Eur. Phys. J. A **16**, 331–336 (2003)
DOI 10.1140/epja/i2002-10107-8

The European Physical Journal A

Conversion electron measurement in the β^--decay of ^{151}Pr

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Received: 28 June 2002 / Revised version: 21 October 2002 /
Published online: 25 February 2003 –
Communicated by J. Äystö

Abstract. The β^--decay of ^{151}Pr produced by the thermal neutron-induced fission of ^{235}U has been studied using an on-line isotope separator. From an internal-conversion electron measurement with a Si(Li) detector, K-conversion coefficients were obtained for 20 γ-transitions. Spins and parities of 6 excited levels in ^{151}Nd were newly determined from the deduced multipolarities: even parities for the 543 and 627 keV levels, odd parities for 250 and 599 keV, $(3/2, 5/2)^+$ for 685 keV, and $(1/2, 3/2)^+$ for 880 keV. The level structure was compared with the rotation-vibration coupling Nilsson model.

PACS. 21.10.Hw Spin, parity, and isobaric spin – 23.20.Nx Internal conversion and extranuclear effects – 27.70.+q $150 \leq A \leq 189$

1 Introduction

Level structures of neutron-rich deformed nuclei are dominated by the interplay between collective and single-particle motion. Thus, systematic studies on their nuclear properties, for instance level energies, transition probabilities, spins and parities, play a crucial role in the development of a theoretical description of the nuclear structure.

Low-energy level schemes of ^{153}Sm and ^{155}Gd with a neutron number $N = 91$ have been well studied via β-decays and nuclear reactions [1]. For these nuclides, single-particle orbitals were assigned to the band heads, and the existence of octupole deformation at low spin was proposed from the observation of parity doublet bands connected by enhanced $E1$ transitions [2]. For the more unstable $N = 91$ isotone ^{151}Nd, the level scheme has been reported from γ-ray measurements in the β-decay of ^{151}Pr [3], in the ^{150}Nd(d, p) [4,5] and ^{150}Nd$(n_{\rm th}, \gamma)$ reactions [6]. In these studies, the ground state and some low-lying odd-parity bands were interpreted by the Nilsson model. On the other hand, the 685 and 880 keV odd-parity levels, which were strongly populated by the β-decay of ^{151}Pr, were not reproduced in the calculation [3]. One explanation for this discrepancy is that the previous parity assignments are wrong. The previous experimental method seems to support this explanation as follows. The spins and parities of these levels were estimated only on the basis of the log ft values. The previous γ-ray measurements were, however, performed mainly in the low-energy region below 1 MeV. Thus, some γ-rays above 1 MeV may be missing and there remain uncertainties in the experimental log ft values. For a better understanding of ^{151}Nd, it is to be requested that the spins and parities are unambiguously determined.

In the present study, internal-conversion coefficients of γ-transitions in ^{151}Nd are measured for mass-separated ^{151}Pr nuclei. Spins and parities of excited levels in ^{151}Nd are determined from the deduced multipolarities. Nilsson orbitals of excited levels are discussed in the framework of the rotation-vibration coupling model (RVCM).

2 Experiment

The ^{151}Pr radioactive sources were produced by the thermal neutron-induced fission of ^{235}U, followed by a mass-separation using an on-line isotope separator installed at the Kyoto University Reactor (KUR-ISOL) [7,8]. A UF_4 target of 50 mg was irradiated with a thermal neutron flux of 3×10^{12} $n/\text{cm}^2\text{s}$. The fission products thermalized in the target chamber were transported with a He-N_2 mixed gas-jet system to a surface-ionization-type ion source. After ionization, ^{151}Pr nuclei were mass-separated with a chemical form of $^{151}PrO^+$ to improve the ionization efficiency [9]. The mass-separated ions were implanted into an aluminized Mylar tape in a tape transport system and periodically moved to a lead-shielded detection position at

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time intervals of 3.6 s. The ^{146}La nuclei were also mass-separated for calibration measurement, as described later. The tape cycle for ^{146}La sources was set at 20 s.

Internal-conversion electrons from the β^--decay of ^{151}Pr were measured with a 500 mm^2 area and 5 mm thick Si(Li) detector (FWHM of 2.0 keV at 624 keV) for 54 h. The distance from the source to the detector surface was 15 mm. The small vacuum chamber for the Si(Li) detector was separated from the ISOL chamber by a 0.5 μm thick polyester film to prevent residual vapors from being trapped on the cooled surface of the detector. Since energy loss in this film was about 0.3 keV for electrons with energies above 100 keV [10], distortion of the measured electron spectrum was negligible. For energy and efficiency calibration of the Si(Li) detector, conversion electrons from the decay of ^{146}La were also measured for 4 h. In order to deduce internal-conversion coefficients, the γ-ray spectra were simultaneously measured with a 30% n-type HPGe detector. The energy resolution (FWHM) at 1332 keV was 2.0 keV, and the source-to-detector distance was 10 mm. Energy and efficiency calibration of the HPGe detector was performed using standard γ-ray sources of ^{133}Ba, ^{137}Cs, ^{60}Co and ^{152}Eu. Coincidence summing effects were taken into account in deducing the full-energy peak efficiency. The uncertainty of the peak efficiency was estimated to be less than 10%.

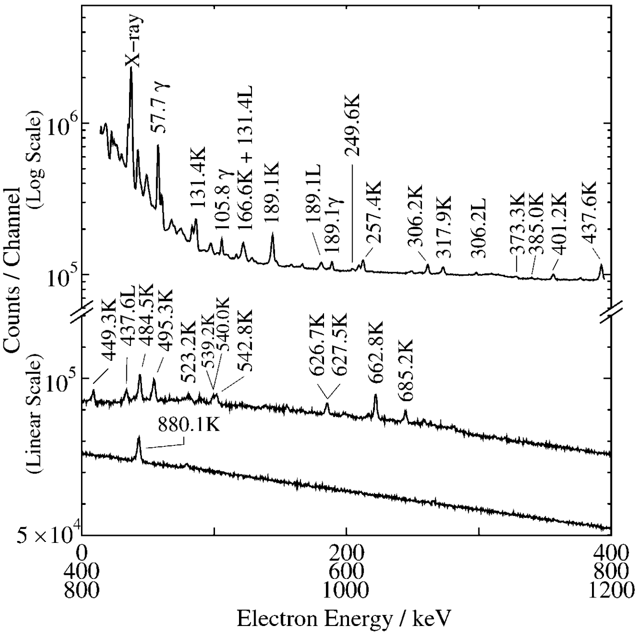

Fig. 1. A conversion electron spectrum measured with a Si(Li) detector for a mass fraction $A = 151 + 16$. Electron peaks from the β^--decay of ^{151}Pr are indicated with their energies in keV.

3 Results

An electron spectrum measured for a mass fraction $A = 151 + 16$ is shown in fig. 1. Internal-conversion electron peaks were observed for 20 γ-transitions in the decay of ^{151}Pr. The K-conversion coefficient was obtained from the ratio of the electron peak count to the corresponding γ-ray intensity. Coincidence summing effects were taken into account in evaluating peak intensities. The normalization of conversion coefficients was made using the known pure $E2$ transition of 258 keV observed in the decay of ^{146}La with the theoretical K-conversion coefficient equal to 0.0617 by Rösel *et al.* [11]. The normalization factor was also deduced using the 410 keV $E2$ transition in ^{146}Ce. These two values agreed within their experimental uncertainties. It means that the detection efficiency of the Si(Li) detector is constant in this energy region. Flatness of the efficiency curve was also confirmed by Monte Carlo calculations using the EGS4 code [12]; the calculations taking account of the 0.5 μm thick polyester film showed that the efficiency was almost constant for electrons with energies of 70–1000 keV. Thus, we concluded that the detection efficiency, namely, the normalization factor, was constant in an energy range of 70–1000 keV.

The experimental K-conversion coefficients are presented in table 1 and fig. 2 together with theoretical values [11]. Special comments on deducing the conversion coefficients for γ-transitions of 167, 627, 523 and 543 keV are given in the following. First, a 123 keV electron peak is a doublet of the 166.6 keV K- and 131.4 keV L-conversion lines. Only the total electron count was obtained from the spectrum because this peak could not be resolved into its components. The contribution of the 131.4 keV L-conversion line was evaluated from the experimental 131.4 keV K-conversion electron count and the theoretical K/L ratio of 2.29 [11] for $E2$ transitions. After subtraction of the contribution, a K-conversion coefficient of 0.0394(57) was obtained for the 166.6 keV transition. Second, an electron peak with an energy of about 583 keV is also a multiplet of the 626.7 and 627.5 keV K-conversion electrons. After subtracting the contribution of the 627.5 keV transition from the total, the K-conversion coefficient for the 626.7 keV transition was found to be 0.0137(25). Here, the electron count of the 627.5 keV $E1$ transition was evaluated using the theoretical K-conversion coefficient of 0.00206 [11] and its γ-ray peak count. The $E1$ multipolarity of the 627.5 keV γ-ray was deduced from our $(3/2, 5/2)^+$ assignment for the 685 keV level, as described later. Third, the 523 keV γ-ray is multiply placed in the level scheme of ^{151}Nd in ref. [13]: a transition from the 581.0 to the 57.7 keV level, and that from 599.2 to 75.9 keV level. The 581 → 58 keV transition, however, was not supported by γ-γ coincidence measurement by Shibata *et al.* [3]. Thus, in the present study, we assumed that the 523 keV γ-ray was a singlet. Finally, an electron peak was observed in a low-energy part of the 543 keV K-conversion line. This peak is due to K-conversions of the 539.2 and 540.0 keV γ-transitions, which were observed in the ^{150}Nd($n_{\rm th}$, γ) reaction [6] but not placed in the level scheme. In our electron spectrum, the 543 keV conversion electron was distinguished from the 539 and 540 keV electron doublet. Thus, the K-conversion coefficient for the 543 keV transition was determined to be 0.0126(19).

Table 1. K-internal-conversion coefficients for γ-transitions observed in the β^--decay of ^{151}Pr together with theoretical values by Rösel *et al.* [11].

Transition energy (keV)	K-conversion coefficient					Assignment	
	Experiment	Theory $E1$	Theory $M1$	Theory $E2$	Theory $M2$	Present work	Previous works [3,13]
131.4	0.358(39)	0.10465	0.56824	0.53505	4.0815	$M1/E2$	$(3/2)^- \to (3/2)^-$
166.6	0.0394(57)	0.05493	0.29273	0.25675	1.76414	$E1$	$(3/2)^- \to (5/2)^+$
189.1	0.0429(32)	0.03906	0.20680	0.17318	1.14107	$E1$	$(3/2)^- \to 3/2^+$
249.6	0.0166(21)	0.01872	0.09747	0.07291	0.44839	$E1$	$(5/2^-) \to 3/2^+$
257.4	0.068(6)	0.01725	0.08957	0.06614	0.40407	$M1/E2$	$(3/2)^- \to (5/2^-)$
306.2	0.0524(42)	0.01106	0.05660	0.03903	0.23031	$M1/E2$	$(1/2)^- \to (3/2)^-$
317.9	0.0550(45)	0.01007	0.05128	0.03488	0.20425	$M1/E2$	$(3/2)^- \to (3/2)^-$
373.3	0.0084(9)	0.00677	0.03376	0.02183	0.12306	$E1$	$(\ )^- \to (3/2)^-$
385.0	0.00554(43)	0.00628	0.03118	0.01999	0.11180	$E1$	$(\ )^- \to (1/2)^-$
401.2	0.0246(23)	0.00568	0.02803	0.01778	0.09836	$M1/E2$	$(3/2)^- \to 5/2^-$
437.6	0.0191(15)	0.00463	0.02247	0.01398	0.07548	$M1/E2$	$(1/2)^- \to (3/2)^-$
449.3	0.0153(18)	0.00435	0.02102	0.01300	0.06968	$M1/E2$	$(3/2)^- \to (3/2)^-$
484.5	0.00344(28)	0.00366	0.01737	0.01063	0.05556	$E1$	$(3/2)^- \to (5/2)^+$
495.3	0.00392(47)	0.00348	0.01643	0.01002	0.05202	$E1$	$(1/2)^- \to 3/2^+$
523.2	0.0037(7)	0.00307	0.01430	0.00868	0.04416	$E1$	$(5/2^+) \to (7/2)^+$
542.8	0.0126(19)	0.00305	0.01307	0.00791	0.03970	$M1/E2$	$(5/2^-) \to 3/2^+$
626.7	0.0137(25)	0.00207	0.00916	0.00553	0.02621	$M1/E2$	$(\ ) \to 3/2^+$
662.8	0.00787(71)	0.00184	0.00798	0.00483	0.0224	$M1/E2$	$(\ )^- \to (5/2)^+$
685.2	0.0083(9)	0.00171	0.00736	0.00446	0.02036	$M1/E2$	$(\ )^- \to 3/2^+$
880.1	0.00451(43)	0.00103	0.00404	0.00251	0.01026	$M1/E2$	$(\ )^- \to 3/2^+$

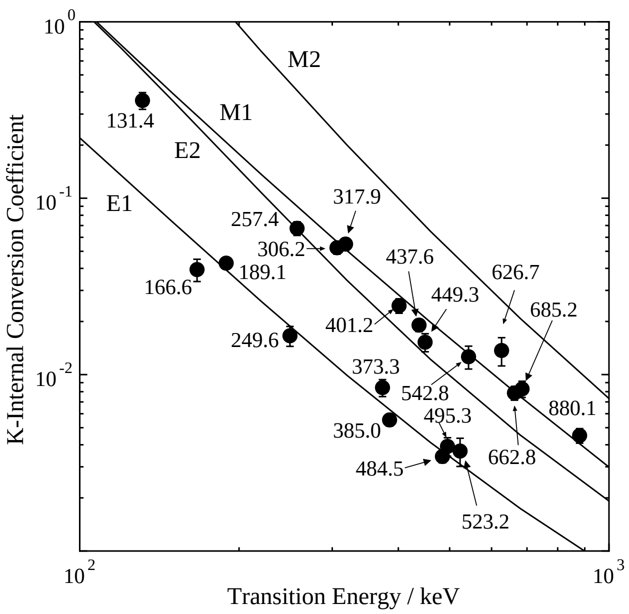

Fig. 2. Experimental K-internal-conversion coefficients of γ-transitions observed in the β^--decay of ^{151}Pr. Solid curves show theoretical values by Rösel *et al.* [11].

The K-conversion coefficients obtained for the 167, 189, 485 and 495 keV transitions agreed with the theoretical values for $E1$ transitions. These $E1$ assignments are consistent with the previous results [3]. Assignments of $M1/E2$ for the 131, 306, 318, 401, 438 and 449 keV γ-transitions are also in agreement with the previous works [3,6]. These facts confirmed the reliability of our experimental technique including our assumption that the normalization factor was constant. The multipolarities of $E1$ were newly assigned to the 250, 373, 385 and 524 keV transitions, and $M1/E2$ to the 257, 543, 627, 663, 685 and 880 keV ones.

4 Discussion

4.1 Spins and parities of excited levels

The level scheme of ^{151}Nd has been studied by several experimental groups. A partial decay scheme taken from ref. [13] is shown in fig. 3. In the following discussion, spins and parities of excited levels are deduced from the multipolarities obtained in the present study and from the known γ-transition patterns.

The parity of the 189 keV level was deduced to be odd from the $M1/E2$ multipolarity of the 131 keV transition and from the $E1$ multipolarity of the 167 and 189 keV transitions. Odd parities were also assigned to the 495 keV level from the multipolarities of the 306, 438 and 495 keV transitions, and to the 507 keV level from those of the 257, 318, 401, 449 and 485 keV transitions. These assignments are consistent with the previous results [13]. From the $E1$ assignment for the 250 keV transition, the parity of the 250 keV level was found to be odd. The odd parity for the 250 keV level was tentatively assigned from the γ-decay pattern in the previous work [6], and unambiguously determined in this study. The even parity was newly proposed to the 627 keV level from the $M1/E2$ multipolarity of the 627 keV γ-ray populating the $3/2^+$ ground state.

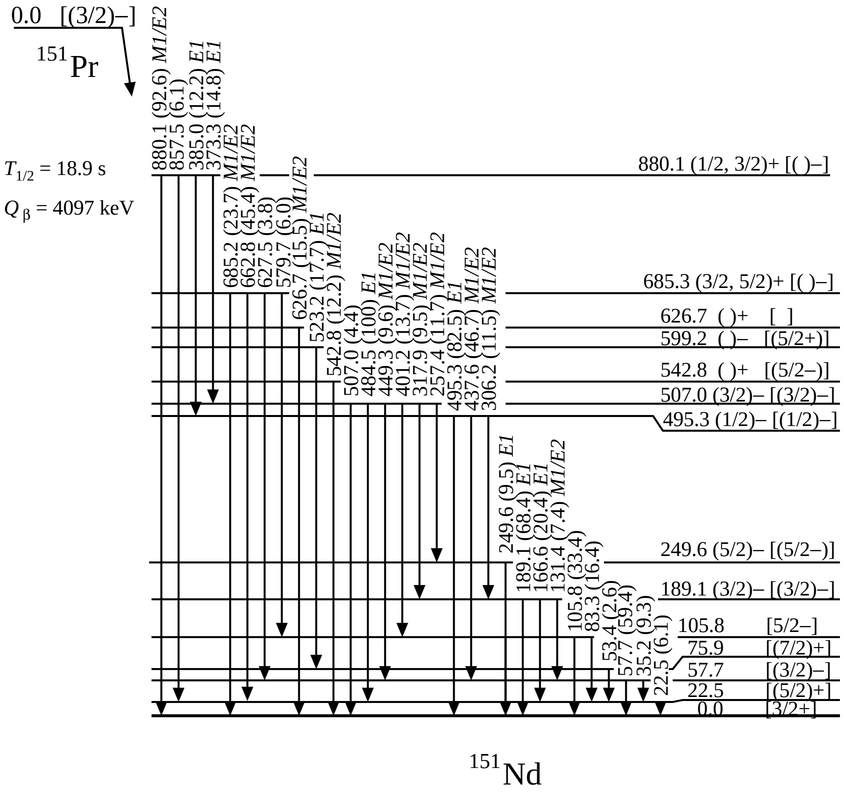

Fig. 3. A partial decay scheme of ^{151}Pr taken from ref. [13]. Gamma-ray intensities, multipolarities, spin and parity presented in the figure were deduced in our study. Spin and parities reported in previous works [3,13] are also shown in square brackets for comparison.

The parity of the 543 keV level was found to be even from the $M1/E2$ multipolarity of the 543 keV γ-ray. Our assignment disagrees with the previous results [13]; the parity of the 543 keV level was reported to be odd from an angular distribution of protons observed in the ^{150}Nd(d, p)^{151}Nd reaction, which showed a distribution pattern of $\Delta l_{\rm n} = 3$. The reason for this discrepancy is unclear because this experiment was reported only as a private communication in ref. [13].

The odd parity was assigned to the 599 keV level from the 524 keV $E1$ transition. On the other hand, this level was reported to be a $(5/2^+)$ state [13] on the basis of a γ-transition pattern observed in the ^{150}Nd$(n_{\rm th}, \gamma)^{151}$Nd reaction: a 4735 keV γ-ray from the compound state with $I^\pi = 1/2^+$ to the 599 keV level, and the successive γ-rays depopulating to levels with $(7/2^+)$ and $(7/2^-)$. We should notice that the 4735 keV γ-ray was reported only by one experimental group as a private communication in ref. [13] and that this γ-ray was not observed in the other studies using the ^{150}Nd$(n_{\rm th}, \gamma)^{151}$Nd reaction. Pinston *et al.* [6], for example, have not reported the 4735 keV γ-transition, while they observed γ-rays whose intensities were weaker than that of the 4735 keV γ-ray. As far as the γ-transition pattern observed in β-decay studies is concerned, the odd-parity assignment is possible for the 599 keV level. It should also be noted that the present work removed the possibility of a $K^\pi = 5/2^\pm$ parity doublet with band heads at 532 keV ($I^\pi = (5/2^-, 7/2^-)$ [13]) and 599 keV; the possibility was suggested by Sheline and Sood [2] from the systematics for $N = 91$ isotones and from the tentative parity assignments.

Since the 663 and 685 keV γ-rays were $M1/E2$ transitions, the parity of the 685 keV level was found to be even. In addition, the spin and parity of the 685 keV level were restricted to $(3/2)^\pm$ or $(5/2)^\pm$ because γ-rays from this level populate $(3/2)^\pm$ and $(5/2)^\pm$ states [13]. Thus, the 685 keV level was assigned to be a $(3/2,\ 5/2)^+$ state. In a similar way, spin and parity $(1/2,\ 3/2)^+$ were assigned to the 880 keV level from the $M1/E2$ multipolarity of the 880 keV transition, and from $E1$ multipolarity of the 373 and 385 keV transitions. On the other hand, odd parities were previously assigned to these two levels from small $\log ft$ values of 5.5–5.8 [3]. A most probable explanation for this discrepancy is that some γ-rays populating these levels were missing in the previous study and that the β-feeding intensities to them were overestimated. This explanation is considerably valid because the previous γ-ray measurement was performed mainly in a low-energy region ($\sim$ 1 MeV). From our parity assignments, β^--transitions from ^{151}Pr ($I^\pi = (3/2)^-$ [13]) to these 2 levels are found to be first-forbidden non-unique ones. For these transitions, $\log ft$ values are expected to be larger than or equal to 5.9 [14]. Thus, intensities of the missing γ-transitions to the 685 and 880 keV levels are estimated to be $I_\gamma \leq 8\%$ and $\leq 79\%$, respectively, relative to that of the 484.5 keV γ-ray. To confirm this interpretation, detailed

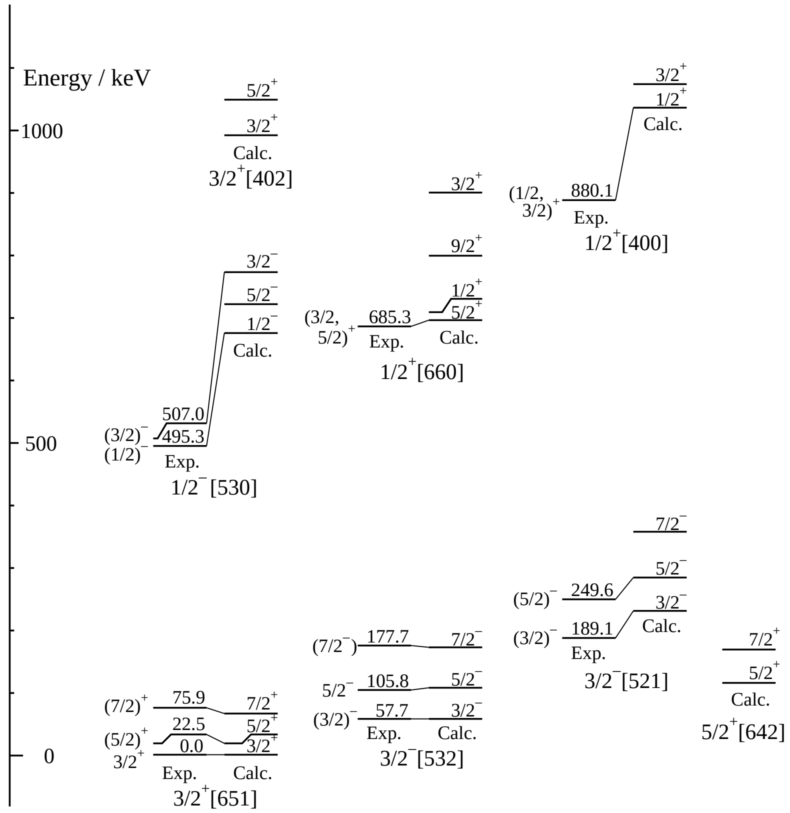

Fig. 4. Comparison of experimental and calculated level energies of ^{151}Nd. The calculation is based on the rotation-vibration coupling model with parameters of $\kappa = 0.0637$, $\mu = 0.42$, $\beta_2 = 0.25$ and $\epsilon_4 = -0.05$.

experimental data on γ-γ coincidence relationships are required, in particular, in a higher-energy region above 1 MeV.

4.2 The RVCM calculation

The spin and parity of 685 and 880 keV levels were newly determined, as described above. To propose Nilsson orbitals for these levels, we compared experimental results with the RVCM calculation. The Hamiltonian H for the RVCM is written as

$$H = H_{\rm sp} + H_{\rm coll} + H_{\rm int},$$

where $H_{\rm sp}$ is a term for the single-particle motion, $H_{\rm coll}$ the collective motion and $H_{\rm int}$ the interaction between them. The Hamiltonian $H_{\rm int}$ includes the quasiparticle-phonon interaction, the rotation-vibration interaction and the Coriolis coupling. A detailed description of this model is given in ref. [15].

The RVCM calculation was performed using the Nilsson parameters $\kappa = 0.0637$ and $\mu = 0.42$, and the deformation parameters $\beta_2 = 0.250$ [16] and $\epsilon_4 = -0.05$. Here, we note that ϵ_4 was reported to be -0.07 in ref. [16]. The RVCM calculation using ϵ_4 equal to -0.07, however, predicted that the ground state of ^{151}Nd was the band head of the $5/2^+[642]$ orbital, which disagreed with the experimental assignment of $I^\pi = 3/2^+$ [13]. Thus, $\epsilon_4 = -0.05$ was adopted in our calculation to reproduce the experimental results. A rotational parameter $\hbar^2/2\mathcal{J}$ of 10 keV was chosen for even-parity bands and 12 keV for odd-parity bands to reproduce experimental level spacing. The attenuation factor for the Coriolis matrix elements was employed to be 1.0. The β- and γ-vibration energies of $E_\beta = 0.68$ MeV and $E_\gamma = 1.06$ MeV were taken from experimental data for the neighboring even-even nuclide of ^{150}Nd [1]. The gyromagnetic factors $g_s = -2.681$ and $g_R = Z/A$ were used for calculation of transition probabilities.

Figure 4 shows a comparison between the calculated and the experimental level energies. The RVCM calculation reproduces the ground-state and low-lying odd-parity bands with band head energies of 58, 189 and 495 keV. These results are consistent with the previous works [3,5,6].

The 685 keV $(3/2,\, 5/2)^+$ level is likely the band head ($I^\pi = 5/2^+$) of the $1/2^+[660]$ orbital. This assignment is supported by a γ-ray branching ratio to the $3/2^+$ and $5/2^+$ members of the $3/2^+[651]$ band (ground-state band): the experimental branching ratio $R = I_\gamma(685 \to 0)/I_\gamma(685 \to 23)$ is 0.52(5) and the calculated value is 0.54. The experimental ratio $I_\gamma(685 \to 58)/I_\gamma(685 \to 106) = 0.63(5)$ is also consistent with the calculated value 0.21. In addition, the 695 keV calculated level energy well agrees with the 685 keV experimental value. Other candidates for the 685 keV level are the band heads of the $5/2^+[642]$ and $3/2^+[402]$ orbitals. However, a calculated branching ratio R from the band head of the $5/2^+[642]$ orbital is 4.0,

Table 2. Calculated branching ratios from 5 levels to $3/2^+$ and $5/2^+$ members of the $3/2^+$[651] orbital. The experimental value for the 880 keV level is presented for comparison.

	Calculated					Experimental
	$1/2^+$[600]		$1/2^+$[400]		$3/2^+$[402]	880 keV
Branching ratio	$I = 1/2^+$	$I = 3/2^+$	$I = 1/2^+$	$I = 3/2^+$	$I = 3/2^+$	$I = (1/2, 3/2)^+$
$\frac{I_\gamma(I \rightarrow 3/2)}{I_\gamma(I \rightarrow 5/2)}$	4.97	1.19	4.84	1.35	0.45	15.2(11)

which is larger than the experimental value by the order of unity. Thus, the $5/2^+$[642] assignment is unfavored. For the band head of the $3/2^+$[402] orbital, a calculated ratio R of 0.47 is consistent with the experimental value 0.52(5). The RVCM calculation, however, predicts that a γ-transition from this level to the $3/2^-$ state of the $3/2^-$[532] band is stronger than that to the $5/2^-$ member by a factor of 2; it disagrees with the experimental results. Thus, the 685 keV level is most probably the $1/2^+$[660] band head.

The 880 keV $(1/2,\ 3/2)^+$ level is considered to be a member of the $1/2^+$[660], $3/2^+$[402] or $1/2^+$[400] orbital. To identify the Nilsson orbital for the 880 keV level, calculated branching ratios from these members to the ground-state band were compared with the experimental value of $I_\gamma(880 \rightarrow 0)/I_\gamma(880 \rightarrow 23) = 15.2(11)$. Table 2 shows that the calculated ratios from the $I = 3/2^+$ states are smaller than the experimental value by an order of 1 or more. Thus, the 880 keV level is probably a $1/2^+$ state, namely, the $1/2^+$ member of the $1/2^+$[660] or $1/2^+$[400] band. The $1/2^+$[660] assignment is, however, unfavored because the calculation predicts that the $1/2^+$ state ($E_{\rm cal} = 698$ keV) of this band appears very close to the $5/2^+$ state ($E_{\rm cal} = 695$ keV). Therefore, the band head of the $1/2^+$[400] orbital is assigned to the 880 keV level.

The 543 and 627 keV even-parity levels only populate the ground state [13]. The $5/2^+$ state of the $5/2^+$[642] orbital and the $1/2^+$ of the $1/2^+$[660] are candidates for these levels because strong γ-transitions from them to the ground state are expected in our calculation. However, Nilsson orbitals for the two levels could not be assigned definitely in the present work because their spins were not determined experimentally. It is to be desired that the spins are deduced by further experiments.

5 Conclusions

We have determined K-conversion coefficients for 20 γ-transitions observed in the β^--decay of ^{151}Pr. Spins and parities of 6 excited levels in ^{151}Nd were newly obtained from the deduced multipolarities. The band head of the $1/2^+$[660] orbital was assigned to the 685 keV level, and that of the $1/2^+$[400] to the 880 keV from the rotation-vibration coupling model calculation. The present study also showed that previous parity assignments for the 543, 599, 685 and 880 keV levels were wrong. A most probable explanation for this discrepancy is that the previous level scheme of ^{151}Nd is incomplete. More detailed γ-ray measurements, in particular, in an energy range above 1 MeV are strongly requested for further discussion.

This work was partly supported by the Research Collaboration Program of Research Reactor Institute, Kyoto University.

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