High-spin shell model states in neutron-rich Sn isotopes

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Abstract. High-spin states with the seniority $v \geq 2$ have been investigated in the neutron-rich ^{118,120,122,124,126}Sn isotopes. They were produced in fusion-fission processes following ^{48}Ca + ^{208}Pb, ^{48}Ca + ^{238}U reactions and via fission of target nuclei in the ^{64}Ni + ^{238}U system. By employing techniques of delayed- and cross-coincidences, it was possible to establish level schemes up to an 8 MeV excitation energy. The 13^- and 15^- states were identified as being isomeric and their half-lives were determined. The reduced transition probabilities extracted for isomeric transitions behave very regularly with the mass number *A*. The spin-parity values assigned to or suggested for the identified states were supported by shell-model calculations and by systematics.

1. Introduction

Spectroscopic studies of Sn isotopes with the closed $Z = 50$ proton shell are important to verify predictions of the shell model for excitations which involve the orbitals filled by neutrons between the $N = 50$ and $N = 82$ major shells. In the neutron-rich region, the high-j $h_{11/2}$ orbital plays a dominant role in the structure of the yrast states. The maximum spin coupling of the $h_{11/2}$ neutrons leads to the formation of isomeric states starting from the ^{116}Sn isotope. The seniority $v = 2$ and 3 $(h_{11/2})^n$ 10^+ and $27/2^-$ isomers were established in a series of deep-inelastic heavy ion reactions [1-4] up to the ^{128}Sn nucleus. They exhibit an impressive regularity in the excitation energies and especially in the reduced transition probabilities of the isomeric transitions (*B(E2)* values). The latter reflect the filling of the $h_{11/2}$ neutron orbital and define the half-filling to occur for the ^{123}Sn isotope. The present report aims at a considerable extension of the study of the Sn isotopes, involving the identification of hitherto unknown states with high values of seniority. Investigations with the same goal have also been carried out by two other groups which reported results of their parallel studies in recent publications. Several transitions located above the 10^+ isomers in Sn isotopes have been identified by Fotiades *et al*. [5] and a more complete study revealing also structures in the odd Sn isotopes as well was presented by Astier *et al*. [6]. The detailed results of the present study were reported in a recent publication [7]. Apart from

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the comforting similarity of the results obtained in independent experimental efforts, the level schemes presented here and in [7] are often more detailed, especially in instances which may turn out to be critical for the interpretation of some of the observed structures. Additionally, shell-model calculations have been performed for isotopes down to the *A* = 122 mass number and the results convincingly confirm the experimental findings.

2. Experimental procedures and data analysis techniques

The analysis was based on gamma coincidence data collected during three experiments performed at the Argonne National Laboratory. In all cases, the Argonne Tandem Linear Accelerator System (ATLAS) and the GAMMASPHERE [8] germanium detector array, which consisted of 101 Compton-suppressed Ge detectors, were employed. During the first experiment, a 330-MeV ^{48}Ca beam was bombarding a 55 mg/cm^2 ^{238}U target. In the second one, the target was changed to a 50 mg/cm^2 ^{208}Pb foil. Finally, in the last experiment, the uranium target was bombarded by a 430-MeV ^{64}Ni beam. In the ^{48}Ca + ^{238}U and ^{48}Ca + ^{208}Pb experiments, the $^{118\text{-}126}$Sn isotopes were produced in fusion-fission reactions, whereas fission of ^{238}U target nuclei populated these isotopes predominantly in the ^{64}Ni + ^{238}U measurement. In all experiments, gamma-ray coincidence data were collected with a trigger requiring that three or more Compton-suppressed gamma quanta be detected in coincidence. The beams were pulsed with a 412 ns repetition rate to provide a clean separation between prompt and delayed transitions.

The identification of gamma rays in a specific Sn isotope was obtained using two techniques described in detail in Refs. [9,10]. In the first, the delayed gamma coincidence technique was used requiring a delayed time condition for gamma rays selected by gates placed on previously known transitions in the corresponding isomeric decays. In this way it was possible to identify states above isomers with half-lives of less than a few μs. In order to identify states above much longer-lived isomeric states, the method of gamma cross-coincidences had to be applied. In the case of the ^{48}Ca + ^{238}U data, for example, gamma rays associated with the complementary Sm isotopes were found in mutual coincidence with the prompt gamma rays emitted by Sn nuclei. The fairly complex analysis of such data allowed to unambiguously identify the most intense gamma transitions located above the states with long half-lives in the respective Sn isotopes. These also include transitions occurring in the decay of higher-lying isomers. The cross-coincidence technique also allows to determine the number of evaporated neutrons in fission of the compound nucleus and serves as an important observable that can be used in studies of the reaction mechanism [11]. Following the crucial identification of the most intense gamma transitions above the isomers, a standard analysis of the data involving prompt and delayed gamma coincidence techniques established fairly detailed level schemes for all the Sn isotopes of interest.

3. Results

The data analysis outlined above established many states which can be classified as seniority v = 4,6 excitations in even neutron-rich Sn isotopes in the mass range *A* = 118-126. In all the isotopes, the level schemes above the 10^+ isomers show rather similar features and extend up to about 8 MeV in excitation energy and I ~ 20 in spin value. The ^{122}Sn level scheme is displayed in Fig. 1 as a representative example of the results obtained in this work. In this case, the identification of the three most intense transitions above the 10^+ (62 μs) isomer required the use of the gamma cross-coincidence method. It turned out that all three transitions were found to be delayed and the analysis established the presence of two isomeric states with respective half-lives of 134 and 40 ns. Using the delayed coincidence technique, the gamma rays preceding in time the isomers could be safely identified, simplifying the construction of the level scheme above the new long-lived states. A detailed analysis has shown that the 4721-keV isomeric state decays in a complex way to the 10^+, 8^+ and 7^- levels. The consideration of the observed decay pathways strongly supported the 15^- and 13^- spin-parity assignments to the 4721- and 4479-keV isomers, respectively. Two of the observed branches involve four transitions connecting the upper isomer with the well-established 7^- level. Whereas the

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intermediate state lifetimes (< 3ns) exclude *M2* and higher multipolarities, all four gamma rays can be characterized as *E2* transitions settling spin-parity assignments to all the intermediate levels. Consideration of any spin-parity values lower than the 15^- assignment to the isomer would be in contradiction with the branching observed in the isomer decay. In addition, the 12^+-14^+-16^+ multiplet with a seniority 4 value is expected above the 10^+ isomer. These prompt transitions have been identified as bypassing the 4479- and 4721-keV isomeric states and the observed 666-keV decay to the 15^- isomer is fully consistent with the 16^+ assignment to the 5387-keV level depopulated by competing *E1* and *E2* branches.

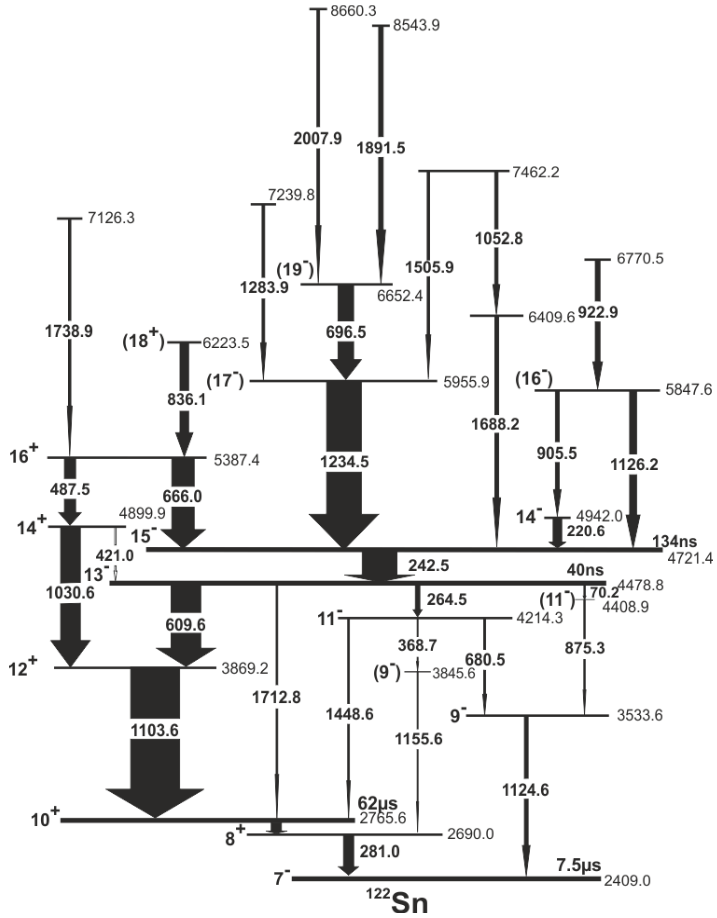

Figure 1. The ^{122}Sn level scheme established in the present study. The arrow widths reflect the observed transition intensities. Figure taken from Ref. [7].

Similar analyses and considerations established level schemes in all other even Sn isotopes and the deduced spin-parity assignments to the observed states were strongly supported by shell-model predictions. Calculations carried out for the tin isotopes with *A* from 122 to 130, with the OXBASH code [12], assumed ^{132}Sn as the closed core with the neutron holes occupying the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ orbitals. The respective single-particle energies were selected to reproduce the experimental level energies in the ^{131}Sn isotope. A set of two-body matrix elements was computed using the shell-model interaction described in detail in Ref. [13]. Comparison of the experimental and calculated energies for the yrast and near yrast levels in ^{122}Sn is presented in Fig. 2. Similar comparisons of experimental and calculation results were made also for the heavier Sn isotopes. In general, the calculations reproduce the experimental levels rather well. However, some systematic deviations indicate that further adjustments of shell-model interactions might improve the agreement. The calculated wave functions indicate the high complexity of the intrinsic structure of many observed states. Nevertheless, the results of the calculations fully confirmed the spin-parity assignments deduced from experiment.

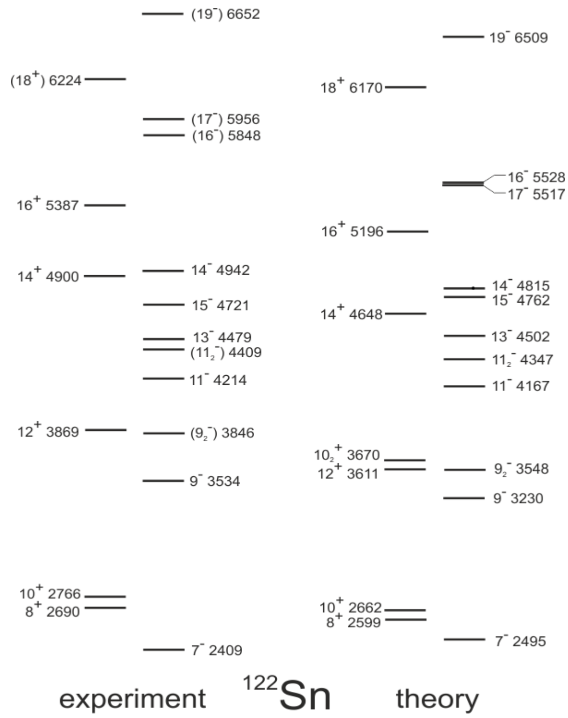

Figure 2. Comparison of the level energies established in the experiments with the theoretical shell-model calculations for ^{122}Sn. Figure taken from Ref. [7].

Furthermore, the systematics of the level energies in the isotopic chain of the even neutron-rich Sn nuclei (Fig. 3) looks consistent with the identified structures. The 2^+ state energies are very stable for all of the isotopes up to ^{130}Sn, with a shallow minimum in the vicinity of ^{124}Sn which is the result of the half-filling the $h_{11/2}$ subshell. However, higher lying states exhibit a regular pattern as well with a smooth decrease of level energies for heavier isotopes. This behavior is also consistent with trends predicted by the shell-model calculations.

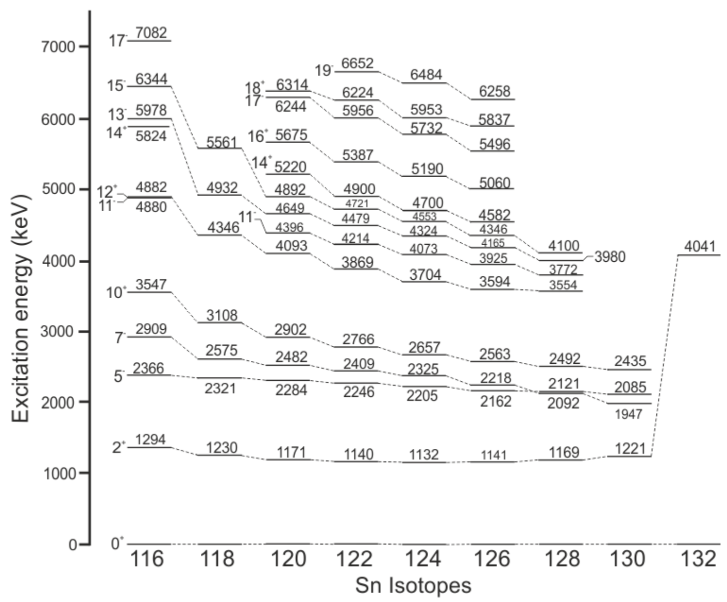

Figure 3. Systematics of the energies of yrast levels established in neutron-rich even Sn isotopes. Figure taken from Ref. [7].

The precise half-life determinations for the isomeric states in the ^{120,122,124,126}Sn isotopes assigned as 13^- and 15^- [7] and the isomeric *E2* transition energies allowed to extract the reduced transition probabilities *B(E2)* as presented in Fig. 4. At the top of this figure, *B(E2)* amplitudes for these 13^- and 15^- isomeric decays are shown, including also the value for the ^{128}Sn isotope, where a similar 15^- isomer had been identified previously [14]. In the lower part, the reduced transition probabilities *B(E2)* for the low-lying 10^+ and $27/2^-$ isomers are displayed showing a remarkable similarity in the *B(E2)* behavior. The smooth variation with mass number *A* of the *B*(*E*2) reduced transition probabilities, extracted for the isomeric transitions, reflects the filling of the neutron $h_{11/2}$ subshell. The same phenomenon was studied earlier for protons in proton-rich region of the chart of nuclides [15]. In this case an analogous behavior of the *B(E2)* values was obtained and the half filling of the proton $h_{11/2}$ subshell was determined to occur for the Z = 71, ^{153}Lu nucleus. Surprisingly, also the *B(E1)* values calculated for the observed *E1* decays of the 13^- isomers in the Sn isotopes exhibit a similar regularity. It should be pointed out that the convention introduced in Refs. [1-4] was adopted here as well; i.e., *B*(*E*2) amplitudes are shown rather than the *B*(*E*2) values, and arbitrarily the positive sign is assigned to the amplitudes of the light Sn isotopes with a change to negative values when the *B*(*E*2) = 0 line is crossed.

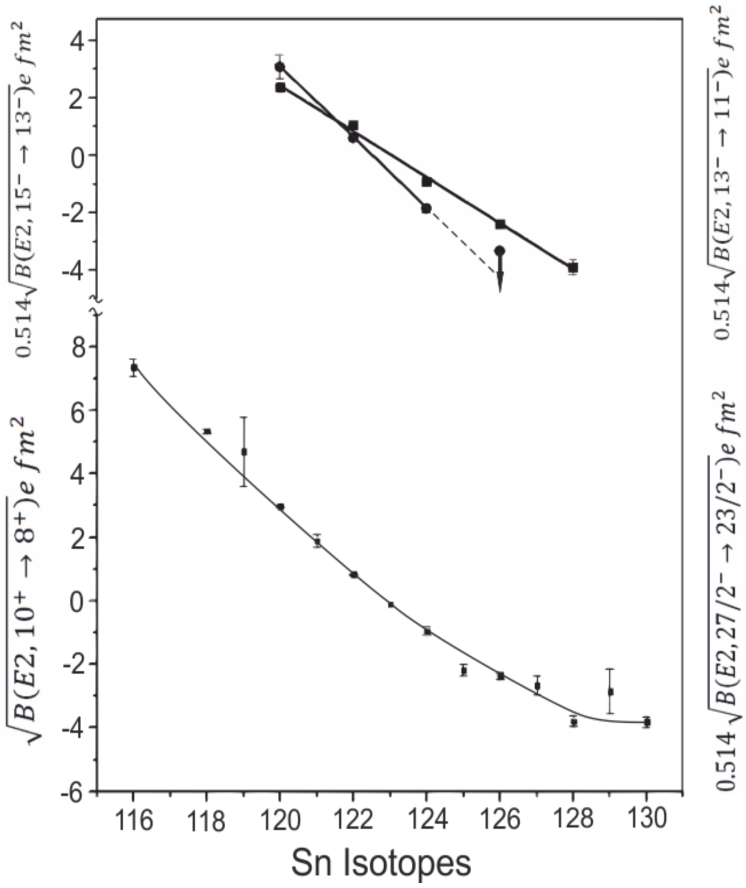

Figure 4. Transition amplitudes for isomeric decays observed in the Sn isotopes as calculated from the reduced transition rates *B(E2)*. On the bottom of the graph, the mass dependence related to the decay of the 10^+ and $27/2^-$ isomers is shown [16]. On the top, the corresponding values for the 13^- (circles) and 15^- (squares) established in the present study are given. In the ^{126}Sn isotope, only a limit could be determined. Figure taken from Ref. [7].

4. Conclusions

In the present work, extended level structures located above the 10^+ and 7^- isomers were established in the even $^{118-126}$Sn isotopes. It was demonstrated that with complex fusion-fission reactions such an identification is possible across the full range of neutron-rich isotopes and allows to construct level schemes up to relatively high spins. In the ^{120,122,124,126}Sn isotopes, the presence of 13^- and 15^- isomeric states could be established, yielding reduced transition probability *B(E2)* values for isomeric transitions which resemble closely the *B(E2)* values and mass dependence observed earlier in the 10^+ and $27/2^-$ isomeric decays. A number of states located above these 15^- isomers could also be identified. They correspond to seniority v = 6 excitations. Theoretical shell-model calculations performed for all isotopes down to A = 122 reproduced reasonably well the experimental levels. The results obtained from the same experiments for the neutron-rich odd Sn isotopes will be presented in a forthcoming publication [17].

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