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A POCKETFUL OF TIN ISOMERS FROM HEAVY-ION COLLISIONS

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ABSTRACT

Reaction products of $^{122,124}Sn + {}^{76}Ge(^{80}Se)$ collisions 10-15% above the barrier have been studied by γ-ray spectroscopy, and new yrast isomers in $^{119\text{-}124}Sn$ isotopes have been identified and characterized. B(E2) values determined for $(\nu h_{11/2})^n\ 10^+ \rightarrow 8^+$ transitions in even-A Sn nuclei pinpoint half-filling of the $\nu h_{11/2}$ subshell close to N = 73. In odd-A Sn isotopes, $19/2^+$ isomers with 1-10 μs half-lives occur systematically, and higher-lying $(\nu h_{11/2})^n\ v=3\ 27/2^-$ isomers in ^{119}Sn and ^{121}Sn have also been identified. These deep inelastic excitation processes were found to populate a large number of neutron-rich nuclei strongly enough for yrast spectroscopy studies.

1. Introduction

The decays of $(\pi h_{11/2})^n\ 10^+$ and $27/2^-$ isomers in proton-rich N=82 isotones have provided[1] an outstanding illustration of the dependence of E2 transition rates between j^n states on subshell occupation number, and have demonstrated that half-filling of the proton $h_{11/2}$ subshell occurs just below Z=71 ^{153}Lu. The counterpart neutron $h_{11/2}$ subshell is being filled in the A = 116-132 tin isotopes, and one should, in principle, be able to study the $(\nu h_{11/2})^n$ excitations through this complete series. From previous work, $(\nu h_{11/2})^n\ 10^+$ isomers are known in $^{116,118,120}Sn$ at one end, and in the fission products $^{128,130}Sn$ at the other. Missing are the $^{122,124,126}Sn$ isotopes with N = 72, 74, 76; theory predicts[2] for them 10^+ half-lives in the range 5-100 μs, but these isomers cannot be made by fusion-evaporation.

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We have now managed to identify the 10^+ isomers in ^{122}Sn and ^{124}Sn (but not ^{126}Sn) among the products of heavy ion collisions on tin targets 10-15% above the Coulomb barrier. Gamma-ray yield measurements for these reactions have shown that yrast states in In, Sn, Sb and other nuclei extending over a broad range in A and Z are populated quite strongly, offering attractive opportunities for wide-ranging spectroscopic studies. Here, we emphasize new spectroscopic findings for even-A and odd-A Sn nuclei, with brief additional remarks concerning reaction yields and probable mechanisms.

2. Experimental and Results

In the experiments 1 mg/cm^2 ^{124}Sn and ^{122}Sn targets (backed with Pb) were bombarded with pulsed 325 MeV ^{76}Ge and 344 MeV ^{80}Se beams from the ATLAS accelerator. In-beam and off-beam γ-ray singles and coincidence measurements were performed using the Argonne-Notre Dame γ-ray facility consisting of 12 Compton-suppressed Ge detectors and an inner ball of BGO hexagons.

2.1. Results for Even-A Sn Isotopes

The Sn nuclei of interest have known 7^- isomers with μs half-lives. The basic aim in our first experiment using the reaction ^{124}Sn + 325 MeV ^{76}Ge was to detect the $10^+ \rightarrow 8^+ \rightarrow 7^-$ γ-ray cascades connecting the 10^+ and 7^- isomers by demanding a μs delayed coincidence with the γ-rays following the 7^- isomers. In the way, the decays of the 10^+ isomers in $^{120,122,124}Sn$ were all clearly seen[3] but there was no sign of ^{126}Sn. For the new isomers the results (Fig. 1) are:

	$10^+ \rightarrow 8^+$	$T_{1/2}$	B(E2)
^{122}Sn	75.2(3) keV	62(3) μs	0.70(4) e^2fm^4
^{124}Sn	78.2(5) keV	45(5) μs	0.89(11) e^2fm^4

These results virtually complete a series of B(E2) determinations for $(\nu h_{11/2})^n$ states in even-A $^{116\text{-}130}Sn$ isotopes, with ^{126}Sn now the only missing one. In Fig. 2, the transition amplitudes $\sqrt{B(E2;\ 10\rightarrow 8)}$ for the Sn isotopes are plotted versus A. In the BCS approximation, the E2 transition amplitude is proportional to u^2-v^2, where $v^2 = 1-u^2$ is the degree of filling of the $h_{11/2}$ subshell. At the point of half-filling, $u^2 = v^2 = 0.5$, particle and hole contributions are equal in magnitude with opposite signs, hence the total amplitude is zero. This happens in the Sn isotopes close to A = 123 or N = 73. On the other hand, in N = 82 isotones the proton $h_{11/2}$ half-filling occurs[1] just below Z = 71, two units lower than for neutrons. By means of BCS calculations, this marked difference between protons and neutrons has been traced to the relative $s_{1/2}$, $d_{3/2}$ and $h_{11/2}$ single particle energies. For protons at N = 82 the orbitals are actually nearly degenerate, but for neutrons the $s_{1/2}$ state and, to a lesser extent, the $d_{3/2}$ come well below the $h_{11/2}$ state. The differences in

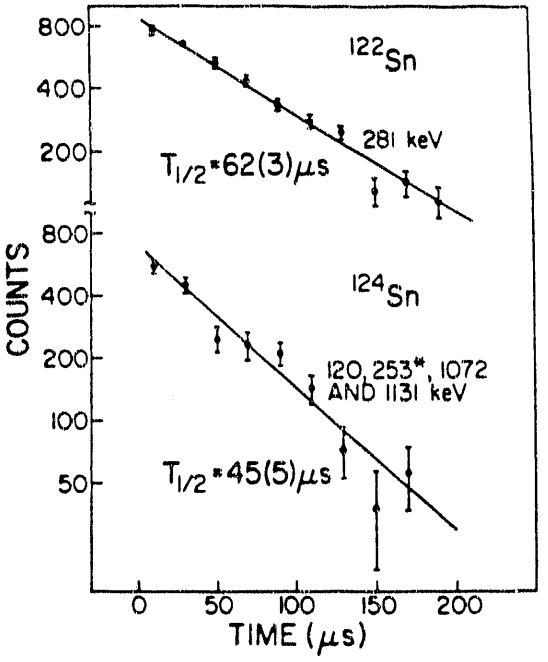

Fig. 1: Decay data for the ^{122}Sn and ^{124}Sn 10^+ isomeric half-life determinations.

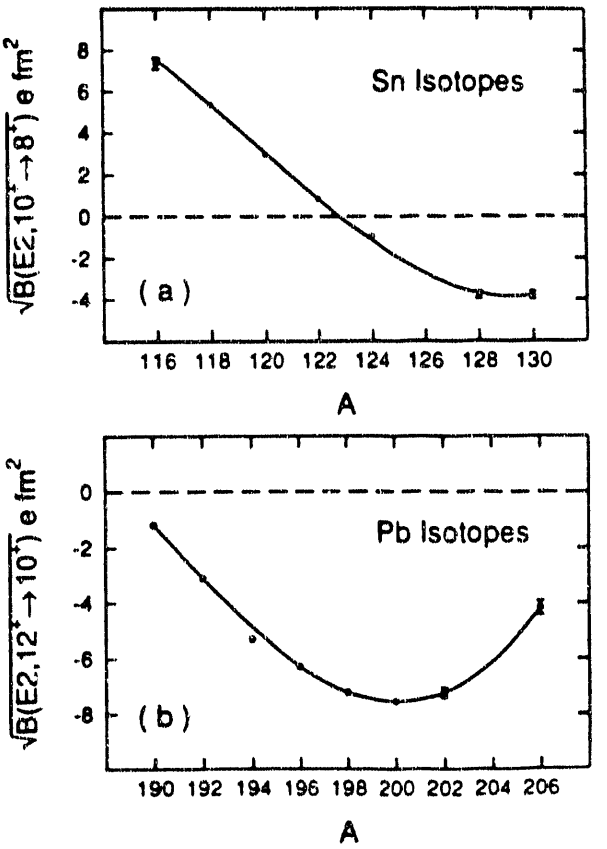

Fig. 2: a) Measured E2 transition amplitudes for $(\nu h_{11/2})^n$ $10^+ \rightarrow 8^+$ transitions in even-A Sn isotopes. Where error bars are not shown, they lie within the plotted point. (b) A similar presentation for $(\nu i_{13/2})^n$ $12^+ \rightarrow 10^+$ transitions in even-A Pb isotopes.

single particle energy spacings are a consequence of the Coulomb potential, which for protons raises the $s_{1/2}$ and $d_{3/2}$ energies more than the $h_{11/2}$ energy.

An enlightening comparison between the effective E2 charges observed in tin and lead isotopes[4] has also been developed (Fig. 2). In the two-hole nuclei ^{130}Sn and ^{206}Pb, the neutron effective charges are very similar, close to 0.9 e. However, in both cases the effective charge more than doubles to values of about 2.0 e in the lighter isotopes around the middle of the major shell, where E2 excitations within the shell can build up low-lying E2 collectivity.

2.2. Results for odd-A Sn Isotopes

The off-beam spectra obtained with the ^{124}Sn target (e.g. Fig. 3) showed unknown γ-rays, decaying with 5-10 μs half-lives, that we suspected might be due to isomerism in odd-A Sn nuclei. Specifically, six strong new γ-rays could be grouped in pairs as follows: 818 and 1220 keV, 841 and 1151 keV, and 838 and 1107 keV. Within each pair, the γ-rays had similar intensities, were mutually coincident and decayed with similar half-lives:

$$T_{1/2}\ (818 \text{ and } 1220 \text{ keV}) = 9.6 \pm 1.2\ \mu s$$

$$T_{1/2}\ (841 \text{ and } 1151 \text{ keV}) = 5.3 \pm 0.5\ \mu s$$

and

$$T_{1/2}\ (838 \text{ and } 1107 \text{ keV}) = 7.4 \pm 2.6\ \mu s$$

These three new isomers have been interpreted by analogy with a known 1.75 μs isomer[5] in ^{117}Sn as $19/2^+$ states of $\nu h_{11/2} \times 5^-$ character in the ^{119,121,123}Sn nuclei, each of them decaying to $15/2^-$ and $11/2^-$ states by a cascade of M2 and E2 transitions (Fig. 4). The 0^+, 2^+ and 5^- states in the neighboring even-A Sn nuclei are also shown in this figure and it is obvious that the $15/2^-$ and $19/2^+$ energies follow closely the highly regular systematics of the 2^+ and 5^- energies.

The $(\nu h_{11/2}{}^2 s_{1/2})19/2^+$ states are long-lived because they can decay only by configuration-forbidden M2 transitions to the $15/2^-$ states. The B(M2) values deduced are smaller than 10^{-3} W.u., but there is a possibility that higher-lying μs isomers in these nuclei may have influenced the half-life determinations. In any case, the identification[6] of the $15/2^- \rightarrow 11/2^-$ transitions in ^{119,121,123}Sn was a significant first step toward further studies of $(\nu h_{11/2})^n$ v = 3 yrast states in these nuclei. For example, by setting coincidence gates on these lowest transitions (Fig. 5), γ-rays of 175, 513 and 1105 keV in ^{119}Sn and of 176, 471 and 1030 keV in ^{121}Sn could be firmly identified as $27/2^- \rightarrow 23/2^- \rightarrow 19/2^- \rightarrow 15/2^-$ cascades between $(\nu h_{11/2})^n$ v=3 states in the two nuclei. Half-lives for the $27/2^-$ isomers have yet to be determined accurately; they will also yield B(E2) values reflecting the degree of occupation of the $\nu h_{11/2}$ subshell.

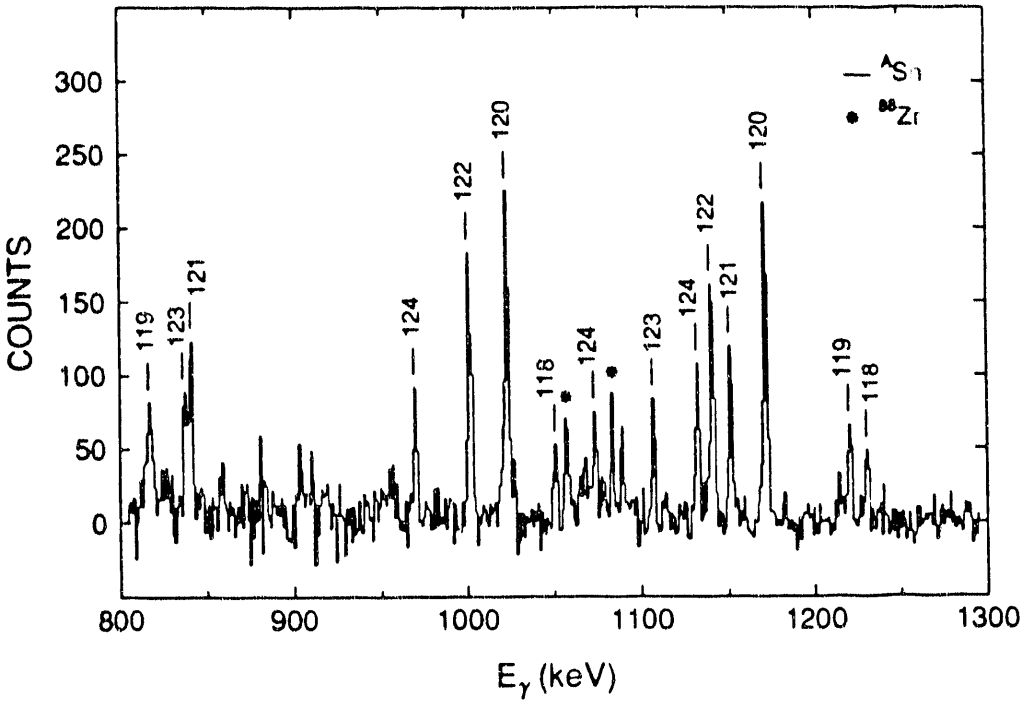

Fig. 3: Off-beam γ-ray spectrum measured 2-12 μs after beam pulses for the reaction ^{124}Sn + 344 MeV ^{80}Se; radioactivities have been subtracted. Mass assignments are indicated for individual γ-rays in $^{118\text{-}124}$Sn isotopes.

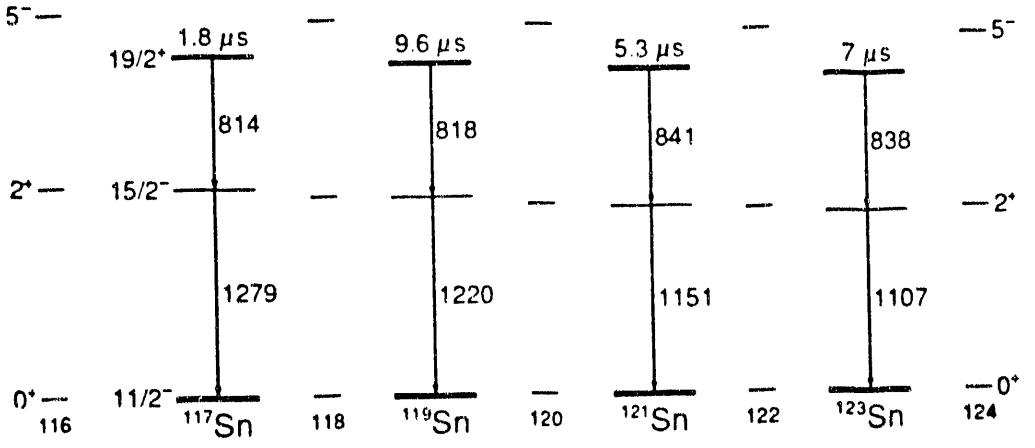

Fig. 4: Energy systematics for even-A and odd-A Sn nuclei in the A = 116-124 mass range.

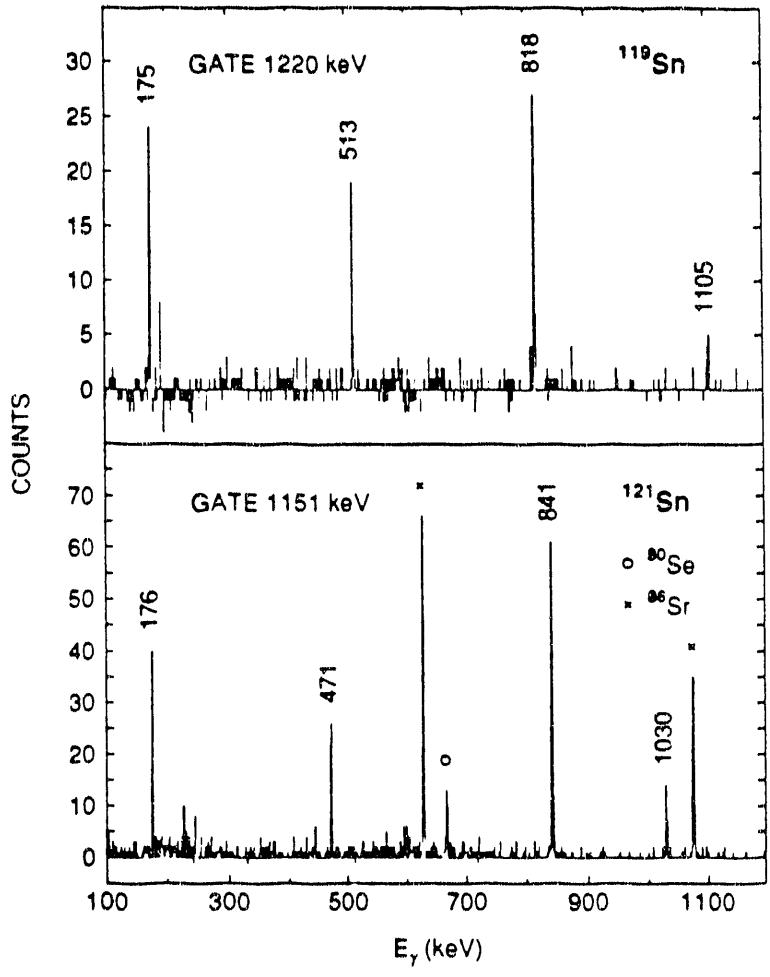

Fig. 5: Off-beam γ-γ coincidence spectra gated on the $15/2^- \rightarrow 11/2^-$ transitions in ^{119}Sn and ^{121}Sn. The labelled γ-rays are identified as transitions de-exciting the $19/2^+$ isomers (see Fig. 4) or the $(\nu h_{11/2})^n$ $27/2^-$ isomers in these nuclei.

2.3. Reaction Yields and Mechanisms

Gamma-ray yield determinations in the ^{122,124}Sn + 344 MeV ^{80}Se experiments have demonstrated that this deep inelastic method of excitation delivers dozens of nuclei with comparable yields, which are sufficient for yrast spectroscopy in a largely untouched region of neutron excessive nuclei around ^{124}Sn. Making isotopic assignments for the previously unknown γ-ray cascades is one of the biggest problems. Thus far we have been able to identify yrast cascades in A = 115, 117, 119 isotopes of In and in A = 121, 123, 125 isotopes of Sb; the assignments are based in part on some overlap with radioactivity data, and in part on observed $\gamma\gamma$ coincidences between heavy and light reaction partners. For example, some γ-rays of ^{125}Sb (from 1p pick-up) could be assigned based on their coincidences with known γ-rays of ^{79}As (from 1p stripping).

The overall distribution of yields with A and Z observed in these reactions is illustrated for both projectile-like and target-like even-even products in Fig. 6, which shows relative $4^+ \rightarrow 2^+, 2^+ \rightarrow 0^+$ $\gamma\gamma$ coincidence intensities measured for the different nuclei. Analysis of these distributions gave an estimate of the average number of neutrons evaporated from the excited reaction products, which was used to extract the pattern of primary reaction products. This pattern may be broadly understood in terms of N/Z equilibration[7] in the dinuclear system formed in the deep inelastic collision. Calculations of minimum potential energy surfaces can be used to explain the gross features of the observed product distribution (Fig. 6) as well as to predict the outcome of future experiments using other target-projectile combinations.

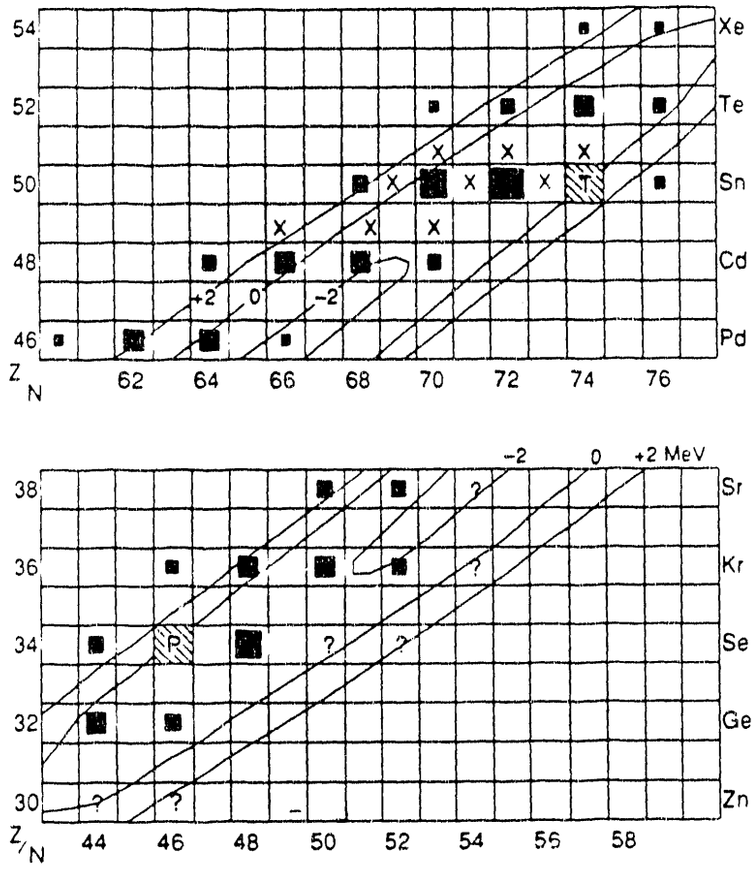

Fig. 6: Relative yields determined for even-even products of the reaction ^{124}Sn + 344 MeV ^{80}Se. (Possible products with poorly known level schemes are labelled with question marks). The larger yields are well correlated with the minimum potential energy contours calculated for this dinuclear system. Crosses mask nine odd-A nuclei in which new yrast cascades are currently being examined.

3. Acknowledgement

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