PHYSICAL REVIEW C **78**, 037301 (2008)

Experimental study of the 2p-2h band in ^{111}Sn

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(Received 11 July 2008; published 5 September 2008)

The $\Delta I = 2$ intruder band in ^{111}Sn, built upon the 4074.3 keV state, was studied. The states were populated in the ^{100}Mo(^{20}Ne, $\alpha 5n$) reaction at a beam energy of 136 MeV. Mean lifetimes of five states up to 8737.2 keV (spin $43/2^-$) have been measured for the first time using the Doppler shift attenuation method. In addition, an upper limit of mean lifetime has been estimated for the 9860.0 keV (spin $47/2^-$) state. The $B(E2)$ values, derived from the present lifetime results, indicate a quadrupole deformation of $\beta_2 = 0.28 \pm 0.02$ for the $31/2^-$ state and decrease progressively with spin, suggesting a reduction in collectivity. The dynamic moment of inertia for the band also decreases continuously up to the highest observed frequencies. These results, along with the predictions of a total Routhian surface calculation, suggest that the $\Delta I = 2$ band in ^{111}Sn undergoes a change of shape from collective prolate to triaxial with increase in spin and possibly terminates in a noncollective oblate state at a high spin.

DOI: 10.1103/PhysRevC.78.037301 PACS number(s): 21.10.Re, 21.10.Tg, 25.70.Gh, 27.60.+j

Several nuclei with proton number $Z = 49$–53 in the $A \sim 110$ mass region have been reported to possess rotational bands besides other states that arise from single-particle excitations [1–5]. These bands are interpreted as due to a 2p-2h proton configuration where a pair of $g_{9/2}$ protons are excited across the $Z = 50$ closed shell to the down-sloping $g_{7/2}d_{5/2}$ Nilsson orbitals. The neutrons outside the ^{100}Sn core are also distributed in the same orbitals with some occupying the intruder $h_{11/2}$ shell. Angular momentum in these intruder bands that have a near prolate shape at low spins, is built from the gradual alignments of the extra-core nucleons till the final states are formed, usually at a large energy cost, leading finally to termination of the band in a noncollective oblate state when all the particles and holes outside the closed core are fully aligned. Afanasjev *et al.* [6] have identified 40 bands in 18 nuclei in this mass region, including one in ^{111}Sn, with well-defined configurations that are expected to exhibit band termination.

Experimentally, such intruder bands have been observed up to high spins in several Sn, Sb, and Te isotopes [2,4,7,8]. A general feature of these intruder bands is that their dynamic moment of inertia ($J^{(2)}$) decrease gradually with increasing spin up to the highest observed frequency. Lifetimes have been reported for two such bands in ^{108}Sn and one band each in ^{109}Sb [2] and ^{112}Sn [9]. The electric quadrupole moments, deduced from the measured lifetimes for the bands in ^{108}Sn and ^{109}Sb, were found to decrease with increase in spin, in excellent agreement with the predictions of the cranked Nilsson-Strutinsky calculations and have been interpreted as signifying smooth band termination. However, such measurements are not reported in the literature for the $\Delta I = 2$ intruder band built upon the $23/2^-$ state in ^{111}Sn although excited states up to 17.7 MeV with spin ($67/2^-$) have been reported [10]. The configuration $[20,3]^-$ assigned for this band [6] (two proton holes in the $g_{9/2}$, no proton in the $h_{11/2}$ and 3 neutrons in the $h_{11/2}$ orbitals) leads to a total spin of $79/2^-$. In this work, we report the first measurement of the lifetimes of the states of the intruder band in ^{111}Sn. This would permit a study of the structure of these states and help in the understanding of their behavior with spin in view of the interesting findings in the neighboring Sn and Sb isotopes.

High spin states of ^{111}Sn were populated in the ^{100}Mo(^{20}Ne, $\alpha 5n$) reaction at a beam energy of 136 MeV at the Variable Energy Cyclotron Centre, Kolkata. The target consisted of isotopically enriched (99.5%) ^{100}Mo, 4.7 mg/cm^2 thick, evaporated on an aluminium backing. Two- and higher-fold $\gamma\gamma$-coincident events were collected using an array of six Compton-suppressed Clover detectors belonging to the Indian National Gamma Array (INGA) with the detectors arranged in three groups of two detectors each, at angles of 40°, 90°, and 125° with respect to the beam direction. The raw data were sorted into different 4096×4096 matrices after gain matching of all the spectra to a dispersion of 1.0 keV per channel. The data were analyzed using the computer code INGASORT [11]. Other relevant experimental details are available in Ref. [9].

The negative-parity intruder band in ^{111}Sn built upon the 4074.3 keV state, with γ-ray energies and intensities determined from the present work, is shown as band 1 in Fig. 1. Other states connected to band 1 through interband transitions are grouped together as band 2. The figure also includes a partial spectrum obtained by summing the gates on a few low-lying transitions in the level scheme. The γ-rays belonging to band 1 are marked in this spectrum. Table I summarizes the results on the γ-ray relative intensities, DCO ratios, level lifetimes (τ), the $B(E2)$ rates, the transition quadrupole moments (Q_t), and the quadrupole deformations (β_2) for band 1.

The rotational band in ^{111}Sn has been previously reported in Refs. [10,12,13] up to different spins. In the present work, the band has been observed up to an excitation energy of 12445.6 keV and spin ($55/2^-$). Only Lafosse *et al.* [10] have reported the band up to higher spins ($67/2^-$). All γ-rays

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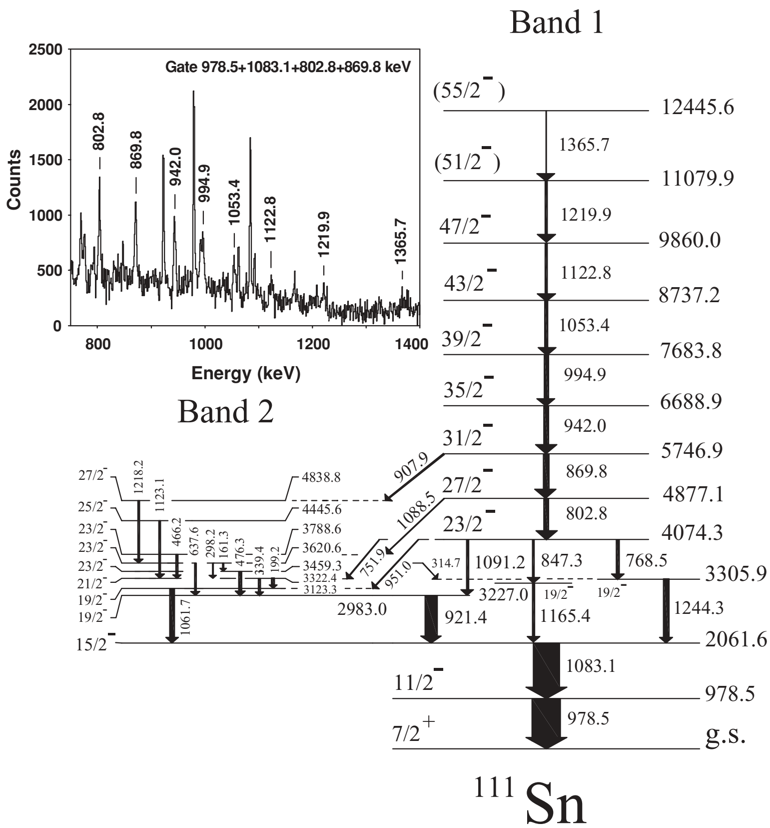

FIG. 1. Level scheme of ^{111}Sn based on the present work. Bands 1 and 2 are explained in the text. The level and γ-ray energies are given in keV. The relative intensities of the transitions are indicated by the widths of the arrows. On the top left is shown the sum of the spectra gated by the 978.5, 1083.1, 802.8, and 869.8 keV transitions. Only the γ-rays belonging to band 1 are marked in the spectrum.

shown in band 2 as well as the interband transitions have been previously reported in the literature [13].

The γ-ray multipolarities were determined for several transitions from the experimental DCO ratios (R_{DCO}) using the computer code ANGCOR [14] as outlined in Ref. [9]. Gates were set on known $E2$ transitions only. Such gates yield R_{DCO} values close to unity for quadrupole transitions and values ranging from 0 to 2 for $\Delta I = 1$ transitions, depending on the γ-ray multipole mixing ratio δ. The DCO ratios in Table I are consistent with a stretched quadrupole nature for all transitions in the band with energies up to 1053.4 keV, in support of the spin assignments proposed in Ref. [10]. The higher energy transitions in the band did not permit a DCO measurement either due to their weak intensity or interference from neighboring γ-rays, as in the case of the 1122.8 and 1219.9 keV transitions (see level scheme). However, firm spin assignments are indicated for states up to 9860.0 keV, deexciting by the 1122.8 keV γ-ray, in Fig. 1 and Table I on the basis of earlier results [10].

The lifetimes of the excited states were extracted from the Doppler shift attenuation (DSA) data using the analysis

TABLE I. Results on level energies (E_x), gamma-ray energies (E_γ), gamma-ray relative intensities (I_γ), DCO ratios, mean lifetimes (τ), reduced transition probabilities $B(E2)$, transition quadrupole moments (Q_t), and quadrupole deformations (β_2) for band 1 in ^{111}Sn. Errors assigned to the level lifetimes are discussed in the text. Errors in E_x and E_γ are similar to those in Ref. [9].

E_x (keV)	E_γ (keV)	I_γ	R_{DCO}	$J_i^\pi \rightarrow J_f^\pi$	τ(ps)	$B(E2)$ (W.u.)	Q_t (eb)	β_2
4877.1	802.8	17.4 ± 2.3	0.81 ± 0.15	$27/2^- \rightarrow 23/2^-$	$0.71^{+0.03}_{-0.04}$	93 ± 4	2.93 ± 0.10	0.21 ± 0.01
	1088.5	3.0 ± 0.6	–	$27/2^- \rightarrow 23/2^-$		3.5 ± 0.2[a]		
5746.9	869.8	19.6 ± 2.5	1.07 ± 0.16	$31/2^- \rightarrow 27/2^-$	0.25 ± 0.02	171^{+13}_{-11}	$3.95^{+0.21}_{-0.18}$	0.28 ± 0.02
	907.9	4.2[b]	–	$31/2^- \rightarrow 27/2^-$		28^{+4}_{-3}[a]		
6688.9	942.0	16.7 ± 2.2	1.18 ± 0.22	$35/2^- \rightarrow 31/2^-$	0.22 ± 0.02	158^{+16}_{-14}	$3.77^{+0.27}_{-0.24}$	0.26 ± 0.02
7683.8	994.9	15.0 ± 2.4	1.19 ± 0.24	$39/2^- \rightarrow 35/2^-$	0.23 ± 0.03	116^{+14}_{-13}	$3.23^{+0.28}_{-0.26}$	0.23 ± 0.02
8737.2	1053.4	11.4 ± 2.0	0.97 ± 0.22	$43/2^- \rightarrow 39/2^-$	$0.18^{+0.03}_{-0.02}$	108 ± 14	$3.10^{+0.29}_{-0.28}$	0.22 ± 0.02
9860.6	1122.8	8.2 ± 2.6	–	$47/2^- \rightarrow 43/2^-$	<0.20	>72	>2.53	>0.18

[a]Assuming the γ-ray to be pure quadrupole.
[b]Relative intensity deduced using branching ratio reported in Ref. [13].

package LINESHAPE [15]. The details of the slowing down history of the recoils (moving with an initial recoil velocity of $\beta = 0.0201$) in the target and backing were simulated using a Monte Carlo technique, which involved 10000 histories with a time step of 0.002 ps, and the results sorted according to detector geometry. The shell-corrected stopping powers of Northcliffe-Schilling [16] were used. The fitting process was started with the highest observed transition with adequate statistics (in this case the 1122.8 keV transition depopulating the 9860.0 keV state) and considering that the feeding time information to this state has large uncertainties, only an effective lifetime (stated as the upper limit) was determined. This was then used as an input parameter for the estimation of the lifetimes of the lower-lying states in the band. Following this procedure, the average transition quadrupole moment (Q_t) for five low-lying states of a similar intruder band in ^{113}Sb, populated in the same experiment, was estimated to be $Q_t = 4.69 \pm 0.48$ eb. This result is in agreement with the previously reported average $Q_t = 4.40 \pm 0.60$ eb for the band [8]. The side-feeding times (τ_{sf}) used in the analysis of the data for ^{111}Sn were then constrained to be similar to those used in the analysis for ^{113}Sb. The τ_{sf} value was about 0.1 ps for a state with an excitation energy of 8 MeV and followed the general trend that they increased with decrease in excitation energy. Side-feeding intensities, used in the present analyses, were obtained from the γ-ray relative intensities measured at 125° to the beam from spectra gated mostly by the 978.5 and 1083.1 keV transitions (see Fig. 1).

Mean lifetimes of $0.71^{+0.03}_{-0.04}$, 0.25 ± 0.02, 0.22 ± 0.02, 0.23 ± 0.03, and $0.18^{+0.03}_{-0.02}$ ps have been measured for the first time for five states belonging to band 1 with energies 4877.1, 5746.9, 6688.9, 7683.8, and 8737.2 keV, respectively, from the DSA data. In addition, an upper limit of mean lifetime of 0.20 ps has been estimated for the 9860.0 keV state. The experimental lineshapes were obtained by gating on the strong 978.5 and 1083.1 keV γ-rays depopulating the 978.5 and 2061.6 keV states, respectively, and fitted with the theoretical lineshapes. Both the forward (40°) as well as the backward angle (125°) spectra, along with the ones at 90° to the beam direction, were used in the fitting procedure simultaneously for the 802.8, 869.8, and 1053.4 keV transitions. However, the presence of several contaminant γ-ray lines in the spectra for the 942.0 and 994.9 keV γ-rays in the forward angle data did not permit their fitting procedure to be carried out at this angle. Theoretical lineshapes were therefore fitted only to the 90° and 125° data for these two γ-rays for the estimation of the level lifetimes. Typical theoretical fits to the observed spectra for the 869.8 and 994.9 keV γ-rays deexciting the 5746.9 and 7683.8 keV states, respectively, are shown in Fig. 2. Interferences from weak contamination γ-rays are indicated in the figure.

The errors in the lifetime results reflect the statistical uncertainties in the data and does not include the systematic errors of up to 15%, inherent in the electronic stopping powers and the uncertainties in the side-feeding times. However, it was ascertained that an assumed error of 30% in the side-feeding times leads to errors within 5% in the transition quadrupole moments for all states except the 5746.9 keV level for which the error is about 10%.

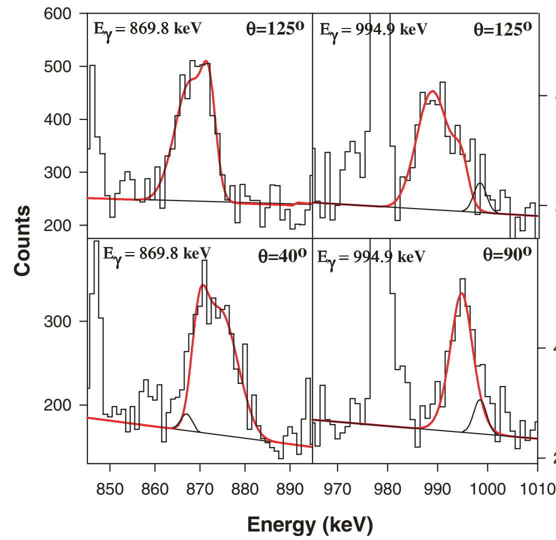

FIG. 2. (Color online) Gated DSA spectra for the 869.8 (left) and 994.9 keV (right) transitions. The angles at which the spectra were recorded are indicated at the top right-hand corner of each panel. Continuous lines are theoretical fits to the experimental data using LINESHAPE (see text). Weak contaminant peaks are also shown.

The low spin structure of ^{111}Sn, as in most of the neighboring tin and antimony isotopes, is dominated by spherical states that arise from the presence of neutron $g_{7/2}$, $d_{5/2}$, and $h_{11/2}$ orbitals near the Fermi level. The intruder band built on the 4074.3 keV, $23/2^-$ state (band 1) undergoes a probable $\nu h_{11/2}$ alignment at a rotational frequency of 0.45 MeV/$\hbar$ [10]. Following this alignment, the band has the configuration $[20,3]^-$ [6], relative to the ^{100}Sn core, using the shorthand notation of Ref. [3]. The reduced transition probabilities $B(E2)$ of the γ-rays in this band, deduced from the present lifetimes results and branching ratios, show large enhancements over the single-particle estimates (Table I), indicating sizable collectivity. The transition quadrupole moments (Q_t), plotted in Fig. 3, obtained from the experimental $B(E2)$ values, using

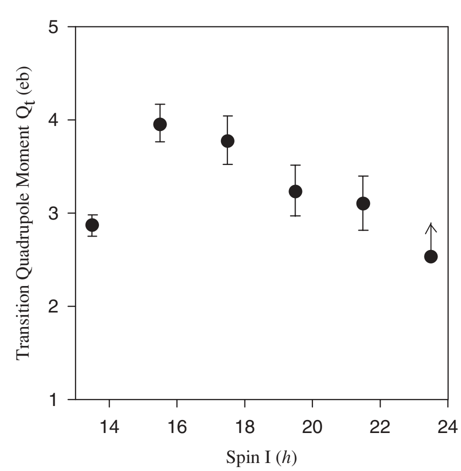

FIG. 3. Transition quadrupole moments for band 1, plotted as a function of level spin. The last data point represents a lower limit.

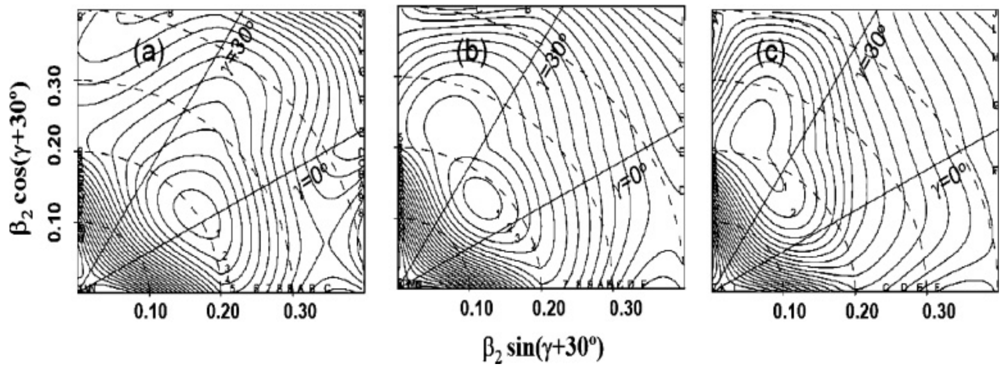

FIG. 4. Total Routhian surface plots for band 1 in the β_2-γ plane for rotational frequencies of (a) 0.51 MeV, (b) 0.66 MeV, and (c) 0.81 MeV. The interval between successive contours is 0.50 MeV.

the expression

$$B(E2) = \frac{5}{16\pi} Q_t^2 \langle I_i K 20 \| I_f K \rangle^2$$

decrease from $3.95^{+0.21}_{-0.18}$ eb for the $31/2^-$, 5746.9 keV state to $3.10^{+0.29}_{-0.28}$ eb for the $43/2^-$, 8737.2 keV state. The decrease of Q_t suggests a reduction in the collectivity of the states with increase in spin. Also, the dynamic moment of inertia (see Fig. 3 in Ref. [10]) decreases smoothly to less than a third of the rigid-body value up to the $63/2^-$ state. The smooth decrease in the dynamic moment of inertia indicates that the configuration remains pure up to the highest observed state and the states become progressively noncollective.

The evolution of the total Routhian surface (TRS) with rotational frequency has been studied for the $[20,3]^-$ configuration for band 1 in ^{111}Sn. These calculations were performed using a deformed Woods-Saxon potential and monopole pairing [17]. The total Routhian was minimized on a lattice in the (β_2, γ) space with respect to the hexadecapole deformation β_4 and displayed in Fig. 4 for the three rotational frequencies ($\hbar\omega$) 0.51, 0.66, and 0.81 MeV. The hexadecapole deformations β_4 is small (about 0.01) at all frequencies. The TRS plots clearly indicate that the shape of the nucleus evolves from collective prolate at $\hbar\omega = 0.51$ MeV to a triaxial shape at 0.66 MeV before assuming a near noncollective oblate shape at 0.81 MeV with $(\beta_2, \gamma) = (0.23, 47.6°)$. The transition quadrupole moments calculated using the (β_2, γ) values from the TRS calculations are in reasonably good agreement with the experimental values for the $39/2^-$ and the $43/2^-$ states. The experimental results for Q_t, that indicate a reduction in collectivity with increase in spin, are consistent with the theoretical predictions.

In summary, the present experimental results for the transition quadrupole moments and the behavior of the dynamic moment of inertia with spin, along with the predictions of a total Routhian surface calculation, suggest that the intruder band in ^{111}Sn undergoes a change of shape from collective prolate to triaxial with increase in spin and is favoured to terminate in an oblate noncollective state at a high spin. There is however a need to extend the experimental study to higher spins in order to make a more conclusive inference about band termination.

The authors thank the members of the INGA Collaboration. They gratefully acknowledge the contributions of Dr. Ambar Chatterjee, Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai and Dr. R. K. Bhowmik and Dr. S. Venkataramanan of the Inter University Accelerator Centre, New Delhi for the Data Acquisition System and the electronics module for the Clover detectors, respectively. Thanks are due to the staff of the Cyclotron and the Target Laboratory at the VECC, Kolkata, for their co-operation.

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