HIGH-SENIORITY EXCITATIONS IN EVEN NEUTRON-RICH Sn ISOTOPES POPULATED IN FUSION–FISSION REACTIONS*

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(Received December 19, 2012)

High-seniority excitations above the 10^+ and $27/2^-$ isomeric states were investigated with gamma coincidence techniques in neutron-rich Sn isotopes produced in fission processes following ^{48}Ca+^{208}Pb, ^{48}Ca+^{238}U and ^{64}Ni+^{238}U reactions. In the data analysis, the delayed gamma coincidence technique was used to establish high-spin state structures in all Sn isotopes with isomeric half-lives below 10 μsec. For cases with long-lived isomeric states, the gamma cross-coincidence method was employed to identify such structures. The relevant features of the fusion–fission process were investigated to enable these identifications. The discussion of some details of these analyses is followed by two examples of the results obtained: the ^{124}Sn level scheme and the level energy systematics for selected states established in even Sn isotopes.

DOI:10.5506/APhysPolB.44.395
PACS numbers: 27.60.+j, 25.70.Jj, 21.60.Cs, 23.20.Lv

The investigation of neutron-rich Sn isotopes, with their closed $Z = 50$ proton shell and neutrons filling the $s_{1/2}$, $d_{3/2}$ and $h_{11/2}$ orbitals above the $N = 64$ neutron number, revealed level structures that can be well understood within a simple shell-model description. A notable feature is the

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 27–September 2, 2012.

appearance of isomers involving the high-j $h_{11/2}$ intruder orbital. Indeed, the characteristic highest-spin seniority $\nu = 2$ and 3 $(h_{11/2})^n$ 10^+ and $27/2^-$ isomers have been established in all neutron-rich Sn isotopes through a series of deep-inelastic [1–3] and fusion–evaporation [4] reactions with heavy ions. Whereas the energies of these isomers decrease smoothly with the mass number and the first excited 2^+ state, energy remains stable throughout the whole series of Sn isotopes, the filling of the $h_{11/2}$ neutron orbital is reflected in a transparent behavior of the $B(E2)$ values extracted for isomeric transitions depopulating the 10^+ and $27/2^-$ isomers. The latter behavior indicates that this sub-shell is half-filled in the ^{123}Sn isotope. Until recently, similar features could not be tested for higher-seniority excitations, since no information was available on higher-spin states located above the seniority 2 and 3 isomers. In the present report, the attempt to study such states in all neutron-rich Sn isotopes will be described with a focus on the experimental techniques used to identify these structures.

The complementary data from three "standard" gamma coincidence experiments were used to perform an extensive analysis of high-spin levels in the Sn isotopes produced in fusion–fission reactions. The measurements were performed at the Argonne National Laboratory with the ATLAS superconducting linear accelerator and the Gammasphere [5] detector array, which consisted of 100 Compton-suppressed Ge detectors. In two of these experiments, a 330-MeV ^{48}Ca beam was bombarding 55 mg/cm^2 ^{238}U and 50 mg/cm^2 ^{208}Pb targets, and in the third one, a 430-MeV ^{64}Ni beam was used with the ^{238}U target. All of the experimental projects were primarily devoted to investigations of nuclei produced in deep-inelastic reactions, but the observed abundant population of Sn isotopes in the desired $A = 118$ to 126 mass range enabled the search for the hitherto unknown structures in these nuclei. The analysis clearly established that, in the ^{48}Ca+^{238}U and ^{48}Ca+^{208}Pb experiments, the $^{118-126}$Sn isotopes were produced in fusion–fission reactions, whereas the fission of the ^{238}U target nuclei populated them predominantly in the third colliding system: ^{64}Ni+^{238}U. In all the experimental runs, γ-ray coincidence data were collected with a trigger requiring three or more Compton-suppressed gamma quanta to be in coincidence. The beams were pulsed with a 412 ns repetition rate to provide a clean separation between prompt and delayed γ rays. For the detailed analysis, the data were unfolded into triple-γ coincidence events and sorted into separate prompt (PPP) and delayed (DDD) three-dimensional cubes. PPD (PDD) cubes with two (one) prompt and one (two) delayed γ rays were also sorted. The delay between γ rays was chosen taking into account the half-lives of isomers in order to optimize selection of specific events and to reduce contributions from random coincidences.

The data analysis established extended level structures above the seniority 2 and 3 isomers in all Sn isotopes from ^{118}Sn to ^{126}Sn, and confirmed the recently reported levels in ^{128}Sn [6]. Whereas for the even isotopes this analysis has already been completed and a full set of results is being prepared for publication [7], some of the odd isotopes still require further detailed inspections of the data. In the present report, the level scheme established in the ^{124}Sn isotope was selected as a typical example of the final results, but the discussion will be focused mainly on the analysis method applied and on some aspects of the fission processes that proved important to identify new excitations in the Sn isotopes under investigation. The standard delayed γ coincidence technique was employed in the analysis of the Sn isotopes for which the half-lives of the 10^+ or $27/2^-$ isomeric states are shorter than ≈ 10 μsec. In this range of half-lives the rays preceding in time the isomer could be easily identified in the coincidence spectra obtained with gates placed on known transitions below the isomer and delayed within the appropriately selected time-range. Typically, the prompt (P) spectra obtained from the PDD coincidence cubes with a requirement of two delayed γ rays provided a unique identification of transitions located above the isomers. The subsequent analysis of the prompt (PP) matrices, obtained from the PPD cubes by selecting all of the delayed transitions below the isomers, allowed for the construction of the level schemes above the long-lived levels. It turned out that, except for ^{118}Sn, in all other even Sn isotopes the presence of higher-lying isomers could be detected with the main decay proceeding via cascades of three transitions. The existence of isomers allowed us to exploit further the delayed coincidence technique in such cases, as this feature significantly increased the sensitivity to the detailed level sequences in the upper parts of these level schemes and enabled to delineate the decay of new isomers accurately.

The long half-lives of the seniority 2 and 3 isomers in some of the Sn isotopes (*e.g.*, 62 μsec in ^{122}Sn and 45 μsec in ^{124}Sn) did not allow to apply the simple delayed coincidence analysis discussed above, and γ transitions located above the isomers had to be identified using the cross-coincidence technique [8]. This required a more detailed knowledge of the fusion–fission process in order to establish which of the complementary fragments accompanying a specific Sn isotope should be expected in the reaction exit channel. In the ^{48}Ca+^{238}U data, the coincidence spectra of prompt transitions preceding in time isomeric decays in the selected Sn isotopes revealed the presence of sequences of transitions from the ground-state bands of Sm isotopes. This observation clarified that Sn isotopes are produced in the fission of the highly excited compound nucleus ($Z = 112$ and $A = 286$), which is followed by the evaporation of a large number of neutrons, as concluded from the observed mass distribution of Sm isotopes. The production yields of Sm isotopes displayed in Fig. 1 (a), (b), (c) were extracted from the coincidence spectra with delayed gates placed on the corresponding isomeric decay transitions in the ^{121}Sn, ^{119}Sn and ^{118}Sn nuclei, respectively. It is apparent that the mass distributions obtained in this way are rather broad and only a small shift of the average mass is observed for Sm fragments complementary to each of the selected Sn isotopes. A similar analysis performed for the ^{48}Ca+^{208}Pb data established that, also in this case, the predominant process populating Sn isotopes is fission of the compound nucleus ($Z = 102$, $A = 256$). This was inferred from the presence of known transitions in the complementary Te isotopes. The numbers of evaporated neutrons obtained from the balance of masses are displayed for both reactions in Fig. 1 (d) and (e). The high average values of 15 and 10 neutrons obtained for the ^{48}Ca+^{238}U and ^{48}Ca+^{208}Pb reactions, respectively, are to be expected when one takes into account the high excitation energies of the compound nuclei undergoing fission. It has to be noted that the wide ranges of neutron evaporation numbers observed in Fig. 1 (d) and (e) are arising also from the broad projectile energy range achieved in these thick target experiments. In the same analysis of the ^{64}Ni+^{238}U reaction data, the absence of known transitions in Yb iso-

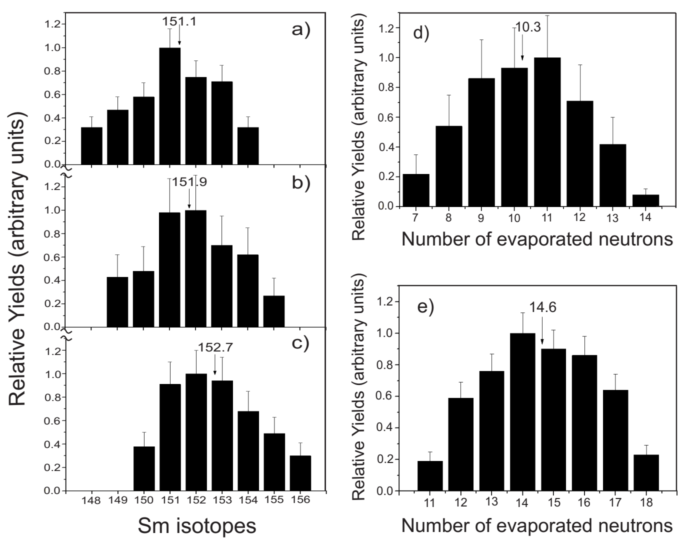

Fig. 1. Left panels: Population of Sm isotopes produced in the fusion–fission ^{48}Ca+^{238}U reaction as complementary fragments to the ^{121}Sn (a), ^{119}Sn (b) and ^{118}Sn (c) isotopes selected in the gamma cross-coincidence analysis. Right panels: Number of neutrons evaporated in the ^{48}Ca+^{208}Pb (d) and ^{48}Ca+^{238}U (e) fusion–fission reactions obtained from the mass balance of Sn isotopes and the Te and Sm isotopes observed as complementary fragments in the gamma-cross coincidence analysis of the respective reaction data. See the text for details.

topes, and the presence of γ rays from Mo isotopes, allowed to conclude that, in this case, the investigated Sn isotopes arise from fission of the ^{238}U target nuclei and, furthermore, that the compound nucleus is practically never formed. Here, the cross-coincidence results were not as transparent due to the apparent contribution to the Sn isotopic production of fission of other target-like reaction products. Therefore, only the first two experiments were used for the cross-coincidence identification of γ rays located in Sn isotopes above the long-lived isomeric states.

The detailed inspection of the coincidence spectra obtained from the PPP cubes with double gates placed on transitions from the series of Sm and Te isotopes, in the ^{48}Ca+^{238}U and ^{48}Ca+^{208}Pb data, respectively, provided the identification of several new transitions in each of the Sn isotopes under investigation, including those associated with long-lived isomers. Further conclusive identifications were made with the PPD cubes, where the same gate selection provided delayed coincidence spectra exhibiting the clear presence of transitions from the new higher-lying isomeric states in the even Sn isotopes. Using this initial information as a starting point, the subsequent detailed analysis could delineate level schemes above the long-lived seniority 2 and 3 isomers in several Sn isotopes. In Fig. 2, the ^{124}Sn level scheme is displayed as an example of the established structures. Whereas the detailed discussion of the level scheme construction, the suggested spin-parity assignments and interpretation will be presented in a forthcoming publication [7], the main features observed can be pointed out in the present report. The presence of the $T_{1/2} = 260$ ns isomeric state at 4553 keV is characteristic of the even Sn isotopes. It was assigned as $I^\pi = 15^-$, in analogy to the similar isomer observed in ^{128}Sn [6]. The observed γ-decay sequences to the 10^+ and 7^- lower-lying isomers are consistent with this assignment and the shell-model expectations identify this level as the seniority-4 excitation with a main $\nu(h_{11/2})^3 d_{3/2}$ configuration. The strongly populated states feeding the lowest 12^+ level placed in parallel to the isomer are tentatively assigned as the 14^+ (4700 keV) and 16^+ (5190 keV) levels and are naturally interpreted as the seniority-4 $(h_{11/2})^4$ excitations. States of higher spins, above the 16^+ level, and yrast states above the 15^- isomer must then correspond to the highest seniority-6 excitations. Similar sequences of levels were established in all neutron-rich even Sn isotopes across the investigated mass range and a systematics of selected level energies is displayed in Fig. 3. It exhibits the regularity expected, based on the shell-model interpretation of the observed states.

In conclusion, high-seniority excitations were studied in the neutron-rich Sn isotopes populated in fusion–fission reactions. The delayed gamma coincidence and the gamma cross-coincidence techniques were used to identify level structures above the seniority 2 and 3 isomers in all Sn isotopes in the

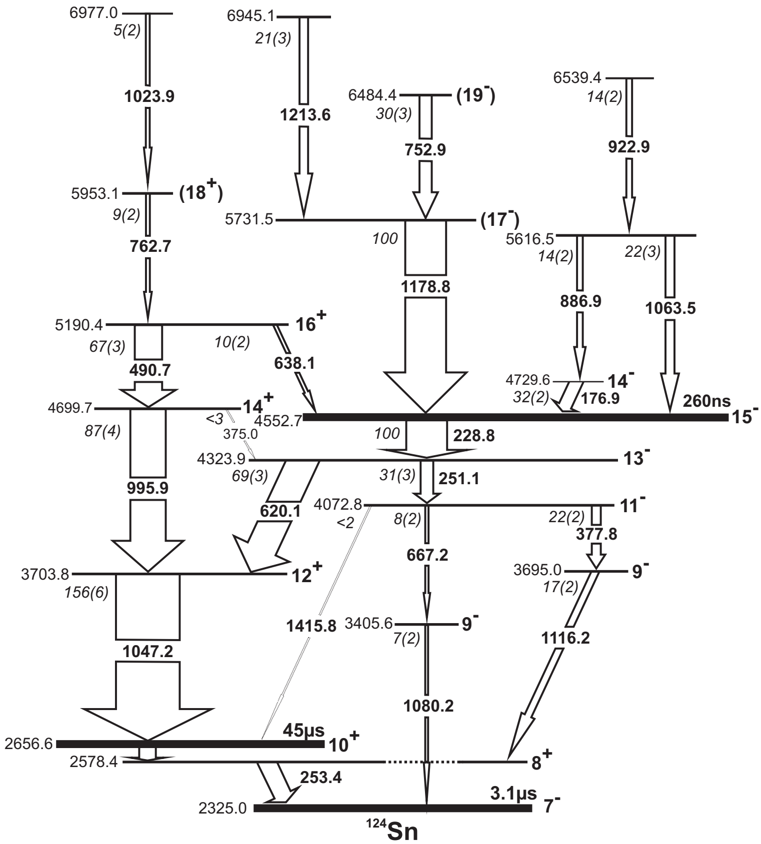

Fig. 2. Level scheme in ^{124}Sn established in the present study above the seniority 2 isomers. Transition intensities are marked by the widths of the arrows and values indicated in italic numbers. A separate intensity normalization was used for transitions located above the 260-ns 15^- isomer. Tentative spin-parity assignments are based on the observed gamma decays, shell-model expectations and systematics of levels observed in Sn isotopes.

$A = 118$ to 126 mass range. Some features of the fusion–fission reactions used in the present study were investigated in order to enable the efficient use of the cross-coincidence technique in the assignment of gamma rays to specific reaction channels of interest.

During the course of this study, the results of a parallel investigation of the same Sn isotopes, performed with the (n, xn) [9] and fusion–fission reactions [10], were reported. The results obtained here, which will be fully reported in a forthcoming publication, are more detailed, but are generally in a good agreement with the results of Refs. [9, 10].

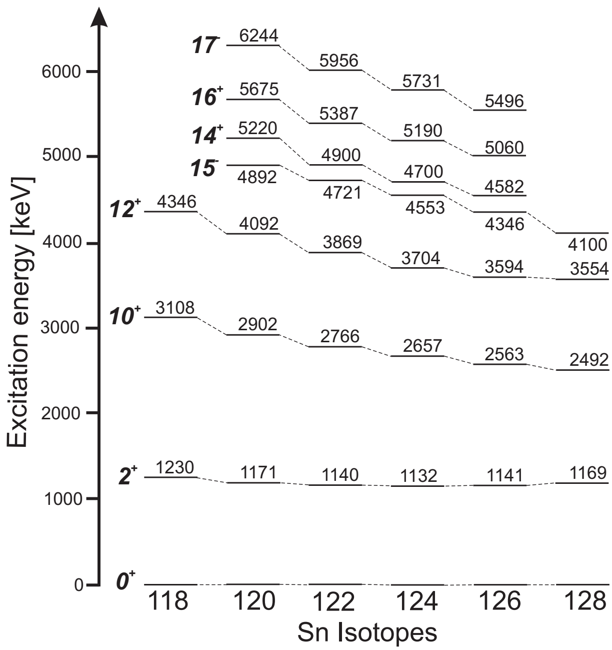

Fig. 3. Systematics of level energies for selected states states in even Sn isotopes in the mass range $A = 118$ to 128. The 10^+ and 15^- states are isomeric.

The authors thank the ATLAS operating staff for the efficient running of the accelerator and J.P. Greene for target preparations. This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 (ANL) and Grant No. DE-FG02-94ER40834 (UM), and by the Polish National Science Center, Project No. NN202-008640.

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