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Identical transitions in the strongly deformed ^{99}Sr and ^{100}Sr

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The decay of the very neutron-rich nucleus ^{100}Rb has been studied by γ spectroscopy of online mass-separated samples. Schemes for β decay to ^{100}Sr and βn decay to ^{99}Sr are presented. New sets of transitions in ^{99}Sr and ^{100}Sr with identical energies are observed. All identical bands so far observed in neutron-rich Sr isotopes obey a simple energy rule valid for even-even, odd-even, and odd-odd bands.

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I. INTRODUCTION

Neutron-rich isotopes with $N\geqslant 60$ and $A\simeq 100$ are characterized by strong axial deformation. Strontium isotopes are the most deformed nuclei known so far in this region. Quadrupole deformations of $\beta\simeq 0.4$ have been deduced for ^{98}Sr, ^{99}Sr, and ^{100}Sr from the lifetimes of the first excited states and from mean-square radii measured by collinear laser spectroscopy [1–5]. According to these results, ground-state deformation remains constant after its sudden onset at $N=60$. This trend might even continue at larger neutron number since neither the ^{101}Sr level spacings [6] nor the 2^+-state energy of 126 keV in the $N=64$ isotone ^{102}Sr [7] indicate any large change of deformation. A peculiar feature of neutron-rich Sr nuclei is the occurrence of identical bands in isotopes with $\Delta A=2$. Transitions in the ground-state bands in the even-even $^{98-100}$Sr and in the $K^\pi=3/2^+$ bands in the odd-neutron $^{99-101}$Sr have very close energies. A local trend of strong dependence of moments of inertia on deformation and the fact that all involved Sr isotopes have the same deformation seem to be the origin of these identical bands [3,6]. However, the intricate mechanism is not yet understood.

Presently, the nucleus ^{100}Sr$_{62}$ is the most neutron-rich even-even Sr isotope for which experiments can yield some structure information. The levels in ^{100}Sr were first observed at the CERN-ISOLDE facility in a β-decay study of ^{100}Rb by Azuma *et al.* who identified the $4^+\rightarrow 2^+\rightarrow 0^+$ cascade and performed the first lifetime measurement of the 2^+ state [8], establishing large deformation. A more accurate lifetime measurement performed later by our group, lead to the deformation of $\beta=0.40$ [3]. In the same experiment, a 85 ns lifetime was observed for the 1619 keV level and attributed to K hindrance of the decay to the 4^+ state by the 1202 keV transition [9]. Recently, further members of the ground-state band up to $I^\pi=10^+$ were identified in prompt-fission studies [10]. The large moment of inertia shows very little variation with angular momentum. Thus, ^{100}Sr is a strongly deformed nucleus with properties close to the rotational limit.

Yet, data on nonyrast levels in ^{100}Sr remained scarce. Here we present a more comprehensive decay scheme of ^{100}Rb to ^{100}Sr, including new nonyrast levels and band structure built on the K isomer. In addition, β-delayed neutron emission from ^{100}Rb [11] provides a new access to levels in ^{99}Sr, complementing data from ^{99}Rb β decay [12].

II. EXPERIMENT AND ANALYSIS

A. Experiment

The ^{100}Rb activity was produced by fission of natural uranium induced by 600 MeV protons, followed by online mass separation at the ISOLDE facility. The main goal of the experiment was to determine the deformation of the β-decay daughter nucleus ^{100}Sr from the lifetime of its 2^+ state at 129 keV, as presented in Ref. [3]. We now report on the result of a detailed analysis of γ singles and γ-γ-t coincidence measurements recorded with the planar Ge detector used for the lifetime measurement (4.9 cm^2 area by 1.3 cm depth) and a coaxial Ge detector of 27% relative efficiency. The highest energy to be recorded with the planar detector was set to about 1250 keV, in order to allow gating of the 1202 keV line. The coaxial detector covered energies up to 4.2 MeV, which still is lower than the neutron separation energy S_n of 6.12 MeV for ^{100}Sr [14]. The low efficiency for coincidences where both transition energies are above, say, 1 MeV prevents the construction of a ''complete'' decay scheme. Nevertheless, the setup allows detection of the γ rays important for the discussion of the low-lying levels of ^{99}Sr and ^{100}Sr.

B. Analysis

Since ^{100}Rb is situated very far from β stability, γ spectra are very complex due to the long chain of $A=100$ isobaric activities produced by filiation and some other $A=99$ activities following β-delayed neutron emission from ^{100}Rb.

In a first step, the identification of transitions to ^{100}Rb decay was made by requiring a coincidence with either the 129.2 keV ($2^+\rightarrow 0^+$) transition in ^{100}Sr or with the 90.8 keV ($5/2^+\rightarrow 3/2^+$) transition in ^{99}Sr, detected in the planar

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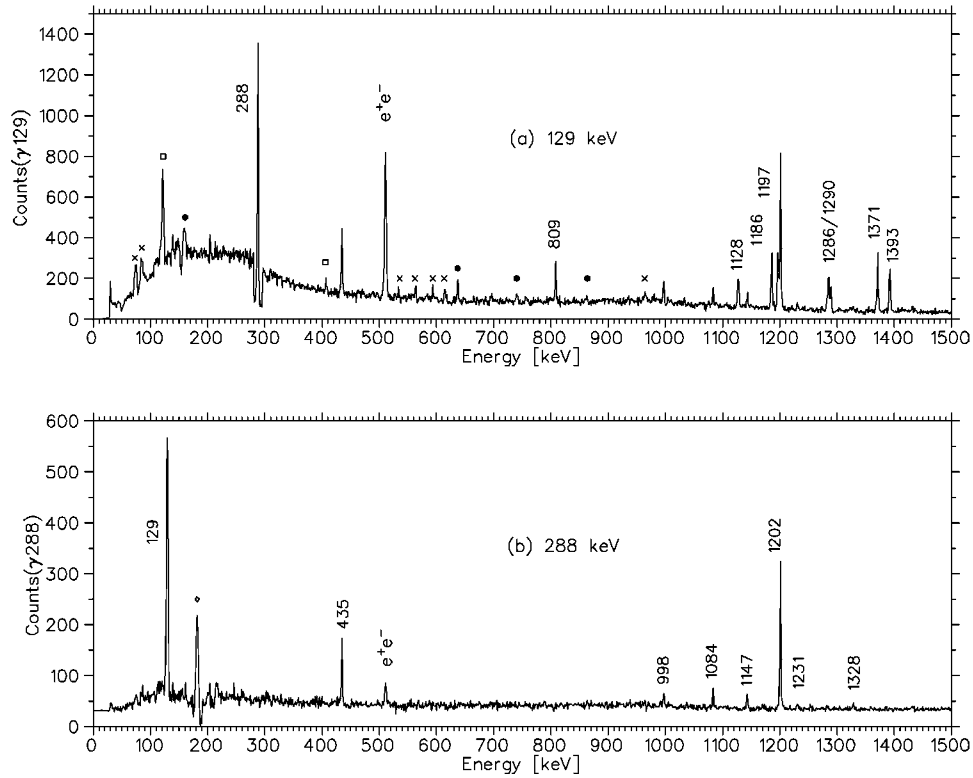

FIG. 1. Gamma spectra recorded with the coaxial Ge detector gated by the 129 keV ($2^+\rightarrow0^+$) and 288 keV ($4^+\rightarrow2^+$) transitions in ^{100}Sr. The counts near the 288 keV peak in the 129 keV gate have been divided by 4. The scales are adjusted to yield about equal heights for the lines placed on top of the 4^+ level. Transitions included in the level scheme are marked by their energy if placed directly above the gating transition or by a closed circle if placed elsewhere. In the 129 keV gate a minor amount of contamination is due to the 130 keV transition (^{99}Zr, open squares). Peaks marked with crosses are interferences from K x rays of Pb due to fluorescence and lines in various decays without clear statistical significance mostly due to random coincidences. The large amount of annihilation radiation due to pair production reflects the large population of the 2^+ level by high-energy transitions. In the 288 keV gate, a strong cross talk due to the 469 keV transition in ^{99}Nb is visible at 181 keV (diamond).

detector. These projections are shown in Figs. 1 and 2. Gates were set on all the coincident transitions in the coaxial Ge detector, and the new projections on the planar detector were analyzed. Prompt coincidences with a window of about 60 ns and delayed coincidences were analyzed to help placing transitions with respect to the 85 ns isomer in ^{100}Sr. Many ground-state transitions have been placed on the sole basis of their good energy fit between levels established by coincidence relationships. The weakest of them must be regarded as tentative since there is a chance that such transitions also belong to other activities and could have been overlooked in previous studies. Fortunately, decay schemes of ^{100}Sr and of its descendants are well known [15–19], and several decays in the $A=99$ mass chain were also reinvestigated recently [19–21].

Owing to its superior energy resolution, the planar detector is very effective for the identification of low-energy transitions depopulating the K isomer in ^{100}Sr and of the band structures in ^{99}Sr. However, its efficiency decreases rapidly with increasing energy. This made the placement of the weakest high-energy transitions uncertain, since these may be seen in coincidence with the 129 keV $2^+\rightarrow0^+$ transition in ^{100}Sr or the 91 or 125 keV transitions in ^{99}Sr, but no longer with occasional intermediate higher-energy transitions. Consequently, the high-energy part of the level schemes remains tentative. Thus, log ft values for low-lying levels might be strongly underestimated in these cases where feeding high-energy γ rays have been overlooked.

It has finally to be noted that the surface-ionization ion source used in our experiment produced rubidium and strontium beams with high efficiency. As a matter of fact, the presence of an intense ^{100}Sr beam prevents the use of intensity balance considerations to determine the ground-state β branching from ^{100}Rb to ^{100}Sr. As a consequence of the unknown amount of produced ^{100}Rb, the β-delayed neutron emission probability P_n cannot be deduced from γ-ray intensities.

III. RESULTS

A. Decay of ^{100}Rb to ^{100}Sr

The levels known prior to this analysis were members of the ground-state band [3,10] and the 85 ns isomer at 1619 keV [9]. Based on nuclear structure arguments, it was assumed that both the ^{100}Rb ground state and the isomer in ^{100}Sr are $I^\pi=4^-$ states. In this particular case, the delayed γ-γ coincidences across the isomer allow a high sensitivity for detecting feeding transitions. The strong β-decay branch

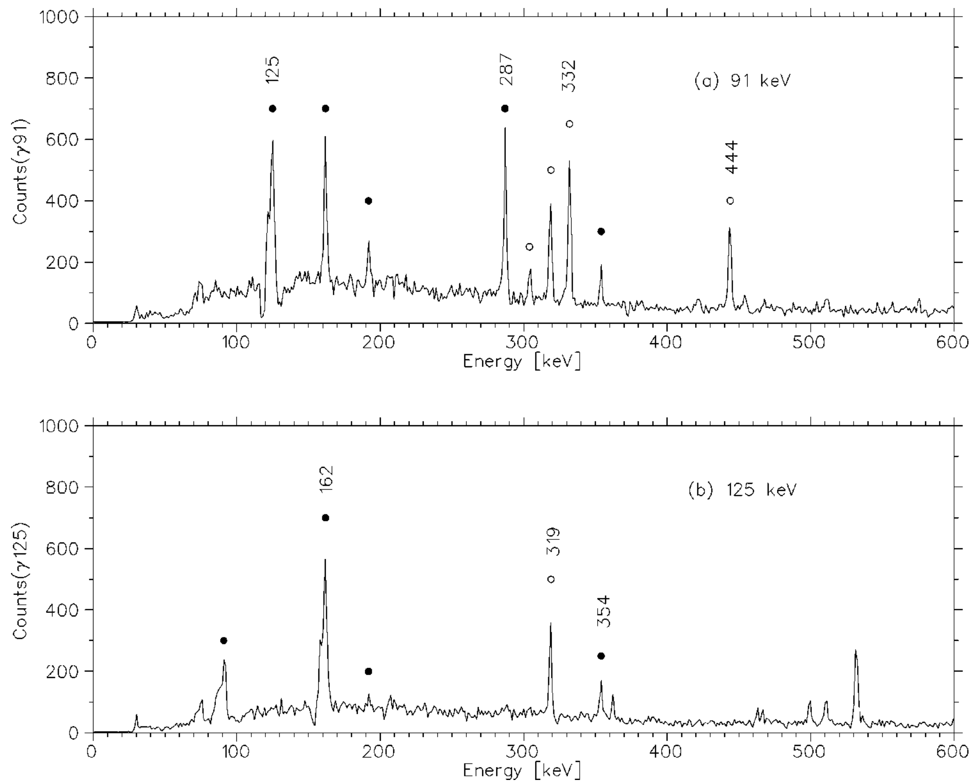

FIG. 2. Part of gamma spectra recorded with the coaxial detector gated by the 91 keV ($5/2^+ \rightarrow 3/2^+$) and 125 keV ($7/2^+ \rightarrow 5/2^+$) transitions in ^{99}Sr. The counts near the 125 keV peak in the 91 keV gate have been divided by 2. Transitions are marked by their energy if placed directly on the gating transition. Transitions belonging to the ground-state band are marked by closed circles and those linking the $K=5/2$ excited band to the g.s. band are indicated by open circles. A moderate contamination in the upper spectrum is due to a doublet near 90 keV in ^{99}Zr, accounting among others for a peak at 122 keV visible on the left of the 125 keV peak. The lower spectrum is dominated by the coincidences due to the 125 keV line in ^{99}Y which is another $7/2^+ \rightarrow 5/2^+$ transitions. A new level in the ground-state band is indicated by the 192 and 354 keV lines.

to the isomer is accordingly the most reliable one deduced in this work. A log ft of 5.6 is obtained if intensity balances are calculated including the tentatively placed transitions (it becomes somewhat lower by removing them). This value is in agreement with the allowed character for this 4^- to 4^- transition.

Transitions in the decay of ^{100}Rb to ^{100}Sr are listed in Table I. The decay scheme is shown in Fig. 3. In the following, we present the arguments for placing the most important levels.

The 937.8 keV level is based on the coincidence of the 809 keV line with the 129 keV $2^+ \rightarrow 0^+$ transition. The intensity of this coincidence is high enough to ensure that further coincidences with the 288 keV line and with the most intense lines in the 1 MeV region have not been overlooked. No line of energy suitable as a ground-state transition is found in the singles spectra.

The coincidence of a line in the 129 keV gate and a ground-state transition establish the next levels at 1257.1 and 1315.4 keV with spin and parity of $I^\pi = 2^+$. It must be mentioned here that both logft values, 5.6 and 5.8, respectively, are clearly too low for the assumed first-forbidden unique transitions. Alternatives to solve the discrepancies will be discussed in a later section.

The levels at 1414.6, 1500.6, and 1560.6 keV are supported by low-energy feeding transitions from the 1619 keV ($I^\pi = 4^-$) level and deexcitation to both the 129 ($I^\pi = 2^+$) and 417 keV ($I^\pi = 4^+$) levels. No transitions to the ground state are found. Transition rates for the 58.3, 118.0, and 204.4 keV transitions from the 85 ns isomer are consistent with strongly retarded dipole transitions or moderately delayed $E2$ transitions. Thus, $I=3$ of either parity or 4^+ are possible for these levels.

The isomeric level at 1619 keV ($t_{1/2} = 85$ ns) has been proposed as $I^\pi = 4^-$ [9]. The strongly hindered 1202 keV $E1$ transition to the 417 keV 4^+ state has to compete with transitions of very much lower energies to the levels at 1415, 1501, and 1561 keV. Delayed coincidences indicate that the 161.8, 194.4, and 864.0 keV transitions are above the isomeric level. The prompt 162–702 keV weak coincidence could indicate a 702.3 keV transition above the 1781 keV level, but may also be due to the cross talk of the strong 864 keV transition belonging to the decay of ^{100}Y [14]. A complex structure is associated with the prompt 162–194 keV coincidence. A contribution is due to lines placed in ^{99}Sr. Another one, so far not reported, belongs to ^{99}Zr. Due to these interferences a 161.8–194.4 keV coincidence in ^{100}Sr remains tentative. We nevertheless assume the 194 and 162 keV transitions to be coincident and to form a band structure on top of the 1619 keV $I^\pi = 4^-$ isomer for two reasons. First,

TABLE I. Gamma rays following the β decay of ^{100}Rb to ^{100}Sr. Coincidences are listed for gates on the coaxial detector and projections onto the x-ray detector. Coincidences without brackets are significant at 3 standard deviations (σ) or better. The single occurrence of a coincidence less significant than 2σ is not listed if not further supported by another coincidence or a g.s. transition. Uncertain placements are indicated by brackets. The intensity of unplaced transitions is calculated assuming they directly feed the 129 keV level.

E_γ [keV]	I_γ [%]	Initial level	Final level		Coincidences
58.3 (2)	0.20 (5)	1619	1561		
106.4 (6)	0.16 (9)	1522	1415	[a]	
118.0 (2)	1.1 (2)	1619	1501		
129.2 (1)	100	129	0		58, (118), 162,[b] (194),[b] 204, 288, 435, (1186), (1197), 1202
161.8 (2)	4.9 (8)	1781	1619	[b]	129, 288, (1202)
194.4 (3)	0.6 (2)	(1975	1781)	[b]	(162)
204.4 (3)	1.1 (2)	1619	1415		(288)
287.8 (2)	40.9 (38)	417	129		(118), 129, 162,[b] 435, 864,[b] 1202
434.8 (2)	3.3 (4)	852	417	[c]	129, 288
593.8 (4)	1.0 (4)			[d]	129
614.8 (4)	1.2 (4)			[e]	129
637.4 (3)	1.7 (3)	(2056	1419)	[f]	129
702.3 (4)	0.8 (3)	(2483	1781)	[g]	162
740.7 (5)	0.9 (3)	(2056	1315)	[h]	(129)
808.6 (3)	3.6 (4)	938	129	[i]	129
864.0 (3)	2.8 (7)	2483	1619	[b]	129, 288, (1202)
871.1 (4)	0.5 (2)				(162)
997.5 (4)	1.8 (4)	1415	417		(129), (204), (288)
1083.7 (3)	2.9 (6)	1501	417		129, 288
1127.8 (3)	4.0 (5)	1257	129	[j]	129
1143.4 (3)	1.7 (3)	1561	417		58, 129, 288
1186.2 (3)	7.5 (8)	1315	129	[j]	129
1197.4 (4)	9.0 (15)	1327	129	[i]	129
1201.7 (2)	21.3 (26)	1619	417		129, 162,[b] (194),[b] 288, 864 [b]
1231.0 (4)	0.9 (5)	(1648	417)		(129), (288)
1257.1 (3)	9.7 (17)	1257	0	[l]	
1285.5 (4)	5.4 (6)	1415	129		(106), 129, 204
1289.5 (3)	3.7 (5)	(1419	129)	[m]	129
1315.3 (4)	4.6 (8)	1315	0	[k]	
1328.7 (4)	1.0 (3)	(1746	417)		129, (288)
1371.3 (4)	8.7 (10)	1501	129		118, 129
1392.6 (3)	7.6 (9)	1522	129		129
1431.8 (5)	0.6 (4)	1561	129	[a]	(129)
1504.0 (5)	1.0 (5)				(129)
1539.4 (7)	1.0 (4)	1957	417		(129), (288)
1699.0 (5)	1.3 (4)	2116	417		(129), (288)
1807.8 (8)	0.9 (5)				(129)
1827.8 (6)	1.0 (5)	1957	129		(129)
1883.0 (6)	0.8 (3)				(129)
1926.8 (3)	8.4 (9)	2056	129		129
1945.9 (7)	0.8 (4)				(129)
1986.7 (4)	1.9 (5)	2116	129	[j]	129
2055.9 (4)	3.3 (6)	2056	0	[k]	
2082.2 (3)	3.6 (7)	2211	129	[j]	129
2115.6 (3)	3.7 (7)	2116	0	[k]	
2148.4 (3)	7.4 (9)	2278	129	[j]	129
2211.6 (3)	7.1 (12)	2211	0	[k]	
2277.3 (3)	1.8 (4)	2278	0	[k]	
2336.9 (9)	0.8 (5)				(129)

TABLE I *(Continued)*.

E_γ [keV]	I_γ [%]	Initial level	Final level		Coincidences
2376.7 (4)	2.1 (5)	(2506	129)	n	129
2635.9 (8)	0.8 (5)				(129)
2929.0 (9)	0.7 (4)	(3346	417)	o	(129), (288)
2967.8 (7)	1.0 (6)	3097	129	j	(129)
3035.9 (8)	1.8 (5)	3165	129	j	129
3097.3 (7)	1.4 (5)	3097	0	k	
3164.9 (8)	0.2 (1)	3165	0	k	
3187.1 (6)	1.6 (6)	(3316	129)	n	129
4306.4 (9)	0.9 (5)			(129)	
4483.3 (8)	1.2 (7)			(129)	

[a]Placement supported by weak coincidence and energy fitting.
[b]Transition enhanced in the delayed coincidences, due to the isomeric level at 1619 keV [9].
[c]Transition also observed in prompt fission [10].
[d]Might be due to accidental coincidence, a strong transition of same energy is placed in the level scheme of ^{99}Nb.
[e]Might be due to accidental coincidence, transition of same energy is placed in the level schemes of ^{99}Zr and ^{100}Zr.
[f]Tentative placement, see remark for 1290 keV transition.
[g]Other possible placement from level 2116 keV to level 1415 keV.
[h]Placement by energy fitting only.
[i]Placement supported by a strong coincidence but no other relationship.
[j]Placement supported by probable ground-state transition.
[k]Seen in singles only while fitting as a g.s. transition.
[l]Only in singles while about 25% of the intensity is due to a line in ^{100}Mo.
[m]Other possible placement from level 3346 keV to 2056 keV.
[n]Tentative due to the weak statistics and no other relationship.
[o]A doubly placed 1290 keV transition could further support this level.

the energies are in perfect agreement with the rotational formula for a $6\rightarrow5\rightarrow4$ spin sequence. Second, β feedings to the 1781 and 1619 keV levels are in a ratio of 0.19(4) to 0.81(4). This is calculated neglecting conversion of the weak lines from the 1619 keV level and the possible feeding to the 1781 keV level by the 702 keV weak transition, but these corrections remain within the quoted error. The β-feeding intensities are thus in excellent agreement with the theoretical values of 0.20 ($I=5$) and 0.80 ($I=4$) according to the Alaga rule [22].

The deduced β-decay branchings are inconsistent with the 2^+ spin and parity of the first excited state ($\log ft=5.8$) and of the new levels at 1257 keV (5.6) and 1315 keV (5.8). These inconsistencies could be removed by lowering the ground-state spin of ^{100}Rb to $I=3$, but contradicting the arguments for $I^\pi=4^-$ in Ref. [9] and the strong population of the $11/2^+$ state of the ^{99}Sr ground-state band (see next section). As stated above, they could be a consequence of the partial nature of the decay scheme. Alternatively, a not yet identified low-spin isomer in ^{100}Rb could be invoked. This issue remains presently unsolved. Level properties are listed in Table II, where β feedings have been calculated under the assumption of a single β-decaying parent nucleus.

B. Decay of ^{100}Rb to ^{99}Sr

Transitions in the decay of ^{100}Rb to ^{99}Sr via β-delayed neutron emisssion are listed in Table III. The decay scheme is shown in Fig. 4. There is only a partial overlap between the levels observed in β decay of ^{99}Rb [12] and in this work. The highest members of the $K=3/2$ ground-state band of ^{99}Sr are more strongly populated in β-delayed neutron decay of ^{100}Rb than in β decay of ^{99}Rb.

The new 570 keV level has transitions only to the $7/2^+$ and $9/2^+$ levels of the ground-state band (g.s.b.) at 216 and 378 keV. The excellent energy fitting and the consistency of the $|(g_K-g_R)/Q_0|$ parameter extracted from the branching ratios suggest the 570 keV level to be the $11/2^+$ member of the g.s.b. (see Tables IV and V).

The levels at 423, 535, and 684 keV have been assigned $5/2^+$, $7/2^+$, and $9/2^+$, respectively, in Refs. [14,23]. The energy of the 304.4 keV transition was unluckily stated as 307 keV. The energy of the last level is thus 682.1 keV. The highest-spin level of this band is weakly populated and there is no evidence for a 11/2 level. Odd parity logically accounts for the nondetection of a γ branch from the 682 keV $I=9/2$ level to the $5/2^+$ state at 91 keV, in spite of the high efficiency for the expected coincidence, since the missing transition had to be a $M2$. The difference of populations of the g.s.b. and the excited band enable some insight in the decay mechanism. For the levels in the g.s.b. The parity change requires a p-wave neutron if β decay has allowed character or a s-wave and first-forbidden decay. There are several ways to reach the new $11/2^+$ level at 570 keV and this is consistent with the experimental strong population. In contrast, the $K=5/2$ excited band could mainly be reached via allowed β decay with the emission of s-wave neutrons, leading to a smaller range of populated spins and fewer ways to reach the final levels.

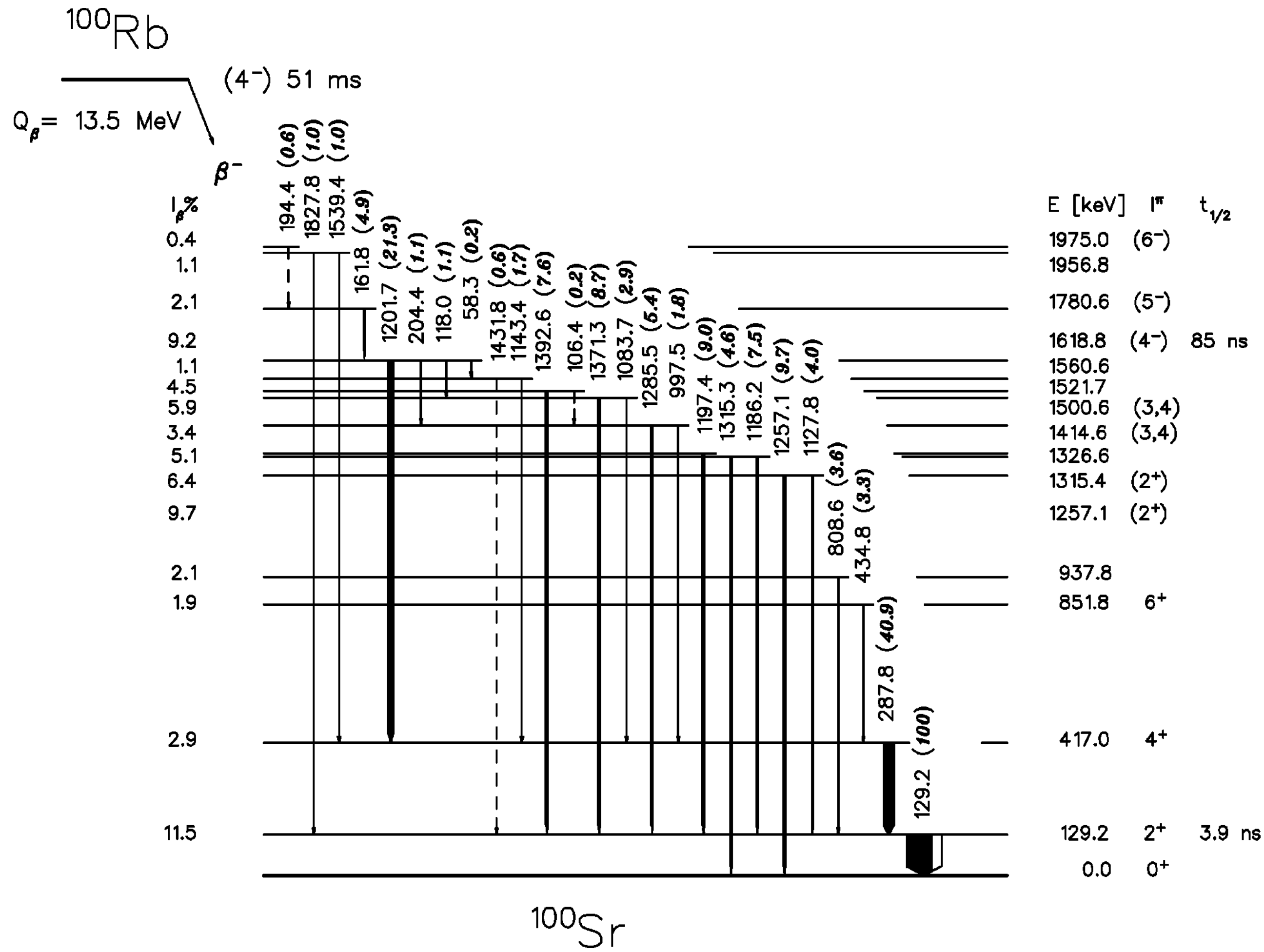

FIG. 3. Partial decay scheme of ^{100}Rb to ^{100}Sr. Only the levels up to the K isomer at 1619 keV and the proposed band members are shown since most of the high-energy transitions are tentatively placed. The complete list of levels, including log ft values not shown here, is presented in Table II. The inconsistencies of the β feedings and proposed spins are discussed in the text.

Comparing the intensity of the 91–125 keV coincidences in ^{99}Sr with those of various coincidence pairs in the level schemes of ^{99}Y and ^{99}Zr, one obtains a branching of 0.13(3) for the 125 keV line per β-delayed neutron decay of ^{100}Rb. Consequently, about 50% of the feeding bypasses the excited levels of ^{99}Sr and directly feeds its $3/2^+$ ground state. This looks to be a rather high value. It could be a consequence of β decay of ^{99}Rb due to some, even modest, mass contamination or, alternatively, by additional population from a hypothetical low-spin isomer in ^{100}Rb.

IV. DISCUSSION

A. Levels in ^{100}Sr

The systematics of deformed neutron-rich Sr isotopes is limited to ^{98}Sr, ^{100}Sr, and ^{102}Sr (see Fig. 5). This is due to the sudden onset of deformation resulting from the energy shifts of coexisting shapes [24]. Thus, the deformed 1465 keV level in ^{96}Sr$_{58}$ corresponds to the ^{98}Sr$_{60}$ ground state while the ^{96}Sr spherical ground state is associated with the excited 0^+ state at 215 keV in ^{98}Sr. The deformation of the 1465 keV level in ^{96}Sr is unknown. However, in a very recent paper, the EUROGAM Collaboration presents high-spin data suggesting a gradual increase of deformation with neutron [25]. We note that the lowest deformed state reported so far in the odd-neutron nucleus ^{97}Sr is a $K^\pi=3/2^+$ band head at 585 keV [10,26]. The rate of lowering of the deformed minimum with N is almost constant. Extrapolating to ^{100}Sr, a spherical 0^+ state is expected near 1.7 MeV. Several levels above 0.9 MeV with only a decay to the 2^+ state could be 0^+ states. However, no spin and parity assignments are possible for them. In contrast, the systematics of $N=62$ isotones spans a larger number of nuclides and is much smoother (see Fig. 6). Several low-spin collective levels can be followed from the spherical plus γ-soft ^{108}Pd [27] to the strongly deformed ^{102}Zr [28,29], owing to the gradual evolution of their energies and decay branchings. Extrapolation to ^{100}Sr predicts a rather low-lying 0^+ state for which the 938 keV level is a good candidate and, at somewhat higher energy, of two 2^+ states which could be the 1257 and 1315 keV experimental 2^+ levels. These levels could be regarded as nonyrast collective deformed levels, i.e., as the head of the β band, its 2^+ and the 2^+ γ band head, the order of the latter two being rather arbitrarily chosen in Fig. 6. However, another interpretation was put to our attention by Heyde [30]. Some of these states (the 0^+ and a

TABLE II. Levels in ^{100}Sr populated in the decay of ^{100}Rb. The transition intensities used are experimental ones. The existence of an isomer could solve inconsistencies of $\log ft$ values and adopted spins, but it still remains speculative. It has therefore not been attempted to decompose the β-feeding pattern into contributions of a low and medium spin level in ^{100}Rb. Following this, 100 relative γ-intensity units correspond to 57% β decays. The $\log ft$ values have been calculated with $T_{1/2}=51$ ms, $Q_\beta=13.5$ MeV, and $P_n=6\%$ [14], under the assumption of no direct ground-state feeding.

Energy [keV]	β feeding [%]	logft	I^π
0.0			0^+
129.2 (1)	11.5(24)	5.7	2^+ [a]
417.0 (2)	2.9(26)	6.3	4^+ [a]
851.8 (3)	1.9 (2)	6.4	6^+ [a]
937.8 (3)	2.1 (3)	6.4	(0^+) [b]
1257.1 (3)	9.7(10)	5.6	(2^+)
1315.4 (3)	6.4 (6)	5.8	(2^+)
1326.6 (4)	5.1 (8)	5.9	
1414.6 (3)	3.4 (4)	6.1	(3,4)
1418.7 (3)	1.1 (3)	6.5	[c]
1500.6 (3)	5.9 (6)	5.8	(3,4)
1521.7 (3)	4.5 (5)	5.9	
1560.6 (3)	1.1 (2)	6.5	(2,3,4)
1618.8 (2)	9.2(15)	5.6	(4^-) [d]
1648.0 (5)	0.5 (3)	6.9	[c]
1745.7 (5)	0.6 (2)	6.8	[c]
1780.6 (3)	2.1 (5)	6.2	(5^-)
1956.8 (5)	1.1 (2)	6.5	(2,3,4)
1975.0 (4)	0.4 (1)	6.9	(6^-)
2056.0 (2)	8.2 (7)	5.6	(1,2) [e]
2115.8 (2)	4.0 (4)	5.9	2^+ [e]
2211.5 (2)	6.1 (7)	5.7	(1,2) [e]
2277.4 (2)	5.2 (5)	5.7	(1,2) [e]
2482.8 (3)	2.0 (4)	6.1	[e]
2505.8 (4)	1.2 (2)	6.3	[e]
3097.2 (5)	1.4 (4)	6.2	(1,2) [e]
3165.0 (6)	1.2 (2)	6.2	(1,2) [e]
3316.4 (7)	0.9 (2)	6.3	[e]
3346.0 (9)	0.4 (2)	6.7	[e]

[a]Member of the ground state band [10].
[b]Spin and parity based on systematics only.
[c]Level based on weak evidence, not shown in Fig. 3.
[d]Isomeric level with 85 ns [9].
[e]Level not shown in Fig. 3.

2^+) could be spherical, corresponding to the complex structures in ^{96}Sr and other $N=58$ isotones associated with vibrational ''normal'' states or two-particle-two-hole excitations across the $Z=40$ spherical subshell [31]. In this interpretation, they would be lying much lower than expected. This could happen if, as approaching neutron midshell, the deformed states nearly reach their minimum energy relative to the spherical ones and the change of relative energies becomes smaller. It might even be possible to consider a minimum of deformation energy before $N=66$. An indication could be the lowest excitation energies of intruder states in the Rh and Pd isotopes [32,33] which occur at $N=64$. The difficulties to establish the nature of low-lying 0^+ states are made apparent by the numerous studies devoted to ^{152}Sm, a nucleus close to stability where detailed experiments are possible. In that region, a rapid shape transition also occurs and while the ^{152}Sm ground-state band exhibits rotational structure, other interpretations have been proposed for the excited 0^+ band, see, e.g., Refs. [34–36] and therein. In order to clarify the nature of the new 938, 1257, and 1315 keV levels in ^{100}Sr, it would be of great importance to search for band structure and to measure transition rates. According to systematics showing that the largest $\rho^2(E0)$ values have been measured in this region [31], an especially large value for the decay of the tentatively 0^+ level at 938 keV would be a signature of shape coexistence.

The 1619 keV isomeric level has been interpreted as a $I^\pi=4^-$ state, based on considerations of hindrances of its decay to the 4^+ level of the ground-state band [9]. The proposed [411]3/2⊗[532]5/2 neutron configuration involves the lowest quasiparticles for $N=61$ and $N=63$ in this region [6,37–39]. A band built on a similar level has been identified in ^{102}Zr by Durell *et al.* using prompt fission [29]. They observed the band up to the $I^\pi=9^-$ level, but did not report a lifetime for the band head at 1821 keV. The postulated two-quasiparticle configuration has been reproduced by quantum Monte Carlo calculations for ^{100}Sr and ^{102}Zr performed by Capote *et al.* [40]. The decrease of pairing confirms numerous calculations of decay properties by the QRPA model [41,42]. The Gallagher rule [43] favors coupling of antiparallel intrinsic spins. Thus, a 1^- spin-singlet level is expected below the 4^- spin-triplet state. Such a level has not been identified in this work nor in β-decay or prompt fission studies of ^{102}Zr [28,29]. It has to be mentioned that if the ground-state transition is the only strong decay mode, such a low-spin level could have easily escaped observation in experiments strongly relying on coincidence data.

B. Levels in ^{99}Sr

The new level at 570 keV is the $11/2^+$ member of the previously established $K=3/2$ ground-state band [12]. The band analysis shown in Table V yields the absolute value of the $E2/M1$ mixing ratio for the $5/2^+\rightarrow 3/2^+$ transition, $|\delta(91\ \text{keV})|=0.171(13)$. From the lifetime of the 91 keV level, $t_{1/2}=0.58(9)$ ns [2] we derive $B(M1)=0.040(6)$ W.u., $B(E2)=131(27)$ W.u. for the 91 keV transition. The quadrupole moment extracted from the $B(E2)$ value is $|Q_0|=3.27(34)$ b. It corresponds to a deformation parameter (with second order term included) β=0.35(4), a value slightly lower than in Ref. [2] where branching ratios from decay of ^{99}Rb were used. This result is in modest agreement with β=0.44(4) extracted from a $\langle r^2\rangle$ measurement by collinear laser spectroscopy [5]. Part of the difference might be due to the fact that the β value from the $B(E2)$ measurement and from the laser spectroscopy are not exactly the same quantity. Anyway, the average value is close to β=0.40 which is the deformation parameter for ^{98}Sr and ^{100}Sr [1,3,4]. From $B(M1)$ one gets $|g_K-g_R|=0.70(6)$ and, with further assumptions of $g_s=0.6\cdot g_{s(\text{free})}=-2.3$ and g_R

TABLE III. Gamma rays in ^{99}Sr following β-delayed neutron decay of ^{100}Rb. The same conventions are used as in Table I.

E_γ [keV]	I_γ [%]	Initial level	Final level		Coincidences
90.8 (1)	100	91	0		125, 162, (319)
111.9 (5)	0.6 (3)	535	423	a	(423)
125.1 (2)	40.3(59)	216	91	b	91, (112), 162, (192), (319)
147.6 (5)	0.7 (4)	(682	535)	c	(423)
161.9 (3)	11.1(13)	378	216		91, (112),[a] 125, 192, 216
192.0 (4)	2.8(12)	570	378	d	91, 125, 162
215.9 (3)	10.8(15)	216	0		162, 319
287.2 (3)	7.4(13)	378	91		91, (192)
304.4 (4)	0.9 (4)	682	378	e	91, (125), (162), (287)
318.7 (3)	5.7 (6)	535	216		91, 125, 216
332.0 (2)	7.9 (9)	423	91		91
353.9 (3)	2.6 (5)	570	216	d	91, 125, (216)
422.8 (4)	14.0(21)	423	0		
443.8 (3)	6.7 (8)	535	91		91
466.4 (5)	0.3 (2)	(682	216)	d	(125)
646.2 (4)	0.9 (4)	(862	216)	d	91, 125, (216)
683.7 (4)	3.9(13)	1106	423		91, (125), (332), (422)
764.0 (3)	5.7 (8)	855	91	f	91
777.4 (3)	1.8 (4)	994	216		91, (125)
846.8 (3)	2.1 (5)	1063	216	d	91, 125, (216)
854.7 (4)	6.1 (8)	855	0	g	
902.9 (3)	4.9 (6)	994	91	f	91
936.0 (3)	1.9 (4)	1152	216		91, 125, (216)
965.1 (5)	1.8 (4)	1182	216	d	(91), (125)
971.4 (9)	1.0 (5)	(1063	91)	d	(91)
981.3 (4)	2.3 (5)	1072	91	f	91
993.7 (5)	2.0 (4)	994	0	g	
1015.0 (4)	2.1 (5)	1106	91		91
1060.9 (7)	1.0 (5)	1152	91	h	91
1072.1 (4)	2.8 (7)	1072	0	g	
1090.1 (5)	1.0 (5)	1182	91	d	(91)
1104.9 (4)	3.1 (7)	1196	91	i	91
1112.0 (7)	0.8 (4)	(1328	216)	d	(91), (125)
1149.8 (8)	1.0 (5)	(1241	91)	d	(91)
1211.1 (9)	0.5 (3)	(1427	216)	d	(91), (125)
1291.8 (9)	0.7 (4)	(1383	91)	d	(91)

[a]The transition can also be placed from the 682 to 570 keV levels.
[b]About half of the observed intensity comes from the decay of ^{99}Sr which causes a large error on the calculated value.
[c]Transition placed by energy fitting.
[d]Transition not reported in β decay of ^{99}Rb [23].
[e]Transition reported as 307.0 keV due to a misprint in Ref. [23].
[f]Placement supported by a probable g.s. transition.
[g]Seen in singles only while fitting as a g.s transition.
[h]Transition masked in singles by the 1059.5 keV line in ^{100}Zr.
[i]The existence of a g.s. transition is unclear due to the line at 1197.4 keV in ^{100}Sr.

$=Z/A$, one obtains the solutions $\langle s_z \rangle = +0.22$ and -0.71. The negative value is out of range while the positive one is consistent with the assignment of the [411]3/2 orbital [12]. We note that $\langle s_z \rangle = 0.29$ has been calculated for this orbital at deformation of 0.4 in ^{99}Y where it is part of a three-quasiparticle isomer [13].

Such an analysis cannot be performed for the proposed $K^\pi = 5/2^-$ excited band due to the weakness of the population and the nonobservation of the crossover transitions. The inertial parameter is close to 16.0 keV, which corresponds to 96% of the rigid-rotor estimate. This energy compression is systematically observed in this region for odd-parity bands,

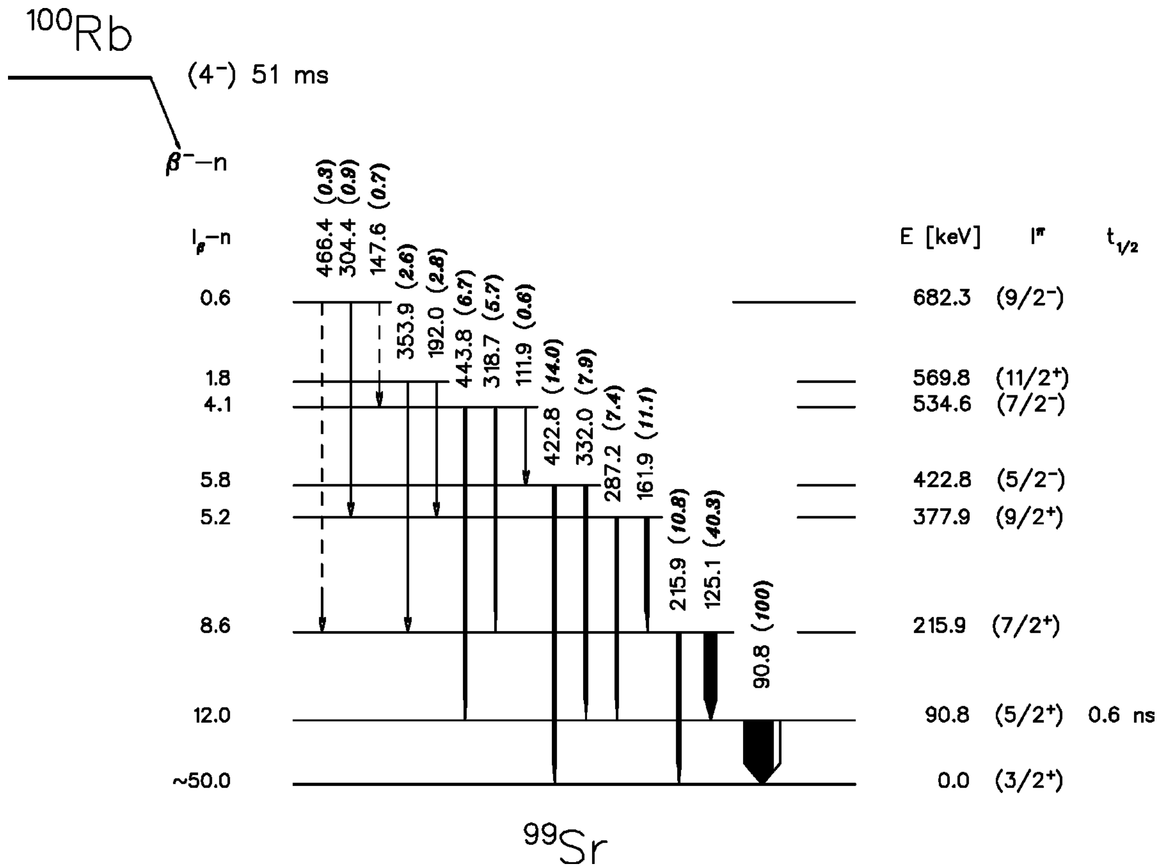

FIG. 4. Partial decay scheme of ^{100}Rb to ^{99}Sr. As in Fig. 3 only the levels discussed in the text are shown. Level feedings have been calculated for 100 β-delayed neutron decays. Conversion coefficients were calculated using $\delta(E2/M1)$ mixing ratios deduced from band properties, see Table V.

where it has been attributed to Coriolis mixing [39]. The [532]5/2 orbital is clearly favored as being the only one of odd parity near the Fermi surface. The systematics of odd-neutron quasiparticle levels for $N=61$ has to be partly revised since the $5/2^-$ energy in ^{99}Sr turns out to be higher than expected from a simple extrapolation versus deformation [37]. It would have been in principle possible to determine the parity of the band from branching ratios. If one assumes rather arbitrarily $\langle s_z \rangle = +0.5$ and -0.2 for the [532]5/2 and [413]5/2 orbitals, respectively, the crossover transition from the 9/2 state is roughly ten times stronger for even parity than for the odd one. However, even then, its intensity of 0.08 relative γ-intensity units is far below the detection limit.

C. Identical transitions

Large moments of inertia and rigid rotations are exhibited by a number of odd or odd-odd nuclei in the $A\simeq 100$ region of neutron-rich nuclei but ^{98}Sr and ^{100}Sr are the only even-even nuclei showing such pronounced features [10,13,44]. The ^{100}Sr 2^+ state (129 keV) is among the lowest ones, being second only to the 2^+ state (126 keV) of ^{102}Sr [7]. The moment of inertia extracted from the lowest members of the

TABLE IV. Level energies of the $K=3/2$ ground-state band of ^{99}Sr. The symbols refer to fits with the leading term in $I(I+1)-K^2$ only (a), with terms in first and second order in $I(I+1)-K^2$ (b) and with leading term plus signature term (c).

	Level energies [keV]			
I	Exp.	(a)	(b)	(c)
5/2	90.8	89.4	90.8	90.3
7/2	215.9	214.5	216.8	214.9
9/2	377.9	375.5	377.0	378.1
11/2	569.8	572.1	570.1	570.5

TABLE V. Analysis of the $K=3/2$ ground-state band of ^{99}Sr according to the formalism shown in Ref. [13]. (a) The average value of $|(g_K-g_R)/Q_0|=0.215(15)$ b^{-1} is used to deduce $|\delta(91)|=0.171(13)$.

γ ray	$I_i \to I_f$	$\lvert\delta(I\to I-1)\rvert$	$\lvert(g_K-g_R)/Q_0\rvert$ $[b^{-1}]$
90.8	$5/2^+\to 3/2^+$	0.171(13)	(a)
125.1	$7/2^+\to 5/2^+$	0.164(16)	0.212(21)
161.9	$9/2^+\to 7/2^+$	0.160(18)	0.215(24)
192.0	$11/2^+\to 9/2^+$	0.131(38)	0.254(74)

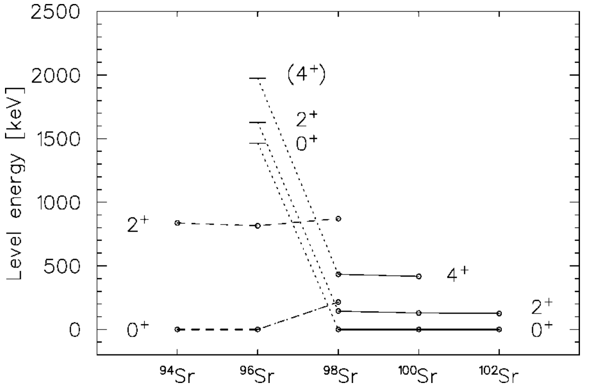

FIG. 5. Level systematics for neutron-rich Sr isotopes [1,3,7,10,14,24] suggests spherical states could be expected below 2 MeV in ^{100}Sr.

ground-state band represents 72% of the rigid rotor value J_{rigid} and the $E(4^+)/E(2^+)$ ratio is 3.23. With increasing spin, the g.s.b. still shows little compression with $E(10^+)/E(2^+)=16.3$. These very good rotational properties are very comparable with those of the classical rotors in the rare earth and actinide regions.

The deformed isotopes ^{98}Sr, ^{99}Sr, and ^{100}Sr all have deformation close to $\beta = 0.4$. One therefore expects transition energies to scale with the mass dependence of the moments of inertia, i.e., $\Delta J/J = 5/3\,\Delta A/A = 3.3\%$ for transitions in ^{98}Sr and ^{100}Sr. However, the deviation is much smaller. The identity of the $6^+\rightarrow 4^+\rightarrow 2^+$ transitions was discussed in Ref. [3]. It has to be noted that the different energies of the 2^+ states, 144 and 129 keV for ^{98}Sr and ^{100}Sr, respectively, are due to shape coexistence in ^{98}Sr where the low-lying 0^+ state at 215 keV perturbs the ground-state band [45]. Identity of transition energies persists at higher spins [10]. The relative deviation of the $E(10^+)-E(2^+)$ difference of 0.23% still remains much smaller than the mass scaling contribution. A comparable degree of identity was also reported for the few levels observed in the $K^\pi=3/2^+$ bands in the odd-neutron nuclei ^{99}Sr and ^{101}Sr [6].

In this work, two levels have been identified in the $K^\pi=4^-$ two-quasiparticle band in ^{100}Sr and the $11/2^+$ level has

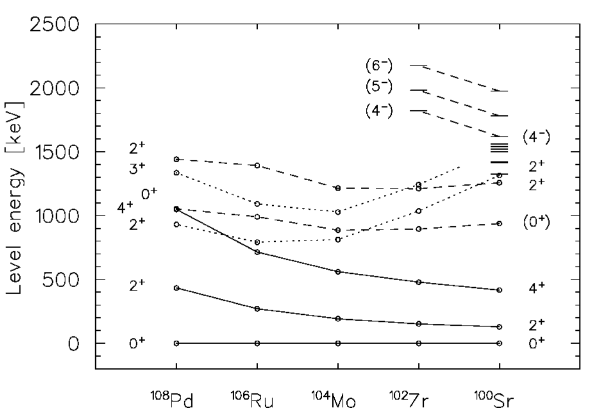

FIG. 6. Level systematics of $N=62$ isotones. There is a gradual evolution of structure from the vibrator limit in the Cd-Pd region via the γ-soft limit dominating the structure of Ru isotopes to the axial symmetry limit in Zr-Sr isotopes. The nature of the 938, 1257, and 1315 keV levels in ^{100}Sr yet remains unclear.

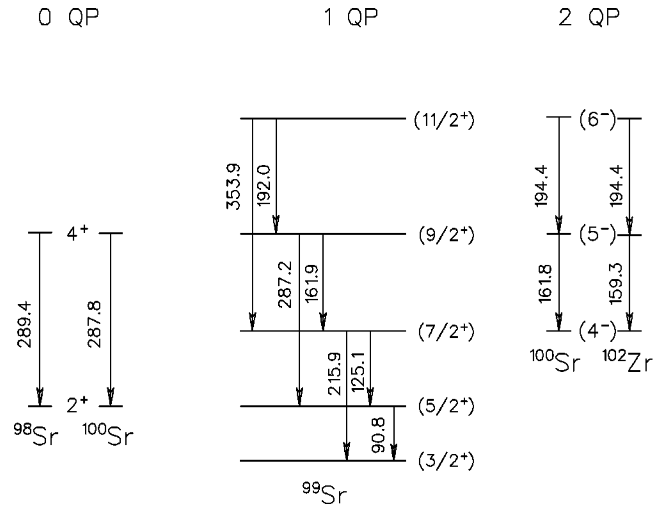

FIG. 7. Selected transitions with very similar energies in ^{99}Sr, ^{100}Sr, and ^{102}Zr. An offset has been added in order to better show the identical transitions as a function of the number of quasineutrons.

been added to the g.s.b. of ^{99}Sr. This leads to observation of new identical transitions now in the immediate neighbors ^{99}Sr and ^{100}Sr (see Fig. 7). First, the $9/2^+$ to $5/2^+$ energy difference of 287.2 keV in the [411]3/2 g.s. band of ^{99}Sr is almost the same as the energies of the $4^+\rightarrow 2^+$ transitions in ^{98}Sr and ^{100}Sr, 289.4 and 287.8 keV, respectively. In this case, we note that $j_{\text{odd-}A}=j_{\text{even-}A}+1/2$ or, in other words, the transition energy remains the same by increasing the number of unpaired particles and the spin of the initial level. It is well known that for a $K=1/2$ band with decoupling parameter $a=1$, there is a degenerate doublet structure with $\Delta I=2$ energy spacings as in the even-even core. However, this simple explanation faces the problem that no $K=1/2$ bands have been observed so far in the odd neighbors and there is no $K=1/2$ orbital close to the Fermi surface. The $11/2^+$ to $7/2^+$ energy difference of 353.9 keV in the g.s.b. of ^{99}Sr is also fairly close to the 6^- to 4^- energy difference of 356.2 keV in the $K^\pi=4^-$ band in ^{100}Sr. This can be written as $j_{\text{odd-}A,\text{odd-}A}=j_{\text{odd-}A}+1/2$. In both cases, the increase in transition energy due to the extra half-a-unit of spin [via the $I(I+1)$ term] is counteracted by the increase of the moment of inertia due to the additional unpaired neutron. These effects turn out to compensate almost perfectly, thus keeping the transition energies equal. *A priori*, there is no reason why this happens to be so. The increment of half-a-spin unit perhaps could indicate a treatment in the pseudospin framework as appropriate [46]. We also note that this simple rule includes the formerly reported identical bands with $\Delta A=2$, in which case there are no unpaired particles or one in both partners and the spins of the levels are the same.

We note a further trend towards identical energies in Sr and Zr isotopes by breaking a neutron pair. The deformation of ^{102}Zr is large ($\beta=0.38$ [47]) but, its moment of inertia still is significantly smaller than the one of ^{100}Sr [$E_{2^+}(^{102}\text{Zr})=151.9$ keV]. Nevertheless, the energies for the transitions in the two-quasineutron $K^\pi=4^-$ bands,

TABLE VI. Energies of transitions in the $K=5/2$ bands in $N=61$ and 63 Sr and Zr nuclei.

Nucleus	$E(7/2^- \rightarrow 5/2^-)$ [keV]	$E(9/2^- \rightarrow 7/2^-)$ [keV]	
^{99}Sr	111.9	147.6	this work
^{101}Sr	(111.6)		[6]
^{101}Zr	104.4	146.6	[37,39]
^{103}Zr	109.4	146.6	[39]

161.8 and 194.4 keV for ^{100}Sr and 159.3 and 194.4 keV for ^{102}Zr [29] are also similar, see Fig. 7. Breaking a neutron pair to form the 4^- isomer does not increase the already large moment of inertia of ^{100}Sr as much as the one of ^{102}Zr. Finally, the $K^\pi=5/2^-$ bands of odd-neutron nuclei tend to become identical at the largest deformations, as a further increase is expected at larger N for Zr isotopes. In particular, the $7/2^- \rightarrow 5/2^-$ energies of Zr isotopes come closer to the energies in Sr, see Table VI.

D. Ground states of ^{99}Rb and ^{100}Rb

According to the table of isotopes [14], the ground state of ^{99}Rb is $5/2^+$. This assignment is requested to account for sizable β feeding to the $7/2^+$ state of the g.s.b. of ^{99}Sr. However, the β-decay branching to the $5/2^+$ state is nonexistent. This pattern in contradiction with the Alaga rule (the 5/2 level is calculated to be 6 times more populated than the 7/2 state) casts some doubts about the reliability of intensity balances. In fact, systematics suggests $3/2^+$. For ^{97}Rb $I=3/2$ was measured by laser spectroscopy [48] and the decay of ^{101}Rb also suggested $I(^{101}\mathrm{Rb})=3/2$ [6]. The Nilsson scheme indeed predicts the [431]3/2 proton orbital to be the last one occupied for $Z=37$.

According to Ref. [9] the 4^- ground state of ^{100}Rb originates from the coupling of this [431]3/2 proton with the [532]5/2 neutron which is shown experimentally to be the ground state of $N=63$ isotones [6,38,39]. The Gallagher-Moszkowski rule [49] depresses the 4^- level with respect to its 1^- partner to create the 4^- ground state. From purely experimental considerations it is not possible to determine the spin of ^{100}Rb. Nevertheless, odd parity is in agreement with the large β feeding to the isomeric 4^- level in ^{100}Sr.

In addition, the existence of a low-spin isomer in ^{100}Rb has been conjectured as a source of feeding to low-spin levels in ^{100}Sr in addition to consequences of the low efficiency for detecting high-energy coincidence pairs. Another observation, less sensitive on the details of the level scheme, gives further support to this assumption. The P_n value cannot be calculated since the ground-state branch to ^{100}Sr cannot be measured. Nevertheless, $I^\pi=4^-$ for ^{100}Rb does not allow sizable g.s. feeding. In this case, a P_n value of 26(8)% is calculated by comparing the intensities of γ rays in ^{100}Sr and in $A=99$ activities. This is a subtantially higher value than obtained from direct neutron measurement yielding only about 6% [11]. Allowing nonzero ground-state feeding to ^{100}Sr, the calculated P_n value is lowered. This way, these values could come in better agreement.

The 1^- level from the $\pi[431]3/2 \otimes \nu[532]5/2$ coupling mentioned above could indeed be associated with this hypothetical isomer. First-forbidden decay could populate 2^+ states and also the tentative 0^+ state at 938 keV. Then, $\log ft$ values to 2^+ states would be only slightly too low, which is acceptable considering the uncertainties in γ-ray feedings by high-energy transitions. This is only one of the possible alternatives to generate low-spin and low-lying levels since there are several experimentally known low-lying neutron levels at $N=63$. Ultimately, the existence of an isomer depends on the presence at low energy of $I=(2,3)$ levels. The lowest lying level after the 4^- ground state is probably the 3^+ state built on $\pi[431]3/2 \otimes \nu[411]3/2$ since the [411]3/2 level is only a few hundred of keV above the ground state, e.g., 271 keV in ^{101}Sr [6] and 259 keV in ^{103}Zr [38]. The existence of a low-spin isomer thus critically depends on the amplitude of the Gallagher-Moszkowski splittings.

V. CONCLUSION

We have studied the decay of the very neutron-rich nucleus ^{100}Rb to its β daughter ^{100}Sr and β-n daughter ^{99}Sr. The level scheme of ^{100}Sr, a strongly deformed nucleus with very good rotational properties, has been considerably extended. Among the lowest-lying levels we have introduced two 2^+ states at 1257 and 1315 keV and a tentative 0^+ state at 938 keV, all smoothly extending the energy systematics of $N=62$ isotones. Yet the nature of members of β and γ bands or spherical intruder states is unknown and has to be investigated further. The identification of the 5^- and 6^- levels of the band built on the 85 ns $K^\pi=4^-$ isomer is suggested by transition energies and β-feeding intensities. It creates an appealing analogy with ^{102}Zr where a similar band is known from prompt fission. The large moment of inertia of the g.s. band and the low energy (1619 keV) of the 4^- isomer indicate a strong reduction of pairing with respect to the standard estimate. These features are more pronounced for ^{100}Sr than for its isotone ^{102}Zr. However, the transition energies of the 4^- two-quasineutron bands are nearly identical.

β-delayed neutron decay has allowed an extension of the [411]3/2 ground-state band in ^{99}Sr by adding the $11/2^+$ level assigned from energy fitting and branching ratios. Based on weaker arguments of β-n feedings and γ-ray branchings, the [532]5/2 orbital has been assigned to the 423 keV level, head of a band whose 7/2 and 9/2 levels are also observed.

The new transitions in ^{99}Sr and ^{100}Sr define a new group of transitions with very similar energies. All identical transitions in strontium isotopes appear to follow a simple rule given as $j_{n+1}=j_n+1/2$ where n is the number of unpaired neutrons and j the spin of the initial level. This extends the systematics of previously reported identical transitions in $\Delta A=2$ nuclei which are a particular case with the same number of unpaired neutrons. Moreover, with increasing neutron number (i.e., presumably of deformation), energies of the $5/2^-$ band members in odd-Zr isotopes tend to become close to those in Sr isotopes. These peculiarities are surely worth further investigation.

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