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First observation of the decay of a 15^- seniority $v = 4$ isomer in ^{128}Sn

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Isomeric states in the semimagic $^{128-130}$Sn isotopes were populated in the fragmentation of a ^{136}Xe beam on a ^{9}Be target at an energy of 750 A·MeV. The decay of an isomeric state in ^{128}Sn at an excitation energy of 4098 keV has been observed. Its half live has been determined to be $T_{1/2} = 220(30)$ ns from the time distributions of the delayed γ rays emitted in its decay. $\gamma\gamma$ coincidence relations were analyzed in order to establish the decay pattern of the newly established state toward the known (7^-) and (10^+) isomers at excitation energies of 2092 and 2492 keV, respectively. Based on a comparison with results of state-of-the-art shell-model calculations the new isomeric state is proposed to have the $\nu h_{11/2}^{-3} d_{3/2}^{-1}$ configuration with the four neutron holes in ^{132}Sn maximally aligned to a total spin of $I^\pi = 15^-$.

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I. INTRODUCTION

The series of semimagic Sn isotopes have long attracted a particular interest in nuclear structure research both from an experimental as well as a theoretical point of view. With the 33 experimentally accessible isotopes between the two double-magic cornerstones ^{100}Sn and ^{132}Sn, it allows for systematic and stringent tests of the validity of theoretical models across an entire span of a large major neutron shell and beyond, from the proton dripline with $N = Z$ to the isotope which has 10 neutrons more than the most neutron-rich stable tin isotope. In the upper half of the major neutron shell the filling of the unique-parity $h_{11/2}$ orbital gives rise to the observation of seniority isomers. Indeed in all even Sn isotopes in the range $A = 116$–130 10^+ $\nu h_{11/2}^{-2}$ isomeric states have been observed using deep-inelastic reactions, the β decay of long-lived isomeric states in the In isotopes, as well as fragmentation and fission at relativistic energies [1–4]. In the odd isotopes the experimental information on the corresponding $27/2^-$ $\nu h_{11/2}^{-3}$ isomer has been recently extended up to the ^{129}Sn isotope [5]. These complete sets of excitation energies as well as decay properties allowed us to study in detail the filling of the $h_{11/2}$ orbital and to determine the effective $E2$ charges. In addition to the $\nu h_{11/2}^{-n}$ states, other long-lived levels involving the $d_{3/2}$ neutron orbital, which is lying close in energy to the $h_{11/2}$ orbit, have been observed in all $A = 116$–130 Sn isotopes. In detail these are $\nu h_{11/2}^{-1} d_{3/2}^{-1}$ states with spin 7^- in the even and $\nu h_{11/2}^{-2} d_{3/2}^{-1}$ levels with spin $23/2^+$ in the odd Sn isotopes. However, what is still lacking is the information from seniority $v > 3$ states involving both orbitals. The purpose of the present article is to report on the identification of the first $v = 4$, $\nu h_{11/2}^{-3} d_{3/2}^{-1}$ isomeric state with spin (15^-) in the nucleus ^{128}Sn.

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II. EXPERIMENT AND RESULTS

Isomeric states in the $A = 128$–130 Sn isotopes were populated by means of relativistic fragmentation of a ^{136}Xe beam at an energy of 750 A·MeV on a 4 g/cm^2 thick ^{9}Be target within the RISING campaign at GSI, Darmstadt. The fragment separator (FRS) [6] was set to optimize the transmission of ^{126}Cd and the reaction products were identified ion by ion in the FRS via the measurement of the energy loss, the magnetic rigidity, the positions in the intermediate, and the final focal plane and the time-of-flight between the two. Finally, after being slowed down in an Al degrader, the ions were implanted in a passive stopper in the final focal plane of the FRS. The fraction of nuclei which were populated in an excited isomeric state and also implanted in this state after surviving the flight through the separator then decay to the ground state by γ-ray emission. These γ rays were detected by 15 large volume Ge cluster detectors [7] from the former EUROBALL spectrometer arranged in close geometry around the stopper [8]. With the requirement of a delayed coincidence relationship between the implanted ion and the detected γ ray the radiation can be unequivocally assigned to the decay of an isomeric state of a particular isotope. More details about the experimental setup and the data handling are given in Refs. [9–12] in which results concerning the nuclei ^{127,128,130}Cd and ^{131}In studied in the same experiment have been presented. In total 1.35×10^4 ^{128}Sn, 5.7×10^5 ^{129}Sn, and 4.8×10^5 ^{130}Sn ions have been identified and implanted in the current experiment.

A spectrum of γ rays observed in delayed coincidence with identified and implanted ^{128}Sn ions is shown in Fig. 1(a). The spectrum is dominated by two lines at 79 and 321 keV, respectively, which are known to be emitted in the decay of the $I^\pi = (10^+)$ isomeric state with a half-life of $T_{1/2} = 2.69(23)$ μs [4]. Furthermore, indications of additional lines were found in this spectrum, for example, at an energy of 426 keV. When the time range is limited to the first 1.5 μs after the implantation six previously unobserved γ transitions with energies of 119, 207, 426, 625, 1055, and 1061 keV are clearly identified in the spectrum of Fig. 1(b). They indicate the existence of an additional isomeric state with a half-life

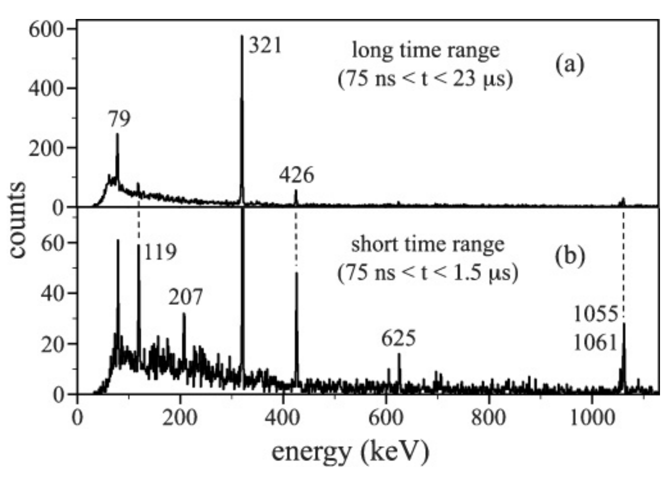

FIG. 1. Delayed γ-ray spectra in coincidence with identified ^{128}Sn ions implanted in the stopper for (a) a long (75 ns–23 μs) and (b) a shorter time range (75 ns $< t <$ 1.5 μs).

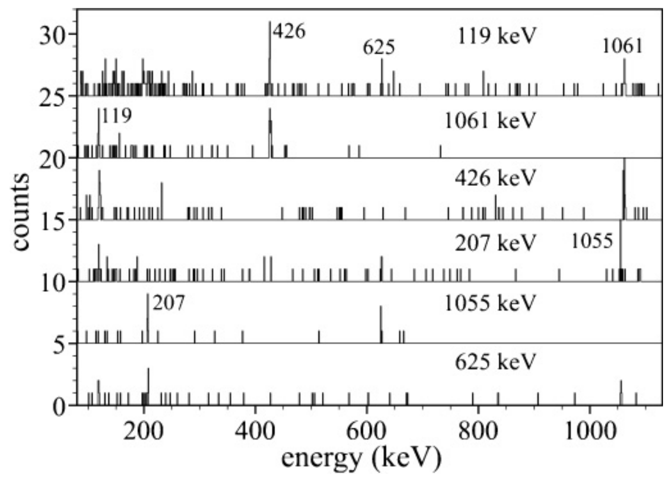

FIG. 2. γ-ray spectra observed in prompt coincidence with the 119, 1061, 426, 207, 1055, and 625 keV transitions, respectively, within the first 1.5 μs after the implantation.

in the submicrosecond range. In order to obtain information about the ordering of the newly observed transitions prompt $\gamma\gamma$ coincidence spectra were sorted for the time range 75 ns $< t <$ 1.5 μs after the implantation. The resulting spectra are shown in Fig. 2. Although the statistics of these spectra is very low there is sufficient evidence that two groups of γ rays, 426–1061 keV and 207–625–1055 keV, are observed in mutual coincidence and therefore form cascades. The 119 keV transition is observed in coincidence with members of both sequences and due to its low energy a natural candidate to be the transition depopulating the isomeric state. It is interesting to note that the sum energies of the three γ rays with 207, 625, and 1055 keV, namely 1887 keV, is equal to the sum of the 426 and 1061 keV transitions plus the known 79 and 321 keV γ rays connecting the (10^+) and (7^-) isomeric states. And indeed, when removing the prompt coincidence condition and opening the time window, the 321 keV γ rays is clearly observed in delayed coincidence with the newly identified 1061 and 426 keV transitions. We therefore place these two transitions on top of the (10^+) state leading to a new level at an excitation energy of 3979 keV and the 207–625–1055 keV cascade in parallel connecting this newly identified level to the (7^-) state at 2092 keV. The relative intensities of the newly identified transitions are summarized in Table I. They have been determined in the delayed singles spectrum to be limited to the first 1.5 μs after the implantation while the intensity of the 426 keV γ ray relative to the 79 and 321 keV transitions has been obtained from the singles spectrum without time condition. We find that the intensity of the 426–1061 keV cascade is about twice that of the 207–625–1055 keV branch. Unfortunately there is no additional experimental information that could help to fix the order of the transitions within the two cascades. The order we propose in Fig. 3 and therefore the position of the intermediate states at 3147, 3553, and 3772 keV consequently is considered to be tentative.

To determine the half-life of the new isomeric state at 4098 keV the time distributions between the ion implantation and the detection of one of the four γ rays with energies of 426,

TABLE I. Energies (E_γ), proposed initial (I_i^π), and final (I_f^π) spin values and relative intensities of the γ transitions observed in a long ($t < 23$ μs) $I_{\rm rel}^l$, respectively short ($t < 1.5$ μs) $I_{\rm rel}^s$, time window after the implantation in the present experiment.

E_γ (keV)	I_i^π	I_f^π	$I_{\rm rel}^l$	$I_{\rm rel}^s$
79	(10^+)	(8^+)	1030(80)[a]	–
119	(15^-)	(13^-)	–	190(25)[a]
207	(13^-)	(11^-)	–	55(10)[a]
321	(8^+)	(7^-)	1110(30)	–
426	(13^-)	(12^+)	100(10)	100(10)
625	(11^-)	(9^-)	–	47(8)
1055	(9^-)	(7^-)	–	33(9)
1061	(12^+)	(10^+)	–	118(14)

[a]Corrected for internal conversion assuming $E2$ multipolarity.

625, 1055, and 1061 keV have been summed and least-squares fitted by a single-exponential decay resulting in a half-life of $T_{1/2} = 220(30)$ ns. Random correlations have been taken into account in this procedure by subtracting the time distributions corresponding to background regions next to the energy peaks under study prior to the fit. The half-life of the known (10^+), 2492 keV isomer has been redetermined from the present data as $T_{1/2} = 3.00(15)$ μs by fitting the time distribution of the 321 keV transition, taking into account the feeding from the newly identified isomeric state at an excitation energy of 4098 keV. This result is in reasonable agreement with the

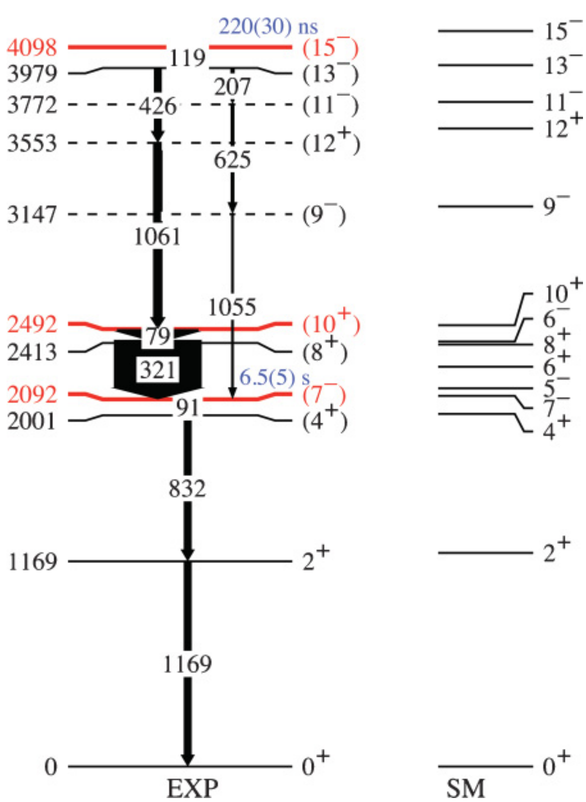

FIG. 3. (Color online) Comparison between the proposed excitation scheme of ^{128}Sn (EXP) with the results of shell-model calculations (SM).

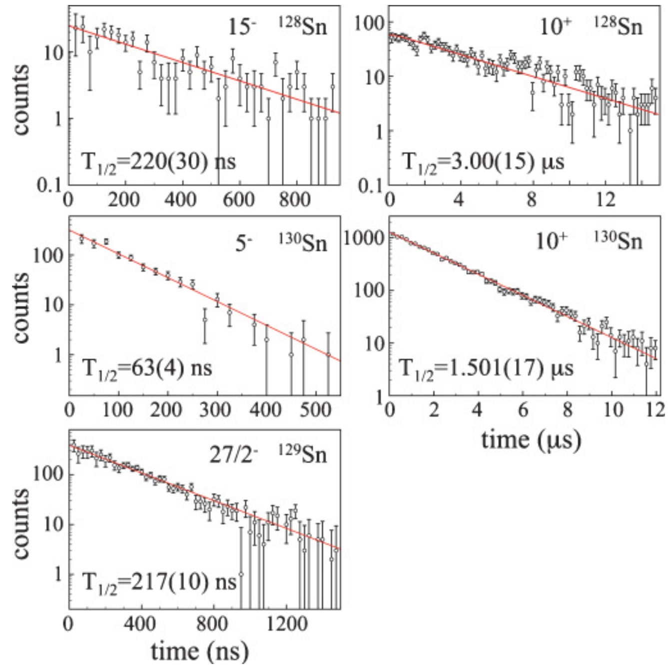

FIG. 4. (Color online) Time distributions between the ion implantation and the detection of one of the 426, 625, 1055, and 1061 keV transitions (15^-), respectively, the 321 keV γ ray (10^+) in ^{128}Sn (top row), one of the 774 and 1221 keV transitions (5^-), respectively, the 393 keV γ ray in ^{130}Sn (middle row), and one of the 145 and 605 keV transitions ($27/2^-$) in ^{129}Sn (bottom row).

literature value of $T_{1/2}^{\rm lit} = 2.69(23)$ μs [4] and $T_{1/2} = 2.77(22)$ μs [13] deduced from the experimental data discussed in Ref. [14]. Both decay curves including the fits are shown in the top row of Fig. 4.

As mentioned before, besides ^{128}Sn the neighboring isotopes ^{129}Sn and ^{130}Sn were also produced in the present experiment with higher yields. Although no new isomeric states were found in these nuclei the half-lifes of the known $27/2^-$ level in ^{129}Sn and the (10^+) and 5^- isomers in ^{130}Sn were redetermined taking advantage of the increased statistics of the present data set. The corresponding decay curves including the fits are shown in Fig. 4. While the resulting half-lives for the $27/2^-$ state in ^{129}Sn and the (10^+) state in ^{130}Sn, $T_{1/2} = 217(19)$ ns, respectively, $T_{1/2} = 1.501(17)$ μs, agree within the experimental uncertainties with the literature values ($T_{1/2} = 270(70)$ ns, respectively, $T_{1/2} = 1.61(15)$ μs from Refs. [4,5]) a small deviation is observed for the short-lived 5^- isomer in ^{130}Sn. Our value of $T_{1/2} = 63(4)$ ns is slightly larger compared to the $T_{1/2} = 52(3)$ ns reported by Fogelberg *et al.* [4].

III. DISCUSSION

In order to interpret the new experimental information obtained from the present data set for isomeric decays in ^{128}Sn, new shell-model calculations were performed in a model space consisting of the $p_{1/2}$, $g_{9/2}$ for protons and $g_{7/2}$, $s_{1/2}$, $d_{5/2}$, $d_{3/2}$, $h_{11/2}$ for neutrons outside an inert ^{88}Sr core. It is important to note that neither proton excitations across the $Z = 50$ nor neutron excitations across the $N = 82$ gap are considered in these calculations. The residual interaction is inferred from a realistic G matrix derived from the CD-Bonn nucleon-nucleon potential [15]. Core polarization has been corrected for following the many-body approach outlined in Ref. [16]. Monopole tuning following $A^{-1/3}$ scaling of the two-body matrix elements (TBME) was performed to reproduce the single-hole energies in ^{132}Sn as described in Refs. [5,9]. For the open proton-neutron ($\pi\nu$) space further modifications were introduced that are described in Ref. [12] but do not concern the Sn isotopes except for a −150 keV correction of the $(\nu h^2_{11/2})_{2^+}$ TBME. Modifications of individual TBME were performed maintaining the monopole of the respective multiplet and thus the ^{132}Sn single-hole energies. It should be noted that monopole tuning of the evolution of effective single-particle energies (SPE) from a closed shell nucleus to single-hole energies (SHE) in the next, here from ^{100}Sn to ^{132}Sn, is ambiguous as there are more multiplets (here $\nu\nu$) than SPE/SHE pairs. To minimize the relative shift of individual multiplets, preferably those with a high-spin partner (here $\nu h_{11/2}$) are chosen as a small monopole change creates a large SPE-SHE shift {see e.g., Eq. (2) in Ref. [17]}. The ambiguity may be reduced however by maintaining the seniority driven experimental evolution of $B(E2)$ values with changing occupation n of the high-spin orbital (here $\nu h^n_{11/2}$). Further details will be given in a forthcoming publication [18]. Effective charges of $e_\pi = 1.5e$ and $e_\nu = 0.7e$ were used for protons and neutrons, respectively [5,9]. The calculations were performed with the OXBASH code [19].

The results of the shell-model calculations with respect to the excitation energies are shown in Fig. 3 in comparison to the experimentally observed states. The agreement between experiment and calculations is extremely good for all known states up to the (10$^+$) isomer at an excitation energy of 2492 keV. This nice agreement together with the fact that the same interaction has already successfully been used in the past to describe other Sn and also Cd isotopes near ^{132}Sn [5,9,12,14,20] encouraged us to use the results of the shell-model calculations as a basis for a tentative spin assignment for the newly observed states above the (10$^+$) state. In the excitation energy range from 2.5 to 4.2 MeV the shell-model calculation predicts the existence of five states with spins of 9$^-$, 12$^+$, 11$^-$, 13$^-$, and 15$^-$. Experimentally two new states at 3979 and 4098 keV have been firmly established and are naturally assigned to the highest two calculated levels with spin 13$^-$ and 15$^-$. Since the order of the transitions within the two parallel cascades could not be fixed on the basis of experimental information, we propose intermediate states at 3147, 3553, and 3772 keV (see Fig. 3) because of their proximity to the calculated levels at 3115, 3565, and 3700 keV, respectively. These assignments, which of course have to be considered tentative, and the resulting multipolarities of the involved transitions are consistent with the observed intensities summarized in Table I.

Besides excitation energies, reduced transition probabilities for a number of $E2$ and $E3$ transitions involved in the decay of the isomeric states in $^{128-130}$Sn were also calculated. They are compared Table II and Fig. 5 to the values deduced from the half-lives measured in the present work using the conversion coefficients from Ref. [21]. In Fig. 5 experimental and shell model $I \rightarrow I-2$ $E2$ transition strengths in W.u. are compared for initial states with leading configurations $\nu h^{2,3}_{11/2}$; $I^\pi = 10^+$, 27/2$^-$ (upper panel) and $\nu h^n_{11/2} d_{3/2}$, $I^\pi = 7^-$ ($n = 1$), 23/2$^+$ ($n = 2$), and 15$^-$ ($n = 3$) (lower panels). Data are from Refs. [5,23] and the present work. The agreement between experimental and theoretical transition probabilities is gratifying and in particular the decay of the newly observed (15$^-$) isomer is very well described by the shell-model calculation. The $E2$ strengths between high-spin states of rather pure configuration with the effective neutron charge used are in general a little underestimated in agreement with the conclusion drawn in Ref. [5] that a value of 0.85 e might be more appropriate. The $E3$ strengths are predicted to be hindered (see Table II) as they are dominated by the neutron $h_{11/2} \rightarrow d_{5/2}$ single-particle transition with the $d_{5/2}$

TABLE II. Half-lives $T_{1/2}$ of isomeric states in ^{128,129,130}Sn and reduced transition probabilities $B(E\lambda)$ in Weisskopf units of $E2$ and $E3$ transitions observed in their decay. The conversion coefficients α are taken from Ref. [21].

Nucleus	I_i^π	E_x (keV)	$T_{1/2}$		I_f^π	E_γ (keV)		α	$B(E\lambda)$ (W.u.)	
			This work	Literature					This work	SM
^{128}Sn	(10$^+$)	2492	3.00(15) μs	2.69(23) μs[a]	8$^+$	$E2$	79	3.69	0.341(17)	0.270
					7$^-$	$E3$	400	0.046	–	8.77×10^{-3}
	(15$^-$)	4098	220(30) ns	–	13$^-$	$E2$	119	0.861	1.51(21)	1.397
					12$^+$	$E3$	545	0.016	–	1.71×10^{-4}
	7$^-$	2092		6.5(5) s[b]	4$^+$	$E3$	91	26.5	0.133(11)[c]	0.0768
^{129}Sn	27/2$^-$	2552	217(19) ns	270(70) ns[d]	23/2$^-$	$E2$	145	0.428	0.735(64)	0.565
^{130}Sn	(10$^+$)	2435	1.501(17) μs	1.61(15) μs[a]	8$^+$	$E2$	95	1.91	0.427(5)	0.266
					7$^-$	$E3$	488	0.023	–	0.0320
	5$^-$	2085	63(4) ns	52(3) ns[a]	7$^-$	$E2$	136	0.537	1.16(7)	1.212

[a]From Ref. [4].
[b]From Ref. [22].
[c]From Ref. [23].
[d]From Ref. [5].

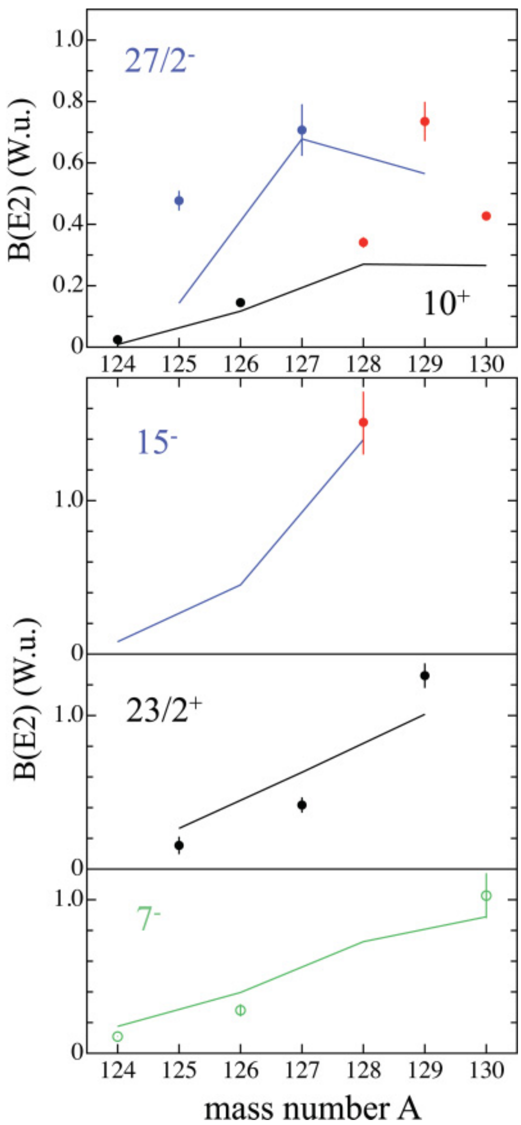

FIG. 5. (Color online) Experimental and shell model $I \rightarrow I-2$ $E2$ transition strengths in Weisskopf units for initial states with leading configurations $\nu h_{11/2}^{2,3}$; $I^{\pi} = 10^{+}$,27/2^{-} (upper panel) and $\nu h_{11/2}^{n} d_{3/2}$, $I^{\pi} = 7^{-}$ ($n = 1$), 23/2^{+} ($n = 2$), and 15^{-} ($n = 3$) (lower panels). The experimental values for the 10^{+} and 15^{-} states in ^{128}Sn, the 27/2^{-} level in ^{129}Sn, and the 10^{+} state in ^{130}Sn have been calculated from the new lifetimes determined in the present work (red symbols) while all other values are taken from Refs. [5,23].

level lying deep in the shell. This expectation is corroborated by the nonobservation of $E3$ branches from the 10^{+} and 15^{-} isomers.

The evolution of $E2$ strength between states of fixed configurations with decreasing occupation of the $\nu h_{11/2}$ orbital shown in Fig. 5 is well reproduced. Deviations in the slope toward midshell have been discussed in Ref. [5] and can be traced back to seniority mixing induced by proton ph excitations across $Z = 50$. The discrepancy for the $E2$ 27/2^{-} →23/2^{-} transition in ^{125}Sn is due to the fact that a second 23/2^{-} is predicted to lie 320 keV higher connected by a strong 2.8 W.u. $E2$ to the 27/2^{-}. This state has dominant seniority $v = 5$ in contrast to $v = 3$ for the yrast 23/2^{-} and 27/2^{-} states. Seniority mixing induced by proton ph excitation across $Z = 50$, which is beyond the present configuration space, will improve the agreement with experiment. The phenomenon was first observed in midshell $\pi g_{9/2}^{n}$ $N = 50$ isotones [17].

IV. CONCLUSIONS

In conclusion, a previously unobserved isomer with a half-live of $T_{1/2} = 220(30)$ ns has been identified in ^{128}Sn at an excitation energy of 4098 keV. It decays via two parallel γ-ray cascades to the well established (7^{-}) and (10^{+}) isomeric states. Based on shell-model calculations a spin value of (15^{-}) and the four-neutron-hole configuration $\nu h_{11/2}^{-3} d_{3/2}^{-1}$ have been tentatively assigned to the new isomer. Reduced transition probabilities for $E2$ and $E3$ transitions involved in the decay of a number of isomeric states in ^{128,129,130}Sn have been deduced from the measured half-lives and were compared to the results of shell-model calculations. A satisfactory agreement was found for both excitation energies as well as transition probabilities. The evolution of $E2$ transitions between selected states of fixed seniority is discussed.

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