In-beam γ-ray spectroscopy in the vicinity of $^{100}$Sn

Dariusz Seweryniak

Argonne National Laboratory, Argonne, IL 60439 USA
and
University of Maryland, College Park, MD 20742 USA

Abstract.
In recent years, in-beam γ-ray experiments supplied a vast amount of data on high-spin states in nuclei in the vicinity of $^{100}$Sn. The present contribution reviews spectroscopic information obtained recently for $N \geq 50$ nuclei around $^{100}$Sn, with emphasis on isomer studies, and discusses selected results in the frame of the shell model.

Introduction
The heaviest existing doubly-magic self-conjugated nucleus, $^{100}$Sn, is situated in the nuclidic chart at the point where the $N=Z$ line crosses the proton drip-line. It is a unique ground for studying single-particle energies and residual interactions far from the line of stability. In addition, neutron-proton correlations are expected to play a significant role in $^{100}$Sn and its properties might possibly be affected by low lying continuum states.

In-beam γ-ray spectroscopy has been a very important tool in studies of nuclear structure in the $^{100}$Sn region. It provides information on energies, spins and parities, and half-lives of yrast, high-spin states, which is very often complementary to β-decay studies. However, the interpretation of the data is complicated by the fact that so far very little is known about one- and two-quasi-particle neighbors of $^{100}$Sn. Multi-particle configurations observed in nuclei located further from $^{100}$Sn are used to place constraints on the single-particle energies and residual interactions with respect to the $^{100}$Sn core.

The status of experimental studies around $^{100}$Sn is shown in Fig. 1. A summary of the results obtained recently using in-beam spectroscopic methods, both on prompt γ-ray transitions and isomers will be presented in the next section and will

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FIGURE 1. The status of experimental studies of N≥50 nuclei situated in the vicinity of 100Sn. Nuclei for which prompt γ rays were observed are marked with "γγ", whereas nuclei where only isomers are known are labeled by "μμ". "β p" and "p" denote beta-delayed proton precursors and a ground-state proton emitter, respectively.

be followed by a shell-model discussion of selected nuclei. The last section contains an outlook for in-beam spectroscopy in the 100Sn region.

Experimental techniques and results

Heavy-ion beams of 50Cr and 58Ni combined with neutron-deficient targets are used to access nuclei around 100Sn. There are two experimental difficulties one has to face when trying to approach 100Sn using heavy-ion induced fusion-evaporation reactions. First, mainly protons are evaporated, bringing the system back to the line of stability, and the most interesting channels, which require evaporation of neutrons, are produced with very low cross sections. Second, the total reaction cross section is highly fragmented (typically about 20 reaction channels are open) resulting in a huge prompt γ-ray background associated with deexcitation of strongly populated nuclei. To overcome these obstacles, large, efficient arrays of Ge detectors are used to detect in-beam γ rays. In addition, charged-particle detectors and neutron detectors are employed to count light evaporated particles, i.e. protons, α particles and neutrons, and thus assign observed γ rays to individual reaction channels. A typical experimental set-up is schematically shown in Fig. 2(a). Alternatively, one could use a recoil mass separator for the reaction channel selection,
but the full potential of this approach has not yet been explored.

The first experiments in the $^{100}$Sn region using this technique were carried out at the Hahn-Meitner Institute in Berlin with the OSIRIS array of Ge detectors and were continued at the Tandem Accelerator Laboratory of the Niels Bohr Institute (NBI) in Riso, Denmark, using NORDBALL. The summary of the results obtained by the two collaborations can be found in Ref. [1]. Among $T_z=3/2$ nuclei, transitions in $^{97}$Ag [2] and $^{101}$In [3] were found. Excited states in $^{103}$Sn have not been found yet despite relatively large calculated cross section. There exist extensive data on $T_z=2$ nuclei $^{98}$Pd [4], $^{98}$Ag [5], $^{100}$Cd [6], $^{102}$In [7], and $^{104}$Sn [8]. Above the $Z=50$ gap $^{106}$Sb and $^{107}$Sb are the lightest Sb isotopes studied in-beam.

Following the success of the early experiments, attempts were made to extend spectroscopic information to nuclei located even closer to $^{100}$Sn using more efficient Ge arrays such as PEX at the NBI or GASP at the Laboratori Nazionali de Legnaro. Because of the rapidly decreasing cross sections with the departure from the line of stability these experiments did not provide data on new nuclei, but the level schemes for already known nuclei were significantly extended. For example, a regular band of M1 transitions was found in $^{105}$Sn [9] and was proposed to originate from magnetic rotation.

The search for isomers in the $^{100}$Sn region turned out to be more successful. Already standard in-beam experiments indicated much better sensitivity for delayed $\gamma$ rays. For example, the $17/2^+$ isomer was observed in $^{93}$Cd [10]. In an experiment performed at the Niels Bohr Institute, in order to optimize the detection of delayed $\gamma$ rays, a catcher foil was placed downstream from the target and was surrounded with Ge cluster detectors. Gamma rays were assigned to individual reaction channels using again charged-particle and neutron detectors. The experimental set-up is shown schematically in Fig. 2(b). As a result, isomers were found in the two $T_z=1$ nuclei $^{98}$Cd [11] and $^{102}$Sn [12]. Four delayed transitions were observed in $^{98}$Cd and were proposed to form the $8^+\rightarrow6^+\rightarrow4^+\rightarrow2^+\rightarrow0^+$ cascade. In $^{102}$Sn, two delayed $\gamma$
rays were assigned as the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions and were suggested to be situated below the $6^+$ isomeric state, but the $6^+ \rightarrow 4^+$ isomeric transitions was not found. In a follow-up experiment carried out at the Argonne National Laboratory (ANL) [13], a box consisting of 5 PiN diodes surrounded by 4 Ge detectors was placed behind the catcher foil at the focal of the Fragment Mass Analyzer to search for conversion electrons corresponding to the $6^+ \rightarrow 4^+$ isomeric transitions in $^{102}$Sn. The experimental set-up is shown schematically in Fig. 2(c). Fig.3 shows electron spectrum detected in coincidence with the two known delayed $\gamma$-ray transitions in $^{102}$Sn. The line at 44 keV was interpreted as the L-conversion line and the energy of 48 keV was proposed for the $6^+ \rightarrow 4^+$ isomeric transition. In a very recent work [14] half-lives of several high-spin states in $^{104}$Sn were measured using GASP equipped with a plunger. In addition, the level scheme for $^{104}$Sn was considerably extended and another case of a regular M1 band was found.

It is worth noting that the $\beta$-decay of $^{101}$Sn [15] and $^{103}$Sn [16] is followed by proton emission, and that protons emitted from the ground-state of $^{105}$Sb [17] were observed, reflecting close the proximity of the proton drip-line.
Excited states of nuclei in the vicinity of $^{100}$Sn can be described using the shell model. However, single-particle energies and residual interactions between valence nucleons are not known. In the shell-model calculations presented in Ref. [1] the $^{88}$Sr core was used to describe neutron-deficient $N \geq 50$, $Z \leq 50$ nuclei. The configuration space consisted of the $\pi p_{1/2}$ and $\pi g_{9/2}$ proton orbitals, which span the $Z=38-50$ shell, and the $\nu g_{7/2}$, $\nu d_{5/2}$, $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu h_{11/2}$ neutron orbitals, which fill the $N=50-82$ shell, with some restrictions on the occupation numbers of the higher lying $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu h_{11/2}$ orbitals. A mixture of measured, adopted from the $^{208}$Pb region, and calculated two-body matrix elements was used in these calculations.

Fig. 4 shows calculated or extrapolated single-particle energies for orbitals which play an important role in the $^{100}$Sn region. Energies of the $\pi p_{1/2}$ and $\pi g_{9/2}$ proton orbitals are known well from the fit to the data on $N=50$ isotones. The energies of the $\pi d_{5/2}$ and $\pi g_{7/2}$ proton orbitals, which are important above the $Z=50$ gap, were extrapolated from the light odd Sb isotopes and are not very well known. For neutrons, the two lowest lying orbitals $\nu d_{5/2}$ and $\nu g_{7/2}$ are almost degenerate. The two low-spin orbitals $\nu s_{1/2}$ and $\nu d_{3/2}$ are located about 2 MeV higher together with the high-spin intruder orbital $\nu h_{11/2}$. The yrast, high-spin states in the neutron-deficient nuclei with $N>50$ can be interpreted as due to the $(\pi g_{9/2}^{-1})^n \otimes \nu (d_{5/2}, g_{7/2})^n$ configuration at lower spins with the $\nu h_{11/2}$ orbital playing an increasingly important role for higher spins.
Usually, good agreement is found between the measured and calculated level energies, spins and parities for nuclei around $^{100}\text{Sn}$, and in most cases it is possible to assign specific configurations to the observed states, especially to the ones with low excitation energies, where the density of the states is still low.

Comparison between calculated and measured transition strength constitutes a more stringent test. The $8^+$ isomer proposed in $^{98}\text{Cd}$ was interpreted as the $(\pi g_9/2^{-1})^2_8^+$ configuration decaying to the $6^+$ member of the same multiplet. A $B(E2,8^+\rightarrow6^+)$ transition strength of $0.44(^{+0.0}_{-0.0})$ W.u. was extracted from the data. A small proton effective charge of $0.85(^{+0.0}_{-0.0})$e was deduced based on a comparison with the shell-model calculations. It implied a very small proton polarization charge suggesting a stiff underlying core. In $^{102}\text{Sn}$, the proposed $6^+$ isomer is dominated by the $(\nu d_5/2, \nu g_7/2)_6^+$ configuration, but the final state has more complicated structure. In contrast to $^{98}\text{Cd}$, an unusually large neutron effective charge of between 1.6 and 2.3 e was obtained for $^{102}\text{Sn}$ from $B(E2,6^+\rightarrow4^+)=4.0^{+2.4}_{-1.1}$ W.u. implying an E2-soft core. The latter result is supported by recent half-life measurements of high-spin states in $^{104}\text{Sn}$ [14] which also indicated a large neutron effective charge. The high neutron effective charge can be partially ascribed to deficiencies of shell-model calculations, in particular to the positions of the $d_3/2$ and $s_1/2$ neutron orbitals which are not known very well. The remaining discrepancy, however, is not presently understood and further effort is needed to improve available experimental information. In Ref. [18] the polarization charges for the orbits near $N=Z=50$ are calculated using the Hartree-Fock method with the Skyrme interaction. Using the values tabulated in Ref. [18] for the SkM* interaction, the neutron polarization charge corresponding to the $6^+\rightarrow4^+$ transition in $^{102}\text{Sn}$ comes to 1.5 e. By scaling the calculated energy of the $2^+_1$ state from 4.5 MeV to 2.7 MeV, and assuming that the isovector part of the polarization charge and the coupling to the isoscalar giant quadrupole vibrations remain unchanged, the calculated polarization charges of Ref. [18] will scale such that 2.0 e [19] is obtained for the transition in $^{102}\text{Sn}$ discussed above, i.e. closer to the experimentally deduced value. It is worth noting that first evidence for E3 collective excitations of the $^{100}\text{Sn}$ core was also found in Ref. [14].

Outlook

A new generation of large Ge arrays, such as EUROBALL and GAMMASPHERE, equipped with state-of-the-art ancillary detectors, offer one more chance to study in-beam immediate neighbors of $^{100}\text{Sn}$. In fact, several experiments are planned in the $^{100}\text{Sn}$ region in the near future. Among the most interesting topics are: the study of excited states in $^{103}\text{Sn}$ which escaped detection so far; a search for states above the isomers in $^{98}\text{Cd}$ and $^{102}\text{Sn}$, which involve core excitations; the study of neutron-proton multiplets in $^{104}\text{In}$. The next logic step on the way to $^{100}\text{Sn}$ would be $^{99}\text{In}$ and $^{101}\text{Sn}$, which offer direct measurement of some of the single-particle energies with respect to $^{100}\text{Sn}$, but this might be very difficult be-
cause of the very small cross sections involved (of the order of 10 nb). The studies of $^{100}$Sn itself are a matter of a more distant future. More detailed spectroscopy of already known nuclei might supply information about core excitations and about more exotic modes of excitations which might appear at high spin, such as rotation or magnetic rotation. The fact that the decay of some of the nuclei in the $^{100}$Sn region is accompanied by proton emission offers the possibility of using the Recoil-Decay Tagging method, with its unprecedented selectivity, to study their excited states.

REFERENCES