Yrast Isomers in Tin Nuclei from Heavy Ion Collisions and the $\nu h_{11/2}$ Subshell Filling

R. Broda,[a] R. H. Mayer, I. G. Bearden, Ph. Benet, P. J. Daly, and Z. W. Grabowski
Chemistry and Physics Departments, Purdue University, West Lafayette, Indiana 47907

M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, and E. F. Moore[b]
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

S. Lunardi
Dipartimento di Fisica, Università di Padova, I-35131 Padova, Italy

J. Blomqvist
Manne Siegbahn Institute of Physics, S-10405 Stockholm, Sweden
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Long-lived 10^+ isomers in ^{122}Sn and ^{124}Sn have been identified among the products of ^{124}Sn+325 MeV ^{76}Ge collisions. The measurements virtually complete a series of $B(E2)$ determinations for $(\nu h_{11/2})^n$ states in $^{116-130}$Sn, which pinpoint half filling of the $\nu h_{11/2}$ subshell very close to $N=73$. Results for these $Z=50$ isotopes and for the $N=82$ isotones are contrasted, and an enlightening comparison between the effective $E2$ charges observed in tin and lead isotopes is developed.

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The decays of $(\pi h_{11/2})^n$ yrast isomers have been studied in a series of proton-rich $N=82$ isotones extending to the vicinity of the proton drip line. The results [1] provide an outstanding illustration of the dependence of $E2$ transition rates between j^n states on subshell occupation number, and they demonstrate that half filling of the proton $h_{11/2}$ subshell occurs just below $Z=71$ ^{153}Lu. However, the prospects for extending the $N=82$ measurements beyond $Z=72$ seem quite poor. On the other hand, the counterpart $h_{11/2}$ neutron subshell is being filled in $A=116$-130 tin isotopes, and one should, in principle, be able to study $(\nu h_{11/2})^n$ excitations through this complete series. Already $(\nu h_{11/2})^n$ 10^+ isomers are known in ^{116}Sn, ^{118}Sn, and ^{120}Sn at one end of the series [2-4], and in the fission products ^{128}Sn and ^{130}Sn at the other [5]. Missing is any information about analogous isomers in ^{122}Sn, ^{124}Sn, and ^{126}Sn, for which long 10^+ half-lives (in the 5-100-μs range) are expected. A serious experimental obstacle is that these $N=72$, 74, and 76 tin isotopes *are not accessible by fusion-evaporation reactions*. In the present work, we sought to identify the missing tin isomers among the products of heavy ion reactions on ^{124}Sn and ^{122}Sn targets.

Even-A Sn nuclei display very regular level systematics. The known 10^+ isomers in the $A=118$-130 isotopes all decay by $10^+\rightarrow 8^+\rightarrow 7^-$ two γ-ray cascades to 7^- isomeric states of $\nu h_{11/2}d_{3/2}$ character. Similar 7^- isomers in ^{122}Sn, ^{124}Sn, and ^{126}Sn with half-lives of 9.3, 3.1, and 6.6 μs, respectively, are known from β-decay studies [6] of high-spin In species. Part of the 7^- feeding in β decay occurs indirectly through γ rays of 281 keV (^{122}Sn), 253 keV (^{124}Sn), and 269 keV (^{126}Sn), which are almost certainly the $8^+\rightarrow 7^-$ $E1$ transitions predicted from systematics. The same γ rays could thus be expected to occur, together with low-energy $10^+\rightarrow 8^+$ $E2$ partners, in the decays of the sought for 10^+ isomers. These considerations were of central importance in planning the course of the investigations.

Since the bombardment of ^{124}Sn with neutron-rich projectiles appeared to offer the best prospects for populating the 10^+ isomers in all three nuclei of interest, the primary reaction chosen for investigation was ^{124}Sn+325 MeV ^{76}Ge ($\sim$15% above the Coulomb barrier). A 1-mg/cm^2 ^{124}Sn target (97% enriched) backed with lead was placed at the center of the Argonne-Notre Dame γ-ray facility, which consisted of twelve Compton-suppressed Ge detectors and an inner ball of 50 BGO hexagons. This target was bombarded with μs pulsed beams of 325-MeV ^{76}Ge ions from the ATLAS superconducting linear accelerator at Argonne. The Ge detectors recorded off-beam γ-ray singles spectra in two-parameter E_γ versus time mode as well as off-beam $\gamma\gamma$ prompt coincidence events. The time interval between a Ge detector pulse and the delayed firing (up to 10 μs later) of a BGO hexagon was also recorded; during subsequent data sorting the γ rays connecting the 10^+ and 7^- Sn isomers in the Sn nuclei of interest could be selectively accentuated by requiring a delayed coincidence in the μs range between Ge and BGO detector signals.

In the main experiment, performed with a 60-μs beam-on, 210-μs beam-off configuration, the key 281- and 253-keV γ rays were clearly seen decaying during the off-beam period, together with the γ rays known to follow the 7^- isomers in ^{122}Sn and ^{124}Sn, but no trace of ^{126}Sn γ rays could be discerned. A big surprise was the discovery in the spectra of clear evidence for appreciable population of the known 10^+ isomers in both ^{120}Sn and ^{118}Sn; we will return to this point. The quality of the data is illustrated in the off-beam spectra of Fig. 1. Imposing the additional requirement that the Ge signal be followed by a delayed BGO pulse gave the lower spectrum, Fig. 1(b), where γ rays feeding μs isomers are pref-

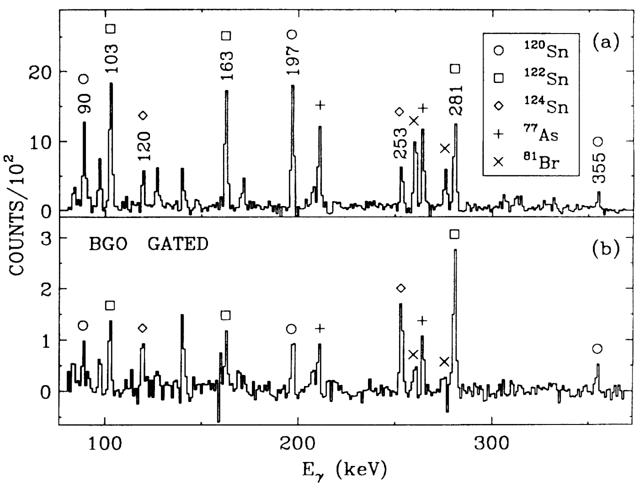

FIG. 1. Off-beam γ-ray spectra for the reaction ^{124}Sn+325 MeV ^{76}Ge measured 2–80 μs after the beam bursts, with radioactivities subtracted. Spectrum (a) is ungated, while (b) required a delayed BGO hexagon pulse 1–9 μs after the Ge detector signal. Random coincidence events are not subtracted.

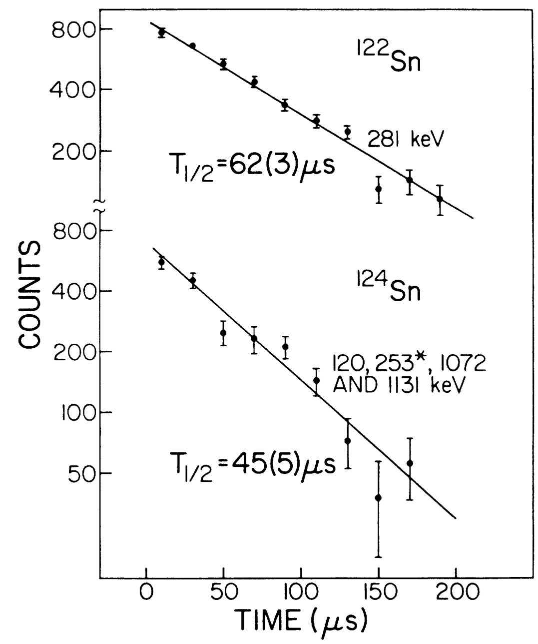

FIG. 2. Decay data for the ^{122}Sn and ^{124}Sn 10^+ isomeric half-life determinations. To minimize interference from an extraneous 254-keV γ ray, only BGO-gated events were included for the ^{124}Sn 253-keV transition.

erentially detected; indeed, the 253-, 281-, and 355-keV peaks representing the $8^+ \to 7^-$ transitions in ^{124}Sn, ^{122}Sn, and ^{120}Sn are the most obviously enhanced spectral features. Detailed examination of the <100 keV region, with and without the delayed BGO condition, revealed 75.2- and 78.2-keV γ rays as prime candidates with correct intensities to be the $10^+ \to 8^+$ $E2$ transitions in ^{122}Sn and ^{124}Sn. The $\gamma\gamma$ coincidence data firmly confirmed the ^{122}Sn $10^+ \to 8^+$ assignment for the 75.2-keV γ ray, this being the only transition observed in prompt coincidence with the 281-keV γ ray. Likewise, the 78-keV γ ray appeared to be coincident with the 253-keV γ ray and it is almost certainly the ^{124}Sn $10^+ \to 8^+$ transition, although the coincidence statistics were poorer for this lower yield product. The measured off-beam intensities of the 75.2- and 78.2-keV γ rays were approximately 20% of those for the corresponding $8^+ \to 7^-$ transitions, implying total conversion coefficients consistent with their $E2$ multipolarity assignments. From the present work, the ^{122}Sn 8^+ and 10^+ states are located at 2689 and 2764 keV, in reasonable accord with results of two studies [7,8] of the ^{124}Sn$(p,t)^{122}$Sn reaction, the more recent of which placed these ^{122}Sn levels at 2695 ± 10 and 2775 ± 10 keV, respectively. The decay data used to extract half-lives for the new 10^+ isomers are displayed in Fig. 2. The results $T_{1/2}(10^+,{}^{122}\mathrm{Sn}) = 62 \pm 3$ μs and $T_{1/2}(10^+,{}^{124}\mathrm{Sn}) = 45 \pm 5$ μs are included in the compilation of Table I, which also shows the $B(E2;10^+ \to 8^+)$ values for the even-A $^{116-130}$Sn isotopes, with ^{126}Sn now the only missing one. These results locate the $B(E2)$ minimum, and hence the half filling of the $\nu h_{11/2}$ subshell, between $A=122$ and $A=124$.

A shorter measurement performed for the reaction ^{122}Sn+325 MeV ^{76}Ge showed significant population of the ^{118}Sn, ^{120}Sn, and ^{122}Sn 10^+ isomers, but little ^{124}Sn production (and again no ^{126}Sn). Relative yields of the various Sn 10^+ isomers were determined for both the ^{124}Sn and ^{122}Sn targets, and the results demonstrated that processes involving 4 and 6 neutron removal populate the 10^+ isomers almost as effectively as those involving 0 and 2 neutron removal. In contrast, 10^+ isomer production by $2n$ addition to the target could not be observed in either reaction despite the choice of neutron-rich ^{76}Ge as projectile. These are obviously not quasielastic neutron transfer processes happening at a grazing angle, for which calculations [9] favor the opposite direction of mass flow. Instead, the observed Sn 10^+ isomers are

TABLE I. Decay data for the 10^+ isomers in Sn isotopes and the $B(E2;10^+ \to 8^+)$ values.

Nucleus	$10^+ \to 8^+$ (keV)	$T_{1/2}$ (μs)	$B(E2)$ (e^2fm^4)	Ref.
^{116}Sn	54.7(2)	0.90(1)	54(4) [a]	[2]
^{118}Sn	55.8(2)	2.63(7) [b]	28.6(8)	[2–4]
^{120}Sn	65.7(2)	6.26(11)	8.9(2)	[4]
^{122}Sn	75.2(3)	62(3)	0.70(4)	Present work
^{124}Sn	78.2(5)	45(5)	0.89(11)	Present work
^{128}Sn	79.3	2.69(23)	14.4(13)	[5]
^{130}Sn	96.5	1.61(15)	14.5(14)	[5]

[a]Isomeric $E2$ branching of 63(4)% adopted from Ref. [2].
[b]Obtained by reanalysis of data from Ref. [4].

probably end products of deep inelastic heavy ion collisions leading to highly excited products, with in many cases subsequent emission of neutrons.

From the results summarized in Table I, the square root of the transition amplitudes $B(E2;10\rightarrow 8)$ are plotted versus A in Fig. 3(a). The square root leaves ambiguity about the sign of the $E2$ matrix element, but in practice this causes no difficulty because opposite signs are required in the bottom and top halves of the subshell. 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 $N=73$. A BCS calculation using the single-particle energies and pairing force strength of Kisslinger and Sorensen [10] indeed predicts a crossing point at $N=72.3$. On the other hand, in $N=82$ isotones the proton $h_{11/2}$ half filling occurs just below $Z=71$, two units lower than for neutrons; however, the calculated crossing point for protons [10] turns out to be 70.1, also about 2 units lower than for neutrons. This marked difference between protons and neutrons can be traced to the relative $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ single-particle energies. For protons at $N=82$ these orbitals are actually nearly degenerate [11], 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 [12,13]. The differences in 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.

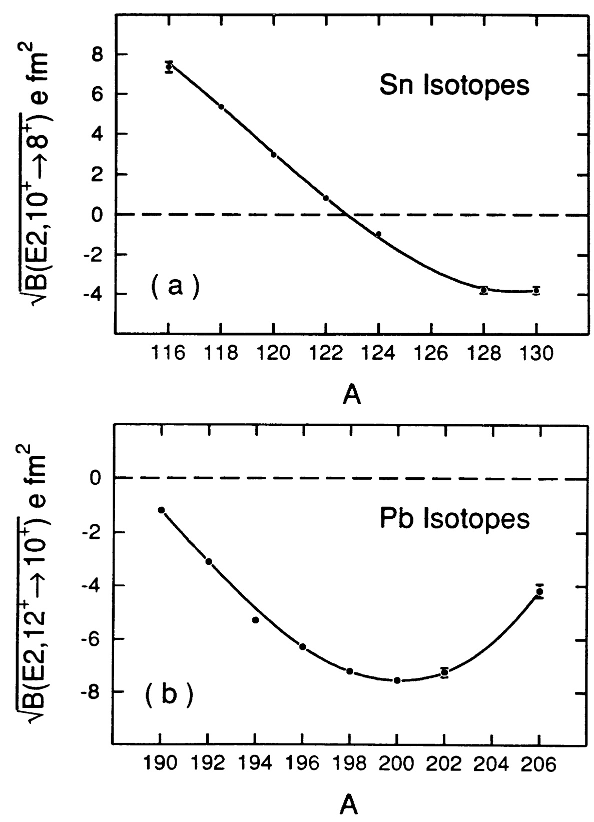

FIG. 3. (a) Measured $E2$ transition amplitudes for the $(\nu h_{11/2})^n$ $10^+\rightarrow 8^+$ transitions in even-A Sn isotopes. Where errors bars are not shown they lie within the plotted point. The solid line is drawn through the points to guide the eye. (b) A similar presentation of $E2$ amplitudes for $(\nu i_{13/2})^n$ $12^+\rightarrow 10^+$ transitions in even-A Pb isotopes.

The $10^+\rightarrow 8^+$ $E2$ amplitudes in the Sn nuclei can be quantitatively described by assigning an effective $E2$ charge $e_{\rm eff}$ to the $\nu h_{11/2}$ particles (holes). The simplest situation is in ^{130}Sn where the $(\nu h_{11/2})^2$ 10^+ and 8^+ states must have pure two-hole character with respect to the closed ^{132}Sn core. Using $\langle h_{11/2}|r^2|h_{11/2}\rangle=32$ fm^2 for the radial matrix element [14], one obtains $e_{\rm eff}(h_{11/2})=0.88(4)e$. This value is very close to that for the $i_{13/2}$ neutron hole near ^{208}Pb, e.g., $e_{\rm eff}(i_{13/2})=0.91(4)e$ from the analogous $12^+\rightarrow 10^+$ transition between $(i_{13/2})^2$ states in ^{206}Pb [15]. In each case, this effective charge must be associated with high-energy 2^+ excitations of the closed core.

For smaller neutron numbers the $\nu h_{11/2}$ occupation is depleted, as described by the u^2-v^2 factor in the relevant $B(E2)$ expression [14]:

$$B(E2;10^+\rightarrow 8^+)=18.7e_{\rm eff}^2(u^2-v^2)^2e^2{\rm fm}^4\,.$$

In the $N<80$ nuclei, the additional neutron holes also open possibilities of low-energy 2^+ excitations which soften the core and increase the $E2$ effective charge. In ^{128}Sn, for example, such an increase in $e_{\rm eff}$ must compensate for the depletion of the $\nu h_{11/2}$ subshell, resulting in a $B(E2)$ unchanged from that in ^{130}Sn. At the lighter end, in ^{116}Sn the $h_{11/2}$ subshell is practically empty apart from the two neutrons that form the 8^+ and 10^+ states. A pairing calculation gives $v^2=0.1$ for $\nu h_{11/2}$ in ^{116}Sn, corresponding to a reduction of the $E2$ amplitude by a factor of 0.8. The measured $B(E2)$ value for this nucleus then implies an effective charge of $2.1e$, twice as large as the value for ^{130}Sn. The enhancement of $e_{\rm eff}$ in the middle of the $N=50$–82 shell is naturally interpreted as a consequence of additional configuration mixing, corresponding to polarization of the softer midshell core. One possibility is that this enhancement may arise from intruder *proton* core 0^+ excitations such as those associated with the "deformed" bands identified [16] in $^{112\text{-}120}$Sn nuclei; qualitatively, this effect could be viewed as a softening of the $Z=50$ shell closure towards the middle of the $N=50$–82 shell. An alternative, perhaps more conventional, explanation would be that four-quasiparticle *neutron* admixtures cause the enhancement around midshell, where $E2$ excitations within the shell of the types $\nu g_{7/2}\rightarrow d_{3/2}$ and $\nu d_{5/2}\rightarrow s_{1/2}$ can build up low-lying $E2$ collectivity.

A comparison of effective $E2$ charges in the Sn and Pb isotopes proves to be illuminating. The $B(E2)$ values for the $12^+\rightarrow 10^+$ transitions between $(\nu i_{13/2})^2$ states have been measured [15] for all even-A Pb isotopes (except ^{204}Pb) from ^{206}Pb to ^{190}Pb. The $i_{13/2}$ single-particle state lies deeper in the $N=82$–126 shell than the $h_{11/2}$ state in the $N=50$–82 shell. Consequently, half filling of the $i_{13/2}$ subshell occurs below $N=108$, and all the Pb isotopes for which $12^+ \rightarrow 10^+$ transitions are known to lie well to the right of the point where the $E2$ amplitude changes sign [Fig. 3(b)]. In the intermediate isotopes ^{202,200,198}Pb, the $i_{13/2}$ subshell is only slightly depleted and the larger $E2$ amplitudes determined clearly reflect considerable enhancement of the $E2$ effective charge. A quantitative treatment of the pair correlations has given [15] the result that the effective $E2$ charge more than doubles from less than $1e$ in ^{206}Pb to about $2e$ in the lighter isotopes, behavior that is strikingly similar to that observed in the tin isotopes.

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[a]On leave from Institut für Kernphysik, Kernforschungsanlage Jülich, D-5170 Jülich, Germany and Institute of Nuclear Physics, PL-31342 Cracow, Poland.

[b]Present address: Gesellshaft für Schwerionenforschung, D-6100 Darmstadt, Germany.

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