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First observation of isomeric transition from ^{148m}Pr and parity assignment for excited levels in ^{148}Pr

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Abstract. Internal conversion electrons from the decay of ^{148}Ce and ^{148m}Pr have been measured with a Si(Li) detector. The radioactive sources were produced by the thermal neutron-induced fission of ^{235}U, followed by an on-line mass separation. K- and L-conversion electrons of the isomeric transition from ^{148m}Pr were newly observed at 34.6 and 70.8 keV, respectively. The $M3$ multipolarity was assigned to this transition from the experimental conversion coefficients, and, consequently, the 76.8 keV isomeric level was found to be a 4^- state. Parities of some excited levels in ^{148}Pr were also deduced.

PACS. 23.20.Nx Internal conversion and extranuclear effects – 27.60.+j $90 \leq A \leq 149$

Level structures of odd-odd nuclei are among the most complex topics in nuclear physics. Unambiguous level schemes with experimental spin assignments are required for a detailed discussion on phenomena in these nuclei. One of the most interesting features around $A = 150$ is a frequent occurrence of isomers with $T_{1/2} \geq 1$ s [1]. In contrast to isomers in odd-mass neighbors, those in odd-odd nuclei have longer half-lives than their ground states, and the dominant decay mode is a β^--decay in many cases. For these isomers, it is difficult to observe isomeric transitions (ITs), in particular, by γ-ray measurements owing to their small probabilities. Hence, experimental data on excitation energies and on electromagnetic properties are scarce for odd-odd isomers.

In ^{148}Pr, the existence of low- and high-spin isomers has been reported in refs. [2–4] on the basis of observation of two different half-lives: 2.29(2) min for low spin and 2.01(7) min for high spin. However, the level ordering, spin and parity of the isomer are not determined definitely because the IT is not observed. At present, only the $I = (4)$ assignment for the high-spin isomer [2] and 1^- for low-spin [3] are proposed from their β^--decay studies.

In this paper, we report the conversion electron measurement for mass-separated ^{148}Ce and ^{148m}Pr nuclei. Electron peaks due to the IT from ^{148m}Pr are clearly observed using a β-electron coincidence technique, and properties of ^{148m}Pr are successively deduced. Parities of excited levels in ^{148}Pr are also determined from multipolarities of γ-rays following the β^--decay of ^{148}Ce.

The ^{148}Ce and ^{148m}Pr sources were prepared by an on-line isotope separator installed at the Kyoto University Reactor (KUR-ISOL) [5], following the thermal neutron-induced fission of ^{235}U. Thermal neutrons with a flux of 3×10^{12} n/cm^{2}s irradiated a UF_4 target of 50 mg. The fission products were ionized in a surface-ionization–type ion source, and mass-separated with a resolution of $M/\Delta M \sim 600$. The mass-separated beams were implanted into an aluminized Mylar tape in a tape-transport system. The source was periodically moved to a detector station at time intervals of 113 s.

The measuring position was equipped with three detectors: a Si(Li) detector (crystal size of 500 mm^2 $\times$ 5 mm) for conversion electrons, a 30% HPGe detector for γ-rays, and a 1 mm thick plastic scintillator (90 mm $\times$ 80 mm) for β-rays. 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. The energy loss due to the film was corrected by calculations using the EGS4 code [6]. The scintillator was installed into the ISOL chamber and mounted closely to the source. To absorb low-energy electrons such as conversion electrons, the scintillator was covered by a 0.2 mm thick aluminum foil. The solid angle subtended by the scintillator was about 45%. The energy and efficiency calibration of the HPGe detector was performed using standard γ-ray sources of

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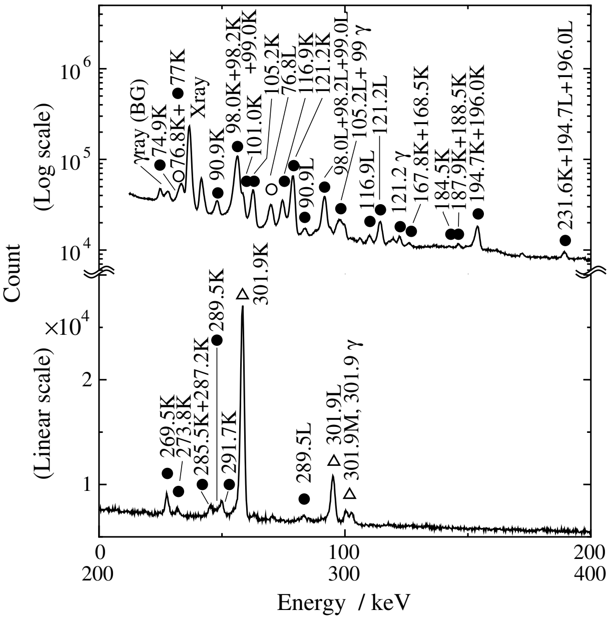

Fig. 1. A conversion electron spectrum for $A = 148$ nuclei. Energies are given in keV. The symbols of closed circles, open circles and triangles mean electrons from the decay of ^{148}Ce, ^{148m}Pr (IT) and ^{148g}Pr, respectively.

^{133}Ba, ^{137}Cs, ^{60}Co and ^{152}Eu. Coincidence summing effects were taken into account in deducing the peak counts. The efficiency calibration for the Si(Li) detector was made on-line, as described later.

Electron and γ-ray singles, β-gated electron and γ-ray singles, and electron-γ coincidence measurements for $A = 148$ nuclei were performed for 18 h. To determine the half-lives, the singles spectra were measured in a multi-spectrum scaling mode in which the 112 s counting time was divided into sixteen 7 s intervals. The β-gate efficiency was evaluated using transitions from mass-separated ^{93m}Y, ^{93}Sr and ^{93}Rb. The deduced efficiency, that is, a ratio between the peak count observed in the β-gated spectrum and that in the singles, was less than 0.01 for ITs and about 0.3 for transitions following β^--decays. Thus, the detection system has a sufficient ability to distinguish transitions due to isomeric decays from β^--decays.

A conversion electron spectrum is shown in fig. 1. The energy resolution (FWHM) was 1.8 keV for the 258 keV electron. In this spectrum, the 302 keV $E2$ K-conversion line from the decay of ^{148}Pr was strongly observed, so that the efficiency calibration of the Si(Li) detector was made using this transition. Here, it is important to note that we assume a constant efficiency for electrons with energies of 70–1000 keV. This assumption is confirmed by Monte Carlo calculations using the EGS4 code [6] and by measurements of three conversion electrons: the 169 keV $E3$ transition from ^{93m}Y, the 259 and 410 keV $E2$ transitions from ^{146}La. In an energy range below 70 keV, on the other hand, the calculated efficiency decreases with decreasing energy owing to absorption by the polyester film. Therefore, the attenuation was corrected by calculations in low energy.

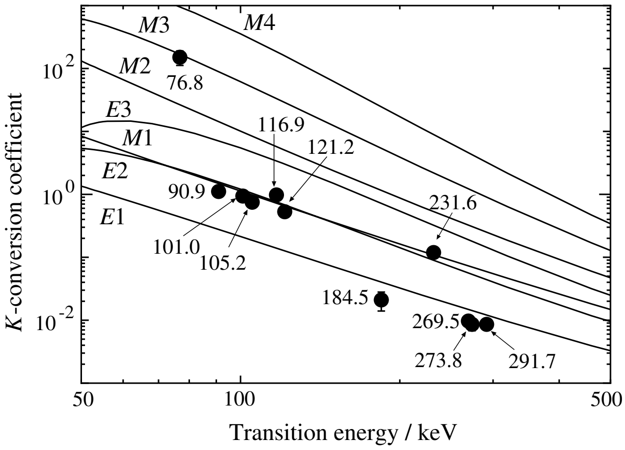

Fig. 2. Experimental K-conversion coefficients of γ-transitions in ^{148}Pr. The solid curves show the theoretical values [7].

Table 1. Experimental K-conversion coefficients for γ-transitions following the β^--decay of ^{148}Ce. The previous assignments are taken from ref. [8].

Transition (keV)	Conversion coefficient	Assignment	
		Present work	Previous work
90.9K	1.11(10)	$M1/E2$	$M1/E2$
101.0K	0.94(6)	$M1/E2$	$E1$
105.2K	0.75(6)	$M1/E2$	$M1$
116.9K	0.98(9)	$M1/E2$	$M1/E2$
121.2K	0.53(4)	$M1/E2$	$M1/E2$
184.5K	0.021(7)	$E1$	–
231.6K	0.119(20)	$M1/E2$	–
269.5K	0.0097(8)	$E1$	$E1$
273.8K	0.0086(18)	$E1$	–
291.7K	0.0086(9)	$E1$	–

In the following, we will describe the experimental results on electrons from the β^--decay of ^{148}Ce firstly, and those on the IT from ^{148m}Pr later.

The experimental K-conversion coefficients are presented in table 1 and fig. 2. The value for the 232 keV transition was deduced after subtracting those contributions of the 195 keV $E1$ and 196 keV $M1$ L-conversion electrons, which were estimated using the theoretical conversion coefficients [7]. The $M1/E2$ multipolarity was assigned to the 91, 105, 117 and 121 keV transitions, and $E1$ to the 270 keV transition from comparison between the experimental and the theoretical conversion coefficients [7]. These results are consistent with the previous assignments [8], and confirm the reliability of our experimental technique. The $E1$ multipolarity was newly assigned to the 185, 274 and 292 keV transitions, and the $M1/E2$ multipolarity to the 232 keV transition. The 101 keV γ-ray was found to be a $M1/E2$ transition because the experimental coefficient of 0.94(6) fairly agreed with the theoretical value of 1.1 for $M1/E2$ [7]. This multipolarity disagrees with the previous $E1$ assignment [8], which is based on the experimental K-conversion coefficient of 0.5(2) obtained by Chung (cited as a private communication in ref. [8]).

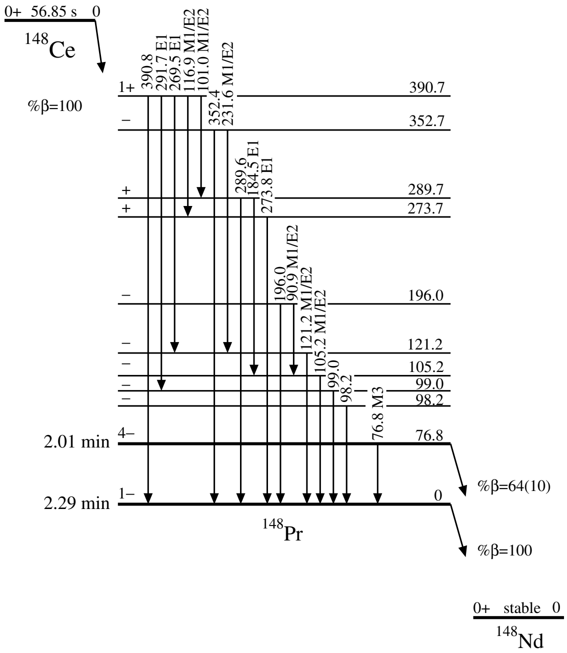

Fig. 3. Partial decay schemes of ^{148}Ce and ^{148m}Pr. Parities and multipolarities presented in this figure are deduced in our work.

Although the reason for this discrepancy is unclear, our assignment appears to be reasonable. This is because the $M1/E2$ multipolarity is consistent with those obtained for the other transitions, as mentioned later.

Parities of excited levels in ^{148}Pr were deduced from the multipolarities and from the published decay scheme [8] (see fig. 3). In this discussion, we consider that the 1^- isomer is the ground state of ^{148}Pr, which is confirmed by our study as described later. The odd parity was assigned to the 105.2 and 121.2 keV levels, and the even parity to the 273.7 keV level. These assignments are based on the multipolarities obtained for the 105, 121 and 274 keV transitions, respectively, and agree with the previous results [8]. The odd-parity assignment for the 196.0 keV level [8] was confirmed by the 91 keV $M1/E2$ transition. Consequently, the β-feeding from ^{148}Ce ($I^\pi = 0^+$) to this level was found to be first-forbidden. This assignment disagrees with a small $\log ft$ value of 5.8 [3], as already pointed out in ref. [8]. The inconsistency is probably due to overestimation of the β-intensity, which has been evaluated from the γ-ray imbalance. This comment is considerably valid because the presence of β-feedings to unestablished high-energy states has been reported from experiments using a total-absorption detector [9]. The 1^+ assignment for the 390.7 keV level [3] was supported by the 117 keV $M1/E2$, 270 keV $E1$ and 292 keV $E1$ transitions. The even parity was newly assigned to the 289.7 keV level from the 185 keV $E1$ γ-ray, and the odd parity to the 352.7 keV level from the 232 keV $M1/E2$ transition. The even parity for the 290 keV level was also obtained from the 101 keV $M1/E2$ γ-ray, which depopulates the 391 keV 1^+ level to the 290 keV level. The consistency strengthens not only our

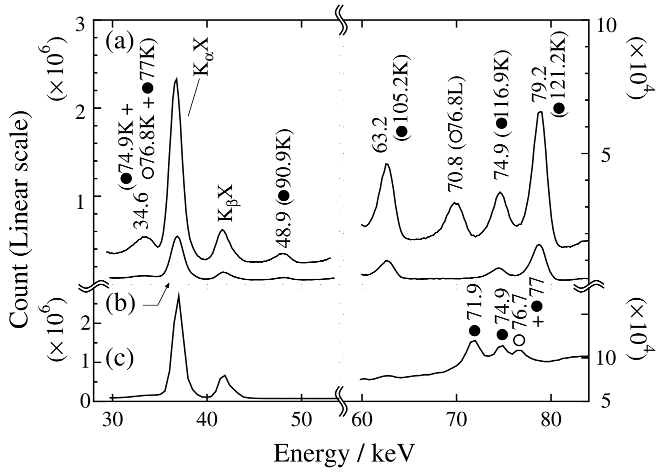

Fig. 4. A part of (a) electron singles, (b) β-gated electron and (c) γ-ray singles spectra for $A = 148$ nuclei. Energies are given in keV. The symbols of closed and open circles mean transitions from the decay of ^{148}Ce and ^{148m}Pr (IT), respectively.

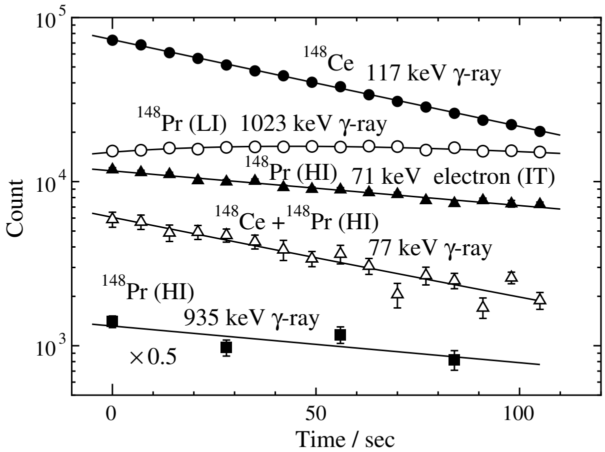

Fig. 5. Decay curves observed in the decay of ^{148}Ce and ^{148}Pr. High- and low-spin isomers are represented by HI and LI, respectively. The solid curves were obtained by least-squares fitting with the following functions: a single-component exponential function for ^{148}Ce and ^{148}Pr (HI), a two-component exponential function for the 77 keV doublet, and a growth-and-decay curve for ^{148}Pr (LI).

parity assignment for the 290 keV level, but the $M1/E2$ multipolarity newly assigned to the 101 keV γ-ray.

A 70.8(3) keV electron peak was clearly observed in the singles spectrum, but not coincident with β-rays, as shown in fig. 4. These results exhibit a striking contrast to the other electron peaks, and mean that the 71 keV electron is due to an IT. In the following, three analyses were performed to identify the origin of this 71 keV electron. First, time-dependent electron spectra were analyzed to determine the half-life. As shown in fig. 5, the decay curve of the 71 keV electron was well reproduced by a single-component exponential function. The half-life was found to be 2.37(5) min. For comparison, fig. 5 also shows typical decay curves observed in the β^--decay of ^{148}Ce and

^{148}Pr. The half-life observed for ^{148}Ce is 56.85(34) s, that for the high-spin isomer of ^{148}Pr is 2.41(16) min, and the γ-ray due to the low-spin isomer of ^{148}Pr show a growth-and-decay time dependence. From this half-life analysis, the 71 keV electron was assigned to the decay of the high-spin isomer of ^{148}Pr. Here, we note that the half-life of 2.41 min observed for the high-spin isomer is longer than the evaluated value of 2.01 min [8]. The disagreement is explained by β-feedings from ^{148}Ce to ^{148}Pr via medium-spin excited states in ^{148}Pr. The experimental value of 2.41 min is reproduced in the assumption that the growth component from ^{148}Ce contributes to 4% of the total population of the high-spin isomer with $T_{1/2} = 2.01$ min.

Second, intensity ratios of the electron counts observed in the β-gated spectrum to those in the singles were deduced for all peaks. The ratios for most of the electrons were ~ 0.3, and small values were observed only for two peaks: 0.137(5) for the 34.6(5) keV electron and ~ 0 for 71 keV. These results mean that the 35 keV electron is also due to an isomeric decay. The energy difference of the two peaks agrees with that of the electron binding energy of Pr: $B_K = 42.0$ keV and $B_L = 6.4$ keV. Thus, the 35 and 71 keV peaks were found to be the K- and L-conversions of a 76.8(2) keV IT from ^{148m}Pr, respectively. The value of 76.8 keV was deduced from a weighted average of the conversion electrons and the corresponding γ-ray energies (see below). Here, it may be worth mentioning that the intensity ratio for the 35 keV peak is larger than the β-gate efficiency for ITs (< 0.01) obtained from the calibration measurement. The disagreement suggests that the 35 keV peak is a multiplet.

Finally, the electron-γ coincidence data were analyzed to obtain cascade relationships. The conversion lines of the IT, however, were not observed in the coincidence spectrum. This probably means that the 77 keV IT directly populates the ground state. It is consistent with the level scheme of ^{148}Pr in which no excited states are established below 98 keV [8]. We conclude, therefore, that the excitation energy of the isomeric state is 76.8 keV.

A 76.7(2) keV γ-ray was observed in the singles spectrum (fig. 4). This peak was found to be a doublet of γ-rays from the isomeric decay of ^{148m}Pr and from the β^--decay of ^{148}Ce. This assignment was based on the following two reasons. First, the peak count observed in the β-gated spectrum was 22(6)% of that in the singles. This ratio is smaller than the value for γ-rays following β^--decays ($\sim 30\%$), but much larger than that for ITs ($< 1\%$). Second, the 77 keV γ-ray was coincident with Pr K X-rays. To obtain the γ-ray intensity originating from ^{148m}Pr, the decay curve of the 77 keV peak was fitted by a two-component exponential function with half-lives of 56.85 s and 2.41 min. From this analysis, the intensity ratio $I(\mathrm{Pr})/I(\mathrm{Ce})$ was found to be 0.15(3) for this doublet.

The L-conversion coefficient of the 77 keV IT was deduced to be 125(33) (table 2), so that the $M3$ multipolarity was assigned to the IT. Summing effects due to the coincidence of the K-conversion electron and K X-rays were corrected. We also note that the 71 keV electron is a singlet of the L-conversion line of the 77 keV IT, in spite of the fact that the 77 keV γ-ray peak is a doublet of transitions from ^{148m}Pr and ^{148}Ce. This assumption is based on the experimental results that the 71 keV electron peak is not observed in the β-gated spectrum. This fact probably means that the multipolarity of the 77 keV γ-ray from the β^--decay of ^{148}Ce is $E1$ or $M1$, and that its L-conversion coefficient is much smaller than that for the IT. The multipolarity of the IT was also obtained from the K-conversion coefficient. Here, we should notice that the 35 keV electron peak is a triplet: the IT from ^{148m}Pr, the 75 keV $M1/E2$ and 77 keV K-conversions from ^{148}Ce. While the 35 keV triplet was easily separated from the K X-ray peak, it could not be resolved into three components owing to the poor energy resolution. To obtain the electron count from ^{148m}Pr, the contributions from ^{148}Ce were evaluated from the experimental γ-ray counts (75 and 77 keV) and from their theoretical K-conversion coefficients [7]. Assuming that the 77 keV γ-ray is an $E1$ transition, the contributions from ^{148}Ce were evaluated to be 29(4)% of the total count of the triplet. The K-conversion coefficient for the IT obtained after subtracting this contribution supports the $M3$ assignment (table 2).

Table 2. Experimental K- and L-conversion coefficients for the 76.8 keV isomeric transition from ^{148m}Pr together with the theoretical values [7].

Shell	Experiment	Theory			
		$E3$	$E4$	$M3$	$M4$
K	151(39)	10.71	44.64	169.5	957.7
L	125(33)	85.64	1951	148.6	2972

The 4^- isomer decays through not only the IT but also the β^--transitions [2,4] (fig. 3). Branching ratios of the β^- and isomeric decays from the 4^- state were evaluated using peak counts of the 935 keV γ-ray and the 77 keV IT. Here, the 935 keV γ-ray is only due to the β^--decay of the 4^- isomer, and its absolute intensity per β^--decay is 1.60(16)% [8]. Using this value and the theoretical total conversion coefficient of 365 for the 77 keV $M3$ transition [7], the branching ratios were obtained to be $I(\beta) = 64(10)\%$ and $I(\mathrm{IT} : \gamma + \mathrm{ce}) = 36(10)\%$. Consequently, the transition probability of the 77 keV isomeric γ-ray was deduced to be $B(M3) = 4.4 \times 10^{-2}$ W.u. This value is consistent with transition rates of 10^{-3}–10^{0} W.u. reported for $M3$ transitions in this mass region [1,10].

To propose configurations of the isomeric states, a tentative interpretation was undertaken on the basis of a systematics of low-lying levels in the neighboring odd-mass nuclei. In $N = 89$ isotones ^{147}Ce and ^{149}Nd, odd-parity levels were established in low energy. The $(5/2^-)$ was assigned to the ground state of ^{147}Ce [11], and $5/2^-$ to that of ^{149}Nd [12]. Previous studies [11,13] reported that these states were admixtures of the $5/2^-[523]$ and $3/2^-[532]$ orbitals. In $Z = 59$ isotope ^{147}Pr, even-parity states with $I = 3/2 - 7/2$ were reported below 100 keV [14, 15]. In a recent publication [15], the Nilsson orbital of $3/2^+[411]$ was assigned to this ground-state band. However, a contribution of the $5/2^+[413]$ orbital cannot be ignored because calculations by the particle-plus-triaxial-rotor model show a mixing of this orbital [14]. Studies on the level structure of ^{149}Pr are scarce, as compared with those of ^{147}Pr. Only the $I = (5/2^+)$ assignment for the ground state and the odd-parity band built on the 59 keV $(11/2^-)$ level are reported [15,16]. They are interpreted as the $3/2^+[411]$ or $5/2^+[413]$ orbital, and a band originating from excitation or decoupling of the $\pi h_{11/2}$ orbital, respectively. From the Gallagher-Moszkowski rules, the configuration of $\pi 3/2^+[411] \otimes \nu 5/2^-[523]$ is a probable candidate for the ground state of ^{148}Pr with $I^\pi = 1^-$, and $\pi 5/2^+[413] \otimes \nu 3/2^-[532]$ for the 4^- isomer.

In conclusion, we have measured conversion electrons of ^{148}Pr through the decay of ^{148}Ce and ^{148m}Pr. The isomeric transition from ^{148m}Pr was newly identified using a β-coincident detection system. The multipolarity of this transition was found to be $M3$, and $I^\pi = 4^-$ were unambiguously assigned to the 76.8 keV isomeric state. Configurations of ^{148m,g}Pr were explained by a proton-neutron coupling within the limit of zero-order approximation.

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