine lifetimes of excited states in the range from ps to ns.

The experimental method is validated by a reproduction of known lifetimes in ^{105}In. Data analysis is now oriented to the study of the ^{105}Sn nucleus. With the collected statistics, it will be possible to estimate several lifetimes of ^{105}Sn excited states, and precisely measure the lifetimes of the long-lived $7/2^+$ and $25/2^+$ excited states, the latter corresponding to a possible core breaking.

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