Low-Energy Conversion Electrons of Ag^{106} and Rh^{106}; Pd^{106} Levels*

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The low-energy (less than 0.935 Mev) conversion electrons emitted in the decays of Ag^{106} and Rh^{106} have been observed in two permanent-magnet electron spectrographs. A total of 29 transitions were observed in the Ag^{106} decay; 2 transitions were observed in the Rh^{106} decay. These data and the gamma scintillation results of Robinson *et al.* on the same decays were used to postulate the following levels (in Mev) in Pd^{106}: 0, (0+); 0.5116, (2+); 1.1272, (2+); 1.1331, (0+); 1.2287, (4+); 1.5568, (3, 4+); 1.7020, (2+); 1.9310, (3, 4+); 2.0825, (3+); 2.3040, (3, 4+); 2.3489, (3, 4+); 2.3636 or 1.9469, (3, 4, 5+); 2.7336, (5, 6+); 2.7540, (5+); and 2.9494, (5, 6+). The proposed level scheme indicates that ~5%, ~85%, and ~10% of the electron capture of Ag^{106} proceeds to the 2.9494-, 2.7540-, and 2.7336-Mev levels, respectively.

INTRODUCTION

THE levels of Pd^{106} are populated by the electron capture of the long-lived isomer of Ag^{106}, $t_{\frac{1}{2}}=8.4$ days, and by the negatron emission of Rh^{106}, $t_{\frac{1}{2}}\approx 30$ sec (daughter of 1.0 yr Ru^{106}). The spin of Ag^{106} has been directly determined by Ewbank *et al.*[1] to be 6. Alburger[2] deduced, from the comparative half-lives of the beta-ray transitions to the 0.5116-Mev (2+) level and (0+) ground state in Pd^{106}, that the spin and parity of Rh^{106} are (1+).

The beta and gamma rays and conversion electrons emitted in the Ag^{106} and Rh^{106} decays have been studied by a number of investigators.[2–12] Bendel[12] reported that Ag^{106} decays largely to a level in Pd^{106} at 2.78 Mev. Johnson and Galonsky[13] determined the (p,n) threshold of Pd^{106} to be 3.785 ± 0.010 Mev. Therefore, the decay energy of Ag^{106} is 3.00 Mev.

The levels of Pd^{106} at 0.5116 and 1.1272 Mev have been formed by Coulomb excitation in research by Alder *et al.*[14] and by Stelson and McGowan.[15] Both these levels have been assigned spins and parities of (2+). Gamma-gamma angular correlation functions obtained in Rh^{106} studies are in best agreement with the assignment of spin (0) for the 1.1331-Mev level.[6,7,9]

Robinson, McGowan, and Smith[3] (RMS) have made singles, coincidence, and gamma-gamma angular correlation measurements of Rh^{106} and Ag^{106}. The Ag^{106} data are given in Table I and Table II. In addition to the gamma rays shown in Table I, Horen and Bosch[11] reported one at 2.250 Mev in Ag^{106} decay. The Pd^{106} level scheme proposed by RMS is shown in Fig. 1.

The low-energy (less than 0.935 Mev) conversion electrons emitted in the decays of Ag^{106} and Rh^{106} were studied in the present investigation. A Pd^{106}-level scheme which is consistent with the gamma scintillation results of RMS and the present conversion electron data of this study is presented.

EXPERIMENTAL PROCEDURE AND RESULTS

The Ag^{106} was produced by an (α,n) reaction on Rh^{103}. The helium ion energy was ~15 Mev; it was kept below the 16.2-Mev threshold for the $(\alpha,2n)$ reaction, which would produce 40-day Ag^{105}. The bombarded rhodium foil was heated to the melting point in a vacuum system; the silver was evaporated and collected on a quartz catcher. Anion exchange resin chemistry purifications were made and the silver was electroplated on 0.010-in. platinum wire. This procedure is described in detail elsewhere.[16] The half-life obtained by least squares fitting the decay data of one of the Ag^{106} sources was 8.46 ± 0.1 days.

The conversion electrons were observed in two permanent magnet spectrographs with fields of 90 and 225 gauss. Intensity measurements were made with a photodensitometer and chart recorder. The relative energy measurement errors are estimated to be ~0.05%. The absolute energy errors are estimated to be ~0.1%. The intensity errors of the strong lines are probably ~15% and for the weak lines ~25%.

The experimental results obtained in the decay of Ag^{106} are given in Table III. The conversion electron intensities are normalized to a 0.5116-K electron in-

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TABLE I. Ag^{106} gamma-ray energies and relative intensities (Robinson *et al.*[3]).

E_γ (Mev)	Singles spectrum	Relative intensity: spectra in coincidence with gamma rays of energies (Mev): 0.215[a]	0.513	0.618	0.725	0.81[c]	1.050	1.21[c]	1.54[c]	1.83[a]
0.215±0.006	11 ±3		10 ±3		(1.3±1.0)	(0.7±0.6)			7.5±1.5	
0.31 ±0.02					1.1±0.6					
0.410±0.005	61 ±5	yes	62 ±5	21±3	13 ±5[b]	13 ±3	23 ±3	14 ±3	10 ±2	yes
0.456±0.007										
0.513±0.005	100 ±5	yes		25±4	41 ±8[b]	25 ±9	30 ±5	22 ±3	24 ±2	yes
0.618±0.006	27 ±1		28 ±2			19 ±2		9 ±1		
0.700±0.010					9 ±2					
0.725±0.007								(1.8±1.4)	17 ±2	
0.739±0.012	70 ±7		71 ±7				15 ±3			
0.751±0.012				4±2		⩽2			2 ±1	
0.783±0.012							14 ±3			
0.81 ±0.01	37 ±5		26 ±4	19±3	(1.7±1.3)	19 ±3	(1.6±1.4)	(1.8±1.4)		
0.847±0.012	14 ±3		16 ±3		6 ±4					
1.050±0.010	34 ±2		36 ±3		6 ±3[b]			11.5±1.0		
1.13 ±0.01	13 ±1					8 ±1		3.3±0.6		
1.202±0.012	21 ±1		22 ±2				10 ±1			
1.227±0.012				7±1						
1.38 ±0.02	1.8±0.6									
1.537±0.015	27 ±1	yes	25 ±2		16 ±2			0.3±0.2		
1.56 ±0.02										
1.58 ±0.02										
1.73 ±0.02	1.9±0.5				1.3±0.4					
1.83 ±0.02	3.3±0.3		3.8±0.4							
>1.9	<0.25									

[a] Only parts of these spectra were observed. Thus, lack of a "yes" does not mean the corresponding gamma ray is not in coincidence.
[b] Part or all of the intensity of each of these gamma rays is believed to result from coincidences with the 0.739-Mev gamma ray.
[c] These spectra are in coincidence with composite gamma rays of these energies.

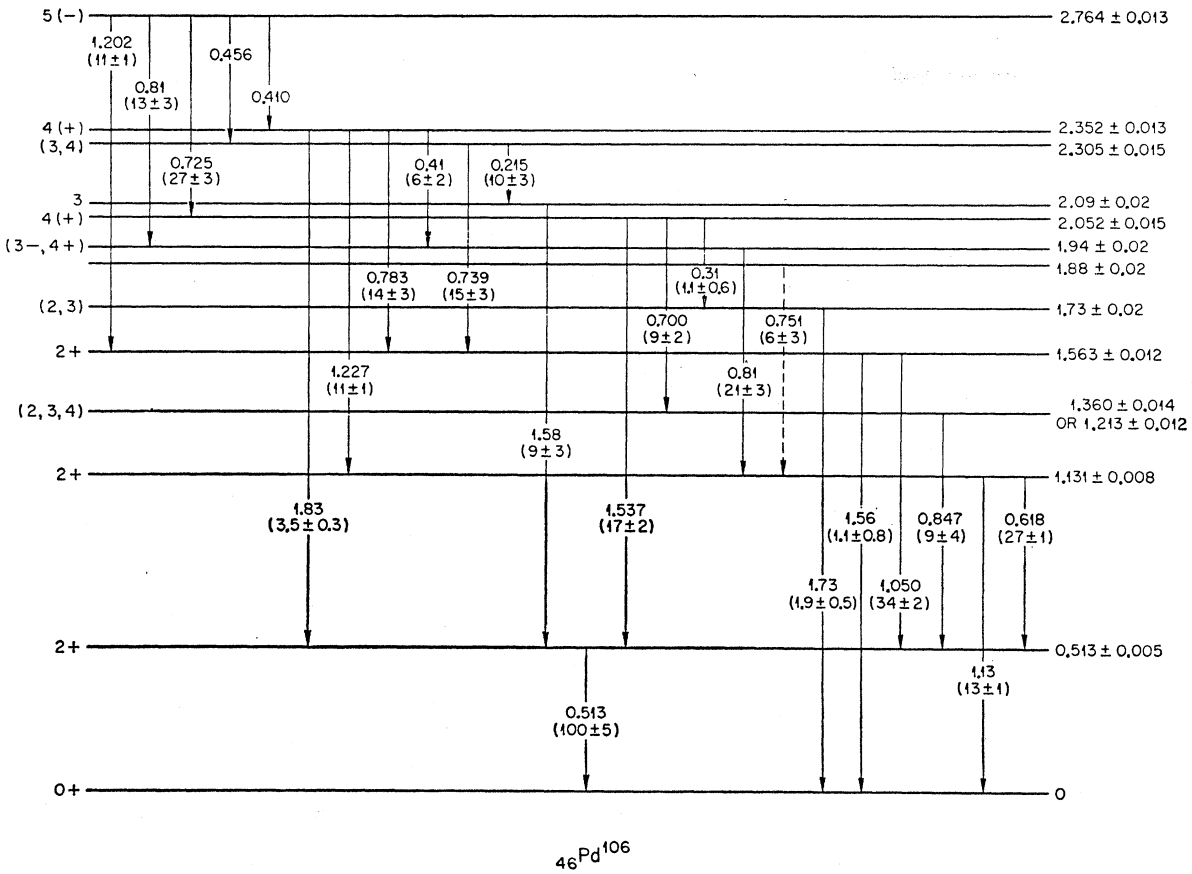

FIG. 1. Pd^{106} level scheme; Robinson *et al.*[3]

TABLE II. Angular correlation of the Ag^{106} 0.618–0.513-Mev cascade (Robinson *et al.*[3]).

Sequence	δ	A_2	A_4
Experimental		-0.052 ± 0.024	$+0.325\pm0.035$
$0(Q)2(Q)0$		$+0.357$	$+1.143$
$1(D+Q)2(Q)0$	$+0.17$	-0.052	-0.021
$2(D+Q)2(Q)0$	$+30$	-0.052	$+0.326$
$3(D+Q)2(Q)0$	-0.024	-0.052	0.000
$4(Q)2(Q)0$		$+0.102$	$+0.009$
Angular correlation of the 0.725–1.537-Mev cascade			
Sequence	δ	A_2	A_4
Experimental		-0.330 ± 0.022	-0.089 ± 0.031
$5(0)2(D+Q)2$	-1.5	-0.157	-0.001
$5(Q)3(D+Q)2$	-0.78	-0.225	-0.005
$5(D+Q)4(Q)2$	$+0.44$	-0.330	-0.010
$5(D+Q)4(Q)2$	$+2.9$	-0.330	-0.053
$6(0)3(D+Q)2$	-1.45	-0.330	$+0.004$
$6(0)3(D+Q)2$	-0.38	-0.330	$+0.001$
$6(Q)4(Q)2$		$+0.102$	$+0.009$
$7(0)4(Q)2$		$+0.179$	-0.004
Angular correlation of the 1.58–0.513-Mev cascade			
Sequence	δ	A_2	A_4
Experimental		-0.98 ± 0.33	-0.05 ± 0.10
$2(D+Q)2(Q)0$	-1.5	-0.31	$+0.23$
$3(D+Q)2(Q)0$	$+1.2$	-0.54	-0.05
$4(Q)2(Q)0$		$+0.10$	$+0.01$
$5(0)2(Q)0$		$+0.18$	0.00

tensity of 567. The results of Alburger and Toppel[10] are also given in this table.

Only two transitions were observed in the Rh^{106} decay. (There was a heavy background from the beta-spectrum continuum.) The energies were determined to be: 0.5116 and 0.6215 Mev.

DISCUSSION

(1) Ag^{106} Conversion Coefficients, K/L Ratio, and Transition Multipolarities

The low-energy transitions of which both the conversion electrons and gamma rays (RMS) were directly observed have the following energies: 0.2215, 0.3281, 0.4506, 0.5116, 0.6156, 0.7026, 0.7171, 0.7472, 0.7921, 0.8028, and 0.8234 Mev. The presently observed 0.8234-Mev transition is interpreted as being the same as the 0.847-Mev transition of RMS.

The experimental conversion coefficients were calculated for these transitions. (It was assumed that the 0.5116-Mev transition is a pure $E2$.) See Table III. The theoretical coefficients are shown in Fig. 2. All of the experimental conversion coefficients are in agreement with $M1$ and/or $E2$ multipolarity assignments. The conversion electron intensity data of Alburger and Toppel[10] were combined with the gamma-ray data of RMS to calculate experimental coefficients for the high-energy transitions. These results are also shown in Table III. All of these values, except for the 1.202- and 1.38-Mev transitions, fall within the experimental errors of $M1$ and/or $E2$ coefficients. The experimental values for both the 1.202- and 1.38-Mev transitions lie between the theoretical $M1$ and $E3$ coefficients, somewhat closer to the $E3$ values. In this work the 1.202-Mev transition will be interpreted as an $M1$ and/or $E2$. The 1.38-Mev transition is quite weak and is not included in the present level scheme; it was not included in the scheme presented by RMS.

The K/L ratio of the 0.2215-Mev transition was experimentally determined to be $8\frac{1}{2}\pm1$. This is in agreement with either an $M1$, $K/L=8.7$, or an $E1$, $K/L=8.5$, transition. However, the conversion coefficient was found to be 4×10^{-2} which is in agreement only with an $M1$ assignment.

(2) Pd^{106} Level Scheme

The presently proposed Pd^{106} level scheme is shown in Fig. 3. The level energies were determined from the conversion electron data. The relative intensities into and out of the levels populated in the Ag^{106} decay are also shown. All of the transitions with measurable electron intensities except the 0.1101-Mev transition are included in the scheme. This level scheme is very similar to that proposed by Robinson *et al.*[3]; see Fig. 1.

(3) Parity Assignments

As noted above, all of the Ag^{106} transitions for which experimental conversion coefficients could be determined were in agreement with $M1$–$E2$ assignments. Therefore all of the Pd^{106} levels are assumed to have the same parity, (+).

(4) Level Populations in Ag^{106} Decay

In order to make the intensities in and out of the 2.3489-Mev level equal, a new level was placed at 2.9494 Mev; with the 0.6009-Mev transition between

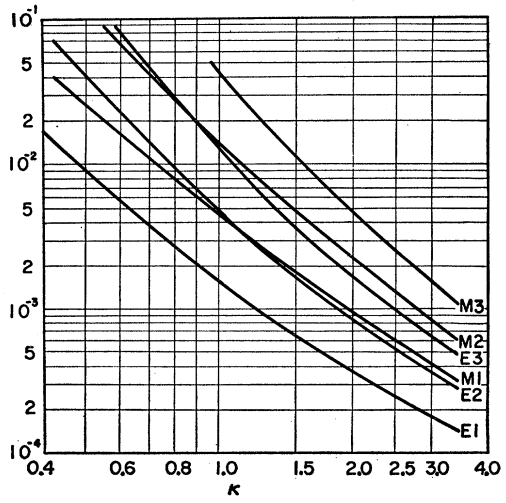

FIG. 2. K-shell conversion coefficients for $Z=46$ [M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).]

TABLE III. Ag^{106} conversion electron and gamma-ray data.

Transition energy (Mev)	Observed intensities K	L	M	K/L	Alburger and Toppel[a] intensities K	K/L	Experimental gamma-ray intensities (RMS)	Experimental conversion coefficients	Multipolarity	Theoretical conversion coefficient[e]	Calculated gamma-ray intensities
0.1101	12										
0.1668	w[b]										
0.1950	35								[M1–E2]	6 $\times10^{-2}$	½
0.2215	430	51	w	8½	180	3.2	10 ±3	3.8×10^{-2}	M1	4 $\times10^{-2}$	
0.2286	53	w							[M1–E2]	5 $\times10^{-2}$	1
0.2820	w										
0.3281	50						1.1±0.6	4 $\times10^{-2}$	M1–E2	1.9 $\times10^{-2}$	
0.3744	w										
0.3907	65	w							[M1–E2]	9.5 $\times10^{-3}$	6
0.3965	w										
0.4058	180	w			135				[M1–E2]	8.5 $\times10^{-3}$	19
0.4185	w										
0.4296	160	[20][c]	w						[M1–E2]	7.0 $\times10^{-3}$	20
0.4506	[90][c,d]	w	w				10 ±2	8×10^{-3}	M1–E2	6.5 $\times10^{-3}$	
0.4573	w										
0.4743	w										
0.5116	[567]	66	w	8½	567	7.7	[100]		[E2]	4.95×10^{-3}	
0.5857	w										
0.6009	~10								[M1–E2]	3.0 $\times10^{-3}$	3
0.6156	95	w			95		27 ±1	3.1×10^{-3}	M1–E2	3.0 $\times10^{-3}$	
0.6798	w										
0.7026	~10						9 ±2	9×10^{-4}	M1–E2	2.0 $\times10^{-3}$	
0.7171	80				78		27 ±3	3.0×10^{-3}	M1–E2	2.0 $\times10^{-3}$	
0.7376	w										
0.7472	24						15 ±3	1.4×10^{-3}	M1–E2	1.7 $\times10^{-3}$	
0.7921	18						14 ±3	1.1×10^{-3}	M1–E2	1.6 $\times10^{-3}$	
0.8028	20				45		13 ±3	1.3×10^{-3}	M1–E2	1.6 $\times10^{-3}$	
0.8071	~10						9 ±4	9×10^{-4}	M1–E2	1.6 $\times10^{-3}$	
0.8234	33						21 ±3	1.4×10^{-4}	M1–E2	1.5 $\times10^{-3}$	
1.045	···				37		35 ±2	9.4×10^{-3}	M1–E2	9 $\times10^{-3}$	
1.131	···				13		13 ±1	8.5×10^{-3}	M1–E2	7 $\times10^{-3}$	
1.205	···				12		11 ±1	9.5×10^{-3}	M1–E2	6.5 $\times10^{-3}$	
1.225	···				7		11 ±1	5.5×10^{-3}	M1–E2	6 $\times10^{-3}$	
1.388	···				1.8		1.8±0.6	7.5×10^{-3}	E3	8 $\times10^{-3}$	
1.53	···				10		17 ±2	3.3×10^{-3}	M1–E2	4 $\times10^{-3}$	

[a] See reference 10.
[b] w = weak.
[c] [ ] = assumed or adjusted value.
[d] 20 intensity units subtracted for contribution of 429.6–L electrons.
[e] Nearly independent of M1–E2 mixing ratio since M1 and E2 conversion coefficients are approximately equal.

the two levels, and the 0.1950-Mev transition was placed between the new 2.9494-Mev level and the 2.7540-Mev level.

There are 25 units of intensity out of the 2.3040-Mev level and only 10 units into it. A possible solution to this difficulty is the following. The 0.4296-Mev transition is really a doublet; one of the members populates the 2.3040-Mev level from a 2.7336-Mev level which is directly populated by electron capture, and the other member occurs between the 1.5568- and 1.1272-Mev levels.

If the intensity of the upper 0.4296-Mev transition were 8 units, this would give 18 units into and 25 units out of the 2.3040-Mev level. This would leave 12 units of intensity for the lower 0.4296-Mev transition; the intensities into and out of the 1.5568-Mev level would be 45 and 48, respectively; into and out of the 1.1272-Mev level, 36 and 40, respectively.

No broadening of the 0.4296-Mev K-electron line could be experimentally detected. Therefore, if there are two transitions present, the energies must differ by not more than approximately 0.2 kev. Another possible explanation is that several of the weak transitions that are not included in the level scheme originate at states which are weakly populated by electron capture and these transitions terminate at the 2.3040-Mev state.

(5) Ag^{106} Electron Capture Branching and logft Values

The relative intensities of the electron capture decay branches of Ag^{106} can be calculated for the Pd^{106} level scheme presented in Fig. 3. If this scheme is correct, only the three highest energy levels are directly populated. These are the levels at 2.9494, 2.7540, and 2.7336 Mev; the relative intensities of the decays to them are 0.05, 0.85, and 0.10, respectively.

Using these data, the half-life of Ag^{106} (8.46 days), and the Ag^{106} decay energy (3.00 Mev) obtained from the Pd^{106} (p,n) threshold data of Johnson and Galonsky,[13] the logft values for the three electron capture branches can be calculated. They are 4.0, 5.1, and 6.0 for the branches to the 2.9494-, 2.7540-, and 2.7336-Mev levels, respectively. These are all interpreted as allowed transitions; $\Delta I=0, +1$, no.

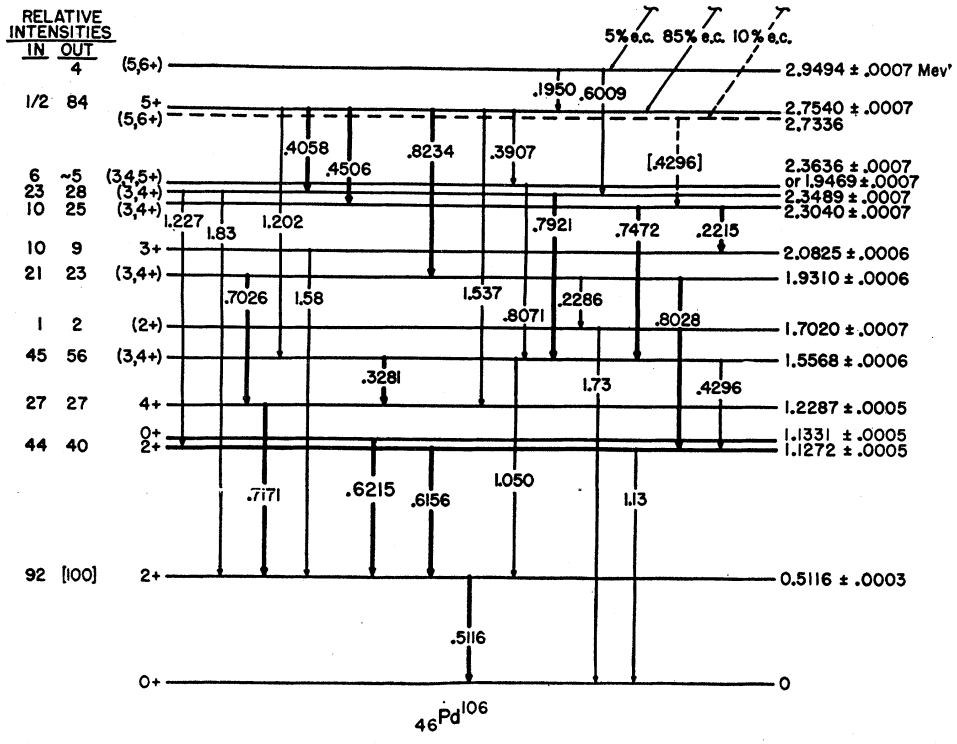

FIG. 3. Pd^{106} level scheme based on present conversion electron data and gamma-ray data of Robinson *et al.*[3] The heavy arrows represent transitions for which both the conversion electrons and the gamma rays were observed; the lighter arrows indicate that only the conversion electrons or the gamma rays were observed. The level populations shown were determined from the decay of Ag^{106}—the (0+) level at 1.1331 Mev was populated only in the decay of Rh^{106}.

(6) Spin Assignments

0.5116- and 1.1272-Mev levels. As noted previously, the (2+) assignments to both the first two excited states at 0.5116 and 1.1272 Mev are based upon Coulomb excitation of these levels[14,15]; these spin (2) assignments are confirmed by angular correlation studies of RMS.

1.2287-Mev level. There was no 1.23-Mev gamma ray, which could be interpreted as the transition from the 1.2287-Mev level to the ground state, observed in coincidence with the 1.54-Mev gamma ray. This indicates the spin of the 1.2287-Mev level is not (2). There are no known cases where a spin (1) or (3) state lies close to the second (2+) state. Therefore, the 1.2287-Mev level is assigned spin and parity (4+). The nuclear models of Scharff-Goldhaber and Weneser,[17] Wilets and Jean,[18] Davydov and Filippov,[19] Raz,[20] and Tamura and Komai[21] predict that a (4+) level should lie near the second (2+) level.

2.7540-Mev level. After making the (4+) assignment to the 1.2287-Mev level, the 2.7540-Mev level can be assigned (5+) from the results of the 1.537–0.755-Mev angular correlation. See Table II.

2.0825-Mev level. The 2.0825-Mev level is assigned (3+) from results of the 1.58–0.513-Mev angular correlation. See Table II.

1.5568-Mev level. The 1.5568-Mev state is assigned (3, 4+) since there is a 1.202-Mev gamma ray to it from the (5+) state at 2.7540-Mev. There is a level in Pd^{106} at 1.56 Mev which is populated by the decay of Rh^{106}. This level has been assigned spin (2) by Klema and McGowan[9] from angular correlation results. The parity of this state is expected to be even, from the comparative half-life of the beta-ray transition to it.[2] It is postulated here that the 1.5568-Mev level populated in the decay of Ag^{106} is not the same as the 1.56-Mev level populated in the decay of Rh^{106}. [Recall that the spin of Ag^{106} is (6) and that of Rh^{106} is (1).] The ratios of the 1.053- to 1.555-Mev gamma rays in Rh^{106} and Ag^{106} decays are $\sim$10 and $\sim$30, respectively. This is presently interpreted as an indication that there are two different levels at $\sim$1.56 Mev in Pd^{106}. The very weak (intensity$=1.1\pm0.8$) 1.56-Mev gamma ray is not included in the present scheme. Davydov and Filippov[19] predict that a (3+) state should lie at about 1.6 Mev. This could be the 1.5568-Mev level presently observed.

1.7020-Mev level. A weak (intensity$=1.9\pm0.5$) 1.73-Mev gamma ray has been placed between the 1.7020-Mev state and the ground state; the former is therefore assigned (2+). In the gamma-gamma coincidence results of RMS, the 1.73-Mev gamma ray was observed in coincidence with a 0.725-Mev gamma ray. In the present level scheme these two gamma rays are not in coincidence; however, the 1.73-Mev gamma ray would

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be in coincidence with the 0.8234-Mev gamma ray and this could contribute to the observed coincidences.

2.7336- and 2.9494-Mev levels. The experimental logft values of the electron capture branches to the 2.9494- and 2.7336-Mev levels are 4.0 and 6.1, respectively. Both of these transitions are presently interpreted as allowed. The spin of Ag^{106} is (6); therefore the spins of the 2.9494- and 2.7336-Mev levels could be (5, 6, or 7). Spin (7) is not likely, and spins of (5) or (6) are suggested. The parity of Ag^{106} would be the same as the parity of the upper levels of Pd^{106}, even.

2.3489-Mev level. The 2.3489-Mev level is connected via an assumed $M1$–$E2$ transition, 0.4058-Mev, to the spin (5), 2.7540-Mev level; and by 1.227- and 1.83-Mev transitions to both of the first two (2+) excited states. There is no observed 2.35-Mev gamma ray to the ground state. The 2.3489-Mev level is therefore suggested to be (3, 4+).

2.3040-Mev level. The 2.3040-Mev level can be only (3, 4+) because it is connected by an $M1$ transition to the (3+) level at 2.0825 Mev; spin (2) is not included because no transition to the ground state is observed.

2.3636-Mev level. The spin and parity of the 2.3636-Mev level is suggested to be (3, 4, 5+).

Rh^{106} DECAY RESULTS

The two transitions observed in the decay of Rh^{106}, 0.5116 and 0.6215 Mev, are interpreted as the transitions from the first (2+) state to the ground state, and from the (0) spin state to the first (2+) state, respectively. This would make the energy of the (0) state 1.1331±0.0005 Mev. The comparative half-life of the beta-ray transition to this state indicates that it has even parity.[2] The 0.6215-Mev transition was not observed in the decay of Ag^{106}.

COMPARISONS WITH SIMILAR NUCLEI

The ratios of the energies of the first (4+), first excited (0+), and second excited (2+) states to the first excited (2+) state are 2.52, 2.22, and 2.20, respectively. All of these values fall within the experimental range observed for other even-even nuclei with neutron number = 24–88.

The only other case in which all three members of the nuclear vibrational states, (0+), (2+), and (4+), which lie at approximately two times the energy of the first excited (2+) state, that has been observed is Cd^{114}. However, this situation is complicated by the fact that the level sequence is (0+), (2+), (4+), and (0+); and it is not clear which of the (0+) states is to be associated with the collective excitation.

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