First β-decay scheme of ^{107}Nb: New insight into the low-energy levels of ^{107}Mo

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Monoisotopic samples of ^{107}Nb nuclei, produced in the proton-induced fission of ^{238}U and separated using the IGISOL mass separator coupled to a Penning trap, were used to perform β- and γ-coincidence spectroscopy of ^{107}Mo. Gamma transitions and excited levels in ^{107}Mo were observed in β decay for the first time. Spin and parity $1/2^+$ for the ground state of ^{107}Mo is proposed, to replace the previous $5/2^+$ assignment. The experimental β-decay half-life of ^{107}Nb was estimated to be 0.27 ± 0.02 s.

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I. INTRODUCTION

We report the first observation of the β decay of ^{107}Nb to ^{107}Mo. With 66 neutrons, $^{107}_{41}$Nb is located exactly at the neutron midshell and still far away from proton closed shell $Z = 50$. The theoretical predictions [1,2] for molybdenum isotopes around $N = 66$ suggest γ-soft triaxial minima around $\beta_2 \approx 0.3$, which can form ground-state levels. In molybdenum isotopes the competition between low-lying prolate and oblate minima is possible [1], and Hartree-Fock-Bogoliubov results predict an oblate ground state for ^{107}Mo [3]. Obviously input from experiments is still indispensable to test and tune the nuclear models.

The β^- decays of the lighter niobium isotopes were studied in the 1980s [4,5], though neither spins nor parities were proposed for the levels fed in their β decay. The information on spins and parities of excited states in molybdenum isotopes of mass $A = 103$–109 was deduced from subsequent experimental studies of γ cascades following spontaneous fission [4,6–8]. These works revealed a variety of band structures in neutron-rich, odd-A isotopes of molybdenum, leaving, however, some open questions.

Fission studies provide information on excitations close to the yrast line at medium-to-high spins. However, due to the complexity of prompt-γ radiation such measurements may show limitations at low-excitation and low-γ energies, because of high background in γ spectra. On the other hand, β^--decay measurements, usually performed in low-background environments often provide information on all low-spin levels in a nucleus. Importantly, the two techniques, which complement each other, can be used to study the same long chains of neutron-rich isotopes produced in fission of heavy nuclei.

Considering some unresolved questions concerning the structure of low-spin levels in ^{107}Mo, reported in Ref. [8], we reinvestigated this nucleus using very precise techniques. The present work reports the first study of excited levels in ^{107}Mo populated in the β^- decay of ^{107}Nb. The use in this work of the powerful Penning-trap separation technique in combination with the use of an array of high-resolution Ge detectors in coincidence with a β counter provided us with spectroscopy data of very low background. This enabled us to search for effects that might escape prompt-γ fission measurements. Indeed, in the present work we have identified a new ground state of ^{107}Mo, which resolves discrepancies encountered in the prompt-γ study [8].

In Sec. II the experimental techniques are described, and in Sec. III we present our experimental results. The results are discussed in Sec. IV, and the work is summarized in Sec. V.

II. EXPERIMENT

The ^{107}Nb nuclei were produced during fission of a natural uranium target, induced by 25-MeV protons from the K-130 cyclotron at the Accelerator Laboratory of the University of Jyväskylä. Fission products were on-line mass separated with the upgraded IGISOL-4 mass separator [9]. At first, a dipol magnet was used to select mass $A = 107$ isobars out of the bulk of fission fragments. The isobaric beam of singly ionized atoms from the IGISOL mass separator, formed into bunches in a radio-frequency cooler and buncher [10], was sent to the JYFLTRAP Penning trap for isobaric purification [11,12]. Figure 1 shows the frequency spectrum of 1^+ ions with mass $A = 107$ measured after the Penning trap using a microchannel plate (MCP) detector. The measurement was done as a function of the cyclotron frequency of ions inside the trap, $\omega_c = q \times B/m$, where q and m are the charge and the mass of an ion and B is the magnetic field inside the trap.

A monoisotopic beam of ^{107}Nb ions, released from the Penning trap, was implanted into a plastic, movable collection tape inside a vacuum chamber. The collection tape was moved at regular intervals of about 4 s to remove the background from long-lived activities. A 2-mm-thick plastic scintillator was mounted around the collection tape to register electrons from β decay. Three thin Kapton windows in the vacuum chamber reduced attenuation of low-energy γ

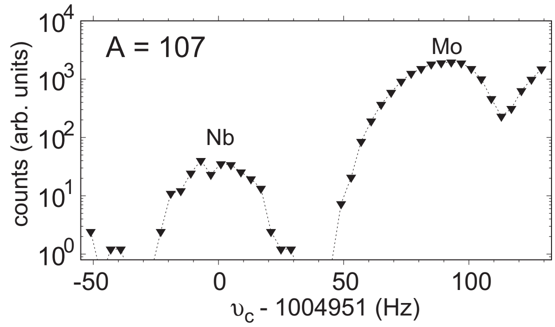

FIG. 1. Ion counts registered with a MCP detector placed after the Penning trap as a function of the purification frequency. The resolved atomic ions from the IGISOL isobaric beam are marked with their element symbols.

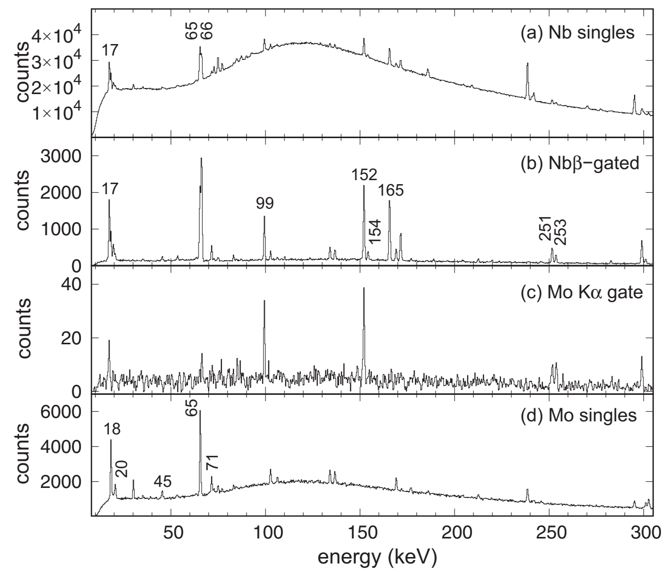

FIG. 2. Singles, β- and Mo(K_αX)-gated spectra registered in the LEGe detectors for the monoisotopic samples of ^{107}Nb (a)–(c) and monoisotopic samples of ^{107}Mo (d). The peaks are marked with their energies in keV.

radiation, which was registered by three low-energy Ge detectors (LEGe), placed at right angles to each other in one plane around the chamber, each facing a Kapton window of the chamber. Broad-energy Ge detectors of high-energy resolution (full width at half maximum of ≈ 0.5 keV at 20 keV) were used as the LEGe spectrometers.

Some of the data were recorded in a pulsed beam mode to enable measurement of β-decay half-lives. Each implantation period of ^{107}Nb samples was followed by a 0.89-s-long period when the beam was blocked to record decay of the collected source, then the tape was moved, and a new cycle started.

A short measurement in the same setup with the purification trap set to ^{107}Mo was also performed. The data set reveals γ lines in the $A = 107$ decay chain, except for those populated directly in the ^{107}Nb decay, helping to identify new lines following the β^- decay of ^{107}Nb.

The experimental data acquisition system, based on the digital gamma finder (DGF) modules, was recording data from all the detectors in a triggerless mode. Later off-line, data were time ordered and sorted into one- and two-dimensional coincidence histograms for further analysis.

III. RESULTS

^{107}Nb was identified for the first time by registration of K_α x rays of its Mo daughter in the $A = 107$ isobaric beam, on-line mass separated from fragments of ^{238}U fission [13]. In the same experiment a β-decay half-life of 330(50) ms was measured by observing the time distribution of β-gated K_α x rays. Transitions in ^{107}Mo were for the first time observed as prompt γ rays from spontaneous fission of ^{248}Cm [14]. Later the band structures in ^{107}Mo were extended during spontaneous fission of ^{252}Cf [15] and ^{248}Cm [7], studied by large arrays of germanium detectors.

In the present study we applied a multistage mass separation, using an electromagnetic separator coupled to a system of ion traps, to select nothing but the ^{107}Nb nuclei from the enormous amount of uranium fission fragments. A sophisticated way of discriminating between nuclei together with $\beta\gamma$ and $\gamma\gamma$ coincidences allowed an unambiguous identification of γ lines resulting from the β decay of ^{107}Nb.

Examples of γ spectra recorded with the LEGe detectors are presented in Fig. 2. A spectrum showing all the recorded events with no additional conditions (so-called singles spectrum) for the ^{107}Nb monoisotopic samples is highlighted in Fig. 2(a). The spectrum in Fig. 2(b) shows all γ events that are in coincidence with β events registered in the plastic scintillator. The coincidence with β particles enhances γ lines emitted from excited levels populated by β decay and suppresses other γ lines, for example, background radiation or isomeric transitions. One can see that the prominent natural background lines around 238 and 295 keV present in Fig. 2(a) are not visible in Fig. 2(b). Figure 2(c) shows γ lines in coincidence with the characteristic K_α radiation of molybdenum; thus one can identify transitions between the excited states in ^{107}Mo. Finally, Fig. 2(d) shows a γ spectrum for the monoisotopic samples of ^{107}Mo, which is one step closer to the β stability valley than ^{107}Nb. Comparing Figs. 2(a) and 2(d) one may identify γ lines belonging solely to the ^{107}Nb β decay, which are present only in Fig. 2(a).

Figure 3, which shows the high quality of our coincidence data from the decay of ^{107}Nb monoisotopic samples, illustrates the main result of our work. The spectra in Figs. 3(a) and 3(b) are gated by strong 99.5- and 152.2-keV γ lines, which belong to two different level structures in ^{107}Mo, reported in Refs. [7,8] on top of the $3/2^+$, 66.0-keV and the $5/2^+$ ground-state levels, respectively. Comparing the spectra in Figs. 3(a) and 3(b), one can see that there are two close-energy but separate γ lines of 65.4 and 66.3 keV. While the 66.0-keV level reported in Refs. [7,8], now placed at 66.3 keV, is confirmed as decaying by the 66.3-keV transition, the former ground state populated by the 152.1-keV transition (152.2-keV in the present work) decays further by the new 65.4-keV transition. Thus, the previous ground state of ^{107}Mo has to be shifted up in energy by 65.4 keV. We propose that

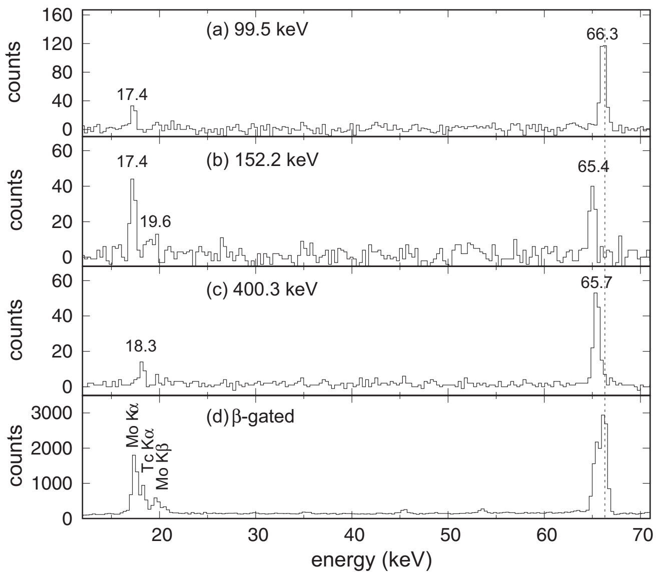

FIG. 3. Coincidence spectra for monoisotopic samples of ^{107}Nb (a)–(c) and the same energy range of β-gated spectrum for comparison (d). Energy in keV of a gating γ line is shown in each spectrum (a)–(c). The peaks are labeled with their energies in keV. A vertical dotted line is drawn to help resolve the 65–66 keV multiplet of γ lines.

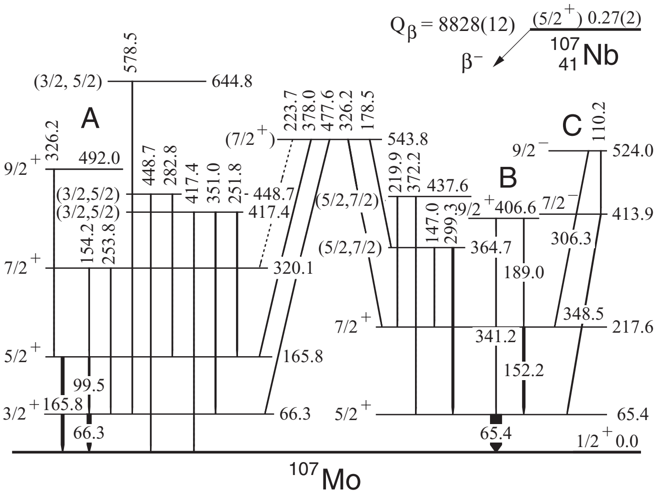

FIG. 4. β-decay scheme of ^{107}Nb. The line widths are approximately proportional to the intensities of the γ lines. The letters A, B, and C mark various band structures to facilitate the discussion. The half-life value is from this work, and the Q_β value (in keV) is from Ref. [18].

there is a new ground state in ^{107}Mo and the two discussed structures decay to this new ground state by the 66.3- and 65.4-keV transitions, respectively.

It should be mentioned that Ref. [8] reported a single 65.4-keV transition in ^{107}Mo, deexciting an isomeric level with a half-life of 420 ns proposed at 65.4 keV with spin-parity $1/2^+$. The multipolarity of the 65.4-keV transition was determined in Ref. [8] to be an $E2$ and the observed half-life indicates the stretched character of this transition. We propose that the 65.4-keV transition reported in Ref. [8] is the same as the 65.4-keV transition observed in the present work and that it deexcites the former $5/2^+$ ground state, now elevated to 65.4 keV, to the new $1/2^+$ ground state of ^{107}Mo.

An explanation is also in order concerning the known 65.8-keV transition in ^{107}Tc [16] populated in β decay of ^{107}Mo produced as a daughter of the decaying ^{107}Nb monoisotopic sources. A spectrum in Fig. 3(c) is gated by the 400.3-keV γ line, the strongest one fed by β decay of ^{107}Mo. The coincidence between the 400.3-keV line and the 65.7-keV line as well as the 18.3-keV x rays of Tc, seen in Fig. 3(c), distinguishes the 65.7-keV γ line from the 65.4- and 66.3-keV lines fed by the β decay of ^{107}Nb. Figure 3(d) shows a spectrum gated by β particles, where one can observe x rays produced by internal conversion processes in molybdenum and technetium nuclei as well as the overlapping γ lines of 65.4, 65.7, and 66.3 keV.

Energies, intensities, and coincidence relations for γ rays measured in this work are presented in Table I. Intensities of γ lines were estimated based on peak areas observed in singles γ spectra recorded with all three LEGe detectors. For γ lines not visible in the singles spectra, their intensities were estimated using coincidence spectra. The coincidence relations between γ lines fed in the β decay of ^{107}Nb were deduced from gated spectra similar to those shown in Figs. 2(c), 3(a), and 3(b). The compilation of $\gamma\gamma$ coincidence relations, shown in Table I, was used to construct the scheme of excited levels in ^{107}Mo, presented in Fig. 4.

The present work confirms the 65.4-, 66.3-, 99.5-, 110.2-, 152.2-, 154.3-, 165.8-, 189.0-, 253.8-, 306.3-, 326.2-, 341.2-, and 348.5-keV transitions reported in the spontaneous fission of ^{252}Cf [15] and ^{248}Cm [7,8,14] and in the fusion-fission study [6] and compiled in Ref. [16]. We also confirm coincidence relations reported in Ref. [16] with one important exception mentioned above, that the 65.4-keV line is in coincidence with the γ lines belonging to bands B and C in Fig. 4. In particular, our data indicate that the 152.2-, 341.2-, and 348.5-keV lines populate the 65.4-keV level and not the ground state. Consequently energies of the related excited levels are increased in our scheme by 65.4 keV, as compared to Ref. [16]. Thus the level scheme of ^{107}Mo reported in a recent ^{252}Cf spontaneous fission work [17] needs to be complemented with a 65.4-keV level as well. Interestingly, the 65.4-keV transition seems to be present in γ-ray coincidence spectra in Fig. 3(a) and in Fig. 4 reported in Ref. [17] (it is not labeled with an energy).

We estimated the K_α internal conversion coefficients (ICC) for low-energy γ lines in ^{107}Mo by comparing their γ intensities to the intensity of the 17.4-keV K_α molybdenum characteristic x-ray line produced in their conversion process. The total ICC for the 99.5-keV transition was estimated on the basis of intensity balance for 66.3- and 99.5-keV lines in γ-gated spectra. Our resulting values of ICC are presented in Table II.

Using data recorded in a pulsed-beam mode we measured half-lives of the three strongest γ lines and molybdenum x rays, populated in β decay. The decay patterns are presented in Fig. 5. A single-component exponential decay curve was fitted to each set of data points for the energies from 17.4 to

TABLE I. Energies, relative intensities I_γ, proposed multipolarities, placement in the scheme, and coincidence relations observed in the β^- decay of ^{107}Nb. The energies 17.4 and 19.6 keV are the K_α and K_β molybdenum characteristic x rays, respectively. The 18.3 keV energy is the K_α x ray of technetium. Energies of weak transitions are in parentheses.

E_γ (keV)	I_γ	Mult.	From	To	Coincident γ lines
17.4(1)					(65.4), 66.3, 99.5, 152.2, 178.5, 251.8, 253.8, 299.2, 326.2, 351.0, 372.2, 378.0
19.6(3)					66.3, 99.5, 152.2
65.4(2)[a]	77(11)	$E2$	65.4	0.0	18.3, 53.6,[a] 71.6,[a] 83.2,[a] 152.2, 299.3, 301.2,[a] (341.2), 354.7,[a] 358.7,[a] 372.2, 384.4,[a] 400.2,[a] 430.3,[a] 483.7, [a] 784.8[a]
66.3(1)	100(5)	$M1$	66.3	0.0	17.4, 99.5, 154.3, 251.8, 253.8, 326.2, 351.0, 378.0
99.5(1)	49(3)	$M1$	165.8	66.3	17.4, 66.3, 154.3, 251.8, 326.2, 378.0
110.2(1)	2.8(5)	$M1$	524.0	413.9	348.5
147.0(3)	2.2(5)	$M1$	364.5	217.6	
152.2(1)	94(5)	$M1$	217.6	65.4	17.4, 65.4, 147.0, 189.0, 326.2
154.3(2)	15(2)	$M1$	320.1	165.8	66.3, 99.5, 165.8
165.8(4)	99(5)	$E2$	165.8	0.0	154.3, 251.8, 282.8, 326.2, 378.0
178.5(4)	0.6(5)	($M1$)	543.8	364.7	
189.0(1)	2.8(7)	$M1$	406.6	217.6	152.2
219.9(2)	4.3(7)	$M1$	437.6	217.6	152.2
223.7(3)	1.6(4)	$M1$	543.8	320.1	(66.3), (253.8)
251.8(2)	40(3)	$M1$	417.4	165.8	17.4, 66.3, 99.5, 152.2, 165.8
253.8(6)	20(2)	$E2$	320.1	66.3	(17.4), 66.3, (223.7)
282.8(1)	8.0(9)	$M1$	448.7	165.8	
299.3(2)	76(5)	$M1$	364.5	65.4	17.4, 19.6, 65.4, 178.5
306.3(1)	3.5(7)	$E1$	413.9	217.6	152.2
326.2(3)	12(3)	$E2$	492.0	165.8	17.4, 66.3, 99.5, 152.2, 165.8 (branch of 66.3 keV)
326.2(3)	8(2)	($M1$)	543.8	217.6	17.4, 66.3, 99.5, 152.2, 165.8 (branch of 65.4 keV)
341.2(1)	10(1)		406.6	65.4	(17.4), 65.4
348.5(1)	35(3)	$E1$	413.9	65.4	65.4, 110.2
351.0(3)	44(4)	($M1$)	417.4	66.3	17.4, 66.3
372.2(2)	42(3)	($M1$)	437.6	65.4	17.4, 65.4
378.0(2)	21(2)	(M1)	543.8	165.8	66.3, 99.5, 165.8
417.4(3)	18(3)		417.4	0.0	
448.7(1)	31(3)		448.7	0.0	
477.6(2)	17(3)		543.8	66.3	(17.4), 66.3
578.5(5)	15(1.4)		644.8	66.3	17.4, 66.3

[a]Also in β decay of ^{107}Mo.

165.8 keV, as shown in Fig. 5. The half-lives resulting from fitting the decay curves are shown in the second column in Table II. The final half-life value of 0.27 ± 0.02 s for the β decay of ^{107}Nb was found as a weighted average of the half-lives in Table II.

The β feedings to the levels in ^{107}Mo were derived from intensity balances, calculated as the differences between γ intensities leaving and populating each of the levels. For the γ transition intensities of energy below 400 keV, the contribution from electron conversion was included. To find the internal conversion coefficients we assumed multipolarities of the γ transitions, as shown in the third column in Table I. These transition multipolarities were found in this work (see Table II), taken from the literature [4], and in other cases assumed as $M1$. The $\log_{10} ft$ values shown in Table III, based on the β feedings presented in the same table, were calculated with an on-line application (see Ref. [20]). Many weak transitions populating a level may escape detection (so-called pandemonium effect), so level feeding is overestimated. Consequently, the β feedings and $\log_{10} ft$ values given in Table III should be considered as the upper and the lower limits, respectively.

TABLE II. Properties of the selected γ transitions and Mo K_α x rays populated by the β^- decay of ^{107}Nb, from this work. The theoretical internal conversion coefficients are from Ref. [19].

E (keV)	Half-life (s)	α_K	α_{tot}	$\alpha^{\mathrm{theor}}_{K,\mathrm{tot}}$ $M1$	$\alpha^{\mathrm{theor}}_{K,\mathrm{tot}}$ $E2$	Mult.
17.4	0.29(4)					
65.4		3.7(6)		0.73	4.1	$E2$
66.3	0.28(4)	1.1(2)		0.70	4.0	$M1$
99.5			0.25(13)	0.25	1.2	$M1$
152.2	0.26(3)					
165.8	0.28(5)	0.35(18)		0.06	0.16	$E2$

IV. DISCUSSION

As mentioned above, new results obtained in the present work indicate that the $5/2^+$ level reported as the ground state in previous works is located at an excitation energy of

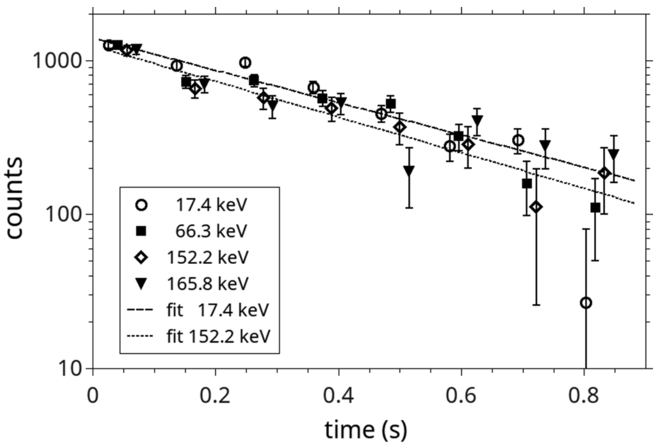

FIG. 5. Time decay pattern of molybdenum K_α x rays and the three strongest γ lines populated in β decay of ^{107}Nb. The fitted exponential decay curves are shown for the longest (17.4 keV) and shortest (152.2 keV) of our experimental half-lives, presented in Table II. Data points are slightly spread apart horizontally for better readability.

65.4 keV and is deexcited by an $E2$ transition to the new ground state. Assuming that the 65.4-keV level corresponds to the 420-ns isomer reported in Ref. [8], this $E2$ decay corresponds to a spin change of $\Delta I = 2$, indicating $1/2^+$ spin-parity for the new ground state.

Bands B and C shown in Fig. 4 were well described in Refs. [7,8,17] as the bands built on the $5/2^+$ and $7/2^-$ levels, respectively. This interpretation is not affected by the new results.

The $3/2^+$ level, reported at 66.0 keV in Refs. [7,8] as a bandhead level, retains its excitation energy (now 66.3 keV) but becomes the first excited level in the band based on the $1/2^+$ ground state. The new structure allows the problem of the high rate calculated in Ref. [8] for the 165.4-keV decay from the $(5/2^+)$ level at 165.4 keV to be resolved. Because the in-band $E2$ decay from the $5/2^+$, 165.8-keV level, proposed in the present work, the 165.8-keV transition may be stronger than the 99.5-keV decay branch, and the observed experimental branchings are in accordance with the predictions [8] for a $1/2^+$ band and are similar to the intensities observed in the $1/2^+$ band in ^{105}Mo (see Table IV). The spin sequence of 1/2, 3/2, and 5/2 in the discussed band is confirmed by experimentally determined multipolarities: $E2$ for the 165.8-keV transition and $M1$ for the 66.3- and 99.5-keV transitions, as shown in Table II.

TABLE III. The levels in ^{107}Mo fed in the β^- decay of ^{107}Nb, their β feeding intensities, and $\log_{10} ft$ values, from this work.

E_{level} (keV)	β feeding (%)	$\log_{10} ft$
0.0	0.0	–
65.4(1)	28(6)	5.27
66.3(1)	2.6(1.4)	6.30
165.8(1)	9.6(1.3)	5.71
217.6(1)	9.4(1.1)	5.71
320.1(1)	4.2(5)	6.04
364.7(1)	9(1)	5.68
406.6(1)	1.5(2)	6.46
413.9(1)	3.7(5)	6.07
417.4(1)	12(1)	5.56
437.6(1)	5.4(6)	5.90
448.7(1)	4.6(5)	5.97
492.0(2)	1.4(3)	6.47
524.0(1)	0.8(1)	6.71
543.8(1)	5.6(7)	5.86
644.8(1)	1.8(3)	6.33

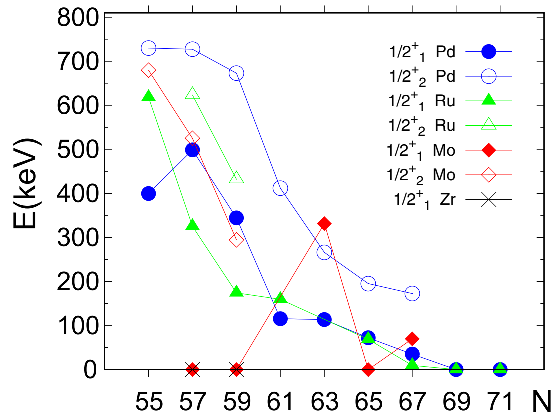

FIG. 6. Excitations energies of the first and the second $1/2^+$ levels in even-Z isotopes from zirconium to palladium, shown as a function of neutron number.

In Ref. [8] a low-energy $3/2^+$ bandhead was predicted. With the new ground-state band one has to find a new candidate for the $3/2^+$ bandhead. The lowest-energy candidate is observed in this work only at 364.7 keV, and there is no clear band structure on top of it.

The experimental feeding intensity to an excited level observed in β decay constitutes an upper limit. The available data on the niobium ground states [4], for $^{101-105}$Nb and ^{109}Nb, suggest $5/2^+$ spin-parity. Thus based on the systematics one can assume $5/2^+$ for the ground state of ^{107}Nb. Our β-feeding intensities listed in Table III show population of both $9/2^+$ and $9/2^-$ levels, which suggests spin-parity $7/2^+$ for the decaying level in ^{107}Nb. This is supported by the relatively low population of the $3/2^+$ level at 66.3 keV, which would receive higher feeding were the spin of ^{107}Nb lower. For the ^{107}Nb to ^{107}Mo β decay the $7/2^+$ spin-parity of the decaying state provides, in general, a better explanation of the feeding to final states than the $5/2^+$ spin-parity suggested by the systematics in the neighboring niobium isotopes.

Figure 6 shows the systematics of the first $1/2^+_1$ and the second $1/2^+_2$ excited levels in even-Z isotopes from zirconium to palladium. For Pd and Ru, the systematics change smoothly and the levels' energies are decreasing with increasing number of neutrons. For isotopes of Zr and Mo, the $1/2^+$ levels are the ground states or are located close to them. An exception in the systematics of Fig. 6 is ^{105}Mo with its $5/2^-$ ground state and the $1/2^+$ levels that do not follow the trend.

In the ^{107}Mo level scheme presented in this work, we changed the spin of the isomeric state proposed in Ref. [8] to

TABLE IV. Comparison of the experimental γ-ray transition intensities between low-lying levels in ^{105}Mo and ^{107}Mo. I^{π} is the spin and parity of the depopulated nuclear level, whose energy is given in column E_{level}.

	^{105}Mo					^{107}Mo				
I^{π}	E_{level} (keV)	E_{γ} (keV)	I_{γ} [8]	I_{γ} [21]	Mult.	E_{level} (keV)	E_{γ} (keV)	I_{γ} [8]	I_{γ} This work	Mult.
$5/2^+$	524.5	127.8	2.3(4)	0.4(1)	$M1$	165.8	99.5	100	49(3)	$M1$
		192.7	2.7(4)	1.6(2)	$E2$		165.8	163(28)	99(5)	$E2$
$7/2^+$	663.1	138.3		0.3(1)	$M1$	320.1	154.3	100	15(2)	$M1$
		266.6		3.4(3)	$E2$		253.8	113(15)	20(2)	$E2$
$9/2^+$	881.0	217.9		< 0.1	$M1$	491.7	171.9	31(6)		$M1$
		356.2		1.7(2)	$E2$		226.3	100		$E2$

$5/2^+$ and the ground state to $1/2^+$. One may ask if a similar situation occurs in ^{109}Mo. The microsecond isomer deexciting by an $E2$ transition, reported in Ref. [22], could be ascribed spin-parity $5/2^+$ and the ground state of ^{109}Mo spin-parity $1/2^+$. The $5/2^+$ band reported in Ref. [23] would then be based on the microsecond isomer.

V. SUMMARY

The present work extends results on ^{107}Mo obtained from measurements of prompt γ rays following fission, collected using large arrays of Ge spectrometers, with new data on low-spin excitations, obtained from measurement of γ radiation following the β^- decay of monoisotopic samples of ^{107}Nb. Both types of data complement each other, as demonstrated earlier [24–26]. The measurement of the β^- decay of ^{107}Nb, performed for the first time, revealed new transitions and excited levels in ^{107}Mo, in particular, establishing a new, $1/2^+$ ground state of ^{107}Mo. It was found that the 420-ns isomer proposed earlier at 65.4 keV with spin-parity $1/2^+$ [8] corresponds to the $5/2^+$ band head located 65.4 keV above the $1/2^+$ ground state. These changes do not alter the conclusions on the properties of the bands based on the $5/2^+$ and $7/2^-$ levels reported in Refs. [7,8,17]. Our results, together with those reported in Refs. [7,8], allowed us to identify a band based on the $1/2^+$ ground state, removing some discrepancies between experiment and calculations reported in Ref. [8].

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[1] J. Skalski, S. Mizutori, and W. Nazarewicz, Nucl. Phys. A **617**, 282 (1997).
[2] F. R. Xu, P. M. Walker, and R. Wyss, Phys. Rev. C **65**, 021303(R) (2002).
[3] S. Hilaire and M. Girod, Eur. Phys. J. A **33**, 237 (2007).
[4] Evaluated Nuclear Structure Data File at www.nndc.bnl.gov.
[5] K. Shizuma, H. Ahrens, J. P. Bocquet, N. Kaffrell, B. D. Kern, H. Lawin, R. A. Meyer, K. Sistemich, G. Tittel, and N. Trautmann, Z. Phys. A **315**, 65 (1984).
[6] H. Hua, C. Y. Wu, D. Cline, A. B. Hayes, R. Teng, R. M. Clark, P. Fallon, A. Goergen, A. O. Macchiavelli, and K. Vetter, Phys. Rev. C **69**, 014317 (2004).
[7] W. Urban, T. Rząca-Urban, J. A. Pinston, J. L. Durell, W. R. Phillips, A. G. Smith, B. J. Varley, I. Ahmad, and N. Schulz, Phys. Rev. C **72**, 027302 (2005).
[8] J. A. Pinston, W. Urban, C. Droste, T. Rząca-Urban, J. Genevey, G. S. Simpson, J. L. Durell, A. G. Smith, B. J. Varley, and I. Ahmad, Phys. Rev. C **74**, 064304 (2006).
[9] I. Moore, T. Eronen, D. Gorelov, J. Hakala, A. Jokinen, A. Kankainen, V. Kolhinen, J. Koponen, H. Penttilä, I. Pohjalainen, M. Reponen, J. Rissanen, A. Saastamoinen, S. Rinta-Antila, V. Sonnenschein, and J. Äystö, Nucl. Instrum. Methods Phys. Res., Sect. B **317**, 208 (2013).
[10] A. Nieminen, J. Huikari, A. Jokinen, J. Äystö, P. Campbell, and E. Cochrane, Nucl. Instrum. Methods Phys. Res., Sect. A **469**, 244 (2001).
[11] T. Eronen, V. S. Kolhinen, V.-V. Elomaa, D. Gorelov, U. Hager, J. Hakala, A. Jokinen, A. Kankainen, P. Karvonen, S. Kopecky, I. D. Moore, H. Penttilä, S. Rahaman, S. Rinta-Antila, J. Rissanen, A. Saastamoinen, J. Szerypo, C. Weber, and J. Äystö, Eur. Phys. J. A **48**, 46 (2012).
[12] V. S. Kolhinen, T. Eronen, D. Gorelov, J. Hakala, A. Jokinen, K. Jokiranta, A. Kankainen, M. Koikkalainen, J. Koponen, H. Kulmala *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **317**, 506 (2013).
[13] J. Äystö, A. Astier, T. Enqvist, K. Eskola, Z. Janas, A. Jokinen, K.-L. Kratz, M. Leino, H. Penttilä, B. Pfeiffer, and J. Żylicz, Phys. Rev. Lett. **69**, 1167 (1992).
[14] M. A. C. Hotchkis, J. L. Durell, J. Fitzgerald, A. S. Mowbray, W. R. Phillips, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, E. F. Moore, L. R. Morss, Ph. Benet, and D. Ye, Nucl. Phys. A **530**, 111 (1991).

[15] J. K. Hwang, A. V. Ramayya, J. H. Hamilton, L. K. Peker, J. Kormicki, B. R. S. Babu, T. N. Ginter, G. M. Ter-Akopian, Yu. Ts. Oganessian, A. V. Daniel *et al.*, Phys. Rev. C **56**, 1344 (1997).
[16] J. Blachot, Nucl. Data Sheets **109**, 1383 (2008).
[17] J. Marcellino, E. H. Wang, C. J. Zachary, J. H. Hamilton, A. V. Ramayya, G. H. Bhat, J. A. Sheikh, A. C. Dai, W. Y. Liang, F. R. Xu, J. K. Hwang, N. T. Brewer, Y. X. Luo, J. O. Rasmussen, S. J. Zhu, G. M. Ter-Akopian, and Y. T. Oganessian, Phys. Rev. C **96**, 034319 (2017).
[18] M. Wang, G. Audi, F. Kondev, W. Huang, S. Naimi, and X. Xu, Chin. Phys. C **41**, 030003 (2017).
[19] T. Kibèdi, T. W. Burrows, M. B. Trzhaskovskaya, P. M. Davidson, and C. W. Nestor, Jr., Nucl. Instrum. Methods Phys. Res., Sect. A **589**, 202 (2008).
[20] National Nuclear Data Center, www.nndc.bnl.gov
[21] H. B. Ding, S. J. Zhu, J. H. Hamilton, A. V. Ramayya, J. K. Hwang, K. Li, Y. X. Luo, J. O. Rasmussen, I. Y. Lee, C. T. Goodin, X. L. Che, Y. J. Chen, and M. L. Li, Phys. Rev. C **74**, 054301 (2006).
[22] D. Kameda, T. Kubo, T. Ohnishi, K. Kusaka, A. Yoshida, K. Yoshida, M. Ohtake, N. Fukuda, H. Takeda, K. Tanaka *et al.*, Phys. Rev. C **86**, 054319 (2012).
[23] W. Urban, C. Droste, T. Rząca-Urban, A. Złomaniec, J. L. Durell, A. G. Smith, B. J. Varley, and I. Ahmad, Phys. Rev. C **73**, 037302 (2006).
[24] J. Kurpeta, W. Urban, C. Droste, A. Płochocki, S. G. Rohoziński, T. Rząca-Urban, T. Morek, L. Próchniak, K. Starosta, J. Äystö, H. Penttilä, J. L. Durell, A. G. Smith, G. Lhersonneau, and I. Ahmad, Eur. Phys. J. A **33**, 307 (2007).
[25] J. Kurpeta, W. Urban, A. Płochocki, J. Rissanen, J. A. Pinston, V.-V. Elomaa, T. Eronen, J. Hakala, A. Jokinen, A. Kankainen, P. Karvonen, I. D. Moore, H. Penttilä, A. Saastamoinen, C. Weber, and J. Äystö, Phys. Rev. C **84**, 044304 (2011).
[26] J. Kurpeta, W. Urban, A. Płochocki, T. Rząca-Urban, A. G. Smith, J. F. Smith, G. S. Simpson, I. Ahmad, J. P. Greene, A. Jokinen, and H. Penttilä, Phys. Rev. C **90**, 064315 (2014).