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Studies on the level structure of ^{152}Nd

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Abstract. The structure of ^{152}Nd, produced via β^- decay of ^{152}Pr, has been investigated using γ-γ coincidence, γ-γ angular correlation, and β-γ-γ triple coincidence measurements. Praseodymium activities were obtained by the thermal neutron fission of ^{235}U and collected by the on-line isotope separator KUR-ISOL. Nineteen γ-rays and four excited states were newly found. The spins of six exited states were determined and the parities of three of them were also deduced. The spin and parity of the ^{152}Pr ground state, which were previously considered as 4^-, are proposed to be 4^+ by the present study.

PACS. 21.10.Hw Spin, parity, and isobaric spin – 23.20.Lv Gamma transitions and level energies

1 Introduction

Neutron-rich rare-earth nuclei have been studied by performing γ-γ coincidence, γ-γ angular correlation, conversion electron, and β-γ-γ triple coincidence measurements using KUR-ISOL [1] of Research Reactor Institute, Kyoto University. Improvements of KUR-ISOL have made possible more detailed studies on the structures of neutron-rich nuclei (A=146-154). Several measurements [2–5] were done on γ-rays and excited states of ^{152}Nd. However, more precise data are required to discuss the band structure and transition rates. In order to get systematics of the nuclear structure data in the A=146-154 region, we have performed with the improved KUR-ISOL system present measurements on ^{152}Nd produced via β^- decay of ^{152}Pr.

In a series of our ^{152}Nd studies, a part of the results obtained by conversion electron measurements have been published in Ref. [6]. These measurements and the present study may contribute to make a systematical map of the structure of neutron-rich rare-earth nuclei. In this report, we propose a detailed decay scheme, including spin and parity assignments of excited states and level lifetimes. Some discrepancies concerning multipolarities of some transitions between the present results and the previous one have been discussed in view of the band structure of ^{152}Nd.

2 Experiments and results

2.1 Source production

The ^{152}Pr activities were obtained from mass separated fission products of ^{235}U using the KUR-ISOL. The ^{235}U target (30 mg, 0.7 mg/cm^2) was irradiated in the through-tube facility of KUR. The fission products were transported by a He + N_2-jet system from the irradiation chamber to the surface-ionization ion source with PbI_2 aerosols. A small amount of O_2 gas was added to the He + N_2-jet to improve ionization efficiencies for rare-earth elements, which were oxidized and produced as the oxides [7,8]. After the ionization, the PrO^+ ions were accelerated by about 30 keV and mass-separated by means of a 45° magnetic sector field with the mass resolution of about 600. Radio activities of $A = 152$ isobars were collected on an aluminized Mylar tape of the transport system.

2.2 γ-γ coincidence measurements

The γ-γ coincidence measurements were performed with two HPGe detectors whose efficiencies and energy resolutions are 58.4% and 32.5%, 1.80 and 1.84 keV (at 1332keV), respectively. The collected activities of $A = 152$ isobars on an aluminized Mylar tape were set between the HPGe detectors which were located 4 cm apart from each other. The tape was moved away and the activities were refreshed every 1 minute. Total coincident events of about 7.0×10^8 were collected for the present measurement. All the γ transitions except 322 keV γ transition reported by Karlewski *et al.* and Smith *et al.* [2,9] were seen in the present experiment. The 322 keV γ transition was found in the β-gated single spectrum but not placed in the decay scheme by Karlewski *et al.*. It was placed in the ground state band from 805.4 keV($I^\pi = 8^+$) level to 483.5 keV ($I^\pi = 6^+$) level by Smith *et al.* [9]. The 223.4 and 1580.0 keV γ transitions reported by Hellström *et al.* [3] could not be confirmed. Nineteen γ-rays and four excited

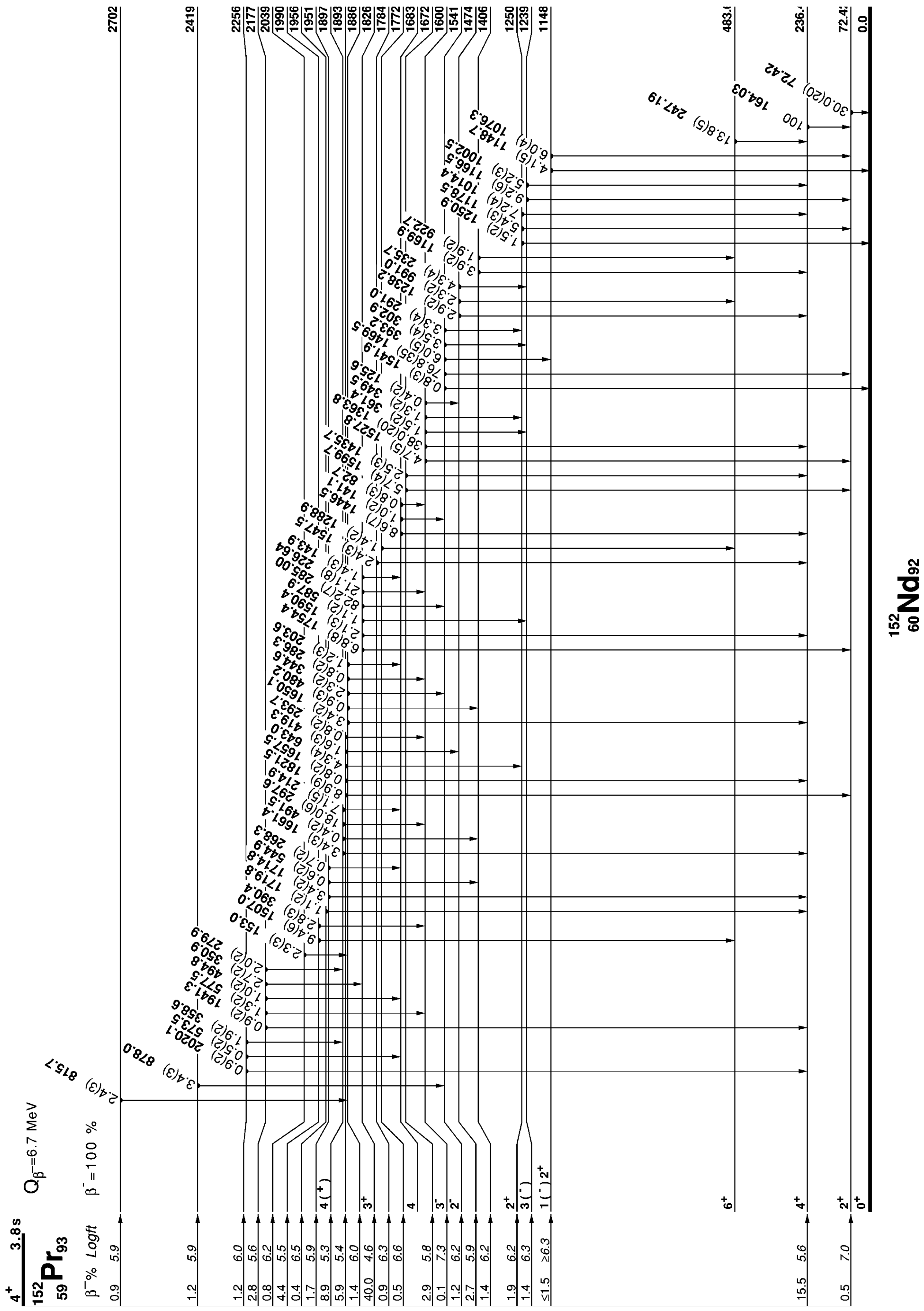

Fig. 1. The decay scheme of ^{152}Pr proposed by the present experiments

Table 1. Energy and intensity of γ-rays following the β-decay of ^{152}Pr

Energy (keV)	Relative intensity[a]	Hellström *et al.*[a] [3]	Karlewski *et al.*[a] [2]	Energy (keV)	Relative intensity[a]	Hellström *et al.*[a] [3]	Karlewski *et al.*[a] [2]
72.42(20)	30.0(20)	28.0(30)	38.9(7)	643.0(5)	4.3(4)	4.4(10)	
82.7(6)	0.8(3)		1.6(8)	815.7(7)[b]	2.4(3)		
125.6(6)[b]	0.4(2)			878.0(7)	3.4(3)	7.6(4)	
141.1(5)	1.0(2)	2.3(5)	1.5(4)	922.7(6)	1.9(2)	3.3(3)	
143.9(6)	1.4(3)	2.3(5)	1.9(5)	991.0(5)	2.3(2)	3.8(4)	
153.0(5)[b]	2.3(3)			1002.5(5)	5.2(3)	4.8(3)	6.3(13)
164.03(10)	100	100	100	1014.4(4)	7.2(4)	7.4(4)	6.3(23)
203.6(5)	1.2(3)	1.4(7)		1076.3(4)	6.0(4)	5.2(4)	7.4(24)
214.9(3)	7.1(5)	8.4(4)	7.9(5)	1148.7(4)	4.1(5)	3.3(5)	5.2(23)
226.64(20)	21.1(8)	18.7(9)	17.8(5)	1166.5(4)	9.2(6)	5.2(5)	8.9(16)
235.7(4)	4.3(4)	2.2(5)		1169.9(5)	3.9(2)	3.7(4)	
247.19(20)	13.8(5)	11.0(6)	10.7(5)	1178.5(4)	5.4(3)	6.1(5)	4.0(12)
268.3(7)[b]	0.7(2)			1238.2(6)	2.9(2)	2.9(5)	
279.9(4)[b]	2.0(2)			1250.9(7)[b]	1.5(2)		
285.00(20)	82.2(7)	72.0(5)	81.0(8)	1288.9(7)	1.4(2)	2.1(3)	
286.3(6)[b]	0.8(2)			1363.8(3)	38.0(20)	34.5(20)	36.6(27)
291.0(5)	3.3(4)	5.1(4)	8.8(13)	1435.7(6)[b]	2.5(3)		
293.7(6)[b]	0.8(2)			1446.5(4)	8.6(7)	8.5(4)	7.7(23)
297.6(3)	18.0(6)	14.1(7)	13.2(6)	1469.5(3)	76.8(35)	70.0(40)	78.1(35)
302.9(5)	3.5(4)	4.4(4)	2.6(8)	1507.0(4)	9.4(6)	2.1(2)	8.1(22)
344.6(4)	2.3(2)	1.8(2)		1527.8(6)	4.7(5)	3.3(3)	4.6(19)
349.5(6)	1.3(2)	3.5(3)		1541.9(7)	0.8(3)	< 0.9(5)	
350.9(5)	2.7(2)	1.7(5)	4.1(6)	1547.5(7)	2.4(3)	2.6(5)	
358.6(6)[b]	1.9(2)			1590.4(7)	2.1(3)	0.6(2)	2.4(10)
361.4(6)	1.5(2)	2.5(2)	1.5(17)	1599.7(6)[b]	5.7(4)		
390.4(5)	2.8(3)		3.1(15)	1650.1(5)	3.4(2)	3.6(3)	
393.2(5)	6.0(5)	8.7(4)	4.9(12)	1657.5(8)	0.8(2)	1.0(3)	
419.3(6)	1.6(3)	3.7(2)		1661.4(5)	3.4(3)	2.0(3)	2.6(14)
480.2(7)[b]	0.9(3)			1714.8(5)	3.4(2)	3.6(3)	
491.5(7)[b]	0.4(2)			1719.8(8)	1.1(2)	1.3(3)	
494.8(6)[b]	1.0(2)			1754.4(6)	6.8(8)		6.7(20)
544.9(7)[b]	0.6(2)			1821.5(6)	8.9(9)	5.0(10)	
573.5(6)[b]	0.5(2)			1941.3(8)	0.9(2)		1.3(11)
577.5(5)[b]	1.3(2)			2020.1(8)[b]	0.9(2)		
587.9(6)[b]	1.1(2)						

[a]Normalized to the 164 keV γ-ray
[b]The γ-rays newly observed

states were newly found. The decay scheme of ^{152}Pr is shown in Fig.1 and the γ-ray energies and intensities in this decay are listed in Table 1.

2.3 γ-γ angular correlation measurements

Gamma-Gamma angular correlation measurements employed four HPGe detectors of different kinds whose efficiencies are 58.4%, 32.5%, 30.0% and 31.3%, and energy resolutions are 1.80, 1.84, 2.00 and 1.85 keV at 1332 keV of ^{60}Co, respectively. In order to average different coincidence efficiencies between the HPGe detector pairs, measurements were made at two different fixed configurations [10]. Measuring angles were 90°, 105°, 120°, 135°, 150° and 165° for the first arrangement and 100°, 110°, 127.5°, 137.5°, 152.5° and 170° for the second arrangement. Twelve measuring points were thereby possible in total with these arrangements, as shown in Fig.2.

All the detectors were placed in the same plane, each being about 6 cm apart from the source point. The activities of $A = 152$ isobars were measured for 70 s, and swept away by the tape in order to suppress γ-rays from the collected daughter activities of ^{152}Nd whose half-life is 11.4 m. The total counting time was about 120 hours, and about 3.8×10^8 coincidence events were obtained. This system was tested on-line, using the known γ-γ angular correlation in the β^- decay of ^{146}La, and off-line, using the correlation in the β^- decay of ^{152}Eu. The γ cascade of the 164 - 72 keV ($4^+ - 2^+ - 0^+$) in the ground state band can be used for checking the γ-γ angular correlation measurement system. The result of fitting to the γ-γ angular correlation function is $A_2 = 0.097(15)$ and $A_4 = 0.010(10)$. In the same way, γ transitions of the 247 and 164 keV in the ground state band can be fitted by the theoretical angular correlation coefficients for the $6^+ - 4^+ - 2^+$ transition. The example of the measured angular correlation for

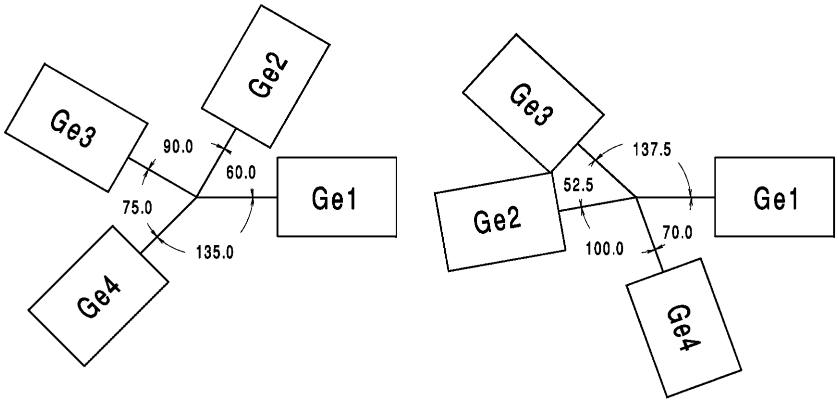

Fig. 2. The 4 HPGe detectors arrangement for γ-γ angular correlation measurements

the 1364-164 keV γ-ray ($3^- \rightarrow 4^+ \rightarrow 2^+$) cascade in the β^- decay of ^{152}Pr is shown in Fig.3. The 236 and 72 keV states are known as 4^+ and 2^+, respectively, because they are levels in ground state band. From this result, the spin of the 1600 keV state was determined as 3. Other results of γ-γ angular correlations are shown in Table 2.

2.4 Level life-time measurements

The β-γ-γ triple coincidence method was employed to measure level life-times in ^{152}Nd. Detectors used in this measurement were a 2 mm thick PilotU plastic scintillator for β-rays, a BaF_2 scintillator and the 30.0 % HPGe detectors for γ-rays. These detectors were placed in the same plane. The plastic and BaF_2 scintillators were mounted on fast XP2020 photomultipliers. The time resolution with this detector system was 180 ps FWHM at 1 MeV. An ORTEC 462 time calibrator was used for the time calibration. A γ-γ coincidence with the HPGe detector and the BaF_2 detector served to select the desired decay path. The collected activities on the Mylar tape were put between two planks of the plastic scintillator. The BaF_2 and the HPGe detectors which sandwiched the activities and the plastic scintillator were placed face to face. This arrangement is illustrated in Fig.4. The tape of the transport system was moved every 60 s in order that γ-rays and β-rays of the daughter decay were suppressed. The total counting time was about 60 hours and the total events were about 3.0×10^6. Fig.6 shows the energy spectra by the BaF_2 detector in coincidence with the 285, 1364 and 1470 keV transitions selected in the HPGe detector. In the case of the 1542 keV level, the coincidence events gated by the β signal and the full energy peak at 1470 keV in the BaF_2 detector were sorted with gates at the 72 , 285 keV transitions by the HPGe detector. The timing spectra were analyzed and averaged with suitable weights. The time spectra obtained in the present measurement are shown in Fig.5.

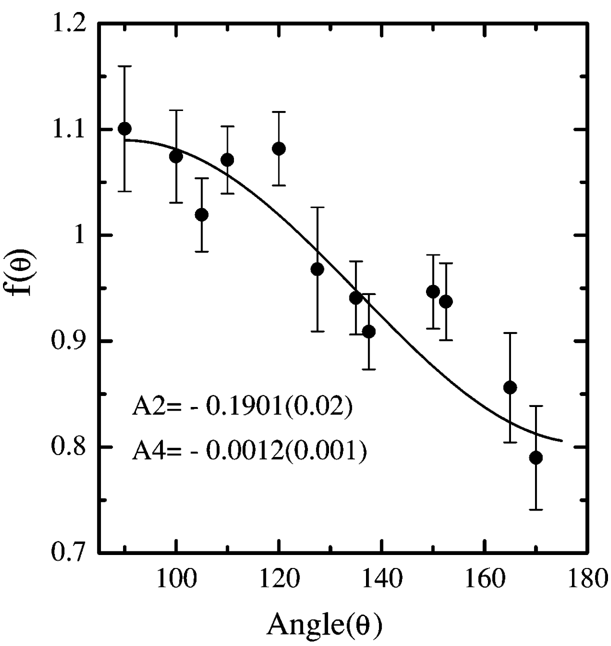

Fig. 3. The result of the angular correlation measurement for the 1364-164 keV γ-cascade

Table 2. Results of angular correlation measurements

Initial level (keV)	γ-ray (keV)	γ-cascade (keV)	Spin (I)	δ value
1542	1470	1470-72	2^a - 2 - 0	0.07(6)
1600	1364	1364-164	3^a - 4 - 2	0.07(5)
1683	1447	1447-164	4^a - 4 - 2	0.00(12)
1827	1470	285-1470	3^a - 2 - 2	-0.07(5)
1827	1364	227-1364	3 - 3 - 4	-0.01(8)
1827	303	285-303	3 - 2 - 3^a	-0.1(2)
1827	393	285-393	3 - 2 - 1^b	-0.6(6)
	393		3 - 2 - 2^b	-0.15(10)
1898	298	298-1364	4^a - 3 - 4	-0.12(11)

[a]Assigned by the present study.
[b]Not determined definitely due to large statistical errors.

3 Discussions

3.1 The decay scheme of ^{152}Pr

In the present study, 19 new γ-rays and 4 new excited states were identified as shown in Fig.1. The 83, 322, 1754

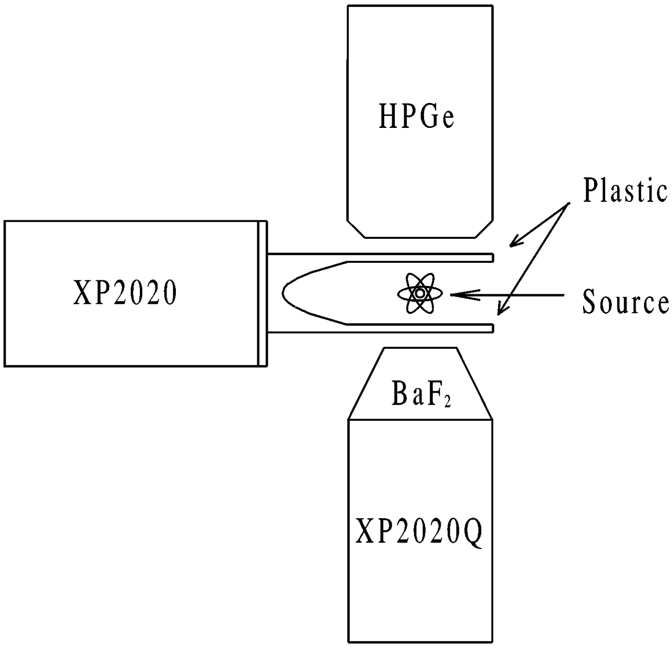

Fig. 4. The detector arrangement for level life-time measurements

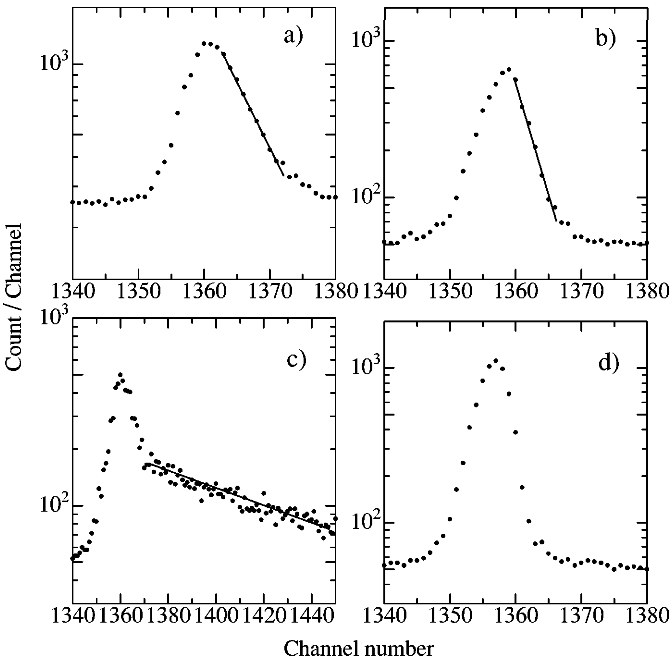

Fig. 5. The time spectra of ^{152}Nd obtained by the BaF_2 detector and the plastic scintillator for a) 236 keV, b) 1542 keV, and c) 72 keV excited states. d) The time spectrum of the prompt γ-cascade. The unit of time is 52.4 psec/channel

and 1941 keV transitions were reported by Karlewski *et al.* [2]. The 322 keV transition was also reported by Smith *et al.* [9]. They were not identified by Hellström *et al.* [3]. However, the 83, 1754 and 1941 keV transitions were also found by us. The 322 keV transition reported by Karlewski *et al.* and Smith *et al.* and the 223 and 1580 keV transitions reported by Hellström *et al.* and the second 0^+ level

Table 3. Results of ^{152}Nd level life-time measurements

Level energy (keV)	Present results (ps)	Hellström *et al.* [12,13] (ps)
72.4	3990(220)	4450(260)
236.5	300(15)	330(14)
1541.9	122(10)	145(11)

at 1139 keV reported by Chapman *et al.* [11] could not be observed. The γ-rays with energies above 2020 keV were not measured in the present measurements. The Q_β value of 5600 keV was used to estimate the log*ft* of the β transition and the β transition to the ground state was not taken into consideration because the spin of the ground state of ^{152}Pr is $I = 4$.

3.2 Level life-times

Results of the present life-time measurements and those by Hellström *et al.* [12,13] are compared in Table 3. All results by Hellström *et al.* are somewhat longer than our results, although they are consistent with our results within statistical errors.

3.3 γ-γ angular correlations

The results obtained by the present study are summarized in Table 2. The spins of 6 excited states were determined. The spin of the 1149 keV state was restricted as either I =1 or 2 owing to the large statistical error. The log*ft* value of the 1149 keV state is 6.3. So there is a possibility that the spin of the 1149 keV state is 2. But, if there are some unknown γ-rays deexiciting to the 1149 keV state, the log*ft* value of this state is raised, and then the spin of this state can be either I =1 or 2.

3.4 The parity of the ^{152}Pr ground state

In order to discuss about the parity of the ^{152}Pr ground state, we have valuable information that two transitions of 227 and 285 keV in ^{152}Nd were determined as E1 in the previous report [6] and that the life-time of the 1542 keV level was measured as 122 ps in the present study. By using the branching ratio from the 1542 keV level, we can calculate the partial life-time of the 1542 keV transition as 1.4×10^{-8}s. This value corresponds to the transition probability of $7.1\times10^{7}s^{-1}$ and the enhancement factor of 0.96×10^{-4} for E2 and hindrance factor of 0.89×10^{-2} for M2 as compared with the Weisskopf estimates. Taking into account the reported values given in Ref. [14], most of E2 enhancement factors lie in $10^1\sim10^2$ while a lot of M2 hindrance factors range from 10^{-1} to 10^{-2}. Therefore, we can say that the 1542 keV transition is M2 more probably than E2, which means that the 1542 keV level is 2^-. The spin and parity of the 1542 keV state was also reported by Karlewski *et al.* [2] to be $I^\pi = 2^-$ from the branching of the depopulating γ-rays. This leads to the 3^+ assignment for the 1827 keV level because the 285 keV transition is

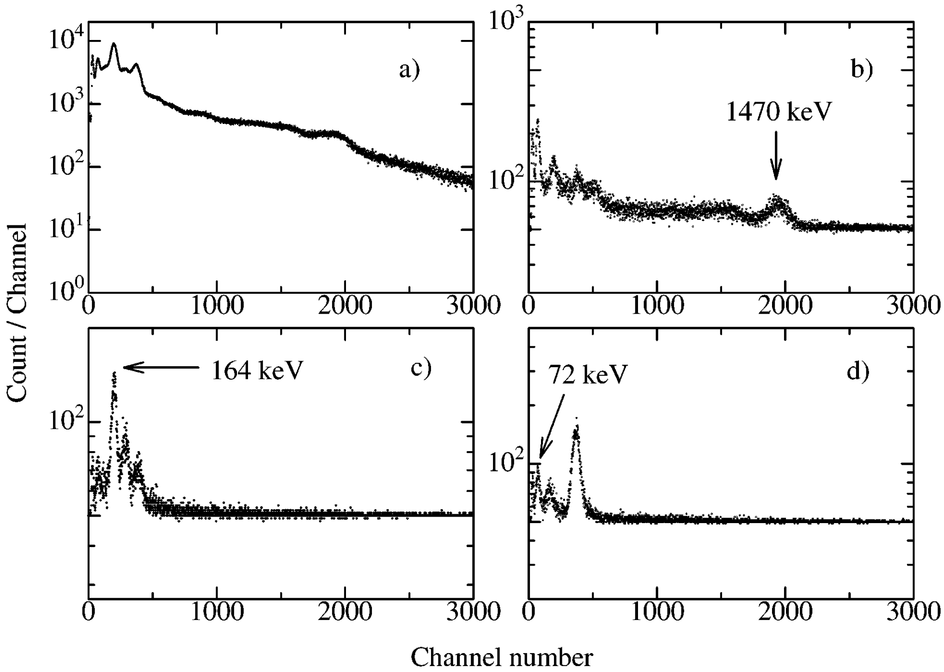

Fig. 6. BaF_2 spectra gated by a) whole spectrum, b) 285 keV, c) 1364 keV and d) 1470 keV γ-peaks of the HPGe detector

E1. Similarly, we can assign the 1600 keV as 3^- since the 277 keV was determined as E1.

The ground state of ^{152}Pr decays to the 1827 keV state in ^{152}Nd by the β^- transition with the logft value of 4.6. This fast β^- transition was interpreted as a spin-flip transition (the allowed unhindered transition) by Karlewski *et al* and Hellström *et al* [2,3] between the two Nilsson states, $\pi 5/2^-[532\uparrow]$ and $\nu 3/2^-[532\downarrow]$. Then, the ground state is considered as $(\pi 5/2^-[532\uparrow] \otimes \nu 3/2^-[521\uparrow])$ $I^\pi = 4^+$. Therefore, we propose that the ground state of ^{152}Pr is 4^+. In order to confirm the above discussion more precisely, we should measure the internal conversion electron of the 291 keV transition which depopulates from the 1542 state to the 1251 keV 2^+ state.

4 Summary and conclusions

Level structures of ^{152}Nd were investigated through the β^- decay of ^{152}Pr. By the γ-γ coincidence, γ-γ angular correlation, conversion electron, β-γ-γ triple coincidence measurements, 19 γ-rays and 4 excited states were newly found and the spins and parities of some excited states were deduced. The spin and parity of the ^{152}Pr ground state is proposed to be 4^+. Some of spins and parities of excited states which were predicted by other groups could not be confirmed by present experiments. For example, it was reported that the spin and parity of the 1149 keV is 1^- from systematic consideration by Karlewski *et al.* and M. Hellström *et al.* [2,3]. However, the β-feeding to this level is not consistent with the 1^- assignment. For confirming the spin and parity of the 1149 keV state and others, better statistical γ-γ angular correlation and conversion electron measurements are planned. The spins and parities of many excited states of ^{152}Nd will be investigated by this planned experiments.

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