High-spin microsecond isomers in ^{129}In and ^{129}Sb

J. Genevey and J. A. Pinston
Institut des Sciences Nucléaires IN2P3-CNRS/Université Joseph Fourier, F-38026 Grenoble Cedex, France

H. R. Faust, R. Orlandi,* A. Scherillo,† G. S. Simpson, and I. S. Tsekhanovich
Institut Laue-Langevin, F-38042 Grenoble Cedex, France

A. Covello and A. Gargano
Dipartimento di Scienze Fisiche, Università di Napoli Federico II,
and Istituto Nazionale di Fisica Nucleare, Complesso Universitario di Monte S. Angelo, Via Cintia, I-80126 Napoli, Italy

W. Urban
Institute of Experimental Physics, Warsaw University, ul Hoża 69, 00-681 Warszawa, Poland
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In this work the microsecond isomers in ^{129}In and ^{129}Sb were investigated. These nuclei were produced by the thermal-neutron-induced fission of ^{241}Pu. The detection is based on a time correlation between the fission fragments selected by the LOHENGRIN spectrometer at the ILL (Grenoble) and the γ rays or conversion electrons from the isomers. The decay schemes of the new $17/2^-$ isomer in ^{129}In and $23/2^+$ isomer in ^{129}Sb are reported. A shell-model study of these two nuclei was performed using a realistic effective interaction derived from the CD–Bonn nucleon-nucleon potential. Comparison shows that the calculated energy levels and electromagnetic transition rates are in very good agreement with the experimental data.

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I. INTRODUCTION

The study of nuclei in the close vicinity to doubly magic ^{132}Sn is currently drawing much attention. This is related to the fact that these nuclei provide the opportunity for testing the predictive power of the shell model well away from the valley of stability.

In this paper, we have studied the yrast structure of the two isobars ^{129}In and ^{129}Sb. In both of them the neutron holes occupy the levels of the 50-82 shell, but while in ^{129}Sb the valence proton is also in this shell, in ^{129}In there is a proton hole in the lower 28-50 shell. The yrast states in these nuclei are expected to have a simple structure and are therefore well suited to test the matrix elements of the effective interaction, in particular the proton-neutron ones in the hole-hole and particle-hole channels.

Nuclear-structure information on the heavy In isotopes is very scarce. For nuclei above ^{129}In, only the ground states and the long-lived isomers, decaying by β emission, are known. For ^{129}In, apart from the known $9/2^+$ ground state and an excited $1/2^-$ state at 380 keV [1], the most important information was the possible evidence, by Fogelberg *et al.* [2], of the high-spin yrast traps $23/2^-$ and $29/2^+$ belonging to the aligned configurations $\pi g_{9/2}^{-1}\nu(d_{3/2}^{-1}h_{11/2}^{-1})$ and $\pi g_{9/2}^{-1}\nu(h_{11/2})^{-2}$, respectively.

Much more information is available for ^{129}Sb. Stone and co-workers [3,4] reported on an extensive level scheme up to about 2 MeV. The spins and parities of the levels were firmly established up to spin $I^\pi = 11/2^+$, and a long-lived isomer $I^\pi = 19/2^-$ was found from β-decay experiments. Our aim in this study is to extend the knowledge of this nucleus to higher spins, and to compare its structure with that of the previously known microsecond isomers of ^{131}Sb [5].

Motivated by the new data made available by the present experiment, we have performed a shell-model study of ^{129}In and ^{129}Sb, assuming ^{132}Sn as a closed core. In our calculations we have employed a realistic effective interaction derived from the CD-Bonn free nucleon-nucleon potential [6]. Similar calculations have been recently carried out [7] for other nuclei with proton particles and neutron holes around ^{132}Sn.

The paper is organized as follows. In Sec. II we describe the experimental method, while in Sec. III we report on the results of our measurements. In Sec. IV we present the results of our shell-model calculations and compare them with the experimental data. Section V contains a summary of our conclusions.

II. EXPERIMENTAL PROCEDURE

The details of the experimental setup are given in Refs. [5,8]. The nuclei of $A = 129$ mass chain were produced by thermal-neutron-induced fission of ^{241}Pu. The LOHENGRIN spectrometer at the ILL has been used to separate the fission fragments recoiling from thin targets of about 400 μg/cm^2 thickness and 1.3 mg total weight according to their A/q ratios. The fission fragments are detected by a ΔE gas detector and subsequently stopped in a Mylar foil of 12 μm thickness. The γ rays deexciting the isomeric states are detected by two large-volume Ge detectors and the conversion electrons are detected by two cooled adjacent Si(Li) detectors covering a total area of 2×6 cm^2, located 7 mm behind the

*Permanent address: Schuster Laboratory, University of Manchester, Manchester M13 9PL, UK.

†Permanent address: Institut für Kernphysick, Universität zu Köln, D-50937 Köln, DE.

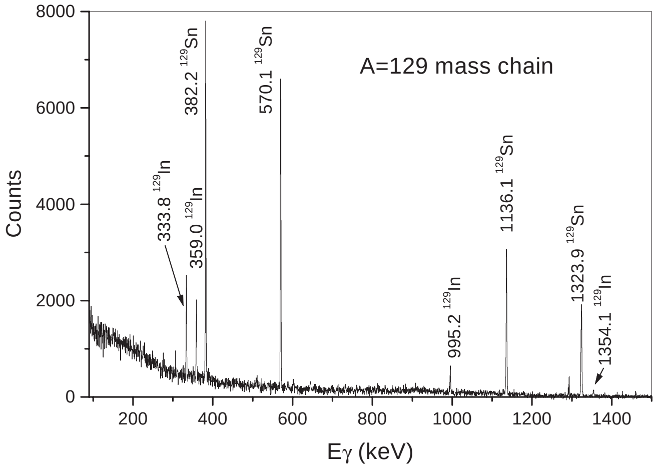

FIG. 1. γ-decay spectrum of the microsecond isomers observed in the $A=129$ mass chain in delayed coincidence with the fission products. The energy error for the lines is 0.2 keV.

Mylar window. The electron detection efficiency is very high, about 30%, and the setup allows one to detect electrons down to a very low energy (~ 15 keV).

III. EXPERIMENTAL RESULTS

A. ^{129}In

In a previous work devoted to new microsecond isomers in ^{129}Sn and ^{130}Sb [9], we also reported on four γ rays belonging to a new isomer in ^{129}In. However, the poor statistics of this measurement were not sufficient to get a precise half-life of the isomer and to build a reliable level scheme. Consequently, a new measurement was performed with better statistics. The new γ-decay spectrum of the $A=129$ mass chain in delayed coincidence with the fission fragments is shown in Fig. 1. The time spectrum of the 333.8-keV γ ray is reported in Fig. 2, and a mean half-life value of 8.5(5) μs was measured for the four lines deexciting the isomer.

The Si(Li) spectrum in coincidence with the 359.0-, 995.2-, and 1354.1-keV γ rays is shown in Fig. 3. The observed lines are interpreted as the In K_α − x rays and the K and L conversion electrons of the 333.8-keV transition also observed in the γ spectrum. The measured value of the conversion coefficient $\alpha_K = 0.08(2)$ is compatible either with an $M2$ ($\alpha_K = 0.071$) or an $E3$ ($\alpha_K = 0.063$) transition. The measured half-life of the isomeric transition allows one to compute the reduced transition probability rates for pure multipolarity $B(M2) = 0.032(2)$ W.u. and $B(E3) = 279(16)$ W.u., respectively. As accelerated $M2$ or $E3$ transitions are not expected, one may conclude that the isomeric transition is predominantly $M2$ in nature.

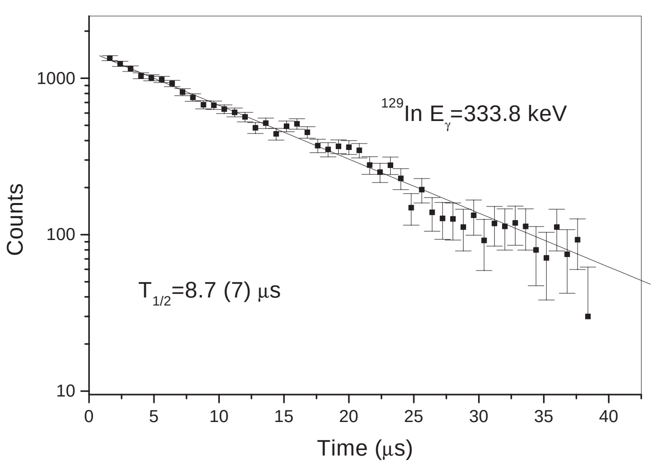

FIG. 2. Half-life spectrum of the 333.8-keV γ ray of the ^{129}In isomer.

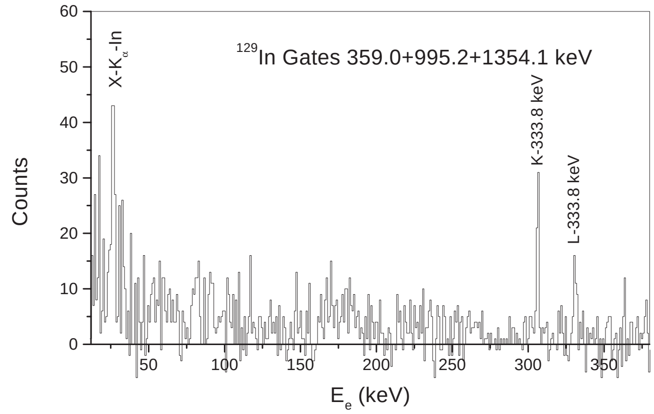

FIG. 3. Si(Li) spectrum of ^{129}In gated by the sum of the 359.0-, 995.2-, and 1354.1-keV γ rays.

The ^{129}In level scheme is shown in Fig. 4. The conversion-electron measurements allow us to fix unambiguously a spin and parity value $I^\pi = 17/2^-$ for this new isomer.

B. ^{129}Sb

Thanks to the high statistics for the $A=129$ mass chain, another weakly produced isomer was also observed. It de-

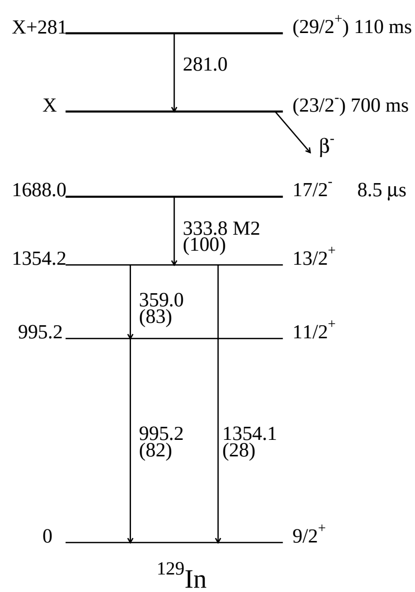

FIG. 4. Decay scheme of the ^{129}In isomer. The relative intensities of the γ rays are reported in parentheses. Two long-lived millisecond isomers, previously found by Fogelberg *et al.* [2], have been added to the figure. The excitation energy of the lowest energy state, which decays by β emission, is unknown.

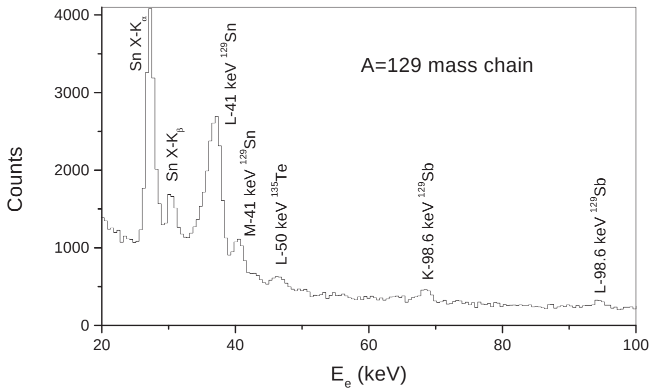

FIG. 5. Si(Li) spectrum of the microsecond isomers observed in the $A=129$ mass chain in delayed coincidence with the fission products. The contamination of ^{135}Te is due to a small admixture of $A=129$ and 135 masses having close A/q ratios.

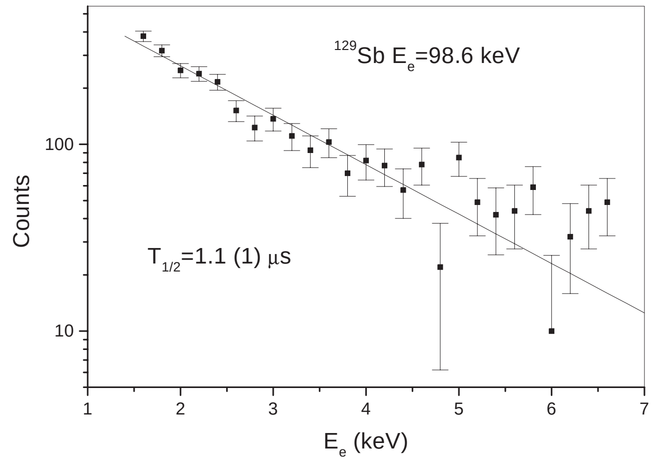

FIG. 7. Half-life spectrum of the electrons of the 98.6-keV transition in ^{129}Sb.

cays by two weak γ rays of 98.6(2) and 189.5(2) keV. Moreover, the K- and L-shell conversion electrons of the 98.6-keV transition were also observed in the Si(Li) spectrum shown in Fig. 5. These two transitions are in coincidence, as shown in Fig. 6, and their half-life reported in Fig. 7 is 1.1(1) μs. The electron energy difference $E_K - E_L$ for the 98.6-keV transition, and the γ and electron energy difference $E_\gamma - E_K$ allows us to assign this new isomer to the Sb element. The experimental conversion coefficient value $\alpha_K = 1.1(2)$ for the 98.6-keV line is compatible only with an $E2$ multipolarity, and the reduced transition probability is $B(E2) = 0.51(9)$ W.u.

This new isomer very likely feeds the $19/2^-$ state at 1851.0 keV excitation energy and of 17.7 min half-life, and is the analog of the one already found in ^{131}Sb [5]. This hypothesis is supported by the fact that the isomeric-transition energies are very close (98.6 and 96.4 keV in ^{129}Sb and ^{131}Sb, respectively), and the excitation energies of the $23/2^+$ isomeric states are also very close (2139 and 2166 keV ^{129}Sb and ^{131}Sb, respectively).

The ^{129}Sb level scheme is shown in Fig. 8 and compared to the previously known level scheme of the ^{131}Sb isomer [5] . We have also added in the level scheme another previously known microsecond isomer of 1860.9 keV energy; its energy was reported in the work of Stone and Walters [4], and we have measured its half-life in a previous work [10]. The main difference between the two Sb isotopes concerns the relative positions of the $15/2^-$ and $19/2^-$ states, which are reversed in these two nuclei. The consequences of this feature are dramatic for the $19/2^-$ state that has a very different half-life in these two nuclei.

IV. COMPARISON WITH THEORY

As mentioned in the Introduction, we have performed a shell-model study of ^{129}In and ^{129}Sb employing a realistic effective interaction derived from the CD-Bonn nucleon-nucleon potential [6]. We consider the doubly magic ^{132}Sn as a closed core and let the valence neutron holes in both nuclei occupy the five levels of the 50-82 shell. The same model space is taken for the valence proton in ^{129}Sb, while the

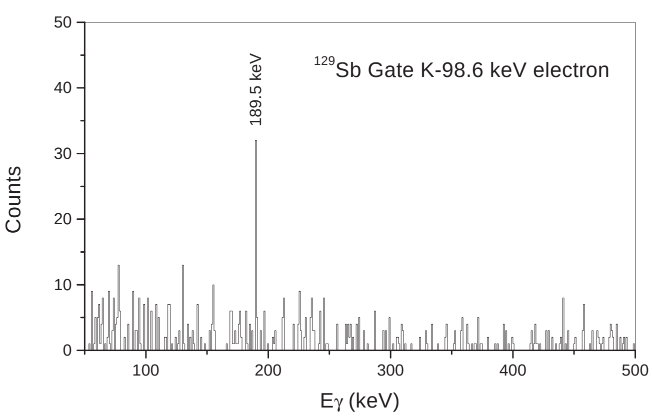

FIG. 6. γ-ray spectrum in coincidence with the K electrons of the 98.6-keV transition of ^{129}Sb.

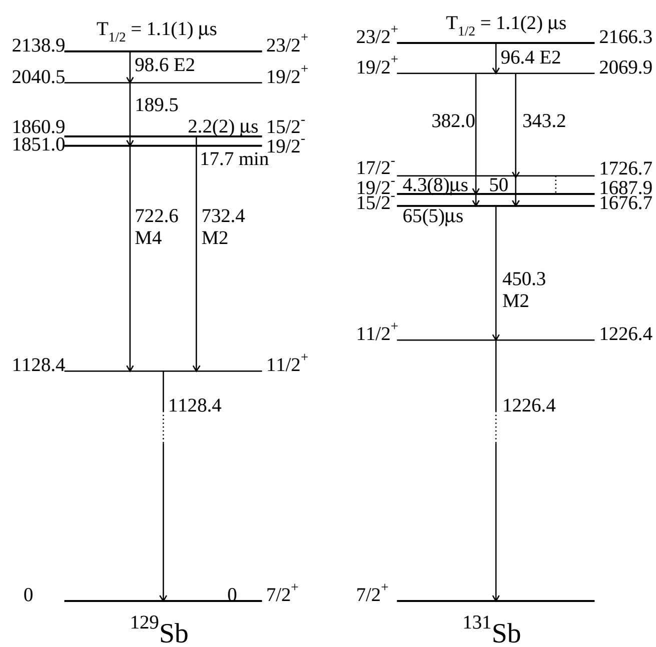

FIG. 8. Decay schemes of the isomers in ^{129}Sb and ^{131}Sb.

TABLE I. Single-particle and single-hole energies ϵ (MeV) adopted in our calculations.

Neutron-hole level	ϵ	Proton-particle level	ϵ	Proton-hole level	ϵ
$1d_{3/2}$	0.000	$0g_{7/2}$	0.000	$0g_{9/2}$	0.000
$0h_{11/2}$	0.100	$1d_{5/2}$	0.962	$1p_{1/2}$	0.365
$2s_{1/2}$	0.332	$1d_{3/2}$	2.439	$1p_{3/2}$	1.650
$1d_{5/2}$	1.655	$0h_{11/2}$	2.793	$0f_{5/2}$	2.750
$0g_{7/2}$	2.434	$2s_{1/2}$	2.800		

proton hole in ^{129}In is assumed to occupy the four levels of the 28-50 shell. Our choice of the proton single-particle and neutron single-hole energies is discussed in Ref. [7], where a similar study of the heavier Sb isotopes (^{130,131,132}Sb), was carried out. As regards the proton single-hole energies, they have been taken from the experimental spectrum of ^{131}In [11]. The adopted values are reported in Table I.

A description of our derivation of the effective interaction including references can be found in Ref. [7]. Here we only mention that the effective interaction in the neutron-neutron channel has been calculated in the hole-hole formalism, while the proton-neutron matrix elements have been derived in the particle-hole and hole-hole representation for ^{129}Sb and ^{129}In, respectively.

We now present the results of our calculations. They have been obtained by using the OXBASH shell-model code [12].

In Fig. 9 we compare the calculated levels in ^{129}In and ^{129}Sb with the experimental ones which have already been reported in Figs. 4 and 8. Some selected levels of ^{131}Sb, namely, those corresponding to the experimental ones of Fig. 8, are also shown. A more complete spectrum is reported in Ref. [7]. The significant similarity between the spectra of these three nuclei makes a comparison of their level structure quite interesting.

The $7/2^+$ and $11/2^+$ states in ^{131}Sb result essentially from the coupling of the valence proton in the $g_{7/2}$ level to the ground and first 2^+ state of ^{130}Sn, respectively. The next two groups of states are dominated by a single configuration, being members of the $\pi g_{7/2}\nu(d_{3/2}^{-1}h_{11/2}^{-1})$ and $\pi g_{7/2}\nu(h_{11/2})^{-2}$ multiplets.

In ^{129}In, the role of the valence proton in the $g_{7/2}$ level is played by the proton hole in the $g_{9/2}$ level, while the structure of the two neutron holes is preserved. In this case, the $11/2^+$ state corresponds to the stretched-minus-one coupling of the proton hole to the 2^+ state of ^{130}Sn while the stretched coupling gives rise to the $13/2^+$ state. The $17/2^-$ state is a member of the $\pi g_{9/2}\nu(d_{3/2}^{-1}h_{11/2}^{-1})$ multiplet. All other members turn out to be higher in energy, with the maximum-spin $J^\pi=23/2^-$ state lying only few tens of keV above the $17/2^-$ one. Aside from the $11/2^+$ state, we find three other states in the energy interval between the $13/2^+$ and $17/2^-$ states. They all have $J\leqslant 9/2$, which is consistent with the isomeric nature of the $17/2^-$ state. The $29/2^+$ state, which we predict at 389 keV above the $23/2^-$ level, is the maximum-spin member of $\pi g_{9/2}\nu(h_{11/2})^{-2}$ configuration.

The states of ^{129}Sb have essentially the same structure as that of the corresponding states in ^{131}Sb, the additional two neutron holes giving rise to a zero-coupled pair (the $17/2^-$ state, which has not been observed, is predicted to lie at 1.86 MeV). It should be noted, however, that configurations other

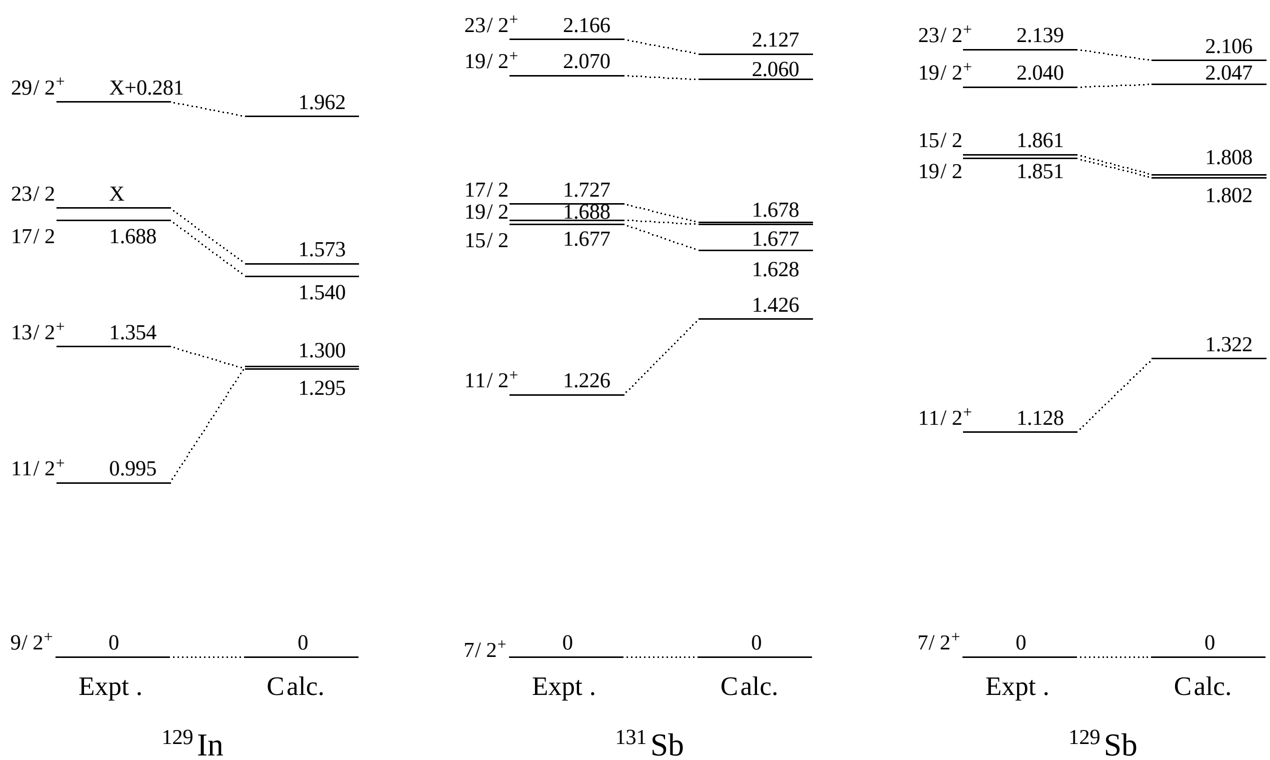

FIG. 9. Experimental and calculated energy levels (MeV) in ^{129}In, ^{131}Sb, and ^{129}Sb.

TABLE II. Calculated and experimental reduced transition probabilities (W.u.) and half-lives in ^{131}Sb, ^{129}In, ^{129}Sb.

Nucleus	Transition	$J_i^\pi \rightarrow J_f^\pi$	Reduced transition probability		$T_{1/2}$	
			Calc.	Expt.	Calc.	Expt.
^{131}Sb	$E2$	$23/2^+ \rightarrow 19/2^+$	0.60	0.53(10)	1.2 μs	1.1(2) μs
	$E2$	$19/2^+ \rightarrow 15/2^+$	1.02		0.6 μs	
	$E2$	$19/2^- \rightarrow 15/2^-$	1.24	0.99(18)	4.4 μs	4.3(8) μs
	$M2$	$15/2^- \rightarrow 11/2^+$	0.33×10^{-2}	$0.66\times 10^{-3}(11)$	18.7 μs	65(5) μs
^{129}In	$E3$	$29/2^+ \rightarrow 23/2^-$	0.52×10^{-1}	$0.66\times 10^{-1}(10)$	170 ms	110(15) ms
	$M2$	$17/2^- \rightarrow 13/2^+$	0.45×10^{-1}	$0.32\times 10^{-1}(2)$	6.0 μs	8.5(5) μs
^{129}Sb	$E2$	$23/2^+ \rightarrow 19/2^+$	0.97	0.51(9)	0.7 μs	1.1(1) μs
	$E2$	$19/2^+ \rightarrow 15/2^+$	1.07		0.2 μs	
	$M2$	$15/2^- \rightarrow 11/2^+$	0.25×10^{-2}	$0.26\times 10^{-2}(3)$	2.2 μs	2.2(2) μs

than the dominant one play a significant role, their percentage ranging from 20% to 48%. In particular, they are responsible for the inversion of the $15/2^-$ and $19/2^-$ states with respect to ^{131}Sb.

As regards the quantitative agreement, we see that the observed excitation energies are very well reproduced by our calculations, the only significant discrepancy occurs (in all three nuclei) for the $11/2^+$ state, which is predicted to lie a few hundred keV above its experimental counterpart. This discrepancy leads to an inversion in the ordering of the $13/2^+$ and $11/2^+$ levels in ^{129}In.

In Table II we compare with the experimental data (data from works other than the present one are taken from Refs. [2,5,13]) our predictions for the electromagnetic transition rates and half-lives, the latter obtained by using experimental γ-ray deexcitation energies, whenever available, and including conversion. The $E2$ transition rates in Sb isotopes have been calculated with an effective proton charge $e_\pi^{\rm eff}=1.55e$, which is the same as that adopted in Ref. [14] for the $N=82$ isotones, while for the proton hole in ^{129}In we use the value $e_\pi^{\rm eff}=1.35e$, as results from our study of the $N=50$ isotones [15]. For the neutron hole we take the value of $0.78e$, which reproduces the experimental value of the $B(E2;10^+ \rightarrow 8^+)$ in ^{130}Sn. In the calculation of the magnetic transitions we have used the free gyromagnetic factors, since reasonable changes in their values would only slightly affect the final results. From a comparison with the experimental data, we see that a quite good agreement is obtained in all cases considered. In Table II we also report for the two Sb isotopes the values of $B(E2;19/2^+ \rightarrow 15/2^+)$. The $15/2^+$ level, which has not been observed, is predicted to lie at about 100 keV below the $19/2^+$ level in both nuclei. The calculated values of the above $B(E2)$ are consistent with the findings of Ref. [5], where the $19/2^+$ state in ^{131}Sb has been found to decay by two competing $E1$ transitions to the $19/2^-$ and $17/2^-$ states.

V. CONCLUSIONS

The present delayed γ-ray and conversion-electron measurements of fission products have allowed the study of the yrast structure of the two isobars ^{129}In and ^{129}Sb. Two high-spin isomers $17/2^-$ and $23/2^+$ have been established. These new data substantially extend our study of these neutron-rich nuclei close to ^{132}Sn to higher-spin states.

In connection with the experimental work, we have performed realistic shell-model calculations for ^{129}In and ^{129}Sb, which are the main subject of this study, as well as for ^{131}Sb. Actually, the energy levels of the latter nucleus were already calculated in the study of Ref. [7]. Here, we have completed this study by calculating the experimental transition rates and comparing them with the available experimental data. As already mentioned in Sec. IV, the inclusion of ^{131}Sb in the present study is motivated by the remarkable similarity between its low-energy properties and those of ^{129}In and ^{129}Sb. As has been shown in Sec. IV, our calculated results provide a very satisfactory interpretation of the experimental spectra and the electromagnetic-transition rates for the three nuclei considered. It should be stressed that no adjustable parameters have been used in our calculations.

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