

Title	β decay of the $21/2^+$ isomer in ^{93}Mo and level structure of ^{93}Nb
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β decay of the $21/2^+$ isomer in ^{93}Mo and level structure of ^{93}Nb T. Hori,¹ T. Masue,¹ A. Odahara,^{1,*} K. Kura,¹ K. Tajiri,¹ T. Shimoda,¹ T. Fukuchi,^{1,2} T. Suzuki,³ Y. Wakabayashi,^{4,5}
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The γ rays associated with β decay of the $21/2^+$ isomer in ^{93}Mo ($E_x = 2.425$ MeV, $T_{1/2} = 6.85$ h) were measured with a selective sensitivity to long-lived isomer decays. A new 1262-keV transition was found in the γ - γ coincidence measurement, and it was attributed to a transition in ^{93}Nb , which is the daughter nucleus of the β decay of the ^{93}Mo isomer, from the 2.753- to the 1.491-MeV levels. Accurate γ -ray intensity balances have determined the β -decay intensity from the ^{93}Mo isomer to the 2.753-MeV level in ^{93}Nb and placed no appreciable intensity for the previously reported β -decay branching to the 2.180-MeV level, for which a recent in-beam γ -ray experiment assigned to be $I^\pi = 17/2^-$. Based on the γ -ray intensities from the 2.753-MeV level, spin-parity assignment of this level was revised from $21/2^+$ to $19/2^+$. The observed β -decay intensity and the spin-parity assignment were explained by the jj -coupling shell model calculations.

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I. INTRODUCTION

The high-spin isomer in ^{93}Mo ($E_x = 2.425$ MeV, $T_{1/2} = 6.85$ h, $I^\pi = 21/2^+$) was first discovered by Kundu *et al.* in 1950 [1]. An $E4$ multipolarity of the 263-keV transition deexciting the isomer was determined from the $K/(L + M)$ ratio of conversion electron [2]. The spin-parity of $21/2^+$ was assigned by observing the γ -ray anisotropy from the spin-oriented nuclei at low temperature [3]. The experimental g factor suggested a fully aligned configuration of $[\pi(g_{9/2}^2)\nu(d_{5/2})]_{21/2^+}$ [3]. Auerbach and Talmi reproduced well the energies of low-lying levels in ^{93}Mo by the shell model calculations [4]. The isomerism was explained that the stretch-coupling of three valence-nucleon spins causes lowering of the $21/2^+$ level energy, and as a result a spin gap between the $21/2^+$ and $13/2^+$ levels occurs. Namely, this isomer is considered to be a spin-gap isomer [4]. It decays to the ground state mostly by γ -ray cascades of 263 keV ($21/2^+ \rightarrow 13/2^+$), 685 keV ($13/2^+ \rightarrow 9/2^+$) and 1477 keV ($9/2^+ \rightarrow 5/2^+(\text{g.s.})$) [2]. The ground state then disintegrates to states in ^{93}Nb with a rather long half-life of $T_{1/2} = 4.0 \times 10^3$ yr.

It is to be noted that the β decay from the ^{93}Mo isomer to the levels in ^{93}Nb are also possible. Small β -decay branches were reported by Meyer and Yaffe [5] for the first time by observing γ transitions in ^{93}Nb with a chemically separated Mo source. They proposed new levels at 2.180 and 2.753 MeV in ^{93}Nb . From the γ -ray intensity balance, β -decay intensities to these levels were determined to be 0.04% ($\log ft = 7.5$) and 0.08% (5.1), respectively, relative to the intensity of the 685-keV transition in ^{93}Mo [5,6]. They also proposed spin-parity assignments for these levels at 2.180 and 2.753 MeV to be $(19/2^+)$ and $21/2^+$, respectively, from the $\log ft$ values as

well as their γ -ray decay branchings and intensities. However, the intensity of the 689-keV transition from the 2.180-MeV level may have large ambiguity in their singles measurements, due to closely located 1000 times more intense 685-keV γ ray in ^{93}Mo . The ambiguity affects the estimated β -decay intensity to the 2.180-MeV level. It is to be noted that a recent in-beam γ -ray spectroscopy measurement in the $^{82}\text{Se}(^{16}\text{O}, p4n)^{93}\text{Nb}$ reaction at 100 MeV made different spin-parity assignment for the 2.180-MeV level to be $(17/2^-)$ [7].

To precisely determine the β -decay branches and to firmly assign the spin-parity of the levels in ^{93}Nb , we have performed a γ - γ coincidence measurement which is selectively sensitive to γ rays after the isomer decay.

II. EXPERIMENT

The experiment was performed at the Research Center for Nuclear Physics (RCNP), Osaka University. The $21/2^+$ isomer in ^{93}Mo was populated by bombarding a ^{13}C target (1.0 mg/cm² thick, 99% enriched) with a 7.4 MeV/u $^{86}\text{Kr}^{21+}$ beam from the azimuthally-varying-field (AVF) cyclotron. A typical beam intensity was 7 pA. The inverse kinematics enabled a high acceptance of the fusion-evaporation residues recoiling out from the target into a secondary beamline, EN beamline, shown in Fig. 1. This beamline was originally designed as a fragment separator for use with high-energy heavy-ion beams [8,9]. The magnetic rigidity selection was optimized for $^{93}\text{Mo}^{35+}$ with an acceptance of $\Delta(B\rho)/B\rho = 5.8\%$ at the dispersive focal plane F1. All fractions of primary beam with various charge states were stopped by the slits upstream of F1. The evaporation residues were achromatically focused into a spot size of ~ 5 mm in diameter and implanted into a Pb foil (42 mg/cm² thick) at the second focus F2, which is located in an experimental hall well-shielded from both the

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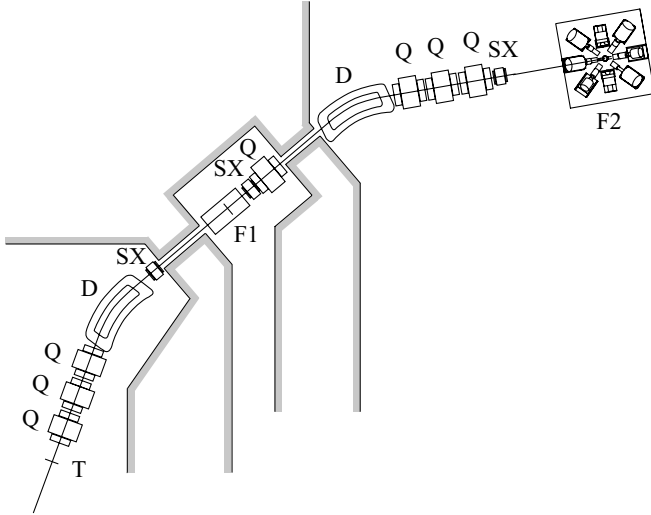


FIG. 1. Layout of the secondary beamline, the EN beamline, at RCNP [8,9]. The dipole, quadrupole, and sextupole magnets are denoted by D, Q and SX, respectively. The reaction products from the target T are focused at the dispersive focal plane F1 and achromatically focused at F2, where a Ge array is placed.

target and the primary-beam stoppers. The prompt γ rays were thoroughly extinguished during the long flight time of ~ 520 ns for the flight length of 16.3 m. Such an arrangement enabled high S/N measurements of γ rays associated with the isomer and β decays. The overall acceptance for ^{93}Mo was estimated to be 3.8%.

The γ rays were measured by 14 high-purity germanium (Ge) detectors surrounding the Pb foil. Two of the detectors were used with BGO anti-Compton shields (ACSs) to check spurious peaks due to cross-talk events between Ge detectors. The detectors were placed at 30° (relative efficiency $25\% \times 2$), 52° [25%, 30%, 45%, low-energy photon spectrometer (LEPS)], 90° (20% with ACS, 30% with ACS), 128° (25%, 30%, LEPS $\times 2$) and 150° (25%, 50%) with respect to the beam direction. All the detectors were placed at a distance of 100 mm from the Pb foil. The total detection efficiency was determined to be 1.8% for a 1.3-MeV γ ray. The total γ - γ coincidence events of 7.6×10^8 were obtained in 120 h.

III. RESULT

The total projection spectrum of the γ - γ coincidence measurement is shown in Fig. 2. The observed γ rays are assigned as the transitions after the β decays of ^{93m}Mo (6.85 h) and ^{92}Y (3.54 h), and various isomer decays of ^{94}Mo [(8^+), 2.956 MeV, 98 ns], ^{93}Mo ($21/2^+$, 2.425 MeV, 6.85 h), ^{92}Mo (8^+ , 2.760 MeV, 190 ns), ^{91}Zr [($21/2^+$), 3.167 MeV, 4.4 μs], ^{90}Y (7^+ , 0.682 MeV, 3.19 h), ^{90}Zr (8^+ , 3.589 MeV, 131 ns; 5^- , 2.319 MeV, 809 ms), and ^{89}Y ($9/2^+$, 0.909 MeV, 16.06 s). No prompt γ rays are seen in Fig. 2, showing the effectiveness of the present method. The very weak but clearly seen three peaks at 385, 541, and 950 keV show good agreement in energy with the reported transitions in ^{93}Nb [5]. The peak at 950 keV

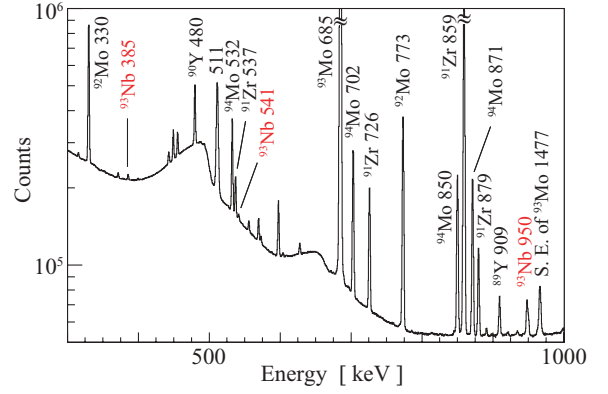


FIG. 2. (Color online) Total projection spectrum of γ - γ coincidence measurement. Energies are shown in keV units.

contains sum peaks of 263 and 685 keV in ^{93}Mo and 90 and 859 keV in ^{91}Zr .

Figures 3(a)–3(c) show γ -ray spectra gated on the 950-, 541- and 573-keV γ rays, respectively. The coincidence time width was 250 ns and the Compton background and chance coincidence counts were subtracted. γ rays of 156, 385, 541, 573, 689, 845, 950, and 1418 keV reported as the transitions in ^{93}Nb [5] are clearly seen in Fig. 3. The peaks marked by diamonds were confirmed as cross-talk peaks. The γ -ray spectra of Fig. 3 show that the 685-keV ^{93}Mo peak has no influence on the 689-keV ^{93}Nb peak.

Note the 1262-keV peaks in Fig. 3. This γ ray is assigned as due to a new transition in ^{93}Nb , as follows. This peak is noticed neither in the total projection spectrum of the present work nor in the singles spectrum by Meyer and Yaffe [5], because of the

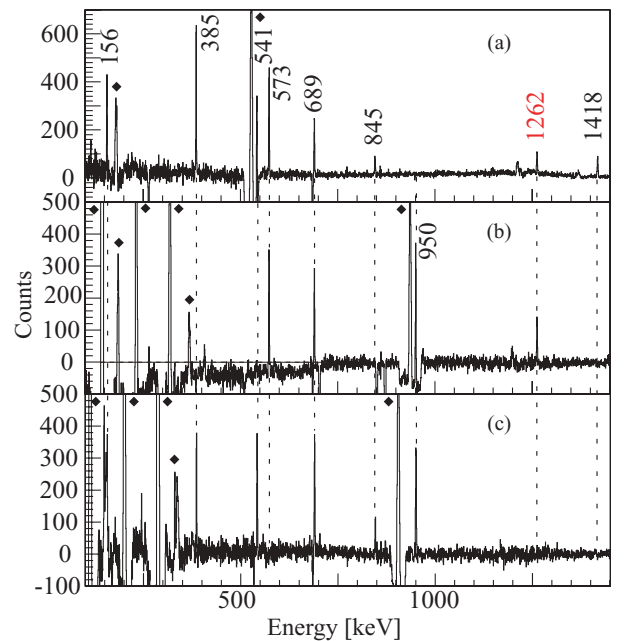


FIG. 3. (Color online) γ -ray spectra gated on (a) 950-, (b) 541-, and (c) 573-keV γ rays in ^{93}Nb . Spurious peaks due to Compton cross talk between Ge detectors are marked by diamonds. The newly found 1262-keV γ ray is seen in (a) and (b) but not in (c).

TABLE I. Coincidence relations with the 1262-keV γ ray. Circles indicate coincidences; \times 's are not in coincidence.

E_γ (keV)	156	385	541	573	689	845	950	1418
	○	○	○	×	×	×	○	×

large Compton edge of the 1477-keV ^{93}Mo γ ray. Coincidence relations of the γ rays are shown in Table I. The 1262-keV γ ray is in coincidence with the 156-, 385-, 541-, 950-keV γ rays and not with the 573-, 689-, 845-, 1418-keV γ rays. The energy of the 1262-keV γ ray is consistent with the sum energy of the 573- and 689-keV ones. Therefore the 1262-keV transition is placed between the 1.491- and 2.753-MeV levels. The γ -ray intensities were evaluated from the γ - γ coincidence counts and the detection efficiencies. Table II lists the γ rays observed in the present work, together with the information obtained by the previous work [5]. The present low-background method could determine the γ -ray intensities with much improved accuracy compared to the previous work [5].

The new transition increases the population of the 2.753-MeV level from 0.08% [5] to 0.120%. Accordingly, the $\log ft$ value is revised from the previous one of 5.05(8) [5] to a slightly decreased one of 4.97(3). The β -decay intensity to the 2.180-MeV level from the ^{93}Mo isomer was estimated based on the following two ways. One is from the intensity balance between decaying-out from the 2.180-MeV level [$0.040(1) + 0.015(1) = 0.055(1)\%$] and feeding-in from the 2.753-MeV level [$0.056(2)\%$]. The other is from the balance between the 950-keV γ ray [$0.117(2)\%$] and decaying-out intensity from the 2.753-MeV level [$0.056(2) + 0.033(2) + 0.031(2) = 0.120(3)\%$], neglecting the β decay feeding to the levels lower than 2.180 MeV. The results are $-0.001(2)\%$ and $-0.003(4)\%$, respectively, and the error-weighted mean of these is $-0.002 \pm 0.004\%$. The upper limit intensity of

$+0.002\%$ gives a larger lower limit $\log ft$ value of 8.1 for the β decay to the 2.180-MeV level than the previous value of 7.5 [5]. Such a small decay probability is inconsistent with the previous ($19/2^+$) assignment [5] for the 2.180-MeV level and supports the recent ($17/2^-$) assignment [7].

IV. DISCUSSION

A. Level scheme

The previous spin-parity assignments of ($19/2^+$) and $21/2^+$ for the levels at 2.180 and 2.753 MeV, respectively, have been made rather tentatively [5]. Also the $15/2^+$ assignment for the 1.491-MeV level is not based on experiment [5], and thus a tentative $15/2^+$ assignment has been adopted in the Nuclear Data Sheets [6]. The recent experiment of in-beam γ -ray spectroscopy by Wakabayashi *et al.* [7] has confirmed the $15/2^+$ assignment from the $M1$ multipolarity of the 541-keV transition, based on the γ -ray angular distribution, DCO ratio, and linear polarization measurements. They also assigned the spin-parity of the 2.180-MeV level to be ($17/2^-$) from the $E1$ multipolarity of the 689-keV transition.

This tentative assignment of $17/2^-$ is reexamined and confirmed in the present work as follows. The DCO ratio of 0.48(9) for the 689-keV γ -transition obtained by Wakabayashi *et al.* [7] is in good agreement with that expected for the stretch dipole transition (0.45). Together with information on the linear polarization [$0.077(70)$] [7], an $E1$ nature of this transition is strongly supported. This firmly assigns the spin-parity of the 2.180-MeV level to be $17/2^-$. The angular distribution coefficient¹ of $A_2 = -0.32 \pm 0.23$ of the 689-keV γ ray also confirms the assignment of the $E1$ transition $17/2^- \rightarrow 15/2^+$.

¹The A_2 value listed in Table I of Ref. [7] is misprinted: the negative sign is missing.

TABLE II. Experimental energies and intensities of γ rays in ^{93}Nb (upper part) and in ^{93}Mo (lower part), and the assigned levels relevant to the transitions. γ -ray intensities are normalized to that of the 685-keV γ ray of ^{93}Mo . Uncertainties are given in parentheses.

E_γ (keV)	Present work			Meyer and Yaffe [5]			
	I_γ (%)	E_i (MeV) \rightarrow E_f (MeV)	$I_i^\pi \rightarrow I_f^\pi$	E_γ (MeV)	I_γ (%)	E_i (MeV) \rightarrow E_f (MeV)	$I_i^\pi \rightarrow I_f^\pi$
155.95(3)	0.014(1)	1.4911 \rightarrow 1.3350	$15/2^+ \rightarrow 17/2^+$	155.841(90)	0.010(3)	1.4911 \rightarrow 1.33520	$15/2^+ \rightarrow 17/2^+$
385.22(2)	0.056(2)	1.3350 \rightarrow 0.9498	$17/2^+ \rightarrow 13/2^+$	385.375(85)	0.06(1)	1.33520 \rightarrow 0.94982	$17/2^+ \rightarrow 13/2^+$
541.35(2)	0.061(1)	1.4911 \rightarrow 0.9498	$15/2^+ \rightarrow 13/2^+$	541.220(65)	0.06(1)	1.4911 \rightarrow 0.94982	$15/2^+ \rightarrow 13/2^+$
572.80(2)	0.056(2)	2.7531 \rightarrow 2.1802	$19/2^+ \rightarrow 17/2^-$	572.760(63)	0.05(1)	2.7531 \rightarrow 2.1802	$21/2^+ \rightarrow (19/2^+)$
689.05(2)	0.040(1)	2.1802 \rightarrow 1.4911	$17/2^- \rightarrow 15/2^+$	689.070(49)	0.07(1)	2.1802 \rightarrow 1.4911	$(19/2^+) \rightarrow 15/2^+$
844.97(6)	0.015(1)	2.1802 \rightarrow 1.3350	$17/2^- \rightarrow 17/2^+$	844.900(200)	0.02(1)	2.1802 \rightarrow 1.33520	$(19/2^+) \rightarrow 17/2^+$
949.79(6)	0.117(2)	0.9498 \rightarrow g.s.	$13/2^+ \rightarrow 9/2^+$	949.817(30)	0.12(1)	0.94982 \rightarrow g.s.	$13/2^+ \rightarrow 9/2^+$
1261.91(14)	0.033(2)	2.7531 \rightarrow 1.4911	$19/2^+ \rightarrow 15/2^+$	—	—	—	—
1417.71(11)	0.031(2)	2.7531 \rightarrow 1.3350	$19/2^+ \rightarrow 17/2^+$	1417.900(200)	0.03(1)	2.7531 \rightarrow 1.33520	$21/2^+ \rightarrow 17/2^+$
114.065(5)	0.67(10)	1.4771 \rightarrow 1.3630	$9/2^+ \rightarrow 7/2^+$	114.024(9)	0.68(1)	1.47711 \rightarrow 1.36302	$9/2^+ \rightarrow 7/2^+$
263.036(1)	58.6(19)	2.4249 \rightarrow 2.1619	$21/2^+ \rightarrow 13/2^+$	263.062(5)	56.9(8)	2.42484 \rightarrow 2.16178	$21/2^+ \rightarrow 13/2^+$
684.714(1)	100.0(9)	2.1619 \rightarrow 1.4771	$13/2^+ \rightarrow 9/2^+$	684.672(9)	100.0(3)	2.16178 \rightarrow 1.47711	$13/2^+ \rightarrow 9/2^+$
1363.01(3)	0.83(2)	1.3630 \rightarrow g.s.	$7/2^+ \rightarrow 5/2^+$	1363.023(32)	0.79(1)	1.36302 \rightarrow g.s.	$7/2^+ \rightarrow 5/2^+$
1477.138(2)	99.2(12)	1.4771 \rightarrow g.s.	$9/2^+ \rightarrow 5/2^+$	1477.113(20)	99.4(15)	1.47711 \rightarrow g.s.	$9/2^+ \rightarrow 5/2^+$

The $17/2^-$ assignment for the 2.180-MeV level requires that the β decay from the $21/2^+$ ^{93m}Mo to the 2.180-MeV level is a first forbidden transition. It is in agreement with the evaluated large $\log ft$ value in the present work.

It is interesting to note that the 2.753-MeV level was not populated in the in-beam γ -ray experiment [7], suggesting a nonyrast nature of this level. Although the spin-parity of the 2.753-MeV level was assigned to be $21/2^+$ [5], non-unique assignments of $(19/2$ or $21/2)^+$ have been adopted in the Nuclear Data Sheets [6]. In the present work, we assign it to be $19/2^+$ by considering the observed γ -ray intensities and their possible multiplicities, as follows. Table III compares experimental γ -ray intensities and partial lifetimes based on the Weisskopf estimate by assuming the most plausible multiplicities. Although the observed γ -ray intensities are in the same order, the estimated partial lifetimes differ by seven orders of magnitude if $21/2^+$ is assumed for the 2.753-MeV level. When $19/2^+$ is assumed, an $E1$ multipolarity is the most plausible for the 573-keV transition. Since the sum rule hinders $E1$ transition probability by about three orders of magnitude in general, the partial lifetime of the 573-keV transition, in practice, is considered to be on the order of 10^{-11} s. As for the 1418-keV $M1$ transition, it is interpreted as an $M1$ forbidden transition $\nu(g_{7/2}) \rightarrow \nu(d_{5/2})$, as discussed later. This again hinders the transition by about three orders of magnitude. As a result, all the estimated partial lifetimes are in the same order, being in good agreement with the present measurements. We therefore assign the spin-parity of the 2.753-MeV level as $19/2^+$. The revised level structures of ^{93}Nb after β decay of the $21/2^+$ isomer in ^{93}Mo is shown in Fig. 4.

B. Configuration

The levels in ^{93}Nb and ^{93}Mo were compared with the jj -coupling model calculations based on a model space of $\pi(2p_{1/2}1g_{9/2})\nu(2d_{5/2}1g_{7/2}3s_{1/2}2d_{3/2}1h_{11/2})$. The interactions were the pp interaction by Gloeckner and Serduke [10], which reproduces well many levels in nuclei with $N, Z \sim 40$ –50, the surface-delta-type nn interaction, and the pn interaction by Schiffer and True [11]. The strength of the surface-delta interaction and the reduction factor to the Schiffer-True interaction were determined to be 0.26 and 0.8, respectively, so as to best reproduce the levels in ^{93}Nb and ^{93}Mo . Figure 5

TABLE III. Partial lifetimes are deduced by the Weisskopf estimate for the proposed $I^\pi = 21/2^+$ or $19/2^+$, assuming most plausible multiplicities.

I^π	E_γ (keV)	I_γ (%)	$\sigma\lambda$	Partial lifetime (s)
$21/2^+$	573	0.056(2)	$M2$	7.4×10^{-7}
	1262	0.033(2)	$M3$	1.9×10^{-4}
	1418	0.031(2)	$E2$	2.5×10^{-11}
$19/2^+$	573	0.056(2)	$E1$	5.3×10^{-14}
	1262	0.033(2)	$E2$	4.5×10^{-11}
	1418	0.031(2)	$M1$	1.1×10^{-14}

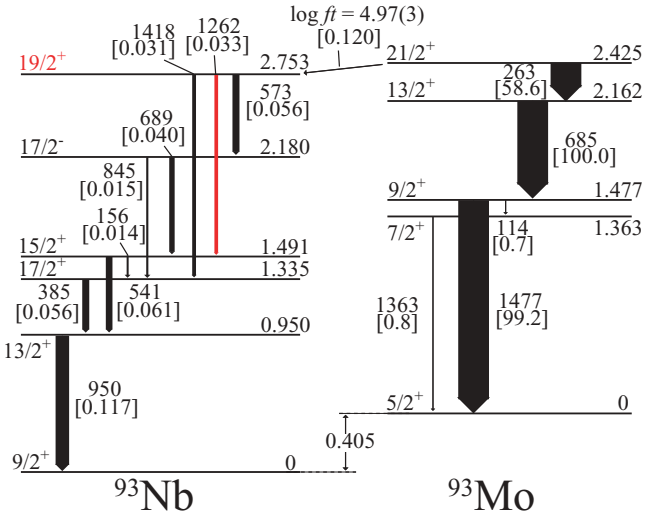


FIG. 4. (Color online) Decay scheme of the $21/2^+$ isomer at 2.425 MeV in ^{93}Mo , established in the present work. Transition and level energies are in units of keV and MeV, respectively. γ -ray intensities relative to that of the 685-keV transition in ^{93}Mo are shown in parentheses.

shows the calculated levels and their major configurations, together with the experimental level schemes. For ^{93}Mo , many levels are reproduced rather well both in excitation energies and spin-parities. A three-particle configuration of seniority $\nu = 3$ type isomer $\pi(g_{9/2}^2)\nu(d_{5/2})$ is calculated for the $21/2^+$ isomer of ^{93}Mo . Less but still reasonable agreement is seen also in ^{93}Nb . The ground state of ^{93}Nb is predicted to have a main single-particle configuration of $\pi(g_{9/2})$. The dominant configurations of the next three levels of $13/2^+$, $17/2^+$, and $15/2^+$ and the fourth excited level of $17/2^-$ are calculated to be $\pi(g_{9/2})\nu(d_{5/2}^2)$ and $\pi(p_{1/2}^{-1}g_{9/2}^2)$, respectively. These configurations are the same as those calculated by the deformed independent particle model [7]. The theoretical energy of the β -decay daughter $19/2^+$ level in ^{93}Nb is somewhat too high, higher than the isomer, indicating need for improvement of the interactions.

The admixture of the $\pi(g_{9/2})\nu(d_{5/2}g_{7/2})$ component into the $19/2^+$ level ensures the Gamow-Teller nature of the isomer decay as $\pi(g_{9/2}) \rightarrow \nu(g_{7/2})$. The theoretical $\log ft$ value of this transition is 4.31, which is much smaller than the experimental one of 4.97(3). Correction for the quenching of 60–70% increases it to 4.46–4.53. The negligibly small β -decay rate to the $17/2^-$ level is understood as the first forbidden transition $\pi p_{1/2} \rightarrow \nu d_{5/2}$.

V. SUMMARY

In summary, we have investigated β decay of the $21/2^+$ isomer in ^{93}Mo ($E_x = 2.425$ MeV, $T_{1/2} = 6.85$ h) by measuring γ rays from the daughter nucleus ^{93}Nb in the fusion-evaporation reaction of the $^{13}\text{C}(^{86}\text{Kr}, 6n)^{93}\text{Mo}$ at 7.4 MeV/u. The evaporation residues were transmitted through a beamline consisting of momentum-dispersive and achromatic focal planes, enabling high S/N γ - γ coincidence measurements

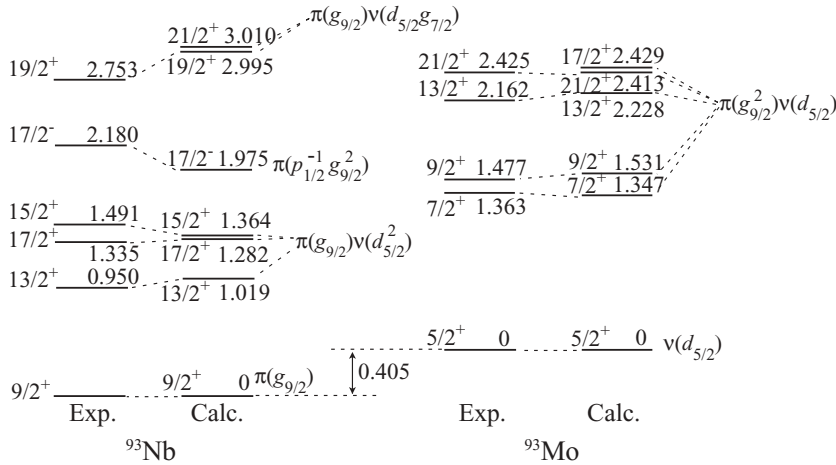


FIG. 5. Levels in ^{93}Mo and ^{93}Nb calculated by the jj -coupling shell model. Main components of the configurations are shown.

which are selectively sensitive to the long-lived isomers. A 1262-keV transition, which was hidden by the large Compton edge of the 1477-keV ^{93}Mo γ ray in the previous work [5], was found in the gated spectrum by the 950-keV γ ray in ^{93}Nb . The coincidence relations attributed the new γ ray to a transition from the 2.753- to the 1.491-MeV levels in ^{93}Nb . The γ -ray intensities were determined with an accuracy much better than that in the previous work. The intensity of the 689-keV γ ray, of which energy is close to the intense 685-keV γ -transition in ^{93}Mo , was revised to a reduced value by a factor of 0.6 from the previous one. The newly found 1262-keV transition also revised the β -decay intensity to the ^{93}Nb 2.753-MeV level by a factor of 1.5. Accurate γ -ray intensity balances placed no appreciable intensity for the previously proposed β -decay branching to the $17/2^-$ level at 2.180 MeV. Taking into account errors in the estimated intensity, we evaluate the lower limit $\log ft$ value for this β -decay branch to be 8.1. Such a large value is incompatible with the previous spin-parity assignment

of $(19/2)^+$ for the 2.180-MeV level [5] and in agreement with the revised assignment of $17/2^-$ by the in-beam γ -ray experiment [7]. Based on the γ -ray intensities to the known levels, the spin-parity of the 2.753-MeV level was assigned to be $19/2^+$.

The β -decay intensity and the spins and parities were compared with the jj -coupling shell model calculations. Except that the jj -coupling model calculated too high energy for the $19/2^+$ level, the experimental results were reasonably explained.

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