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Gamma-ray studies of ^{119,121,123}Sn isomers formed in deep inelastic heavy ion collisions ☆

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Abstract

Yrast isomers in ^{119}Sn, ^{121}Sn and ^{123}Sn have been identified among products of heavy ion collisions with ^{124}Sn targets 10–15% above the Coulomb barrier. Isomeric decay schemes are reported, and further evidence for half-filling of the $\nu h_{11/2}$ subshell at $N = 73$ is presented. For $(\nu h_{11/2})^n$ seniority-3 states, observed level energies agree well with results of fractional parentage calculations.

The neutron $h_{11/2}$ subshell is being filled in A = 116–131 tin nuclei, and it should be possible to study $(\nu h_{11/2})^n$ excitations through this complete series of isotopes. At the start of the present investigations, $(\nu h_{11/2})^n$, seniority $v = 2$, 10^+ isomers and their decays had been well studied in ^{116}Sn, ^{118}Sn and ^{120}Sn at one end of the series [1–3], and in the fission products ^{128}Sn and ^{130}Sn at the other [4], but there was no information about analogous 10^+ isomers in ^{122}Sn, ^{124}Sn and ^{126}Sn, which were expected to have long half-lives. Since tin nuclei with $A > 120$ are not accessible by fusion-evaporation reactions, we searched for the missing isomers among the products of deep-inelastic heavy ion reactions on ^{124}Sn and ^{122}Sn, 10–15% above the Coulomb barrier. The $\gamma\gamma$ coincidence data recorded during our first experiment using a pulsed beam of 325 MeV ^{76}Ge ions on thick ^{122,124}Sn targets were found to include new information about yrast states of moderately high spins (up to $I \sim 14$) in more than 50 neutron-rich nuclei. Specifically, the sought-for $(\nu h_{11/2})^n$ 10^+ isomers in ^{122}Sn and ^{124}Sn were identified with half-lives of 62(3) and 45(5) μs, respectively [5], but little ^{126}Sn was produced. The $B(E2;\ 10^+ \to 8^+)$ values for ^{122}Sn and ^{124}Sn, together with the other values determined earlier, located the half-filling of the neutron $h_{11/2}$ subshell close to $N = 73$ (whereas the $\pi h_{11/2}$ half-filling in $N = 82$ isotones occurs just below $Z = 71$ [6]). The marked difference between neutrons and protons could be traced [5] to the relative $s_{1/2}$, $d_{3/2}$

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and $h_{11/2}$ single particle energies, which are altered by the Coulomb potential; the $s_{1/2}$ and $d_{3/2}$ energies for protons are raised more than the $h_{11/2}$ energy.

The spectra recorded in the ^{122,124}Sn + ^{76}Ge experiments showed in the 800–1250 keV range several strong unknown γ-rays, decaying with 5–10 μs half-lives, that we suspected might be due to isomerism in odd-A Sn nuclei. The decay of a 1.75 μs $19/2^+$ isomer in ^{117}Sn had previously been studied in some detail [7], but nothing was known about yrast isomers in the heavier odd-A isotopes. In follow-up experiments already briefly reported [8], 1 mg/cm^2 ^{122}Sn and ^{124}Sn targets, each enriched to >96% and backed with lead, were bombarded with 344 MeV ^{80}Se ions from the ATLAS accelerator in a 10 μs beam-on, 50 μs beam-off pulsing configuration. Twelve Compton-suppressed Ge detectors of the Argonne–Notre Dame BGO γ-ray facility measured off-beam spectra in two-parameter E_γ versus time mode, as well as $\gamma\gamma$ coincidence events. The data analysis identified three pairs of coincident γ-rays following separate isomers: 818 and 1220 keV transitions in decay of a 10 μs ^{119}Sn isomer; 841 and 1151 keV transitions in decay of a 5 μs ^{121}Sn isomer; and 838 and 1107 keV transitions in decay of a 7 μs ^{123}Sn isomer. As detailed in Ref. [8], isotopic assignments of the γ-ray pairs were based on evidence from these and other in-beam reaction studies and on energy systematics arguments. Like the known $19/2^+$ isomer in ^{117}Sn, the three new isomers were interpreted as $19/2^+$ states of $\nu h_{11/2} \times 5^-$ (or $\nu h^2_{11/2}\, s_{1/2}$) character, decaying to $15/2^-$ and $11/2^-$ states by cascades of M2 and E2 transitions. The $15/2^-$ and $19/2^+$ level energies follow closely the highly regular systematics of the 2^+ and 5^- energies in the neighboring even-A Sn nuclei, and the B(M2) values for the $19/2^+ \to 15/2^-$ isomeric transitions in the four odd-A tin isotopes including ^{117}Sn are equal within a factor of two. A weak E3 isomeric decay branch $19/2^+ \to 13/2^- \to 11/2^-$ was established [7] in the ^{117}Sn nucleus; analogous but even weaker branches were also observed in the decays of the ^{119,121,123}Sn $19/2^+$ isomers.

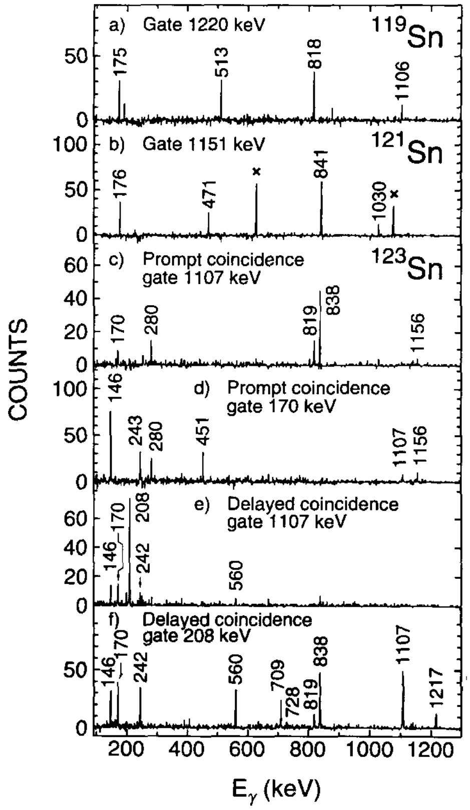

Fig. 1. a), b) Off-beam $\gamma\gamma$ prompt coincidence data for the ^{124}Sn + 344 MeV ^{80}Se system showing γ-ray spectra coincident with $15/2^- \to 11/2^-$ transitions in ^{119}Sn and ^{121}Sn. Labelled γ-rays are assigned as transitions occurring in the $19/2^+$ or $27/2^-$ isomeric decays in these nuclei. Peaks marked X are ^{86}Sr γ-rays resulting from ^{80}Se reactions on carbon or oxygen target impurities. c)–f) show ^{123}Sn $\gamma\gamma$ coincidence data measured 1–30 μs off-beam for the system ^{124}Sn + 665 MeV ^{136}Xe. The prompt spectra c) and d) were recorded with the timing condition $T\gamma\gamma < 300$ ns, and the delayed coincidence spectra e) and f) with the condition $0.1\ \mu s < T\gamma\gamma < 30\ \mu s$.

Identification of the 1220, 1151 and 1107 keV $15/2^- \to 11/2^-$ transitions in ^{119,121,123}Sn was a significant first step towards further studies of $(\nu h_{11/2})^n$ $v = 3$ yrast states in these nuclei. By setting coincidence gates on the 1220 and 1151 keV transitions (Figs. 1 a) and b)), feeding γ-ray cascades of 175, 513 and 1106 keV in ^{119}Sn and of 176, 471 and 1030 keV in ^{121}Sn were identified and assigned as $27/2^- \to 23/2^- \to 19/2^- \to 15/2^-$ sequences deexciting $27/2^-$ isomers of dominant $(\nu h_{11/2})^n$ character (Fig. 2). Although no transition multipolarities were determined, these configuration assignments could be made with confidence because the experimental $23/2^-$ and $27/2^-$ level energies were found to be in close agreement with those predicted for $(\nu h_{11/2})^n$ $v = 3$ states by fractional parentage calculations that will be described later in this article. Half-lives for the $27/2^-$

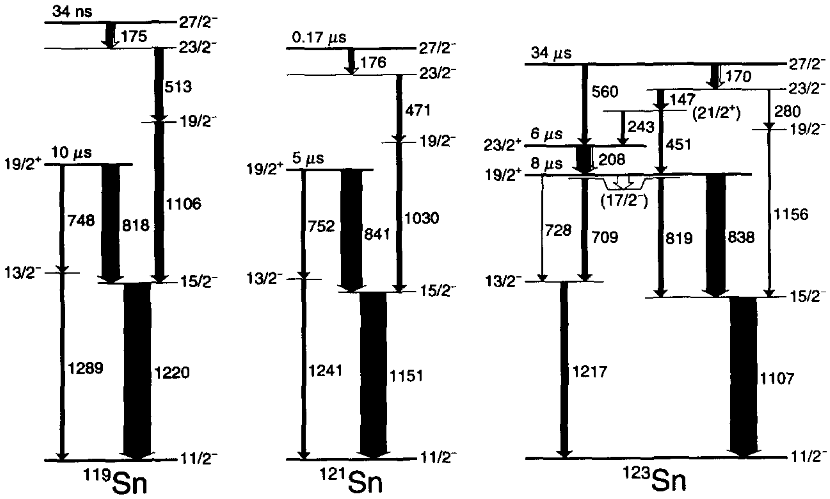

Fig. 2. Isomeric decay schemes for ^{119}Sn, ^{121}Sn and ^{123}Sn. Widths of transition arrows are proportional to the observed intensities, with internal conversion contributions unshaded.

isomers in ^{119}Sn and ^{121}Sn were determined from the ^{124}Sn + ^{80}Se data to be 34(10) ns and 167(25) ns, respectively, and the corresponding transition probabilities for the isomeric E2 transitions are:

$$B(\mathrm{E2};\ 27/2^- \to 23/2^-,\ ^{119}\mathrm{Sn}) = 82(24)\ e^2\,\mathrm{fm}^4$$

and

$$B(\mathrm{E2};\ 27/2^- \to 23/2^-,\ ^{121}\mathrm{Sn}) = 16(2)\ e^2\,\mathrm{fm}^4$$

These values are in good accord with those previously determined for the $10^+ \to 8^+$ transitions in the neighboring even-A tin nuclei. A search through the ^{124}Sn + ^{80}Se data for a γ-ray cascade deexciting a ^{123}Sn $27/2^-$ isomer was not fruitful; neither could any yrast isomers in $A > 124$ tin isotopes be identified in these data. For this reaction system, the observed favored direction of neutron flow in deep inelastic processes was from target to projectile.

We recently extended our investigations by studying the system ^{124}Sn + 665 MeV ^{136}Xe, expecting on the basis of N/Z equilibration considerations [9] that the ^{136}Xe beam would favor production of neutron-rich species (and perhaps ^{123}Sn) more than the ^{76}Ge and ^{80}Se beams used earlier. The first phase of the experiment was devoted to isomeric decay measurements, again using the Argonne–Notre Dame γ-ray facility, but with special attention devoted to detection of $\gamma\gamma$ coincidence events across μs isomers. The overall pattern of reaction yields in the $Z = 50$ region was definitely shifted towards higher neutron numbers, and the missing ^{126}Sn 10^+ isomer with $t_{1/2} \sim 6.5$ μs was finally found [10]. More important in the present context were the high quality prompt and delayed γ-ray coincidence data obtained for ^{123}Sn, as illustrated in Fig. 1 c)–f). They identified, in coincidence with the 1107 keV $15/2^- \to 11/2^-$ ^{123}Sn transition, γ-ray decay paths crossing 6 μs and 8 μs intermediate isomers as well as prompt γ-ray cascades, which together established an interesting ^{123}Sn yrast level scheme up to a 34 μs isomeric level at 2713 keV (Fig. 2). This uppermost isomer and the level 170 keV below it are, without doubt, the $(\nu h_{11/2})^n$ $v = 3$ $27/2^-$ and $23/2^-$ states; their excitation energies agree with predictions within a few keV. The tiny E2 transition probability,

$$B(\mathrm{E2}; 27/2^- \to 23/2^-,\ ^{123}\mathrm{Sn}) = 0.06\ e^2\,\mathrm{fm}^4,$$

which is less than 2×10^{-3} Weisskopf units, manifests anew the half-filling of the $\nu h_{11/2}$ subshell at $N = 73$. In consequence, the configuration-forbidden 560 keV M2 transition is seen to be competitive with the 170 keV E2 in decay of the 34 μs isomer. The thousandfold increase in half-life between the ^{119}Sn and ^{123}Sn $27/2^-$ isomers is a striking illustration of the impact of subshell occupation on transition probabilities. The $23/2^+$ isomer located in ^{123}Sn is an obvious counterpart of the well-established $(\nu h_{11/2} d_{3/2})$ 7^- isomers in even-A tin isotopes, but we could not firmly decide from the available data whether there are similar $23/2^+$ microsecond isomers in ^{119}Sn and ^{121}Sn as well.

The $27/2^-$ and $23/2^-$ levels in ^{119,121,123}Sn nuclei are expected to be rather pure $(\nu h_{11/2})^n$ $v = 3$ states. Such shell model yrast states with single dominant configurations comprising a few high-j valence nucleons can generally be decomposed into simpler configurations with fewer valence particles, which may correspond to known yrast levels in neighboring nuclei. In an earlier extensive analysis [11] of high-spin states in the $N \sim 82$ region above ^{146}Gd, where $h_{11/2}$ valence protons play a dominant role in forming yrast excitations, ground state masses for many shell model nuclei located far from stability were estimated by exploiting fractional parentage relationships between specific few valence nucleon yrast states, whose excitation energies were known from γ-ray studies. The situation in $A = 116$–124 tin nuclei is more favorable, since the masses are accurately known; thus, comparisons of calculated $(\nu h_{11/2})^n$ energies with experiment provide unusually exacting tests of the configuration assignments. For example, the $27/2^-$ aligned $(\nu h_{11/2})^3$ state in ^{123}Sn can be broken up by a fractional parentage decomposition into simpler states with two, one, and zero $h_{11/2}$ neutrons outside a ^{120}Sn 0^+ core [12]. Expressing the total energy of this $27/2^-$ state as a sum of ^{123}Sn ground state mass M_{123} and excitation energy $E(27/2^-)$ gives the relation:

$$M_{123} + E(27/2^-) = 3M_{122} + 3(\text{c.f.p.})\ E(8^+, 10^+) \\ - 3M_{121} - 3E(11/2^-) + M_{120},$$

where $E(8^+,10^+)$ are energies of known $(\nu h_{11/2})^2$ 8^+ and 10^+ states in ^{122}Sn, here weighted by appropriate coefficients of fractional parentage (c.f.p.), and $E(11/2^-)$ in ^{121}Sn is known to be 6 keV. The individual masses may be combined in a mass "window", W, and evaluated using modern mass tables [13]. In the present case,

$$W = M_{120} - 3M_{121} + 3M_{122} - M_{123} = -5512(5)\ \text{keV}$$

and $E(27/2^-) = W + 3(\text{c.f.p.})E(8^+, 10^+) - 3E(11/2^-)$ is calculated to be 2710(5) keV, compared to the experimental 2713 keV. For the ^{123}Sn $23/2^-$ state, with the known 6^+ energy in ^{122}Sn added to the input data, the calculated energy 2540(5) keV is also in near-perfect agreement with experiment. Results of such fractional parentage calculations of $27/2^-$ and $23/2^-$ energies for the three nuclei ^{119}Sn, ^{121}Sn and ^{123}Sn are summarized in Table 1, where the input energies used and the values of the three mass windows are also specified. The excellent agreement with experiment in all three cases is remarkable, considering that the core nuclei ^{116}Sn, ^{118}Sn and ^{120}Sn are only singly magic, and it provides vital support for interpretation of the observed levels as $(\nu h_{11/2})^n$ $v = 3$ states.

For the isomeric transitions between $(\nu h_{11/2})^n$ states in the tin isotopes, the dependence of the E2 transition probability on the $\nu h_{11/2}$ subshell occupation number n, and on the neutron effective charge e_{eff}, may be expressed [14], taking the radial matrix $< r^2 >$ for $\nu h_{11/2}$ to be 32 fm^2, by the equations:

$$B(\text{E2};\ 10^+ \rightarrow 8^+) = 1.17\ (6-n)^2\ e_{\text{eff}}^2$$

and

$$B(\text{E2};\ 27/2^- \rightarrow 23/2^-) = 4.41\ (6-n)^2\ e_{\text{eff}}^2.$$

Following Ref. [5], it is convenient to plot the E2 transition amplitudes (or square roots of the measured B(E2) values) versus A, knowing that the E2 matrix element must have opposite signs in the bottom and top halves of the $\nu h_{11/2}$ subshell, and that it becomes zero at the point of half-filling, $n = 6$, when particle and hole contributions exactly cancel one another. All the E2 amplitudes determined for the Sn isotopes are displayed together in Fig. 3, with the $\sqrt{B(\text{E2})}$ values for the odd-A nuclei multiplied by 0.514 (i.e. $\sqrt{1.17/4.41}$) to compensate for the different geometrical factors entering the $v = 2$ and $v = 3$ B(E2) equations. The results for the odd-A nuclei clearly match up excellently with those previously obtained for the even-A tin nuclei, and they reinforce earlier conclusions about the $\nu h_{11/2}$ subshell filling and about the enhancement of the neutron effective charge towards the middle of the $N = 50$–82 major shell. Not all features of the ^{119,121,123}Sn level spectra are satisfactorily understood, but further discussion must be postponed to a later paper. Regarding the points still missing in Fig. 3, it may well be possible by similar methods to identify and characterize the decay of the $27/2^-$ isomer expected in ^{125}Sn, but a search for corresponding isomers in ^{127}Sn and ^{129}Sn would appear to offer a more difficult experimental challenge.

Table 1
Summary of the fractional parentage calculations of $(\nu h_{11/2})^3$ energies in ^{119}Sn, ^{121}Sn and ^{123}Sn. Input for calculation of the $23/2^-$ and $27/2^-$ energies in the odd-A nucleus ^{A}Sn consisted of the $11/2^-$ level energy in the $^{A-2}$Sn nucleus, the 6^+, 8^+ and 10^+ energies in the $^{A-1}$Sn nucleus, and the mass window W, evaluated using neutron separation energies given in Ref. [13]. For comparison, experimental energies are listed in the right hand columns.

Input level energies (keV)				Mass window W (keV)	Output energies (keV)		Experiment (keV)	
^{117}Sn	^{118}Sn				^{119}Sn		^{119}Sn	
$11/2^-$	6^+	8^+	10^+	−5223(3)	$23/2^-$	$27/2^-$	$23/2^-$	$27/2^-$
315	2879	3052	3108		2926(3)	3118(3)	2928	3103
^{119}Sn	^{120}Sn				^{121}Sn		^{121}Sn	
$11/2^-$	6^+	8^+	10^+	−5558(5)	$23/2^-$	$27/2^-$	$23/2^-$	$27/2^-$
90	2697	2837	2903		2666(5)	2834(5)	2659	2835
^{121}Sn	^{122}Sn				^{123}Sn		^{123}Sn	
$11/2^-$	6^+	8^+	10^+	−5512(5)	$23/2^-$	$27/2^-$	$23/2^-$	$27/2^-$
6	2555	2690	2765		2540(5)	2710(5)	2543	2713

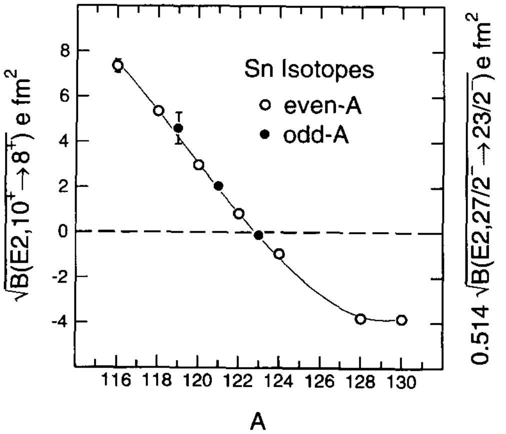

Fig. 3. E2 transition amplitudes for $(\nu h_{11/2})^n$ $10^+ \to 8^+$ and $27/2^- \to 23/2^-$ transitions in even-A and odd-A Sn isotopes. To facilitate intercomparison of the data points, values for the odd-A nuclei have been multiplied by a factor 0.514 (see text). Where error bars are not shown, they lie within the plotted points. A line is drawn through the data points to guide the eye.

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