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Microsecond isomers in ^{125,127,129}Sn

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Microsecond yrast isomers were observed in the ^{125,127,129}Sn isotopes. These nuclei are produced by thermal neutron induced fission of ^{233}U and ^{239}Pu. The detection is based on time correlation between fission fragments selected by the LOHENGRIN spectrometer at ILL (Grenoble) and the γ rays or conversion electrons from isomers. In this paper, the decay schemes of the new $19/2^+$ yrast isomers in ^{125,127,129}Sn are reported. The measured low-lying negative parity states are compared with the results of various calculations. This work suggests also the presence of high spin β isomers in ^{127,129}In.

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I. INTRODUCTION

The study of yrast excitations of the Sn isotopes between the two magic numbers $N=50$ and $N=82$ provides a valuable testing field for the development of the nuclear shell models. However, on the experimental side, the odd neutron rich Sn isotopes in the vicinity of ^{132}Sn are difficult to produce. Recently the neutron rich ^{119,121,123}Sn were produced in deep inelastic reaction [1]. In this work the decay of μs yrast isomers were observed and the intermediate spin region up to $I=27/2$ was explored. Above $A=123$ our knowledge comes exclusively from the β-decay data [2,3] where only the low spin region was explored.

On the theoretical side, if several calculations have been presented recently for the light Sn isotopes, for the heavy ones only a few microscopic calculations are available. In Ref. [4] Insolia *et al.* have studied the odd Sn isotopes in the mass range $A=117$–123, within the framework of a multistep shell-model BCS formalism. The two body interactions used in this calculation were extrapolated from the well known interaction obtained in the Pb region. More recently, Holt *et al.* [5] have computed the low-lying levels of the odd $^{121-129}$Sn isotopes. In this work the effective two body interaction was derived from a nucleon-nucleon potential. Unfortunately, only the low spin levels have been computed.

To gain more experimental information on the heavy odd mass Sn isotopes, we have looked for the expected μs isomers in the ^{125,127,129}Sn nuclei, with half-lives longer than 0.7 μs.

II. EXPERIMENTAL PROCEDURE

The nuclei of the $A=125$, 127, and 129 mass chains were produced by thermal neutron induced fission of ^{233}U and ^{239}Pu targets. The tables of independent yields of England and Rider [6] show that the Sn isotopes in the mass range $A=125$–129 are the most strongly produced elements in the fission of these two targets.

The LOHENGRIN spectrometer at ILL has been used to separate the fission fragments (FF) recoiling from thin targets of about 400 μg/cm^2, according to their A/q ratios. The FF are detected by a ΔE gas-detector of 13 cm length, and subsequently stopped in a Mylar window of 12 μm thickness. The γ rays decaying the isomeric states are detected by two large volume Ge detectors and the conversion electrons are detected by two cooled Si(Li) detectors covering a total area of 2×6 cm^2 and located at 7 mm behind the Mylar window. The electron detection efficiency is about 30%. The gas pressure of the ionization chamber was tuned to stop the FF at about 3 μm from the outer surface of the Mylar window to minimize electron absorption and to have a good energy resolution. This setup is designed to measure x rays and conversion electrons down to 10 and 15 keV, respectively. The ion transport time through the LOHENGRIN spectrometer is about 2.2 μs for the heavy FF, which limits the studies to half-lives longer than ~0.7 μs.

Events were stored on a disk each time a Si(Li) detector or a Ge detector fired within a time range of 40 μs after a FF had reached the focal plan of the spectrometer and was detected. In this case, the parameters recorded are the ΔE signal of the ionization chamber and the signals of the Ge and Si(Li) detectors with their time delays. So, the possible γ-γ, γ-electron, and electron-electron coincidences are detected and registered. The singles spectra of each detector are also recorded. This last information is used to subtract the random events from the spectra measured in delayed coincidences with the FF. The γ-singles spectra are also used to deduce the independent production yields of the isomers. They are obtained by comparison of the intensities of the γ rays deexciting the isomers with lines of the same mass

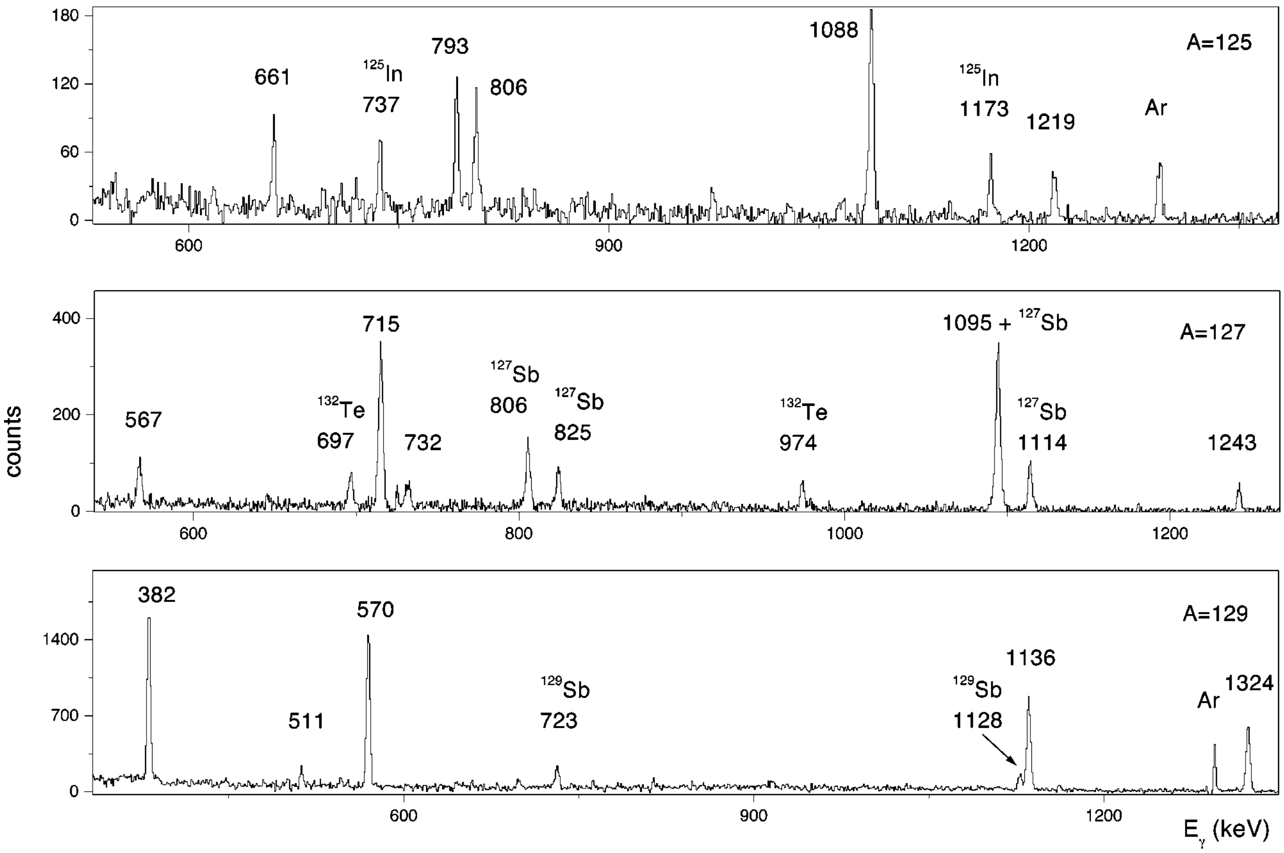

FIG. 1. γ-decay spectra of the μs isomers observed in the $A=125$–129 mass chains. Only the most interesting part of each spectrum is shown to have more readable plots. The Ar line is a high intensity background γ-ray produced by ^{40}Ar(n,γ) reaction. In $A=127$, a weak contamination of ^{132}Te is due to their close A/q values.

chain measured in singles spectra, and of known cumulative yields of Ref. [6].

III. EXPERIMENTAL RESULTS

The level schemes of ^{125,127,129}Sn were already studied through the β decay of the ground states and isomers of ^{125,127,129}In [2,3] and the low spin region up to $I=11/2$ was explored in this work. Moreover, four delayed γ rays of 382.5, 570.2, 1136.0, and 1323.7 keV fed by a β-decay half life $T_{1/2}=0.69$ s, and two delayed γ rays of 715.4 and 1094.7 keV fed by a β-decay half life $T_{1/2}=1.2$ s, were observed in ^{129}Sn and ^{127}Sn, respectively. The authors suggested that they deexcite two unknown isomeric states of 3 and 3.1(9) μs in ^{129}Sn and ^{127}Sn respectively, but they did not place them in the level schemes.

In our measurements several μs isomers have been observed in the $A=125$–129 mass chains. Their γ-spectra and decay curves are shown in Figs. 1 and 2, respectively.

A. $A=129$

Two isomers have been observed in the $A=129$ mass chain. The weak γ lines of 723 and 1128 keV deexcite an isomeric level of 2.2 μs half-life, already assigned to ^{129}Sb [7]. The four other lines of much stronger intensities have a half life of $3.7(2)$ μs and their energies and intensities are reported in Table I. Most probably they are the same as those already observed by De Geer and Holm [2].

The Si(Li) spectrum in coincidence with the 382.2 and 570.1 keV γ rays is shown in Fig. 3. The two lines of 25.0(5) and 36(1) keV are interpreted as the Sn K_α x rays and an L-conversion line of a 40 keV transition, respectively. The experimental ratio of the K-x–ray intensity over L-electron intensity $R=0.7(2)$ is compatible only with an $E2$ multipolarity. In conclusion, the 3.7 μs isomer belongs to the ^{129}Sn isotope and decays by a low energy transition of $E2$ multipolarity.

B. $A=127$

In this mass chain the situation is analogous to the previous one. Two isomers have been observed. The four lines of 806, 825, 1095, and 1114 keV deexcite an isomeric level of 11 μs already assigned to ^{127}Sb [8]. The five other lines, reported in Table I, have a half life of $4.5(3)$ μs. The two strongest lines of 715.3 and 1094.7 keV have already been observed by De Geer and Holm, with a half-life consistent with our measurement. However, the examination of the γ-ray table reported by these authors shows that the three remaining weaker lines are also present but without any indication of time delay. In our work, no electrons were measured in coincidence with the lines deexciting the 4.5 μs isomer.

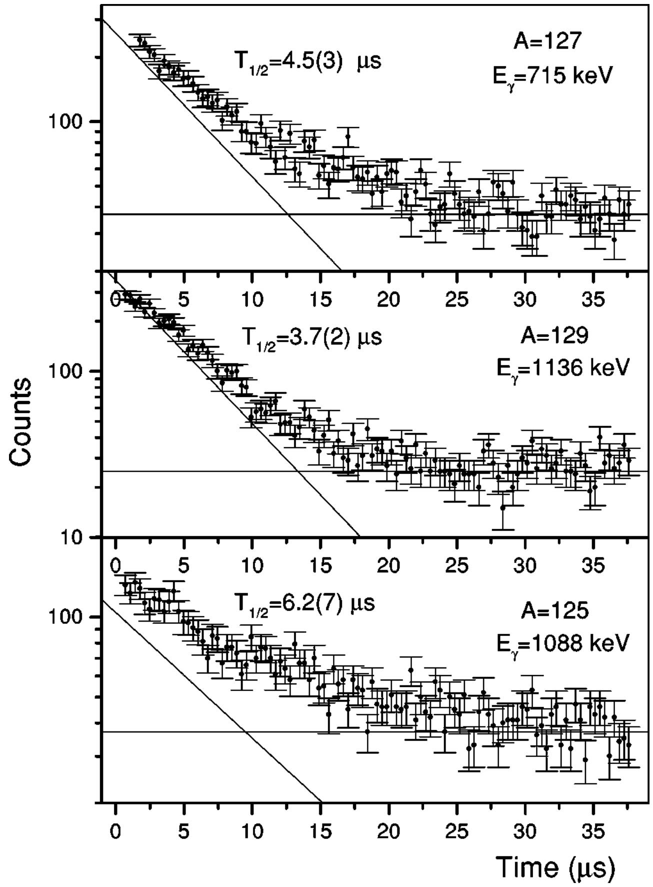

FIG. 2. Half-life spectra of the $A=125$–129 mass chains.

One can then conclude that the 4.5 μs level fed by the β decay of In in the previous experiment and directly fed by the fission of ^{233}U and ^{239}Pu in the present work, is an isomeric level of ^{127}Sn or ^{127}Sb, the only FF produced with significant fission yields. However, the absence of common γ rays between the well established 11 μs isomer in ^{127}Sb and the decay of the 4.5 μs isomer suggests strongly that the latter belongs to the ^{127}Sn isotope.

C. $A=125$

Two μs isomers are also produced in the $A=125$ mass chain. The two lines of 737 and 1173 keV deexcite an isomeric state of 9.4(6) μs very recently found in ^{125}In [9]. The five other lines observed in Fig. 1 and reported in Table I have a half-life of 6.2(7) μs. This isomer is expected to be in ^{125}In or ^{125}Sn, which have sufficient production yields. Again, the absence of common γ rays between the well established 9.4 μs isomer in ^{125}In and the decay of the 6.2 μs isomer suggests strongly that the latter belongs to the ^{125}Sn isotope. No conversion electron were observed in coincidence with the γ lines deexciting this isomer.

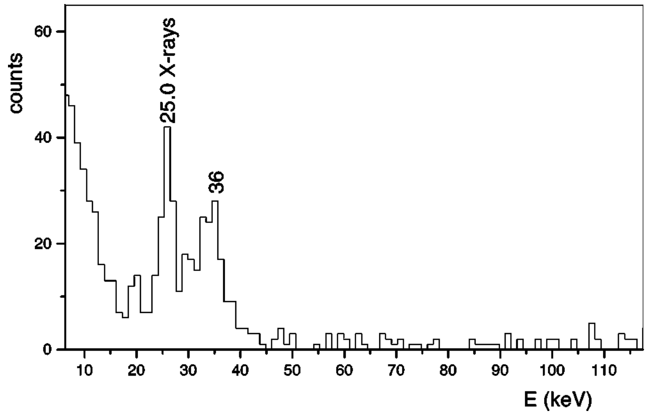

FIG. 3. Si(Li) spectrum gated by the sum of the 382 and 570 keV γ rays assigned to ^{129m}Sn.

D. Isomer fission yields

The independent fission yields of the three isomers observed in this work have been measured for the ^{239}Pu target. The values found are 2×10^{-5}, 1.5×10^{-4}, and 9×10^{-4}, per fission for masses 125, 127, and 129 respectively. The incertainties ($\sim30\%$) on these values are mainly due to the incertainties on the cumulative yields used as reference values in the calculation. Assuming that these three isomers are in the Sn isotopes we have also computed the ratio between the independent yield of the isomer found and the first $3/2^+$ level, which is the ground state in ^{129}Sn and an isomeric level in ^{125}Sn and ^{127}Sn. The independent and cumulative fission yields used in this calculation are extracted from Ref. [6]. The values found 9%, 12%, and 13% for masses 125, 127, and 129 are almost constant; this fact justifies a posteriori that the isomeric levels are in Sn. This result suggests also that most probably these three isomers are of the same nature.

IV. LEVEL SCHEMES AND DISCUSSION

The decay schemes of the three isomers found in ^{125,127,129}Sn are shown in Fig. 5 along with the previously

TABLE I. Half-lives and γ-ray transitions observed in the decay of Sn isomers. $\Delta E_\gamma \sim 0.2$ keV, $\Delta I_\gamma \sim 4\%$, 10% and 15% for ^{129}Sn, ^{127}Sn, and ^{125}Sn, respectively.

Nucleus	$T_{1/2}$ (μs)	E_γ(keV) (I_γ)
^{129}Sn	3.7(2)	382.2 (46), 570.1 (56), 1136.0 (56), 1323.8 (44)
^{127}Sn	4.5(3)	566.8 (15), 715.3 (75), 732.3 (15), 1094.7 (87), 1242.6 (13)
^{125}Sn	6.2(7)	661.0 (20), 792.8 (40), 805.5 (40), 1087.5 (81), 1218.7 (19)

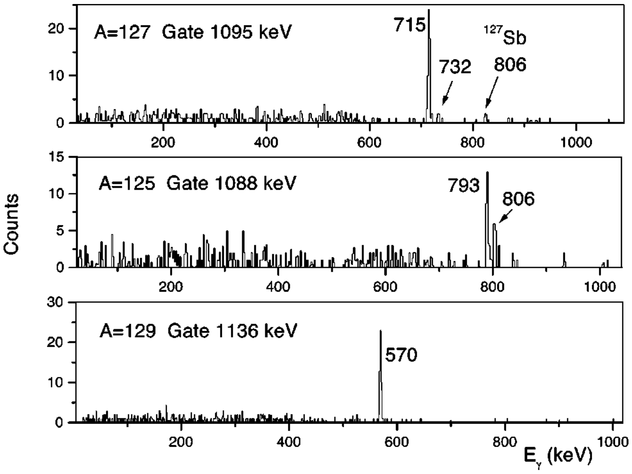

FIG. 4. Examples of γ-γ coincidence spectra.

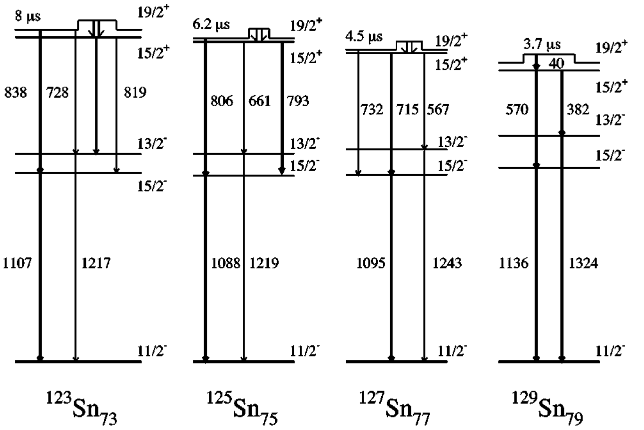

FIG. 5. Decay schemes of the 19/2$^+$ isomers in the heavy odd Sn isotopes.

known ^{123}Sn [1]. They are based on the coincidence relationships shown in Fig. 4.

In all these nuclei, the isomeric state decays mainly by a very low energy transition. In ^{129}Sn we have found that the isomer decays by a low energy transition of 40 keV with an $E2$ multipolarity. The $B(E2)=32(2)e^2\,\text{fm}^4$ value and the hindrance factor $F_W=1.2$ W.u. suggest that the isomeric transition takes place between two levels having a large $E2$ overlap of their respective wave functions. In the three lighter isotopes the transitions are too low in energy to observe their conversion electrons and the energies are deduced from the cross-over transitions which feed directly the first excited level. Assuming that these low energy transitions are also $E2$ in nature, their $B(E2)$ values are reported in Table II. The hindrance factors vary between 1 and 4 from ^{127}Sn to ^{123}Sn, and are roughly comparable with the one for ^{129}Sn.

The spin and parity assignments proposed in Fig. 5 are based on the energy systematic arguments deduced from comparison with the known lighter Sn isotopes and theory considerations.

The decay patterns of the ^{125,127,129}Sn isomers are very similar to the one of the previously known ^{123}Sn. By analogy, a spin and parity $I^\pi=19/2^+$ is assigned for the three new isomers found in this work. Figure 6 shows that the excitation energy of this state for a long set of odd Sn isotopes is remarkably parallel to that of the 5^- two neutron state in the even Sn isotopes. This feature strongly suggests that the $h_{11/2}\otimes 5^-$ configuration is the main component of the isomeric levels in the $^{119-129}$Sn isotopes. The 5^- is not a pure shell model state, but contains an admixture of $(d_{3/2}h_{11/2})$ and $(s_{1/2}h_{11/2})$ configurations.

The very low energy isomeric transition in $^{123-129}$Sn has been assigned as the $19/2^+\rightarrow 15/2^+$ transition taking place between two members of the same mutiplet. The rapid decrease in the $B(E2)$ values between ^{127}Sn and ^{123}Sn can be explained by the $h_{11/2}$ subshell occupation. One expects to have a minimum of the $E2$ amplitude for ^{123}Sn corresponding to the half-filling of this orbital [1]. However, the effect is less important than for the pure $(h_{11/2})^n$ state with seniority $\nu=2$ or 3, because the $d_{3/2}$ and $s_{1/2}$ orbitals play also some role in the $E2$ matrix elements. We have to notice that the 15/2$^+$ assignment proposed in this work does not agree with the previous 17/2$^-$ value proposed in Ref. [1] for ^{123}Sn, without any justification.

The lower energy levels 11/2$^-$, 13/2$^-$ and 15/2$^-$ found in $^{125-129}$Sn are expected to be rather pure members of the $\nu h_{11/2}^{-n}$ multiplet with seniority $\nu=1$ and $\nu=3$ by analogy with the lighter Sn isotopes. The isomeric levels in $^{123-127}$Sn decay partially to the 15/2$^-$ state by a strongly hindered $M2$ transition as reported in Table III. In fact, an $M2$ transition cannot take place between the $h_{11/2}^{-2}d_{3/2}^{-1}$ or $h_{11/2}^{-2}s_{1/2}^{-1}$ configuration and the $h_{11/2}^{-3}$ configuration and therefore an admixture

TABLE II. $B(E2)$ reduced probabilities and hindrance factors of transitions deexciting the isomeric states of $^{123-129}$Sn. The $19/2^+\rightarrow 15/2^+$ isomeric transition was observed only in the ^{129}Sn decay. The data on ^{123}Sn are from Ref. [1].

Transition	Multipolarity	A	$B(E2)$ (e^2 fm^4)	F_W (W.u.)
$19/2^+\rightarrow 15/2^+$	$E2$	129	32 (2)	1.2 (1)
	$E2$	127	34(4)	1.1 (1)
	$E2$	125	18(3)	2.1 (4)
	$E2$	123	~9	~4
$19/2^+\rightarrow 15/2^-$	$M2$	127		5500 (600)
	$M2$	125		4100 (800)
	$M2$	123		~4700

TABLE III. Comparison of the low-lying negative parity states of $^{123-129}$Sn with the calculation of Ref. [5]. The energies in keV are determined relative to 0 keV for the low-lying $11/2^-$ states.

	^{129}Sn		^{127}Sn		^{125}Sn		^{123}Sn	
I^π	Expt.	Calc.	Expt.	Calc.	Expt.	Calc.	Expt.	Calc.
$11/2^-$	0	0	0	0	0	0	0	0
$7/2^-$	1043	920	964	910	937	920	931	910
$9/2^-$	764	1190	646	840	618	710	619	670
$13/2^-$	1324		1243	1440	1219	1330	1217	
$15/2^-$	1136	1150	1094	1090	1088	1070	1107	1050

of $h_{11/2}^{-2}g_{7/2}^{-1}$ is essential. However, this admixture is expected to be very weak, which explains the large hindrance factors measured.

The low-lying negative parity states of ^{129}Sn were computed, assuming they have a pure $h_{11/2}^{-3}$ configuration. Some levels of the multiplet are reported in Fig. 7 and compared with the experiment. In this calculation, the relative residual interactions of the two neutron holes $\nu h_{11/2}^{-2}$ states 0^+, 2^+, 4^+, 6^+, 8^+, and 10^+ are the experimental ^{130}Sn energies [10]. The calculated level energies are normalized to the 11/2 state with seniority $\nu=1$. This simple calculation gives a good agreement with the experiment for the $7/2^-$, $13/2^-$, and $15/2^-$ states, thus providing support for the interpretation of ^{129}Sn. The agreement is however less good for the $9/2^-$, with a deviation of 167 keV to be compared with a mean value of 42 keV for the three other states.

This theory predicts also that the $27/2^-$ state of maximum angular momentum will be another yrast trap with a half-life of about 0.2 μs, decaying by an isomeric transition of about 135 keV energy and $E2$ multipolarity. It is a challenge for the future to look for it in the three $^{125-129}$Sn isotopes.

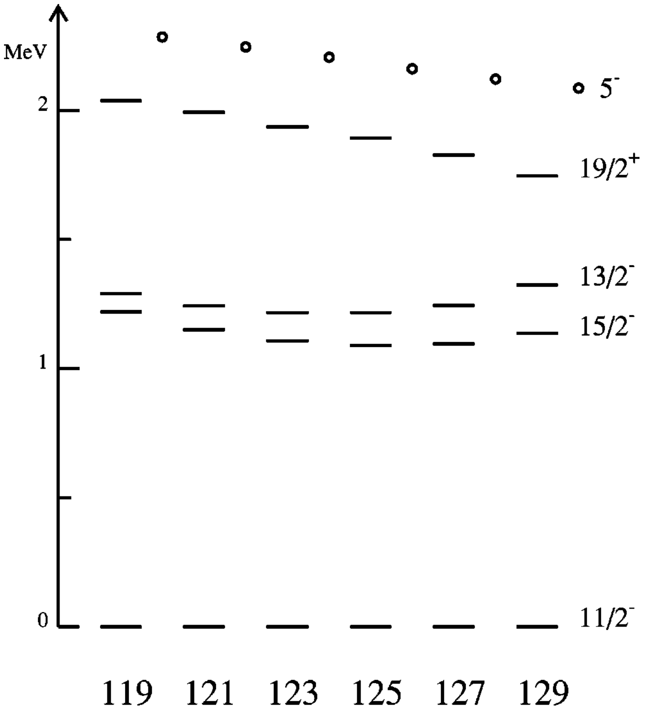

FIG. 6. Energy systematics of the $11/2^-$, $13/2^-$, $15/2^-$, and $19/2^+$ levels in $^{119-129}$Sn. The energies are expressed relative to 0 keV for the low-lying $11/2^-$ states. The open circles correspond to the 5^- two neutron states in even Sn nuclei.

The negative parity states of the lighter Sn isotopes are expected to have a more complex structure than those of ^{129}Sn. In Table III we have compared the known experimental $7/2^-$, $9/2^-$, $13/2^-$, and $15/2^-$ states of $^{123-129}$Sn with the results of the more sophisticated calculations of Ref. [5]. If the $15/2^-$ is very well reproduced for these four heavy Sn isotopes, with a mean deviation of 20 keV, the agreement is worse for the other states. The main discrepancy concerns the $9/2^-$ state, with a deviation between theory and experiment of 425 keV. It is interesting to notice that our much more simple calculation assuming a pure $h_{11/2}^{-3}$ configuration gives much better results for the negative states of ^{129}Sn and that the difference between the two theories is as large as 530 keV for the $9/2^-$ state. We have no simple explanation for this effect.

V. ISOMERISM IN INDIUM ISOTOPES

We have shown in this paper that the 3.7 and 4.5 μs isomers of ^{129}Sn and ^{127}Sn, respectively, are also fed by the β decay of the In isotopes. However, the ground state of ^{129}In and ^{127}In has a spin and parity $I^\pi=9/2^+$ which cannot feed directly or indirectly the $19/2^+$ state found in this work. Consequently these μs isomers are very likely fed from new high spin isomers of ^{129}In and ^{127}In. Two high spin and high energy isomers $29/2^-$ and $23/2^-$ were reported very recently for ^{129}In in Ref. [9]; they could feed the observed μs isomer.

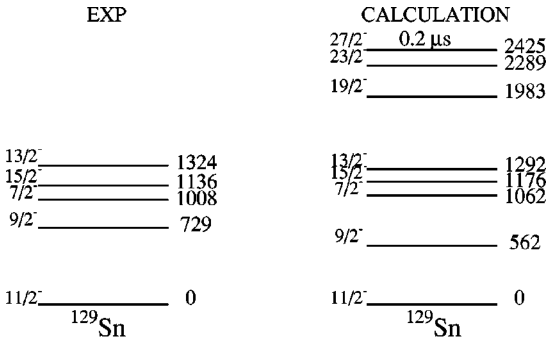

FIG. 7. The experimental and calculated negative parity levels in ^{129}Sn.

It would then be very interesting to look for possible high spin and perhaps high energy β isomers in the heavy In isotopes.

VI. CONCLUSION

In this paper we have identified and studied the decay schemes of three new $19/2^+$ isomers observed in $^{125-129}$Sn. These new data substantially extend our experimental knowledge of the heavy odd Sn isotopes for which the $11/2^-$ were the highest spin states known until now. Comparison with theory of the low-lying negative parity states shows some unexpected discrepancies for Sn isotopes close to the doubly magic ^{132}Sn. This paper stresses the lack of extensive theoretical calculations, including yrast excitations, for the heavy odd Sn isotopes. It is shown also that higher spin yrast traps are expected in these nuclei which could be fed in the fission process.

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[1] R. H. Mayer *et al.*, Phys. Lett. B **336**, 308 (1994).
[2] L. E. De Geer and G. B. Holm, Phys. Rev. C **22**, 2163 (1980).
[3] B. Fogelberg, L.-E De Geer, K. Fransson, and M. af Ugglas, Z. Phys. A **276**, 381 (1976).
[4] A. Insolia, N. Sandulescu, J. Blomqvist, and R.J. Liotta, Nucl. Phys. **A550**, 34 (1992).
[5] A. Holt, T. Engeland, M. Hjorth-Jensen, and E. Osnes, Nucl. Phys. **A634**, 41 (1998).
[6] T. R. England and B. F. Rider, ''Thermal Neutron Induced Fission Data,'' LALN Report No. LA-UR-94-3106, ENDF-349 (1994).
[7] C. A. Stone and W. B. Walters, Z. Phys. A **328**, 257 (1987).
[8] K. E. Apt and W. B. Walters, Phys. Rev. C **9**, 310 (1974).
[9] B. Fogelberg, H. Mach, H. Gausemel, J.P. Omtvedt, and K.A. Mezilev, in *International Workshop Nuclear Fission and Fission Product Spectroscopy*, 2nd, Seyssins, France, edited by G. Fioni, H. Faust, and F.-J. Hambsch, AIP Conf. Proc. 447 (AIP, New York, 1998), p. 191.
[10] *Table of Isotopes*, 8th ed., edited by R.B. Firestone and V.S. Shirley (Wiley, New York, 1998).