Evidence for an oblate-shape isomer in neutron-rich $^{109}$Nb

Hiroshi Watanabe
RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
E-mail: hiroshi@ribf.riken.jp

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 $\beta$-decay of $^{109}$Zr. Based on the difference in feeding pattern between the isomeric and $\beta$ 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.

1. Introduction
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 [2–5] 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 $\beta$-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.

2. Experimental procedures

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 $^{238}$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 $\Delta E$-TOF-$B\rho$ method, in which the energy loss ($\Delta E$), 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 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 $\beta$-decay and internal-conversion processes. Gamma rays were detected by four Compton-suppressed Clover-type Ge detectors and a LaBr$_3$(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 $\gamma$-ray events were time-stamped and recorded by independent data-acquisition systems.

For the analysis of isomeric $\gamma$ rays, the $\gamma$-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-$\gamma$ data assemblies were sorted into two-dimensional matrices which consist of time differences between the identified particle and the detected $\gamma$ radiation ranging from 0 to 50 $\mu$s on one axis and $\gamma$-ray energies on the other. A total of $2.3 \times 10^5$ $^{109}$Nb fragments were identified in the present analysis (see Fig. 1 in Ref. [12]). The origin of the time distribution was defined as the detection of the fragment using a plastic scintillation counter placed at the end of the beam line. Information on isomeric lifetimes was derived from time projections with gates on characteristic $\gamma$ rays.

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

3. Results

Prior to the present work, nothing has been reported on excited states in $^{109}$Nb. As shown in Fig. 1(a), the $\gamma$ rays at energies of 117, 196, and 313 keV have been unambiguously identified in delayed coincidence with $^{109}$Nb ions. These three transitions were found to exhibit similar time behavior in the nanosecond range, suggesting that they originate from the same isomeric state.
Figure 1. 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. Panel (d) shows a 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 panel (a).

Figure 1(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.

As can be seen in Fig. 1(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 transitions 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 [13].

With careful inspection of the γ-ray intensity balance among these transitions and evaluation of total conversion coefficients, if the 196- and 313-keV transitions were emitted in cascade, the former transition would be of $M2$ or $E3$ character irrespective of multipolarity of the latter transition. This is not consistent with the argument on the transition strengths as discussed later, and therefore, allows the 196-keV transition to be placed in parallel with the 313-keV γ ray. Based on this argument and 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. 1(d); no spins and parities could be assigned for the levels in the present work. In Fig. 1(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.

4. Discussion
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 [14] using the formulas given in Ref. [15]), 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 multipoles are evaluated in Table 1. The total conversion coefficients calculated by the code BrIcc [16] 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 [17]. 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 [18, 19]. 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 low-lying states. 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 can be given in terms of shape difference between the isomeric state and the the states to which the isomer decays. In the region of interest, 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 shape transitions between prolate and oblate shapes occur around $N \approx 72$ in $^{40}$Zr and $N \approx 66$ in $^{42}$Mo isotopes, presumably implying the occurrence of prolate-oblate shape coexistence between these neutron numbers in the intermediate $^{41}$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 [20] 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. 2, 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 [14]. Based on the argument on the transition

| $E_\gamma$ (keV) | $I_\gamma$ relative | $E1$ | $B(\sigma \lambda)$ (W.u.) | $M1$ | $M2$ | $E3$ |
|------|----------------|------|----------------|-------|------|------|
|      |                |      | $I_\gamma$  | $T_\gamma$ | $E1$ |       |       |
| 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) | $10^4$ |
| 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) | $10^1$ | $1.2(4) \times 10^4$ |
\[ X = \beta_2 \cos(\gamma + 30^\circ) \pm 0.12 \]

\[ Y = \beta_2 \sin(\gamma + 30^\circ) \pm 0.08 \pm 0.04 \]

**Figure 2.** Potential energy surface plots in the $\beta_2-\gamma$ plane for selected single-proton configurations in $^{109}\text{Nb}$. The energy contour lines are drawn at 200-keV intervals. Each panel shows the calculation for the prolate $K^\pi = 3/2^-\pi$ state (top left); the oblate $K^\pi = 3/2^-\pi$ state (bottom left); the prolate $K^\pi = 7/2^+\pi$ state (top right); and the oblate $K^\pi = 7/2^+\pi$ 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.

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.

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.

**Table 2.** Calculated energies and deformation parameters for single-proton levels in $^{109}\text{Nb}$.

| $K^\pi$ | Main configuration | $\beta_2$ | $\beta_4$ | $\gamma$ (°) | $E_{\text{ex}}$ (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 |
5. Conclusions
The level structure of $^{109}$Nb has been investigated by means of $\beta$-$\gamma$ 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 $\frac{7}{2}^+$ single-proton configuration is predicted at low excitation energy, comparable to that of the observed isomeric state.

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