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NEW RESULTS NEAR ^{100}Sn: OBSERVATION OF SINGLE-NEUTRON STATES IN ^{101}Sn*

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A search for in-beam γ-ray transitions in ^{101}Sn, which contains only one neutron outside the ^{100}Sn core, using a novel approach was carried out at the Argonne Tandem-Linac System. ^{101}Sn nuclei were produced using the ^{46}Ti(^{58}Ni, 3n)^{101}Sn fusion–evaporation reaction. Beta-delayed protons with energies and decay times consistent with previous ^{101}Sn decay studies were observed at the focal plane of the Fragment Mass Analyzer. In-beam γ rays were detected in the Gammasphere Ge-detector array and were correlated with the ^{101}Sn β-delayed protons using the Recoil-Decay Tagging method. As a result, a γ-ray transition between the single-neutron $\nu g_{7/2}$ and $\nu d_{5/2}$ states situated at the Fermi surface was identified. The measured $\nu g_{7/2}$–$\nu d_{5/2}$ energy splitting was compared with predictions corresponding to various mean-field potentials and was used to calculate multi-neutron configurations in light Sn isotopes. Similar approach can be used to study core excitations in ^{101}Sn and other exotic nuclei near ^{100}Sn.

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1. Introduction

Doubly-magic nuclei are the cornerstones of the nuclear landscape. Properties of nuclei such as ^{48}Ni, ^{78}Ni, ^{100}Sn and ^{132}Sn are essential for understanding the evolution of the nuclear structure far from the line of stability.

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The ^{132}Sn nucleus and its neighbors are known quite well as they can be copiously produced as fission products. We have been approaching ^{100}Sn in fragmentation and fusion–evaporation reactions. Studies of the Ni doubly-magic nuclei are still in their infancy.

The ^{100}Sn region, where the $N = Z$ line crosses the proton drip line and where the astrophysical rp-process was proposed to terminate, has been an aim of numerous experimental studies. The ^{100}Sn nucleus can be compared with other known doubly-magic nuclei, the lighter $N = Z$ nucleus, ^{56}Ni, or the neutron-rich counterpart, ^{132}Sn.

However, studies of nuclei in the vicinity of ^{100}Sn are hampered by low cross sections and large backgrounds and require a very sensitive and selective experimental apparatus. As a result, nothing was known about single-particle energies and very little about nucleon–nucleon interactions at ^{100}Sn. In this paper, we describe a search for single-neutron states in ^{101}Sn using a novel experimental approach namely tagging in-beam γ rays with β-delayed protons. Single-particle energies are important characteristics of doubly-magic nuclei and provide stringent tests of nuclear models. They are critical for understanding multi-nucleon configurations in neighboring nuclei within the shell-model framework.

2. The experiment

Nuclei in the ^{100}Sn region have been a goal of many experimental studies using a variety of experimental probes such as in-beam γ-ray spectroscopy, isomers, β decay, α decay or proton decay. Reaction channel selection is the limiting factor for in-beam spectroscopy. Detection of light evaporated particles which is the method of choice is limited to about 1 μb. The cross section for producing ^{101}Sn is only 50 nb, which requires a different approach.

The ^{58}Ni(^{46}Ti, 3n)^{101}Sn reaction at a 192 MeV beam energy was used to populate excited states in ^{101}Sn. This reaction was chosen for two reasons: *(i)* the cross section was expected to peak close to the Coulomb barrier, thus limiting the number of competing reaction channels *(ii)* the evaporation of 3 neutrons does not significantly increase the emission cone of the reaction products allowing their efficient collection in a mass separator.

In order to identify prompt γ rays belonging to ^{101}Sn the Recoil-Decay Tagging method was used [1] which was very successful for studies of weakly produced proton and α emitters. In this work, β-delayed protons were used as a tag, which is much more challenging, due to a wide proton energy distribution and a relatively long half life involved. The ^{101}Sn nucleus β decays with a half life of 1.9(3) s and about 15% of the time the β decay is followed by prompt proton emission [2]. In-beam γ rays were detected in the Gammasphere Ge-detector array [3]. Reaction products were dispersed according to their mass-over-charge ratio in the Argonne Fragment Mass Analyzer (FMA) [4] and were implanted into an 80×80 Double-Sided Si Strip Detector (DSSD). Subsequently, the implants were correlated with their characteristic decays using spatial and temporal relations. In particular, ^{101}Sn nuclei were correlated with their β-delayed protons. Only the most exotic nuclei produced exhibit proton decay branches resulting in unprecedented background suppression. A schematic drawing of the experimental setup is shown in Fig. 1. More experimental details can be found in Ref. [5].

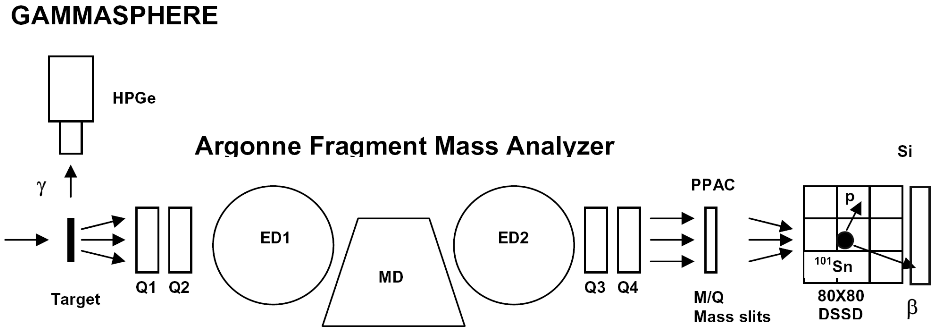

Fig. 1. Schematic drawing of the experimental setup used to correlate in-beam γ rays with subsequent charged particle decays.

In the analysis, protons with energies between 2 and 4 MeV and a half life of 1.3(5) s, consistent with the ^{101}Sn β-delayed protons properties [2], were separated from the intense β-particle background. The spectrum of γ rays correlated with these protons is presented in Fig. 2(a). A γ-ray line at 172 keV visible in this spectrum, which is not present in the random γ-ray spectrum shown in Fig. 2(b), was assigned to ^{101}Sn.

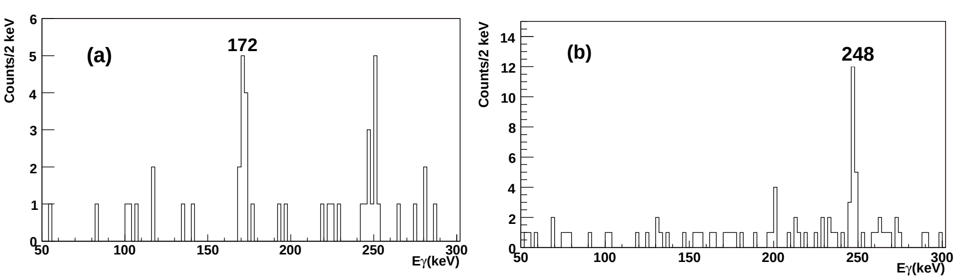

Fig. 2. (a) Spectrum of prompt γ rays correlated with ^{101}Sn protons. (b) Random background γ-ray spectrum associated with long-lived β activities. The 248 keV line corresponds to an intense transition in the strongly populated nucleus, ^{101}Ag.

Based on the systematics of heavy $N = 51$ isotones and light odd-A Sn isotopes (see Fig. 3) the 172 keV transition was proposed to connect a low-lying $7/2^+$ state and the $5/2^+$ ground state in ^{101}Sn. These two levels are clearly separated from other excited states and based on the comparison to shell-model calculations have been assigned as the single-neutron $g_{7/2}$ and $d_{5/2}$ states, respectively. No other γ rays were found which could be assigned to ^{101}Sn. The $7/2^+$ low-lying state is expected to be fed by one or two ~ 3 MeV transitions, in analogy to the ^{103}Sn level scheme [6] (the gap is only ~ 1 MeV in this case). Much lower efficiency at high energies could explain why these transitions were not observed.

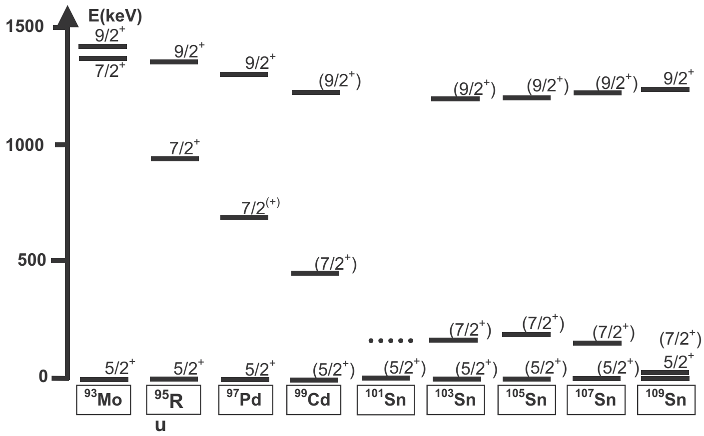

Fig. 3. The systematics of $5/2^+$ and $7/2^+$ states in the heavy $N = 51$ isotones and light odd-A Sn isotopes.

3. Discussion

3.1. Mean-field calculations

The relative single-particle energies can be used to test various forms of the mean-field nuclear potential. Leander *et al.* [7] calculated single-particle energies for the doubly-magic nuclei ^{56}Ni, ^{100}Sn, ^{132}Sn, and ^{208}Pb using the Woods–Saxon potential with the so-called "universal" set of parameters, the folded Yukawa potential, and the self-consistent Hartree–Fock potential obtained with the Skyrme III phenomenological nucleon–nucleon interaction, resulting in $g_{7/2}$–$d_{5/2}$ energy differences in ^{101}Sn of 1.45 MeV, 1.09 MeV, and 0.47 MeV, respectively. The self-consistent potential reproduces the measured $g_{7/2}$–$d_{5/2}$ splitting best. Surprisingly, when a Skyrme interaction was refitted to more recent data across the nuclidic chart, including several single-particle energies, a larger difference of ~ 1 MeV was obtained [8]. This reflects limitations of current mean-field potentials in predicting single-particle energies. For example, to obtain better agreement the form of the interaction used for self-consistent potentials might have to be modified [9].

3.2. Shell-model calculations

The low-lying states in light Sn isotopes are dominated by neutrons occupying the two low-lying orbitals, $d_{5/2}$ and $g_{7/2}$. The two low-spin neutron orbitals, $s_{1/2}$ and $d_{3/2}$, are expected to be located at about 1.5 MeV, while the high-spin $h_{11/2}$ orbital is situated as high as at 3 MeV. Thus, the energy splitting between these orbitals is an essential ingredient for quantitative description of multi-neutron configurations in light Sn isotopes. Comparison between the calculated and measured states can be used to provide constraints for interactions between valence neutrons. As a starting point, the effective neutron–neutron interaction was taken from Ref. [10], where

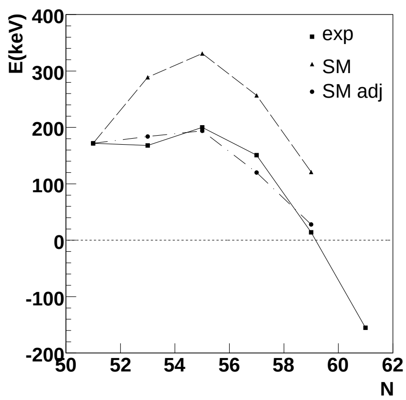

Fig. 4. The measured and calculated energy splitting between the lowest $5/2^+$and $7/2^+$ states, $E(7/2^+)$–$E(5/2^+)$, with the results of shell-model calculations (see the text for details).

it was derived from the Bonn C meson-exchange nucleon–nucleon potential in the one-boson-exchange approximation. In Fig. 4 the experimental and calculated separation energies between the two lowest $5/2^+$ and $7/2^+$ states in the odd Sn isotopes from ^{103}Sn to ^{109}Sn are compared.

The shell model predicts a pair of low-lying $7/2^+$ and $5/2^+$ states. The calculated energy difference follows the experimental trend closely, but is about 200 keV too large. Almost perfect agreement with the data can be achieved if the $(g_{7/2})^2_{0^+}$ matrix element is reduced from -1.4 MeV to -1.1 MeV. This adjustment preserves the agreement between experiment and theory for the 2^+, 4^+, and 6^+ energies in the even Sn isotopes. Interestingly, reversing the $g_{7/2}$ and $d_{5/2}$ orbitals in ^{101}Sn results in a different trend for the $7/2^+$–$5/2^+$ splitting, although the $7/2^+$ level is still located above the ground state in the heavier ^{103}Sn isotopes as in the experiment. This illustrates the ambiguity of extracting the $g_{7/2}$–$d_{5/2}$ energy difference from ^{103}Sn alone.

It should also be noted that in the approach above, the $5/2^+$ and $7/2^+$ in ^{101}Sn states are treated as purely single-particle states. It would be interesting to calculate the energies of these two states including excitations across the magic gaps.

3.3. Ordering of the $d_{5/2}$ and $g_{7/2}$ states

In the present work, it was proposed that the observed γ-ray transition connects a low lying state at 172 keV and the ground state. The spins and parities of the two levels were not measured. However, it is clear that they correspond to a pair of $5/2^+$ and $7/2^+$ states. However, because of very small separation between the two states their order remains an open question. Our data favours placing the $5/2^+$ state below the $7/2^+$ state. The higher lying states, which require breaking the core, will decay preferentially to the $7/2^+$ state. If the $7/2^+$ state were the ground state, the transition between the $5/2^+$ and the $7/2^+$ state would be much weaker than the high-energy transitions feeding the $7/2^+$ ground state. This is in contradiction with the fact that no high-energy transitions were found in the data. Also, the shell-model calculations for light Sn isotopes fit the experimental levels better if the $d_{5/2}$ orbital is assumed to be located below the $g_{7/2}$ orbital. Similar conclusion can be drawn from the systematics of the $N = 51$ isotones.

4. Outlook

Only one transition in ^{101}Sn was observed in the present work. More statistics could reveal the high-energy transitions de-exciting core-excited states. The energy of these transitions is directly related to the energy required to break the ^{100}Sn core. Alternatively, the $h_{11/2}$ neutron orbital could be populated since it is expected at around 3 MeV above the ground state, which is comparable to the expected energy of the 2^+ state in ^{100}Sn.

Tagging in-beam γ rays with charged-particle decays is a very sensitive method to study excited states in exotic proton-rich nuclei. Many nuclei around ^{100}Sn, besides ^{101}Sn studied in this work, exhibit β-delayed proton branches. For example, a 4% β-delayed proton branch was observed in one-neutron–one-proton-hole nucleus, ^{100}In. In more exotic nuclei β-delayed proton branches are expected to increase and half lives are shorter. This will compensate to some degree for lower cross sections. Other candidates for future studies, include, but are not limited to: one-proton-hole nucleus, ^{99}In, one-neutron-hole–one-proton-hole nucleus, ^{98}In, or high-spin isomers in even-Z nuclei, ^{96}Cd and ^{97}Cd. No β-delayed protons have been observed in ^{100}Sn so far. In this case, one would have to develop tagging with β particles. Since the β-particle tag is not very selective, presumably, one would need to detect characteristic γ rays in coincidence with betas.

To achieve sensitivity required for the experiments listed above existing detection systems need to be upgraded to handle higher beam intensities and thus higher implantation rates. A new high-granularity 160×160 strips DSSD was designed and manufactured for experiments at the FMA in order to correlate long lived weak activities. The new DSSD will be surrounded by 5 Ge clover detectors in box geometry to assure simultaneous efficient γ-ray detection.

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