Low-lying level structure of the neutron-rich nucleus ^{109}Nb : a possible oblate-shape isomer

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Abstract

The neutron-rich nuclei ^{109}Nb and ^{109}Zr have been populated using in-flight fission of a ^{238}U beam at 345 MeV/nucleon at the RIBF facility. A $T_{1/2} = 150(30)$ ns isomer at 313 keV has been identified in ^{109}Nb for the first time. The low-lying levels in ^{109}Nb have been also populated following the β -decay of ^{109}Zr . Based on the difference in feeding pattern between the isomeric and β decays, the decay scheme from the isomeric state in ^{109}Nb was established. The observed hindrances of the electromagnetic transitions deexciting the isomeric state are discussed in terms of possible shape coexistence. Potential energy surface calculations for single-proton configurations predict the presence of low-lying oblate-deformed states in ^{109}Nb .

Keywords: ^{109}Nb , Isomer, Oblate deformation, Shape coexistence

Atomic nuclei which have two or more local minima in their potential energy surfaces exhibit shape coexistence phenomena. Such situations depend on a delicate balance between the macroscopic (collective) and microscopic (single-particle) energies, susceptible to the constituent protons and neutrons occupying different quantized orbits in each nucleus. Furthermore, the rotational motion can affect the equilibrium shape of the nucleus through the Coriolis force, which aligns the angular momenta of the orbiting nucleons along the rotation axis. Thus, a shape phase transition can take place with changing the number of protons and neutrons, the excitation energy, and the nuclear spin.

In general, radioactive decay that involves a significant change in the nuclear shape is strongly hindered because of a considerable difference in the intrinsic structure between the initial and final states, resulting in long-lived excited states, so-called shape isomers. A recent global study of the nuclear potential energies calculated in a macroscopic-microscopic model [1] indicates where the coexistence of different shapes occur, i.e., where the shape isomers can exist over a broad range of nuclides. Of particular interest in the shape isomerism are the characteristics of well-deformed oblate shapes, which occur rarely in nature, in contrast to the large abundance of prolate-deformed shapes. Experimentally, prolate-oblate shape coexistence has been observed in the $A \approx 70$ region close to the $N = Z$ line [2, 3, 4, 5] and in the neutron-deficient $A \approx 190$ region [6]. In comparison with these regions, theoretical calculations [7, 8] predict more stable oblate shapes in the neutron-rich $A \approx 110$ region, where the Fermi surfaces for protons and neutrons lie at the upper halves of the respective major shells. This oblate stability is expected to be enhanced by the rotation alignment of both types of nucleons in the high- j orbits [8]. Indeed, it is expected that the competition of shell gaps corresponding to prolate, oblate, and spherical shapes in this region, for both protons and neutrons, can lead to the nuclear shape being sensitive to the addition or removal of only a few nucleons. The $A \approx 110$ region thus serves as a benchmark for testing model calculations. In spite of such theoretical interest, spectroscopic information on the excited states remains scarce due to the difficulties involved in accessing this region, which lies far from the β -stability line. However, the recent development of more intense radioactive isotope (RI) beams, in combination with in-flight fission of uranium, enables

one to populate such exotic nuclei for spectroscopic studies.

A major aim of the present research is the experimental study of nuclear structure of neutron-rich nuclei in the $A \approx 110$ region, with particular attention to the coexistence of prolate and oblate shapes. One type of the experimental evidence for shape coexistence in even-even nuclei is the identification of low-lying excited 0^+ states [9]. In the case of odd- A isotopes, the unpaired nucleon couples to the even-even core and can be manifested as low-lying levels arising from the Nilsson orbits characteristic of the corresponding deformations. In this article, we focus on ^{109}Nb , in which a new isomeric state has been identified. Additional selectivity for the excited states can be provided by the observation of isomeric decay that is sensitive to the level structure.

Experimental studies of low-lying levels in ^{109}Nb were carried out at the RI Beam Factory (RIBF) facility [10] at RIKEN Nishina Center. Neutron-rich $Z \approx 40$, $A \approx 110$ nuclei were populated via in-flight fission of $^{238}\text{U}^{86+}$ projectiles at 345 MeV/nucleon, incident on a beryllium target with a thickness of 3 mm. The average beam intensity was approximately 0.3 pnA during the experiment. The nuclei of interest were separated and transported through the BigRIPS spectrometer [11], operated with a 6-mm-thick wedge-shaped aluminum degrader at the first dispersive focal plane for purification of the secondary beams. An additional degrader placed at the second dispersive focus served as a charge stripper to remove fragments that were not fully stripped. The identification of nuclei by their atomic number (Z) and the mass-to-charge ratio (A/Q) was achieved on the basis of the ΔE -TOF- $B\rho$ method, in which the energy loss (ΔE), time of flight (TOF), and magnetic

rigidity ($B\rho$) were measured using the focal plane detectors in the beam line. A particle identification (PID) spectrum obtained in the present work is displayed in Fig. 1. The techniques of PID and a layout of the beam line are described in detail in Ref. [12].

An aluminum degrader of uniform thickness was employed to slow down the identified fragments. The transmitted ions were implanted into an active stopper consisting of nine double-sided silicon-strip detectors (DSSSD) stacked compactly. Each DSSSD has a 1-mm-thick silicon wafer with a 50 mm $\times$ 50 mm active area segmented into sixteen strips on both sides in the vertical and horizontal dimensions. The DSSSDs also serve as detectors for electrons following β -decay and internal-conversion processes. Gamma rays were detected by four Compton-suppressed Clover-type Ge detectors and a LaBr₃(Ce) detector arranged around the DSSSD telescope in a close geometry. The full-energy peak efficiency at 300 keV was 3 % for the given arrangement of the four Clover detectors. The beam-particle, electron, and γ -ray events were time-stamped and recorded by independent data-acquisition systems.

For the analysis of isomeric γ rays, the γ -ray data sets were combined with those of the beam fragments on an event-by-event basis using information on the time stamp. The beam- γ data assemblies were sorted into two-dimensional matrices which consist of time differences between the identified particle and the detected γ radiation ranging from 0 to 50 μ s on one axis and γ -ray energies on the other. A total of 2.3×10^5 ^{109}Nb fragments were identified in the present analysis (see Fig. 1). The origin of the time distribution was defined as the detection of the fragment using a plastic scin-

tillation counter placed at the end of the beam line. Information on isomeric lifetimes was derived from time projections with gates on characteristic γ rays.

All data sets containing beam, β , and γ events were used for β - γ analyses. The implantation of an identified particle was associated with the following β -decay events that were detected in the same DSSSD pixel. β -decay half-lives were extracted from the time distributions of β -gated γ -ray events relative to the fragment implantation. A total of 2.1×10^3 ^{109}Zr ions were implanted into the DSSSDs throughout the experiment.

Prior to the present work, nothing has been reported on excited states in ^{109}Nb . As shown in Fig. 2(a), the γ rays at energies of 117, 196, and 313 keV have been unambiguously identified in delayed coincidence with ^{109}Nb ions. Transitions of the same energy were confirmed recently using a passive stopper [13] in work carried out at the RIBF facility independently of the present study. These three transitions were found to exhibit similar time behavior in the nanosecond range, suggesting that they originate from the same isomeric state. Figure 2(c) exhibits the sum of three time spectra relative to the implantation of ^{109}Nb , from which a half-life of 150(30) ns was deduced. The measured isomeric half-life is significantly shorter than the flight time of fragments from the production target to the implantation position (~ 715 ns). However, the in-flight half-life would be longer than that measured at rest, since the isomeric decay proceeding by internal conversion is suppressed in the fully stripped ions [14].

As can be seen in Fig. 2(b), the 117-keV line was clearly identified in a β -gated γ -ray spectrum following the decay of ^{109}Zr , while the other two tran-

sitions might be populated very weakly. Based on the difference in feeding pattern between the isomeric and β decays, the 117-keV transition is assigned as feeding the ground state in ^{109}Nb . It was difficult to deduce the half-life of the β -decay parent ^{109}Zr from the time distribution created with a gate on the 117-keV line due to the scarcity of statistics. However, the independent analysis of β -decay half-lives yields $T_{1/2} = 63_{-17}^{+38}$ ms for ^{109}Zr [15].

Based on the consistency in energy with the level at 313 keV, we propose the decay scheme from the $T_{1/2} = 150(30)$ ns isomeric state in ^{109}Nb shown in Fig. 3; no spins and parities could be assigned for the levels in the present work. In Fig. 2(a), the efficiency-corrected intensities for the 117- and 196-keV lines relative to the 313-keV γ ray are 76(28) and 61(24) %, respectively. The isomeric ratio can be determined to be about 10 % by dividing the isomeric yield, which is deduced from the observed γ -ray intensities and corrected for in-flight decay losses, by the total number of the ^{109}Nb ions.

Before discussing the structure of ^{109}Nb , it is worth noting the properties of low-lying levels in the lighter Nb isotopes with odd mass. As observed for the neighboring Zr nuclei, it is known that the Nb isotopes also exhibit a sudden onset of quadrupole collectivity at $N = 60$ [16]. The deformation has been determined to be $\beta_2 = 0.40(4)$ and $0.31(4)$ for the ground-state bands in ^{101}Nb [16] and ^{103}Nb [17], respectively, from the measured partial half-lives for the $E2$ components of the intraband transitions. While the ground state in ^{101}Nb , ^{103}Nb , and ^{105}Nb was tentatively assigned as $I^\pi = 5/2^+$ originating from the $5/2^+[422]$ proton orbit, the two side-bands in ^{101}Nb and ^{103}Nb were interpreted as being built on the $3/2^-[301]$ and $5/2^-[303]$ configurations. The assignment of spins and parities for the band heads was based on the

extraction of the quantity $(g_K - g_R)/Q_0$ from the experimental $E2/M1$ mixing ratios for the $\Delta I = 1$ intraband transitions [18]. In both ^{101}Nb and ^{103}Nb , the $K^\pi = 3/2^-$ and $5/2^-$ band heads were identified at around 200 keV, and decay via "normally-retarded" $E1$ transitions to the ground state with transition strengths of the order of 10^{-5} W.u. [16, 17].

In ^{109}Nb , the isomeric state is identified at 313 keV. This energy is much less than the pairing gaps for both protons and neutrons ($2\Delta_\pi = 2.5$ MeV and $2\Delta_\nu = 2.1$ MeV, extracted from experimental odd-even mass differences [19] using the formulas given in Ref. [20]), indicating that this isomer should have a single-proton configuration. With deduced γ -ray intensities for the two branches from the $T_{1/2} = 150(30)$ ns isomer, the transition strengths for possible multipolarities are evaluated in Table 1. The total conversion coefficients calculated by the code BrIcc [21] are taken into account in the evaluation. This procedure virtually rules out $M2$ and higher-multipole possibilities for both the 313- and 196-keV transitions because their strengths exceed a recommended upper limit for each multipolarity [22]. Although $E1$ transitions could occur with large hindrances relative to the Weisskopf single-particle estimate, the $B(E1)$ values for the γ rays deexciting the isomer in ^{109}Nb would be two or three orders of magnitude smaller than the $E1$ strengths observed for ^{101}Nb and ^{103}Nb [16, 17], as was mentioned in the last paragraph. In a similar way, the isomeric-decay transitions would be extremely retarded given an $M1$ multipolarity, that might be unlikely to take place as the main decay branch if the isomer were similar in structure to the states to which the isomer decays. Assuming that the isomeric decay transitions are of $E2$ character, the implied transition probabilities are 0.024

and 0.15 W.u. for the 313- and 196-keV γ rays, respectively.

A possible explanation for the occurrence of electromagnetic transitions with strong hindrances in odd-proton nuclei below $Z = 50$ may be given in terms of intruder states built on the $1/2^+[431]$ proton orbit, which originates from the $\pi d_{5/2}$ and $\pi g_{7/2}$ subshells above the $Z = 50$ shell gap and falls down very rapidly with increasing prolate deformation. With a large negative decoupling parameter, the $3/2^+$ band member lies below the $I^\pi = K^\pi = 1/2^+$ level. Such intruder levels have been systematically observed for odd- A $_{49}\text{In}$ [23], $_{47}\text{Ag}$ [23, 24], $_{45}\text{Rh}$ [25, 26, 27, 28], and $_{43}\text{Tc}$ [29] isotopes, but not for $_{41}\text{Nb}$ isotopes. It is well known, from previous studies of the intruder states in these nuclei, that the transitions from the members of the intruder band to the normal states, the origin of which is $\pi g_{9/2}$, $\pi f_{5/2}$, or $\pi p_{3/2}$ subshells, are strongly hindered, e.g., $B(E1) = 5.8 \times 10^{-7}$ W.u. for the $3/2^+ \rightarrow 3/2^-$ transition in ^{107}Tc [29] and $B(E2) = 1.2 \times 10^{-2}$ W.u. for the $3/2^+ \rightarrow 7/2^+$ transition in ^{111}Rh [27]. As reviewed in detail in Ref. [23], such retarded electromagnetic transitions are one of the fingerprints of the coexistence between rather spherical and largely prolate-deformed shapes. However, we would expect that the isomeric state identified in ^{109}Nb is different from the intruder state of this kind. This assertion is justified for the following reason:

The excitation energies of the intruder bands reach a minimum at $N = 66$ for $_{47}\text{Ag}$ isotopes [24], but shift to $N = 64$ for $_{45}\text{Rh}$ and $_{43}\text{Tc}$ isotopic chains [27, 29]. It is generally expected that the minimum excitation energy corresponds to the maximum quadrupole deformation of the intruder configuration for a sequence of isotopes on account of the prolate-driving effects of

the $1/2^+[431]$ orbit. For $_{41}\text{Nb}$ isotopes, inspection of the $E(4^+)/E(2^+)$ ratio in the even-even neighbours $_{42}\text{Mo}$ and $_{40}\text{Zr}$ [30] suggests the largest deformation to occur at around $N = 64$. Therefore, if the $T_{1/2} = 150$ ns isomer in ^{109}Nb were of such intruder nature, the analogous isomers would rather appear at excitation energies below 313 keV in the lighter odd- A Nb isotopes with $N \approx 64$, probably leading to longer half-lives due to the lower transition energy; this condition would usually enable the identification of the isomeric state. However, the analogous structures could not be found in ^{107}Nb and the lighter isotopes, despite the sufficient population of ^{107}Nb achieved in the present measurement (see Fig. 1).

There is another argument suggesting a different solution for the observed transition hindrances in ^{109}Nb . In the region of interest, as pointed out in the introduction, an oblate-deformed shape is expected to coexist with a prolate-deformed shape. A model calculation based on the explicit energy minimization at axial shape [7] predicts that the phase transitions between prolate and oblate shapes occur around $N \approx 72$ in $_{40}\text{Zr}$ and $N \approx 66$ in $_{42}\text{Mo}$ isotopes, presumably implying the occurrence of prolate-oblate shape coexistence between these neutron numbers in the intermediate $_{41}\text{Nb}$ isotopes.

A consideration of the Nilsson diagram (e.g. Fig. 1 in Ref. [8]) indicates that the single-proton levels expected near the Fermi surface for $Z = 41$ are the $\Omega^\pi = 7/2^+, 9/2^+$ orbits arising from the $\pi g_{9/2}$ subshell and the $\Omega^\pi = 1/2^-, 3/2^-$ orbits from the $\pi p_{3/2}$ and $\pi f_{5/2}$ subshells, if the nucleus has an oblate shape with $\beta_2 \approx -0.23$. The configuration-constrained method [31] was employed to calculate potential energy surfaces (PES) of the single-proton configurations and to compare the excitation energies. The calculated

quasiparticle energies depend on the correct order and spacing of single-particle levels around the Fermi surface. It is known that the Woods-Saxon potential gives realistic values, though uncertainties in the region of 100 keV can be expected. The configuration-constrained PES calculation then allows us to determine the intrinsic shapes for specific configurations, each of which contains the effects of blocking and polarisation of the unpaired nucleon.

In Fig. 4, the PES calculations for selected orbits exhibit two coexisting minima at prolate ($\gamma \approx 0^\circ$) and oblate ($\gamma \approx -60^\circ$) deformation. The calculated deformation parameters and level energies, which correspond to the respective PES minima, are summarized in Table 2. The PES calculation suggests that the lowest-lying oblate-deformed state has the $7/2[413]$, $K^\pi = 7/2^+$ configuration. Note that the calculation predicts the prolate $3/2[301]$, $K^\pi = 3/2^-$ configuration to be the lowest state, while the ground state is expected to have spin and parity of $5/2^+$ from the systematics for the Nb isotopes with odd mass [19]. Based on the argument on the transition strengths as already discussed, a $7/2^+ \rightarrow 3/2^-$, $M2$ transition is unlikely. Assuming the spin and parity of the isomeric state to be $7/2^+$, the ground state is more likely to have $5/2^+$ or $5/2^-$. Irrespective of the spin and parity of the low-lying states, the electromagnetic transitions that deexcite the oblate-deformed state should be strongly inhibited due to the substantial shape change involved in its decay.

In conclusion, the level structure of ^{109}Nb has been investigated by means of β - γ and isomer spectroscopy with in-flight fission of a ^{238}U beam at 345 MeV/nucleon. A new $T_{1/2} = 150(30)$ ns isomer was identified at an excitation energy of 313 keV, which is much below the pairing gap energies for both

protons and neutrons, suggesting a single-proton configuration for the isomeric state. The transitions that depopulate the isomeric state are found to be strongly hindered, being presumably ascribed to a significant difference in shape between the isomeric state and the states to which the isomer decays. Configuration-constrained potential energy surface calculations were carried out for possible single-proton configurations; an oblate-deformed state based on the $7/2[413]$, $K^\pi = 7/2^+$ single-proton configuration is predicted at low excitation energy, comparable to that of the observed isomeric state.

We propose that the isomer identified in ^{109}Nb may be an oblate-deformed state; this may be the first experimental indication of a shape isomer being attributable to stable-oblate deformation at low excitation energy in the neutron-rich $A \sim 110$ region. To confirm the oblate shapes and associated single-particle orbits, the measurement of quadrupole moments and g -factors will be required in future experiments. In addition, the combination of spin-parity assignments and the transition hindrances discussed here will complete the argument on the prolate-oblate shape coexistence. It is also of great interest to observe the rotational bands above the isomeric state.

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Figure 1: (Color online) Particle identification plot with the atomic number (Z) vs. the mass-to-charge ratio (A/Q) obtained in the present work using a ^{238}U beam at 345 MeV/nucleon. The $A = 109$ isobars ^{109}Nb and ^{109}Zr are indicated with circles.

Figure 2: γ -ray spectra measured (a) with a particle gate on ^{109}Nb within 150–750 ns and (b) in coincidence with β rays detected within 0–170 ms after implantation of ^{109}Zr . The inset (c) shows the time distribution and associated fit for γ -ray coincidence events relative to the beam implantation with a sum of gates on the 117-, 196-, and 313-keV transitions in ^{109}Nb in the nanosecond range.

Figure 3: Partial level scheme of ^{109}Nb established in the present work. The widths of arrows represent relative intensities of γ rays extracted from a particle-gated γ -ray spectrum shown in Fig. 2(a).

Figure 4: Potential energy surface plots in the β_2 - γ plane for selected single-proton configurations in ^{109}Nb . The energy contour lines are drawn at 200-keV intervals. Each panel shows the calculation for the prolate $K^\pi = 3/2^-$ state (top left); the oblate $K^\pi = 3/2^-$ state (bottom left); the prolate $K^\pi = 7/2^+$ state (top right); and the oblate $K^\pi = 7/2^+$ state (bottom right). The prolate and oblate energy minima are indicated with filled circles. The calculated deformations and excitation energies are listed in Table 2.

Table 1: γ -ray relative intensities and $B(\sigma\lambda)$ values for transitions depopulating the $T_{1/2} = 150(30)$ ns isomeric state in ^{109}Nb , assuming different multipolarities.

E_γ (keV)	I_γ relative	$B(\sigma\lambda)$ (W.u.)				
		$E1$	$M1$	$E2$	$M2$	$E3$
313.1	62(20)	$3.9(13) \times 10^{-8}$	$2.9(10) \times 10^{-6}$	$2.4(8) \times 10^{-2}$	1.8(6)	$2.3(7) \times 10^4$
196.3	38(14)	$1.0(4) \times 10^{-7}$	$7.2(26) \times 10^{-6}$	$1.5(5) \times 10^{-1}$	$1.1(4) \times 10^1$	$1.2(4) \times 10^4$

Table 2: Calculated energies and deformation parameters for single-proton levels in ^{109}Nb .

	K^π	Main configuration	β_2	β_4	γ	E_{ex} (keV)
Prolate	$3/2^-$	$3/2[301]$	0.324	-0.030	0°	0
	$1/2^+$	$1/2[431]$	0.364	-0.028	0°	96
	$5/2^-$	$5/2[303]$	0.313	-0.026	0°	310
	$7/2^+$	$7/2[413]$	0.339	-0.046	0°	388
	$5/2^+$	$5/2[422]$	0.312	-0.023	0°	398
Oblate	$7/2^+$	$7/2[413]$	0.219	-0.035	-60°	301
	$1/2^-$	$1/2[321]$	0.251	-0.031	-51°	554
	$3/2^-$	$3/2[321]$	0.247	-0.030	-61°	804
	$9/2^+$	$9/2[404]$	0.211	-0.043	-60°	1051