VARIETY OF BAND STRUCTURES IN LIGHT Sn, In, AND Cd NUCLEI*

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Selected experimental results retrieved from ^{98}Mo(^{16}O, $xnyp$) reaction are discussed and compared with the up-to-day known data. The collective configurations in selected $Z = 48$–50, $N = 55$–66 nuclei are presented in terms of Cranked Shell Model (CSM) and rigid rotor description. The special interest was put on: (1) Systematical behaviour of intruder bands especially for low spin levels, (2) The collective, strongly coupled bands, where the band members are connected by $\Delta I = 1$ transitions, (3) Smooth band termination in the $A = 104$–120 mass region.

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1. Introduction

The available experimental spectroscopic data for light Sn, *e.g.* [1,2], In [3,4] and Cd [5,6] nuclei make possible to trace systematic behaviour of band structures and shape competition in these nuclei. Also convincing theoretical arguments for the existence of the intruder bands in the low spin states region of these nuclei have been presented [7–10]. In the even-A, $_{50}$Sn nuclei these bands are thought to be built on the proton $2p$–$2h$ excitations, $(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-2}$ and $\pi(g_{9/2}^{-2} \otimes g_{7/2}^{1} h_{11/2}^{1})$ leading to the deformed shapes observed in $^{108-118}$Sn. The odd-mass Sn nuclei are believed to have rotational bands constructed on the valence neutron, occupying the $\nu g_{7/2}$, $\nu d_{5/2}$ and $\nu h_{11/2}$ orbitals, coupled to the $2p$–$2h$ intruder states in even-Sn nuclei. In the Cd

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nuclei, having 2 protons less, the picture is not so clear, however, the evidence for the existence of proton intruder structures was found [5,11,12]. The role of protons in these states is not yet fully understood. As an example, the moments of inertia of the intruder bands in the Sn nuclei are significantly larger than in the corresponding bands in the Cd isotopes. As for the ^{111}In nucleus the proton intruder band reported in Ref. [13] was not confirmed in the present investigation. In this contribution, selected spectroscopic results of experimental studies concerning the region of considered nuclei carried out within the OSIRIS-II Collaboration at the Heavy Ion Laboratory of the Warsaw University are revealed.

2. B(E2) branching ratios of (intruder-to-intruder)/(intruder-to-yrast) transitions

The properties of excited states in ^{110}Sn, ^{111}Sn and ^{112}Sn were studied with a special interest put on the observation of intruder bands especially at low spins, where no band members were until now observed [14]. A comparison of the experimentally obtained $\frac{B(\mathrm{E2})_{\mathrm{intruder}}}{B(\mathrm{E2})_{\mathrm{yrast}}}$ ratios of E2 transition probabilities for light Sn nuclei is given in Table I. In spite of the fact that light Sn, In and Cd nuclei are far from being good rotors, one can also follow the common way to use the terms of the CSM [15] to facilitate the discussion of the band structure. The results given in Table I show rather strong intraband B(E2) values as compared to reduced interband decays. This indicates that the intruder band structures at the low spins are mixed with the “normal” spherical structures and therefore the intruder bands are perturbed at low spins, contrary to that what is observed at higher spins. In the alignment plot, this mixing would manifests itself as an irregularity at low rotational frequencies. A simple level mixing calculation was performed in order to see if such mixing of states can account for the observed B(E2) γ-ray branching ratios for transitions between mixed yrast and intruder-band states. The values of the mixing amplitudes, as well as the interaction energies, depend on the B(E2) values between unmixed states. As indicated in Table I, the mixing calculation is able to account for the values of B(E2) ratios of the intruder-to-intruder and intruder-to-yrast transitions. The band crossing in the intruder bands for ^{110}Sn and ^{112}Sn occurs at $\hbar\omega$=0.37 MeV in ^{110}Sn and $\sim$ 0.35 MeV in ^{112}Sn while the increase in the alignment is about $7\hbar$ for both of them. In this mass region the first band crossing has usually been attributed to the $h_{11/2}$ neutrons [7,8]. The intraband B(E2) values in the intruder bands of ^{112,114,116,118}Sn are also analyzed within the framework of the IBM1 model [16]. A detailed comparison of these bands with the ground state bands in the even-mass Xe isotopes allows [16] to find a similarity for the energy spacings as well as for B(E2) values.

TABLE I

Experimental $B(\mathrm{E2})$, γ-ray branching ratios (λ) in light Sn isotopes [14]. Subscripts i and y denote for intruder and yrast, respectively. I_γ intensities are given with reference to 1212 keV, 978 keV and 1257 keV γ-rays in ^{110}Sn, ^{111}Sn and ^{112}Sn, respectively.

Nucleus	$E_x^{\text{init.lev.}}$ (keV)	E_γ (keV)	I_i	I_f	I_γ	$\lambda = \frac{i\to i}{i\to y}$	$R_{\text{exp}} = \frac{B(\mathrm{E2})_{\text{intr.}}}{B(\mathrm{E2})_{\text{yrast}}}$	$\frac{R_{\text{exp}}}{R_{\text{calc.}}}$
^{110}Sn	3229	368	$(4^+)_\mathrm{i}$	$(2^+)_\mathrm{i}$	0.07±0.03	≤5	$\geq 1.7*10^4$	≥0.98
		2017	$(4^+)_\mathrm{i}$	$(2^+)_\mathrm{y}$	≤0.02			
	3824	597	$(6^+)_\mathrm{i}$	$(4^+)_\mathrm{i}$	3.0 ±0.21	≤50	≥4545	≥0.92
		1627	$(6^+)_\mathrm{i}$	$(4^+)_\mathrm{y}$	≤0.1			
	4492	610	$(8^+)_\mathrm{i}$	$(6^+)_\mathrm{i}$	0.7±0.03	≤20	≥4745	≥0.96
		1956	$(8^+)_\mathrm{i}$	$(6^+)_\mathrm{y}$	≤0.05			
	5228	799	$(10^+)_\mathrm{i}$	$(8^+)_\mathrm{i}$	0.48±0.04	2.9±0.6	5.6±1.2	0.99
		912	$(10^+)_\mathrm{i}$	$(8^+)_\mathrm{y}$	0.16±0.03			
	6036	808	$(12^+)_\mathrm{i}$	$(10^+)_\mathrm{i}$	2.89±0.14	24±8	76±25	0.98
		1019	$(12^+)_\mathrm{i}$	$(10^+)_\mathrm{y}$	0.12±0.04			
^{111}Sn	4078	769	$(23/2^-)_\mathrm{i}$	$(19/2^-)_\mathrm{i}$	1.66±0.10	1.0±0.1	6.0±0.5	0.91
		1092	$(23/2^-)_\mathrm{i}$	$(19/2^-)_\mathrm{y}$	1.61±0.10			
	4078	769	$(23/2^-)_\mathrm{i}$	$(19/2^-)_\mathrm{i}$	1.66±0.10	2.3±0.3	6.7±0.8	0.95
		952	$(23/2^-)_\mathrm{i}$	$(19/2^-)_\mathrm{y}$	0.72±0.07			
	4078	769	$(23/2^-)_\mathrm{i}$	$(19/2^-)_\mathrm{i}$	1.66±0.10	2.7±0.3	4.4±0.5	0.82
		846	$(23/2^-)_\mathrm{i}$	$(19/2^-)_\mathrm{y}$	0.61±0.06			
	5752	870	$(31/2^-)_\mathrm{i}$	$(27/2^-)_\mathrm{i}$	2.55±0.12	4.7±0.5	5.8±0.6	0.92
		907	$(31/2^-)_\mathrm{i}$	$(27/2^-)_\mathrm{y}$	0.55±0.05			
^{112}Sn	3416	893	$(6^+)_\mathrm{i}$	$(4^+)_\mathrm{i}$	1.43±0.50	0.4±0.2	1.7±0.7	0.99
		1167	$(6^+)_\mathrm{i}$	$(4^+)_\mathrm{y}$	3.30±0.82			
	3416	631	$(6^+)_\mathrm{i}$	$(4^+)_\mathrm{i}$	2.05±0.64	0.6±0.3	13.4±5.3	0.91
		1167	$(6^+)_\mathrm{i}$	$(4^+)_\mathrm{y}$	3.30±0.82			
	5568	745	$(12^+)_\mathrm{i}$	$(10^+)_\mathrm{i}$	2.86±0.62	7.8±3.7	19±10	0.99
		888	$(12^+)_\mathrm{i}$	$(10^+)_\mathrm{y}$	0.36±0.25			
	6367	800	$(14^+)_\mathrm{i}$	$(12^+)_\mathrm{i}$	5.19±0.81	5.3±2.5	2.4±1.4	0.97
		680	$(14^+)_\mathrm{i}$	$(12^+)_\mathrm{y}$	0.98±0.25			

3. Band termination in the $A = 104$–120 mass region $\Delta I = 1$ bands

The second irregularity in the alignment plot observed [14] in ^{110}Sn takes place at $\hbar\omega \sim 0.5$ MeV and could be tentatively interpreted as a sign of a transition to a terminating band structure. Similar interpretation in terms of smoothly terminating, *i.e.* where all spin vectors of the particles involved in the configuration are fully aligned, bands based on $2p$–$2h$ structures is proposed [17] for ^{108}Sn. The calculations for ^{108}Sn [9] predict that the positive parity $\pi[g_{9/2}^{-2} \otimes (g_{7/2}d_{5/2})^2] \otimes \nu[(d_{5/2}g_{7/2})^6 h_{11/2}^2]$ configuration should be crossed by the $\pi[g_{9/2}^{-2} \otimes (g_{7/2}h_{11/2})] \otimes \nu[(d_{5/2}g_{7/2})^5 h_{11/2}^3]$ configuration at spin $32\hbar$, as seen in the experiment. Considering the excitation energies *versus* spin in terms of $E_x - E_{\mathrm{RR}}$, *i.e.* with a rigid rotor rotation reference subtracted, the various features can be observed: (a) irregularities at low spins of ^{110}Sn and ^{112}Sn associated with spherical structures and very similar behaviour for slightly higher spins, (b) the crossing of the negative parity g.s. and intruder bands in ^{111}Sn at a frequency of about 0.45 MeV as well as (c) rigid rotation-like behaviour of $\Delta I = 1$ band in ^{110}Sn. In ^{111}Sn a band with a smooth-termination properties has previously been reported [18] and is confirmed in the present work. In this case, the $2p$–$2h$ proton structure $(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-2}$ is coupled to an $h_{11/2}$ neutron. Similar structures have also been observed in Te nuclei, where the associated configurations are supposed to involve $4p$–$2h$ proton states, as well as in light I isotopes, with $5p$–$2h$ proton structures. *It was pointed out by Ragnarsson [9], that three different scenarios can occur close to the termination point when the excitation energies are plotted relative to energy of rigid rotation, namely for some bands the $E - E_{RR}$ differences are essentially constant (rigid rotation like), while other slope upwards (unfavoured) or downwards (favoured) before termination.* When comparing the behaviour of experimentally observed bands in the rigid rotor reference frame (Figs 1, 2) it is evident that there are examples of unfavoured and rigid rotation like termination. A group of decay sequences in ^{106,108,110}Sn, ^{104,106}In and ^{110}Cd with many common characteristics which distinguish them from normal collective rotational bands is shown in Fig. 2. All of these sequences start above 3 MeV excitation energy and decay predominantly via $\Delta I = 1$, similarly to oblate M1 bands in Ba and Pb region or to prolate M1 band proposed in ^{108}Cd [19]. Spins of their band heads are usually greater than $12\hbar$ and their parities are most likely negative. Energy spacings within those bands are smaller than for the other observed bands at similar energies. The strongly coupled bands, observed both in ^{106}Sn and ^{108}Sn and now also in ^{110}Sn most likely involve the proton $g_{7/2}g_{9/2}^{-1}$ particle-hole excitation coupled to the neutrons above the $N = 50$ shell gap. Since the parity of levels belonging to these sequences is most likely negative, one can propose the $\pi g_{7/2}g_{9/2}^{-1}\nu(g_{7/2})^5 h_{11/2}$ configuration. The energy difference between strongly coupled bands in ^{106}Sn and ^{108}Sn is similar to the energy difference for the 9^- states $(\nu g_{7/2}h_{11/2})$ in those nuclei, which supports the proposed configuration assignment. The bands are expected to terminate at spin 25^-. Bands characterized by strong dipole transitions have also been observed in ^{114}Sn, ^{115}Sn and ^{105,107,109}In nuclei, as well as Sb, Te and I nuclei. Common to these bands is that their configurations involve a proton $1p$–$1h$ excitation where a hole is in the proton $g_{9/2}$ orbital and the particle in one of the downsloping orbitals from above the $Z = 50$ gap. The $\Delta I = 1$ sequences considered here share many properties of the collectively rotating bands in the $A \sim 80$, $A \sim 130$ regions, and the

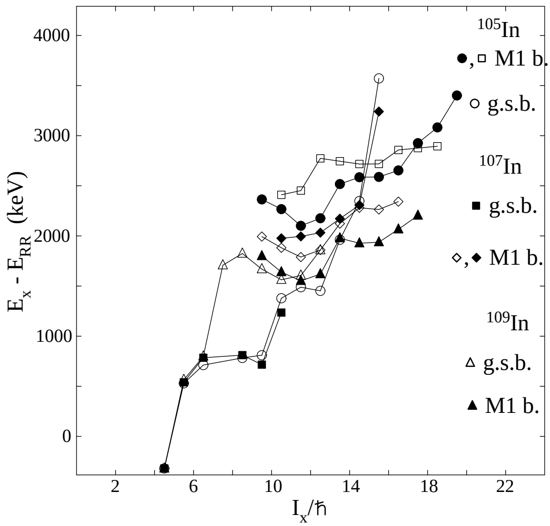

Fig. 1. Excitation energy relative to an $I(I+1)$ rigid rotor reference as a function of spin for $\Delta I = 1$ bands in light odd-A In isotopes [4]. A comparison with g.s.b. dependence is also shown.

"shears bands" in the Pb region. A general question may appear if the observed $\Delta I = 1$ sequences are a manifestation of the magnetic rotation [20] being also a special case of band termination?

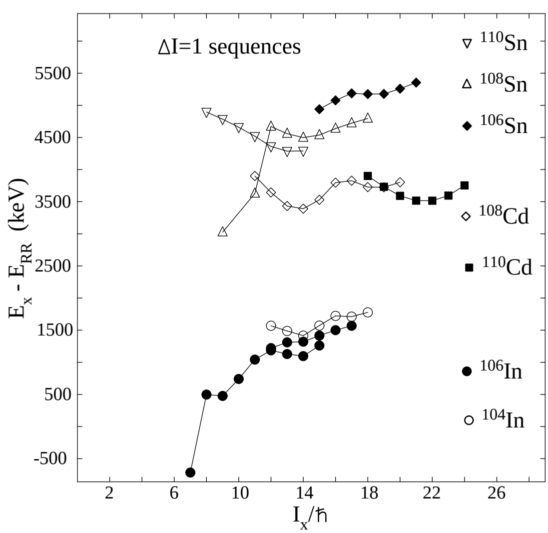

Fig. 2. Excitation energy relative to a rigid rotor reference plotted as function of I_x for the $\Delta I = 1$ bands in ^{108,110}Cd [5, 19], ^{104,106}In [3], ^{106,108}Sn [5] and ^{110}Sn [14] nuclei.

Conclusions: A variety of collective states forming rotational bands and band-like structures is considered with a special emphasis put on: (a) mixing of the low spin states of the intruder bands with states of the spherical origin, (b) the $\Delta I = 1$ negative parity sequences in the A$\sim$110 (neutron deficient) region and (c) the band termination phenomenon in nuclei of close neighbourhood to the ^{114}Sn core.

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