



EXCITED LEVELS OF Pd<105>

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EXCITED LEVELS OF Pd¹⁰⁵

Kyōzō ŌHIRA

As a part of the systematic survey of the medium weight odd-A nuclei, conversion electrons and gamma-rays of Pd¹⁰⁵ following the decay of 40 day Ag¹⁰⁵ have been studied with a double focusing beta-ray spectrometer, a thin lens beta-ray spectrometer and scintillation spectrometers. Gamma-gamma angular correlations have also been measured. The strong 654 keV transition previously considered to be a single transition was decomposed into the 645 keV (E1) and 649 keV (M1, E2) transitions, and further a new weak gamma-ray of 620 keV (M1, E2) was observed. This result removes the ambiguity about the transition rate in the level scheme. On the basis of the multipolarities of transitions and ft values for the electron captures, the following assignments are given: 649 keV (3/2, 5/2+), 620 keV (5/2+) and 501 keV (5/2+). The other results obtained are consistent with the level scheme given in the Nuclear Data Sheets. A value of 4×10^{-5} for the ratio

$$\frac{\{B(M1, 5/2 \rightarrow 7/2)/B(E2, 5/2 \rightarrow 5/2)\}_{exp}}{\{B(M1, 5/2 \rightarrow 7/2)/B(E2, 5/2 \rightarrow 5/2)\}_{SN}}$$

is obtained for the cascade M1 and crossover E2 radiations from the 344 keV level. This indicates that the E2 radiation from the 344 keV level is considerably enhanced; $B(E2)$ is about 25 times as large as single particle estimation.

1. INTRODUCTION

For even-even nuclei in the medium weight region, there are many systematic studies on the level energy, spin and transition probability, and various nuclear models^{1)~6)} are proposed to explain these data. The investigation of the structures of the odd mass nuclei in this mass region is very interesting because it may give some measure for the validity of the above models. There is, however, no systematic study on these odd mass nuclei because of the large variation of the ground state configurations and the lack of information concerning the characters of many excited levels.

In this paper the excited levels of Pd¹⁰⁵, whose level scheme is not fully established until now, are described. This investigation is a part of the systematic study of the odd mass nuclei in the medium weight region.

The levels of Pd¹⁰⁵ have been studied by many authors.^{7)~16)} Hayward and Hoppes⁹⁾ have measured the relative intensity of the 64 keV, 281 keV, 345 keV, 443 keV and 654 keV gamma-rays and found the coincidence pairs of 64 keV γ -281 keV γ , 319 keV γ -331 keV γ and 443 keV γ -654 keV γ . Further they have assigned the 64 keV and 281 keV transitions to be M1 and 345 keV transition to be E2. Raether¹⁰⁾ has confirmed the 1090 keV level by ob-

serving the 1090 keV gamma-ray and established the existence of 281 keV level by studying the coincidence pair of 281 keV γ -393 keV γ . He has assigned the spin and parity of the 281 keV, 345 keV levels to be 7/2+ and 5/2+ respectively from the measurement of the angular correlation, and further estimated the upper limits of the life times of 281 keV and 443 keV levels to be $1 \sim 2 \times 10^{-9}$ sec and 4×10^{-9} sec, respectively. Boedege¹¹⁾ has obtained the following results from the measurement of the external conversion electrons: $\alpha_K(642 \text{ keV}) = (1.2 \pm 0.2) \times 10^{-3}$, $\alpha_K(436 \text{ keV}) = (7.5 \pm 1) \times 10^{-3}$. On the basis of the ft value, Nozawa¹²⁾ has pointed out that the electron capture to the 1085 keV level is an allowed transition. Boyd¹³⁾ has suggested on the basis of the ft values of the beta decay of Rh¹⁰⁵ that the spin and parity of 319 keV level is 7/2+. The data on the Coulomb excitation^{14)~16)} have indicated the E2 enhancement for 270 keV and 430 keV transitions.

In spite of these experimental studies, there remain some uncertainties over the internal conversion coefficients, the relative intensities of transitions, gamma-gamma angular correlations and the spins and parities of levels. Thus the present measurements of the conversion electrons, gamma-rays and gamma-gamma angular correlation were undertaken in order to resolve some of the previ-

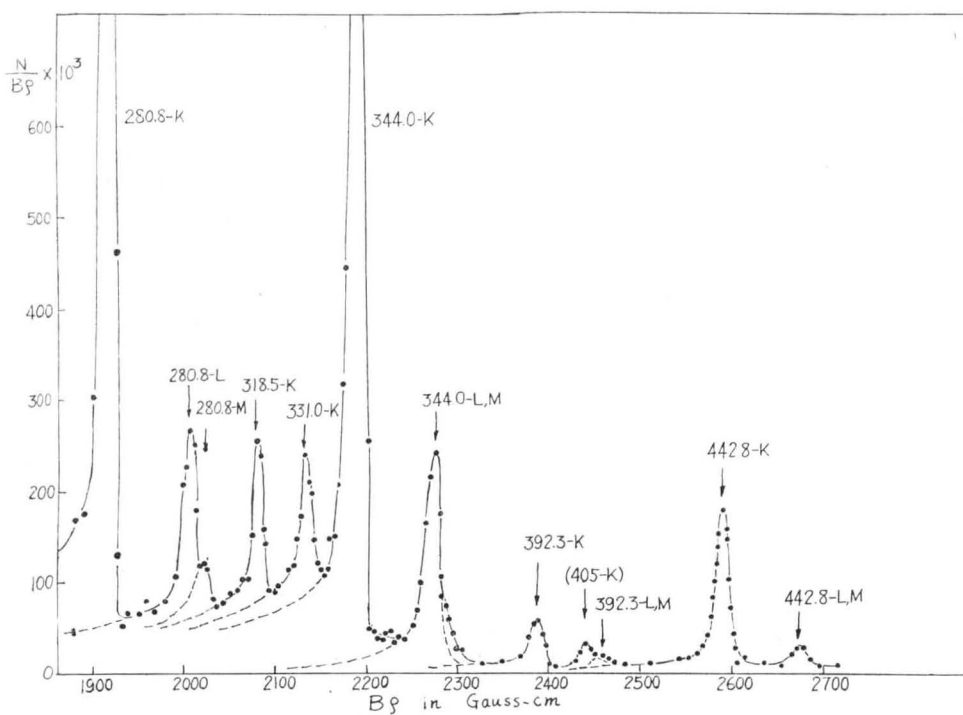
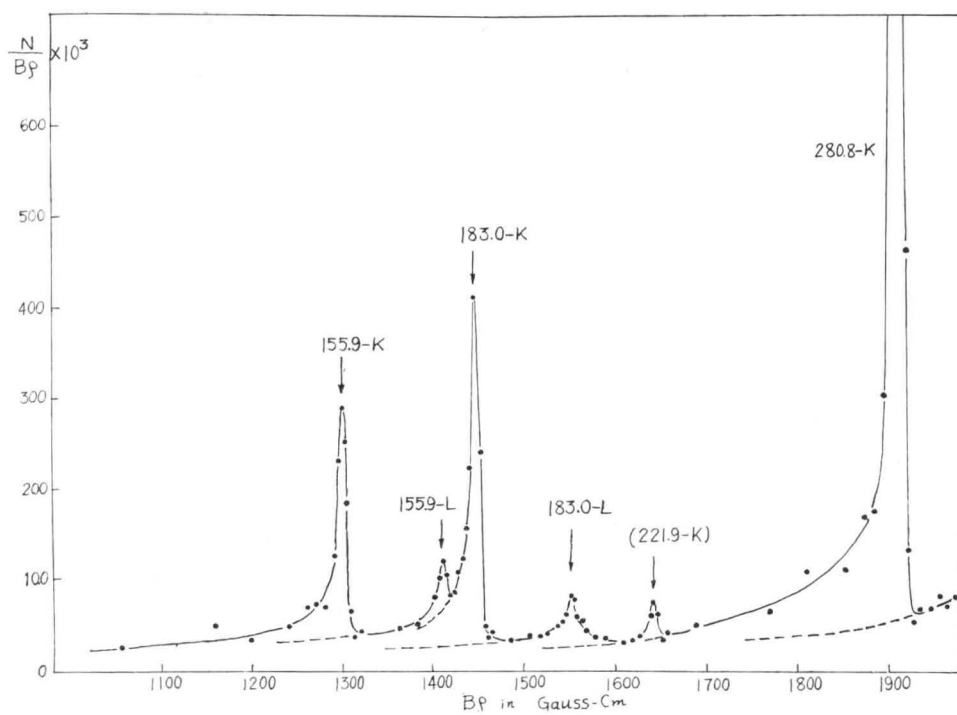


Fig. 1. Conversion electron spectrum

ous uncertainties and to study the level structure more completely.

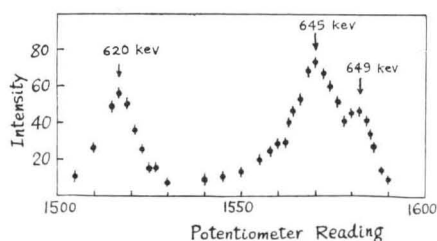


Fig. 2. 620 kev, 645 kev and 649 kev conversion electrons.

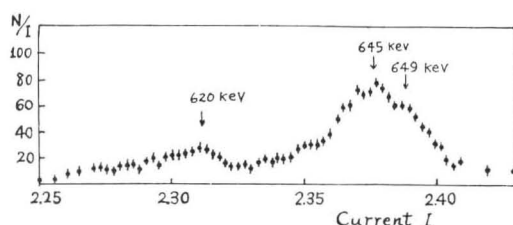


Fig. 3. 620 kev, 645 kev and 649 kev conversion electrons.

2. EXPERIMENTAL PROCEDURES AND RESULTS

2.1. Source Preparation

The Ag^{105} used in the present work was produced in the cyclotron of the Institute for Nuclear Study of the University of Tokyo by an $(\alpha, 2n)$ reaction on Rh^{103} powder, pressed to the thickness of 0.2 mm. The bombarding energy of α -particles was chosen to be 33 Mev so that the ratio of Ag^{105} to Ag^{106} , produced by $\text{Rh}^{103}(\alpha, n)\text{Ag}^{106}$ reaction, was about 10. Total intensity of bombarding α -particles was about 15 to $20\mu\text{A} \times 35$ hours. Electron sources, 3 mm by 20 mm, were prepared by electroplating the Ag^{105} from the AgNO_3 solution, prepared by chemical separation, onto 0.01 mm Al foils.* The AgNO_3 solution, dropped into a cylindrical container with inner diameter of 2 mm and depth of 2.5 mm, was used as the source for the gamma-ray measurement and the gamma-gamma angular correlation measurement.

2.2. Conversion Electron Spectrum

Internal conversion electrons were examined with INS III sector-type double focusing beta-ray spectrometer¹⁷⁾ at 0.7% resolution. The detector was a $1\text{mg}/\text{cm}^2$ mica window G-M counter. Only

Table I. Conversion lines in Pd^{105}

Electron energy (kev)	Shell	Relative intensity	Transition energy (kev)
39.6	K		64.0
60.5	L		
63.5	M		
131.5	K	3.9	155.9
152.1	L	0.5	
158.7	K	6.1	183.0
179.9	L	0.77	
256.4	K	27.	280.8
277.1	L	3.5	
280.6	M	1.	
294.1	K	2.9	318.5
306.7	K	2.5	331.0
328.4	L		
319.7	K	28.	344.0
340.2	L	4.05	
367.9	K	1.2	392.3
418.6	K	3.5	442.8
439.2	L	0.48	
596.	K	~ 0.05	620.
620.	K	0.53	645.
624.	K	0.26	649.
			790.
1061	K	~ 0.07	1085.

the 64 kev-K, L and M lines were corrected for window absorption using the curve published by Saxon.¹⁸⁾ A thin lens beta-ray spectrometer was also used at about 1% resolution with relatively strong source for measurements of relatively higher energy lines.

Transition energies were determined relative to the 64 kev- and 280.8 kev-K lines from the conversion spectrum obtained with the double focusing beta-ray spectrometer and listed in Table I. Typical electron spectra are shown in Figs. 1 and 2. The energy of the 790 kev transition was determined by analyzing scintillation gamma-ray spectrum (Fig. 5). The energy of the 1085 kev transition was obtained from the conversion electron spectrum observed with thin lens beta-ray spectrometer. It was found that the 654 kev transition previously considered to be a single transition splitted into two transitions of energies 645 and 649 kev, as clearly seen in Fig. 2. Further, the conversion spectrum measured with the lens spectrometer two months after bombardment showed clearly the existence of the 620 kev-K line, which

* The chemical procedure will be described in detail elsewhere by M. Koyama et al..

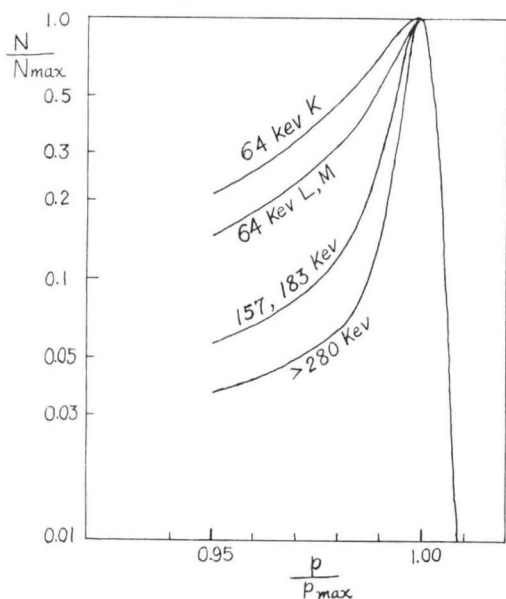
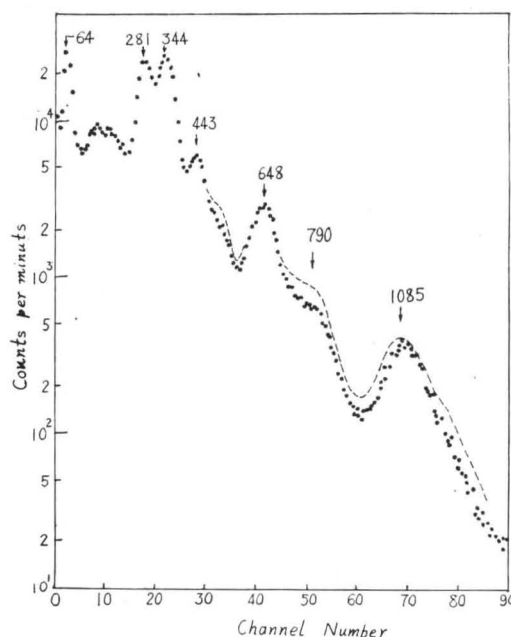


Fig. 4 Reduced line profiles.

was confirmed to be of Pd^{105} from its decay (Fig. 3).

In estimating the relative electron intensities exactly from very complex spectrum, it is a very difficult problem how to subtract the contributions from the higher energy electron lines. The following procedure was used in the present work: The reduced line profile* for all lines above about 250 kev was assumed initially to be that of the 442.8 kev-K line as shown in Fig. 4. Using this line profile for all lower energy lines of 392.3 kev-K, L, 344.0 kev-K, L, 331.0 kev-K, 318.5 kev-K and 280.8 kev-L, and subtracting the contributions from these lines successively from the complex spectrum, the reduced line profile of the 280.8 kev-K line was

Fig. 5 Gamma-ray spectrum of $\text{Pd}^{105+106}$

obtained. This line profile was then compared with initially assumed one. This procedure was repeated until an agreement of two line profiles was attained. It was found that the spectrum can be analysed satisfactorily by use of the identical line profile for all lines in the energy range 250-450 kev. This indicates that the effect of the source thickness is negligible above 250 kev. For the 183.0 kev-K, L lines and the 155.9 kev lines, the effect of the source thickness could not be neglected and another reduced line profile was needed to apply the subtraction method.

The relative intensities of electrons obtained by

Table II Conversion ratio

Transitions (kev)	K/L (Theoretical)				K/L (Experimental)
	E 1	M 1	E 2	M 2	
155.9	8.39	8.13	5.60	6.42	7.9
183.0	8.44	8.17	6.05	6.70	7.9
280.8	8.54	8.24	6.84	7.23	7.9 ± 0.4
344.0	8.57	8.26	7.05	7.43	7.0 ± 0.3
392.3	8.58	(8.28)	7.14	7.54	$8.2 \dagger$
442.8	8.57	(8.30)	7.20	7.63	8.6 ± 0.4

$\dagger$ K/L + M

* $\left(\frac{\text{counts / momentum}}{\text{peak counts / momentum}} \right)$ vs $\left(\frac{\text{momentum}}{\text{peak momentum}} \right)$ -curve is here called as "reduced line profile".

this self-consistent background subtraction method are considered to be in good precision (Table I).

In Table II the experimental K/L and K/L+M ratios are compared with theoretical ones deduced from the Sliv's tabulations.¹⁹⁾ The value of K/L+M for the 392.3 keV and K/L value for the 155.9 keV transition have not been reported previously. The values of K/L for the 442.8 keV, 344 keV and 183 keV transitions obtained in the present work are considerably different from the previously reported ones. The relative electron intensity for the 64 keV line is not discussed because of the ambiguities in absorption correction in the present work.

2.3. Gamma-ray Spectrum

Gamma-ray spectrum was obtained with INS scintillation spectrometers. The detectors were 1 $\frac{3}{4}$ in. $\times$ 2 in. NaI crystals which were mounted on RCA 6342 photo-multiplier tubes. Source to detector distance was 7 cm. The resolution of each detector was 11.8% for the 662 keV gamma-ray peak of Cs¹³⁷. The output pulses were recorded by the 20 channel pulse height analyzer.

The singles spectrum includes the gamma-rays of Pd¹⁰⁶ contamination ($\text{Rh}^{103}(\alpha, n)\text{Ag}^{106} \rightarrow \text{Pd}^{106}$), that is shown by dashed curve in Fig. 5. We subtracted the contributions from the 14 gamma-rays of Pd¹⁰⁶ by referring to the relative intensities of Pd¹⁰⁶ gamma-rays reported by Robinson et al.²⁰⁾ and by normalizing their intensities to that of the 1544 keV peak observed in the present measurement.

The Pd¹⁰⁵ gamma-ray spectrum thus obtained was decomposed into 8 gamma-rays by the usual successive subtraction method. The response curves of gamma-rays were deduced from the spectra of Na²², Zn⁶⁵, Y⁸⁸, Cs¹³⁷, Cr⁵¹ and Hg²⁰³. The gamma-rays of these isotopes were also used as the standards for energy calibration. And further the peak-to-total ratios were estimated from these spectra.

We determined the relative intensities of Pd¹⁰⁵ gamma-rays by measuring the areas under full-

Table III Relative intensity of gamma-rays

γ -rays (keV)	Relative intensity
64	20 $\pm$ 2
156 } 183 }	11
281	61 $\pm$ 5
344	100 $\pm$ 8
443	25 $\pm$ 3
620 } 645 } 649 }	35 $\pm$ 4
790	2.2 $\pm$ 1.4
1085	8.1 $\pm$ 1.2

energy peaks and by correcting for the total intrinsic efficiency²¹⁾ and peak-to-total ratio of the crystal. The intensities, which are normalized to a value of 100 for the intensity of the 344 keV γ -ray, are listed in Table III.

The internal conversion coefficients are determined from these relative intensities and the relative electron intensities by assuming the theoretical E2 value for α_K of the 344 keV transition (Table IV). The multipolarity of this transition is known to be E2 from the K/L conversion ratio observed in the present work. This assignment is in agreement with the result of the previous work.

2.4. Gamma-Gamma Angular Correlations

For the gamma-gamma angular correlation measurements, the source consisted of AgNO₃ solution which was contained in the plastic holder with a cylindrical hole 2 mm i.d. and 2.5 mm depth. The source was 7 cm from each detector. A resolving time 2τ of the fast-slow coincidence circuit, used for this measurement, was 8.5×10^{-8} sec. Data were taken every 18° between 90° and 180°. A least-squares fit of the data was made to the func-

Table IV Conversion coefficient

Transitions (keV)	$10^3 \alpha_K$ (Theoretical)				$10^3 \alpha_K$ (Experimental)
	E 1	M 1	E 2	M 2	
280.8	7.30	20.5	31.3	94.0	24.6 $\pm$ 4.0
344.0	4.23	12.2	16.3	49.4	(16.3)
442.8	2.24	6.45	7.6	22.3	7.1 $\pm$ 1.3
645. †	0.95	2.63	2.54	7.9	1.2 $\pm$ 0.2
1085.	0.324	0.835	0.732	1.92	0.44 $\pm$ 0.1

† 620, 645, 649 keV compound peak

Table V Angular correlation of the 645-443 kev cascade

Sequence	A_2	δ	Mixture
Experimental	-0.124 ± 0.023		
$\frac{1}{2}(D) \frac{3}{2}(Q+D) \frac{5}{2}$	-0.124 ± 0.023	-0.36 -1.60	11.5% Q + 88.5% D 71.8% Q + 28.2% D
$\frac{3}{2}(D) \frac{3}{2}(Q+D) \frac{5}{2}$	"	0.18 -25.4	3.0% Q + 97.0% D 99.8% Q + 0.2% D
$\frac{3}{2}(D) \frac{5}{2}(Q+D) \frac{5}{2}$	"	2.03 -0.09	80.5% Q + 19.5% D 0.8% Q + 99.2% D
$\frac{5}{2}(D) \frac{5}{2}(Q+D) \frac{5}{2}$	"	-0.76 -9.5	36.8% Q + 63.2% D 98.9% Q + 1.1% D
$\frac{5}{2}(D) \frac{7}{2}(Q+D) \frac{5}{2}$	"	5.9 0.40	97.2% Q + 2.8% D 13.7% Q + 86.3% D

tion $W(\theta) = 1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)$. The results were then corrected for the finite angular resolution of the detectors.²²⁾ Since the spin values of the 1085 kev and 443 kev levels were uncertain, the angular correlation of the 645-443 kev cascade was studied. To obtain the angular correlation of this cascade, the effects of 618-513 kev cascade²⁰⁾ (Pd^{106}), 1050-513 kev cascade²³⁾ (Pd^{106}), 1537-725 kev cascade²⁰⁾ (Pd^{106}) and 1544-513 kev cascade²⁰⁾ (Pd^{106}) were taken into account carefully. The gamma-gamma angular correlations of these cascades were measured previously. Further, the effects of 12 coincidence pairs, which were all attributed to Pd^{106} , were estimated using their coincidence data²⁰⁾ and decomposed spectral distributions. The other coincidence pairs have negligible effects. The experimental angular correlation coefficient for the 645-443 kev cascade is given in Table V. Also given in the same table are the theoretical correlation coefficients which are obtained for different spin values of the 1085 kev and 443 kev levels. For upper level spins 1/2, 3/2 and 5/2, and lower level spins 3/2, 5/2 and 7/2, the values of δ and its error $\Delta\delta$ are chosen to give an agreement between the theoretical and experimental coefficients and errors. In the above calculations,

it is assumed that the 645 kev transition is pure E1 and the 443 kev transition is M1+E2 from the observed values of α_K and K/L (discussed in the following section).

3. DISCUSSION

3.1. Multipolarities and Relative Transition Rates

The multipolarity assignments are deduced by comparing the experimental conversion coefficients and conversion ratios with the theoretical $Z=46$ values deduced from Sliv's tabulations,¹⁹⁾ and by considering the changes of spin and parity between the initial and final states (Table VI). The experimental values of α_K and K/L ratio of the 443 kev transition suggest that its multipolarity is M1+ ($\leq 10\%$) E2 or M1. In consideration of the Coulomb excitation data,¹⁴⁾⁻¹⁶⁾ the case of M1+ ($\leq 10\%$) E2 seems to be favourable. The observed value of α_K , $(1.2 \pm 0.2) \times 10^{-3}$, for the compound transition consisting of the 620, 645 and 649 kev transitions is in complete agreement with the result obtained by Boedege¹¹⁾ in the measurements of the external conversion electrons. This value shows that the strongest transition of the above three, the 645 kev transition, must be E1 transition. Among several possible combinations of the multipolarities for the 620 kev and 649 kev transitions, only the combination of (M1, E2) for 620 kev transition and (M1, E2) for 649 kev transition is compatible with the $\log ft$ values of electron captures to the 620 kev and 649 kev levels. The conversion coefficient of the 1085 kev transition indicates it consists primarily of E1 transition. From K/L values both the 155.9 kev and the 183 kev transitions are considered to be M1 predominant. The 392 kev transition is suggested to be (M1, E2) from the observed value of K/L+M and spin parity change between the initial and final states. From these assumed multipolarities, conversion

Table VI Multipolarity

Transitions (kev)	Multipole order	Transitions (kev)	Multipole order
64	(M1)	392.3	(M1, E2)
155.9	(M1)	442.8	M1+E2
183.0	(M1)	620.	(M1, E2)
280.8	(M1)	645.	E1
318.5	(M1, E2)	649.	(M1, E2)
331.0		790.	
344.0	E2	1085.	E1

Table VII Comparative half-lives of the Ag^{105} electron capture

Terminating level (kev)	Log ft	Type
1085	5.5	allowed
790	8.0	1st forbidden
673	7.7	unique 1st forbidden
649	7.5	unique or non-unique 1st forbidden
620	8.6	unique 1st forbidden
501	7.7	unique 1st forbidden
344	6.9	(1st forbidden)

coefficients and the relative intensities of gamma-rays and conversion electrons, the transition rates are deduced and shown in percent per decay in Fig. 6. The intensity of gamma-ray terminating at 443 kev level turns out to agree within the errors with the intensity of gamma-ray originating at this level, by splitting of the compound 654 kev transition into the 645 kev and 649 kev transitions. Thus, the decay scheme with consistent transition rates may be obtained (Fig. 6).

3.2. ft -values and Level Assignments

The log ft values are estimated from the above transition rates and the Q -value, $1.2^{+0.5}_{-0.1}$ Mev, which was given by Raether,¹⁰⁾ and listed in Table VII. If the types of electron capture transition listed in Table VII are assumed, these log ft -values are consistent with the spins and parities of levels in Pd^{105} which are predicted from the multiplicities and the angular correlation. Only the comparative half-life of the transition to the 344 kev level is too small. We have no explanation for this inconsistency.

Since the ground state transition from the 1085 kev level is E1 transition, this level is expected to have odd parity and spin of $3/2$, $5/2$ or $7/2$. Further, a spin assignment of $5/2$ or $7/2$ for this level is eliminated by the log ft value, 5.5, of the transition which populates this level. Thus the 1085 kev level is assigned to be $3, 2^-$.

Among the possible spin sequences for the 645-443 kev cascade listed in Table V, only two sequences $3/2(D)3/2(3\%Q+97\%D)5/2$ and $3/2(D)5/2(0.8\%Q+99.2\%D)5/2$ are compatible with the spin value $3/2$ of the 1085 kev level and the multipolarity of the 443 kev transition, $M1+(\leq 10\%)E2$ or $M1$. Even if there is no criterion by which the most probable spin sequence is decided, the sequence $3/2(D)3/2(3\%Q+97\%D)5/2$ seems to be more pro-

bable in consideration of the fact that the 433 kev gamma-ray is observed in the Coulomb excitation experiments.^{14)~16)} Thus the 443 kev level is assigned to be $3/2^+$ (or $5/2^+$).

The 649 kev transition which was separated from the 654 kev compound peak in the present work, is assumed to be the crossover transition in parallel with the 331-319 kev cascade. The value of the comparative half-life of the transition to the 649 kev level, 7.5, seems to be characteristic of unique or non-unique 1st forbidden transition. Thus the 649 kev level is assumed to have even parity and spin $3/2$ or $5/2$. These spin values are compatible with the probable multipolarity, $(M1, E2)$, for the

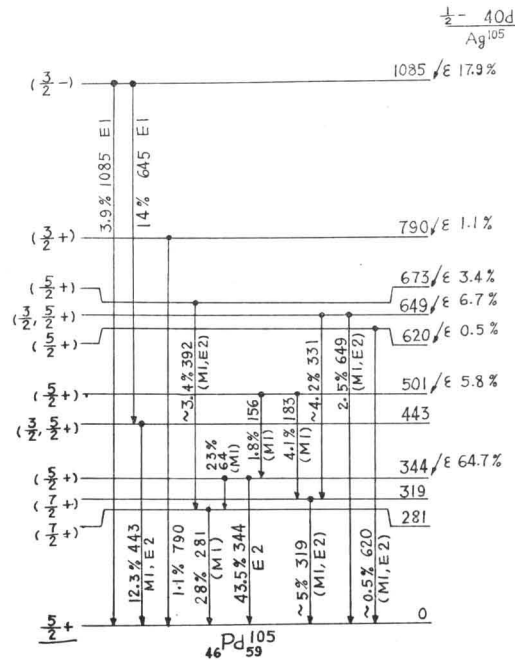


Fig. 6 Proposed level scheme.

649 keV ground state transition.

It is suggested that the 620 keV level has even parity and spin 5/2, from the log ft value, 8.5, of the transition to the tentative 620 keV level and the assumed multipolarity, (M1, E2), for the 620 keV ground state transition.

The log ft value, 7.7, of the transition to the 501 keV level is assumed to be characteristic of the unique 1st forbidden transition. This value and the assigned multipolarity, M1, of the 183 keV transition from this level to the 319 keV level (7/2+), and of the 156 keV transition from this level to the 344 keV level (5/2+), are all consistent with the tentative assignment, 5/2+, of the 501 keV level.

3.3. Reduced Transition Probability

The branching ratio of the cascade to crossover gamma-rays from the 344 keV level (5/2+), which is the uppermost level of the well known 64-281 keV cascade, is 0.229 ± 0.035 . This branching ratio gives a value of 4.12×10^{-5} for the ratio

$$\frac{\{B(M1, 5/2 \rightarrow 7/2)/B(E2, 5/2 \rightarrow 5/2)\}_{exp}}{\{B(M1, 5/2 \rightarrow 7/2)/B(E2, 5/2 \rightarrow 5/2)\}_{SN}} \\ \equiv \frac{B(M1)_{exp}}{B(M1)_{SN}} \cdot \frac{B(E2)_{SN}}{B(E2)_{exp}}$$

where $B(M1, 5/2 \rightarrow 7/2)$ and $B(E2, 5/2 \rightarrow 5/2)$ are the reduced M1 transition probability between the 344 keV 5/2+ level and the 281 keV 7/2+ level and the reduced E2 transition probability between the 344 keV 5/2+ level and the ground state (5/2+), respectively. $\{B(M1)/B(E2)\}_{SN}$ is the single neutron estimate²⁴⁾ of this ratio.

The average value for the various nuclei of the ratio, $\frac{B(M1)_{exp}}{B(M1)_{SN}}$, is 1/10~1/1000.²⁵⁾ The estimation of this ratio for the M1 transition between the 281 keV 7/2+ level and ground state in Pd^{105} gives a value of about 1/1000, using the upper limit of the life time of the 281 keV level, $1 \sim 2 \times 10^{-9}$ sec, which has been given by Raether.¹⁰⁾

If the ratio $\frac{B(M1)_{exp}}{B(M1)_{SN}}$ for the M1 transition between the 344 keV and the 281 keV levels is assumed to be of this order, the following result is obtained

$$\frac{B(E2, 5/2 \rightarrow 5/2)_{SN}}{B(E2, 5/2 \rightarrow 5/2)_{exp}} (\sim) \frac{1}{25}$$

This means that the enhancement factor F of the E2 transition is equal to about (or larger than) 25. Since the average value of F is 20~50 in the vibrational region,¹⁶⁾ while that is 100~150 in the rotational region,²⁶⁾ the 344 keV level may be considered to have probably vibrational character.

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