Coexistence of collective and noncollective structures in ^{118}Sn

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Excited states of ^{118}Sn have been populated in the ^{116}Cd(^{7}Li,1p4n) reaction with a beam energy of 50 MeV. The previously known level scheme is extended in the low-spin region as well as to higher spins. The systematic behavior of the intruder deformed bands in the Sn isotopes is discussed. Total Routhian surface calculations and configuration-fixed constrained triaxial relativistic mean-field approaches are employed for analysis of the nuclear structure of ^{118}Sn.

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The Sn isotopes ($Z = 50$) provide a good laboratory for study of the phenomenon of shape coexistence in nuclei and have attracted extensive experimental and theoretical interest [1–4]. The coexistence of both spherical and prolate shapes has been systematically observed in even-even Sn isotopes. Spherical states are interpreted to arise from the influence of the shell gap. Despite the strong influence of the shell gap, low-lying deformed states are known to exist in Sn isotopes, which result in collective rotational bands [5,6]. These bands are interpreted as owing to a 2p-2h proton configuration where a pair of $g_{9/2}$ protons is excited across the $Z = 50$ closed shell to the down-sloping $g_{7/2}$ orbitals, the so-called intruder band. These $(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-2}$ bands have been observed from ^{110}Sn to ^{118}Sn [5–10]. In $^{112-118}$Sn such bands are observed down to the 0^+ band head, whereas in ^{108,110}Sn no band members below spin 10 have been observed.

Although the neighboring even-even isotopes ^{112}Sn, ^{114}Sn, and ^{116}Sn have been studied in detail, information about excited states in ^{118}Sn is still scarce. This is mainly because of the lack of heavy-ion reactions in previous measurements and the limited selectivity of the techniques used so far. In this paper, we report our investigation of the excited states in ^{118}Sn using the ^{116}Cd(^{7}Li,1p4n) reaction. The present work is an attempt to increase as much as possible the knowledge about the nature of excited states in ^{118}Sn. Total Routhian surface (TRS) calculations and configuration-fixed constrained triaxial relativistic mean-field (RMF) approaches are also employed for analysis of the nuclear structure of ^{118}Sn.

Excited states of ^{118}Sn were populated via the ^{116}Cd(^{7}Li,1p4n) reaction at a beam energy of 50 MeV. The ^{7}Li beam was provided by the HI-13 tandem accelerator at the China Institute of Atomic Energy in Beijing. The ^{116}Cd target was a self-supporting foil 2.5 mg/cm^2 thick. Twofold γ-γ coincident events were collected using an array of 12 Compton-suppressed HPGe detectors and two low-energy photon spectrometer detectors. All detectors were calibrated using the standard ^{152}Eu and ^{133}Ba γ-ray sources. About 2×10^8 γ-γ coincidence events requiring two or more detectors to be fired within 200 ns were accumulated in the event-by-event mode. In the off-line analysis, the outputs of the array were then matched for gain and zero position. Then all the coincidence events were recalibrated to 0.5 keV/channel and sorted into a 4096 × 4096-channel symmetrized E_γ-E_γ matrix. Multipolarity information on the γ ray was extracted from the data using the method of directional correlation of oriented states (DCO). The DCO matrices were created by sorting on one axis the detectors lying at ∼45° and on the other those at ∼90° with respect to the beam direction. With setting gates on stretched quadrupole transitions, DCO ratios were higher than 1.0 for stretched quadrupole transitions and were lower than 0.8 for pure dipole transitions.

After careful analysis of the obtained data, the major evaporation residues of the reaction used were found to be ^{118}Sb (∼58%), ^{118}Sn (∼18%), ^{119}Sb (∼15%), and ^{117}Sb (∼8%). As shown in Fig. 1, γ rays from ^{118}Sn are seen as strong lines in the total projection spectrum deduced from the γ-γ coincidence matrix. Prior to the present work, limited information was available on ^{118}Sn [6]. Some new results for the ^{118}Sn nucleus were obtained in this study. Excited states of ^{118}Sn have already been studied using radioactive decay [11] and the α-induced reaction [5,6]. The level scheme for ^{118}Sn has been extended in the present work, as shown in Fig. 2. Figure 3 shows the sample spectra supporting the level scheme in Fig. 2. The multipolarities for the observed transitions are based on those obtained from previous work and measured DCO ratios. For in-band γ rays at high spin, an electric quadrupole character has been assumed. On the left-hand side of Fig. 2, positive-parity band 1 represents the intruder band based on the deformed 2h-2p proton intruder configuration. On the right-hand side are the spherical states. Five new transitions, at 263.5, 270.5, 713.5, 1160.6, and 1292.8 keV, are observed and placed on the right-hand side

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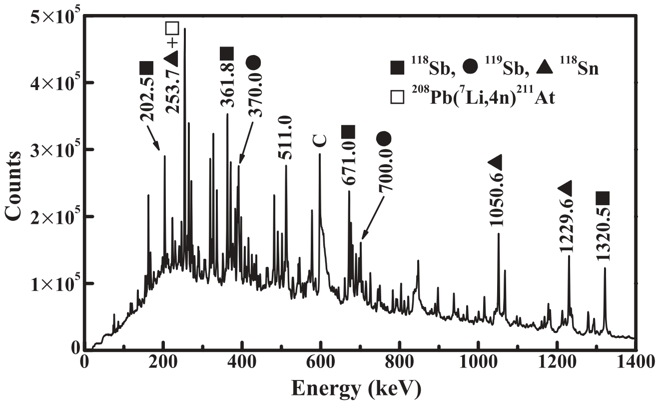

FIG. 1. Total projection spectrum generated from the γ-γ coincidence matrix.

of Fig. 2. The measured DCO ratios for the 1160.6- and 1292.8-keV transitions are consistent with stretched electric quadrupole characters. Thus a new 4753-keV level is proposed, with the spin parity of (6^+), as shown in Fig. 2. Unfortunately, multipolarity information on the transitions at 270.5, 713.5, and 263.5 keV cannot be obtained accurately, owing either to their poor statistics or to interference from the transitions in neighboring ^{118}Sb. However, the 983.5-keV crossover transition has a DCO ratio consistent with the stretched

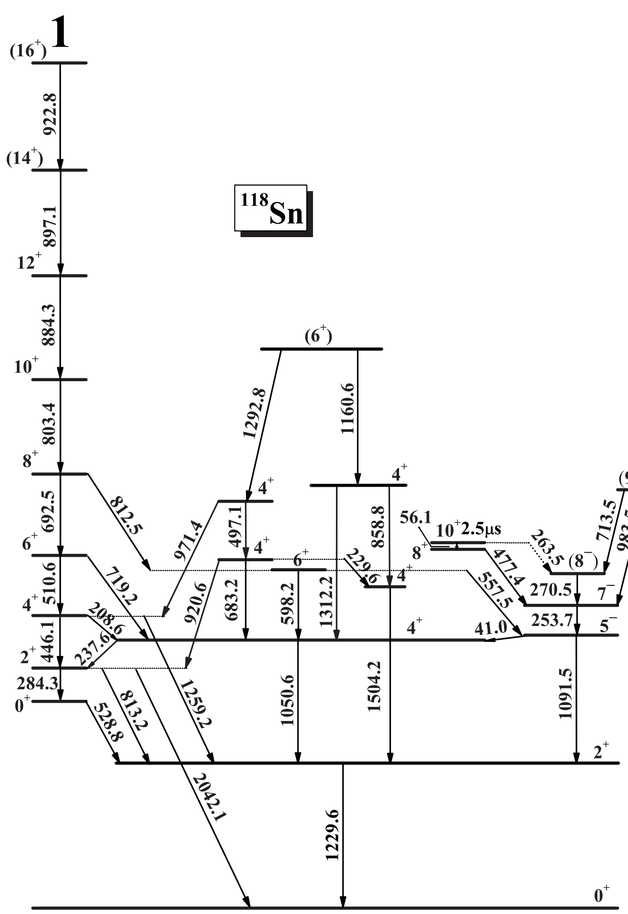

FIG. 2. Level scheme for ^{118}Sn proposed in the present work.

E2 type; we therefore assume that the transitions at 270.5 and 713.5 keV are the $\Delta I = 1$ dipole transition on the basis of the general yrast arguments that levels populated in heavy-ion reactions usually have spins that increased with increasing excitation energy. The 263.5-keV transition is observed to populate the 2845-keV level, establishing a level at 3108 keV. This level is consistent with the excitation energy of the 10^+ isomer. Based on the similar placement of the 319-keV transition in the neighboring ^{116}Sn [10], the 263.5-keV transition has been tentatively placed in the level scheme and is shown as a dashed line in Fig. 2. The ground state of ^{118}Sn was characterized by a spherical shape, and the 2_1^+ and 4_1^+ states arise from the vibrational pattern. Above the 4_1^+ state, the decay sequence becomes irregular and fragments into several parallel branches. The $Z = 50$ proton shell is closed, so one may assume that the low-lying states on the right-hand side of the level scheme (Fig. 2) are predominantly formed by neutron excitations, corresponding to spherical configurations. The lowest one-quasiparticle states in odd-mass $^{115-119}$Sn nuclei are the $5/2^+$ ground state, the first excited $7/2^+$ state just above the ground state, and the $11/2^-$ state around 1.5-MeV excitation energy. These states arise from the five active orbitals $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$. In even-even Sn nuclei low-lying states should thus be built on these orbitals. The low-lying 5^-, 7^-, 8^-, 9^-, and 10^+ states may be interpreted to arise from the shell-model $h_{11/2}s_{1/2}$, $h_{11/2}d_{3/2}$, $h_{11/2}d_{5/2}$, $h_{11/2}g_{7/2}$, and $h_{11/2}^2$ configurations, respectively.

The excited 0_2^+ state was interpreted as proton-pair excitations across the $Z = 50$ shell gap leading to a deformed state, coexisting with the spherical ground state [5]. Rotational bands bulit on the excited 0_2^+ state have been observed in a series of even-mass Sn nuclei. In ^{118}Sn, this $\Delta I = 2$ rotational band was observed up to spin $I = 12^+$ and assigned to be built on the configuration $(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-2}$ [5]. In the present work, this intruder band, labeled 1, has been extended up to spin $I = (16^+)$ beyond the first back-bend. Preliminary results of the intruder band in ^{118}Sn have been published in Ref. [12].

The experimental alignment for the positive-parity intruder band in ^{118}Sn is plotted in Fig. 4 as a function of the rotational frequency. For comparison, alignment plots for the corresponding band structures in ^{112,114,116}Sn are also included in Fig. 4. The same Harris parameters, $J_0 = 15\,\hbar^2$ MeV^{-1} and $J_1 = 25\,\hbar^4$ MeV^{-3} [10], were used to subtract the angular momentum of the core. Obviously, the intruder band in ^{118}Sn shows an up-bend for frequencies of about 0.45 MeV (see Fig. 4). In ^{116}Sn, ^{114}Sn, and ^{112}Sn the corresponding alignment is observed at frequencies of 0.46 MeV [10], 0.41 MeV [9], and 0.37 MeV [13], respectively. The first alignment in this mass region is expected to be caused by the alignment of two quasineutrons $(\nu h_{11/2})^2$ [14]. As shown in Fig 4, it is interesting to note that the alignment in ^{118}Sn happens at almost the same frequency as in ^{116}Sn, whereas there is a different pattern in ^{112}Sn and ^{114}Sn. More theoretical work is required to explain this phenomenon.

To gain a better understanding of the shape coexistence effect, TRS cranking calculations were performed (for details see, e.g., Refs. [15] and [16]). The total energy of the nucleus in the rotating frame was minimized with respect to the deformation parameters β_2 and γ. The TRSs for ^{118}Sn are shown

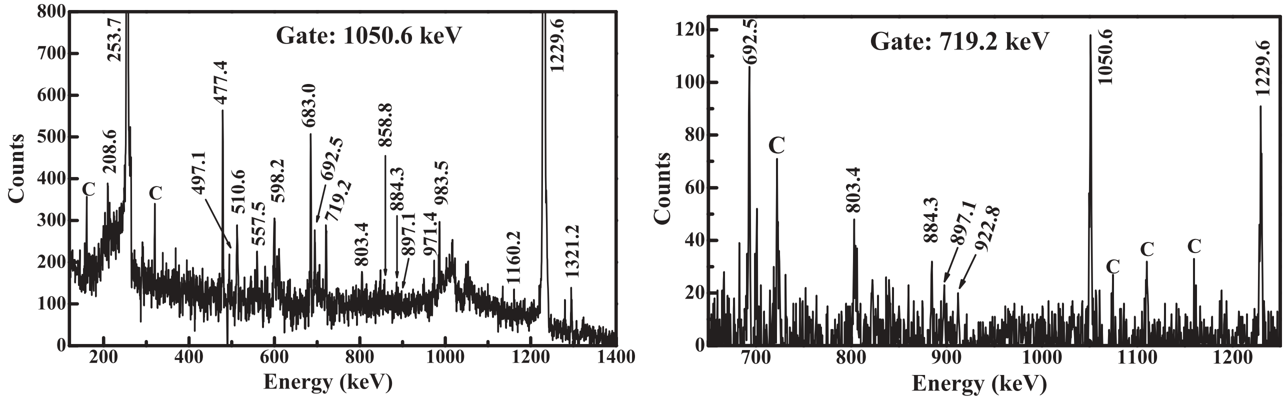

FIG. 3. The γ-ray spectrum gated on the 1050.6- and 719.2-keV transitions. Peaks labeled C indicate contaminations.

in Fig. 5 for four rotational frequencies. Energy contours are at 200-keV intervals. The results of the TRS calculations can be summarized as follows. At rotational frequencies $\hbar\omega = 0$, 0.1, and 0.2 MeV, energy minima are seen in two distinct dots in the (β_2, γ) plane. The minimum at $\beta_2 = 0$ corresponds to a spherical shape. The second energy minimum is seen for a prolate shape ($\beta_2 = 0.23$), corresponding to the $2p$-$2h$ intruder configuration. The energy separation between two minimum states is predicted as 1.8 MeV from our TRS calculation at the rotational frequency $\hbar\omega = 0$ MeV. These features exhibit good agreement with the level scheme for ^{118}Sn, wherein the level separation between two 0 states is 1758.4 keV. Above the alignment of the $h_{11/2}^2$ neutrons at $\hbar\omega >$ 0.45 MeV, the TRS calculations predict that a noncollective oblate configuration ($\beta_2 = 0.102$, $\gamma = 60^\circ$) becomes yrast. The two-quasineutron $h_{11/2}^2$ configuration drives the nucleus toward an oblate deformation; one can therefore conclude that the aligned neutrons will significantly influence the evolution of the shape, inducing the possible band termination. Clearly, band 1 needs to be extended up to the terminating spin to be conclusively interpreted as a terminating band.

Configuration-fixed quadrupole moment constrained calculation through β_2 was carried out to obtain the potential energy surfaces (PESs) for each configuration of ^{118}Sn in the framework of triaxial RMF approaches, which has been successfully applied to study the triaxial structure of candidate chiral nuclei [17–19]. A detailed description of this approach with nucleon-nucleon interactions is given in Ref. [17] and references therein. In Fig. 6, we plot the PESs in ^{118}Sn as functions of deformation β_2 in configuration-fixed constrained triaxial RMF calculations. The minima in the PES of each configuration are labeled A, B, C, and D for quadrupole deformation parameters (β_2, γ) of (0, 0), (0.24, 59.9), (0.31, 0), and (0.39, 13.9), respectively. The energies for these minima, including the ground state, are within 1.5 MeV of each other

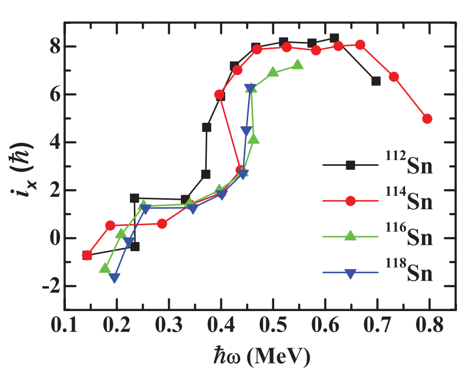

FIG. 4. (Color online) Experimental alignment plots for the intruder band in ^{112,114,116,118}Sn. The Harris parameters used are $J_0 = 15\,\hbar^2$ MeV^{-1} and $J_1 = 25\,\hbar^4$ MeV^{-3}.

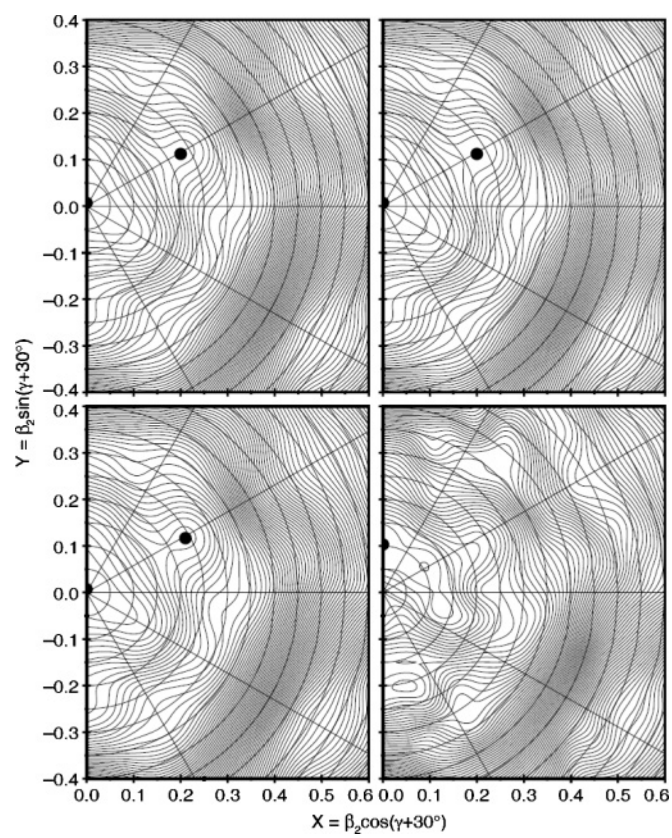

FIG. 5. Total Routhian surface calculations for ^{118}Sn at $\hbar\omega =$ 0.00 MeV (top left), $\hbar\omega = 0.10$ MeV (top right), $\hbar\omega = 0.20$ MeV (bottom left), and $\hbar\omega = 0.50$ MeV (bottom right). Energy contours are at 200-keV intervals.

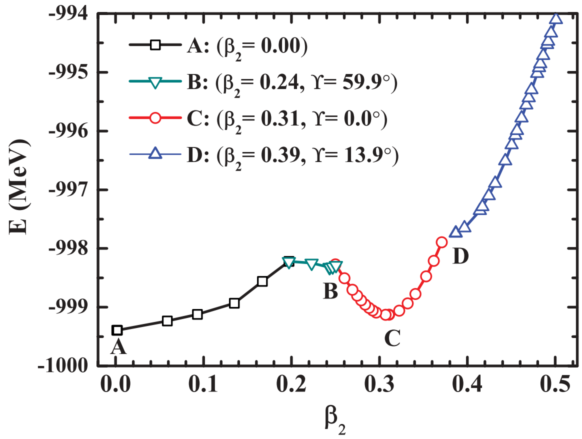

FIG. 6. (Color online) Potential energy surfaces as functions of deformation β_2 in configuration-fixed relativistic mean-field calculations. The minima in the energy surfaces of each configuration are labeled A–D according to their energies.

but correspond to different deformations β_2 and γ, which is a good example of shape coexistence. This shape coexistence includes the spherical, prolate, and oblate shapes; the spherical minimum corresponds to the ground state. It should be noted that the second minimum corresponds to a $2p$-$2h$ configuration. This is consistent with the TRS calculations. However, a larger prolate shape ($\beta_2 = 0.31$) is predicted by the present RMF. Furthermore, the RMF calculation also predicts a superdeformed state D. This minimum is not very deep and was not observed in the present experimental study.

In summary, excited states of ^{118}Sn, populated in the ^{116}Cd(^{7}Li,$1p4n$)^{118}Sn reaction at a beam energy of 50 MeV, have been studied. The intruder deformed band has been extended up to 7187 keV with spin (16^+). In addition, five new levels with low spins and excitation energies have been identified. TRS calculations and configuration-fixed constrained triaxial RMF approaches have been employed for analysis of the nuclear structure of ^{118}Sn. The present study shows that the ^{118}Sn nucleus represents a beautiful case of nuclear shape coexistence where the intruder band is seen in parallel with the spherical discrete structure.

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