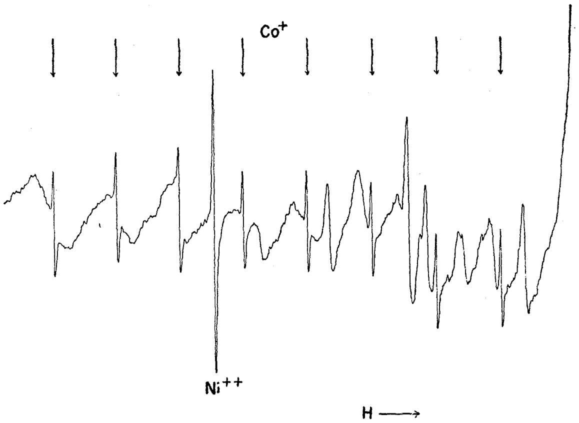

FIG. 2. Spectrum of Co^{+1} in MgO. The eight sharp lines are double quantum transitions, i.e., $\Delta M=2$, $\Delta m=0$. The double quantum line from Ni^{+2} lies between the third and fourth Co^{+1} line. Other lines are due to Fe^{+3}, Mn^{+2}, and Cr^{+3}.

The sharpness of the double quantum lines makes it possible to measure the g value and hyperfine splitting with considerable accuracy. The results are: $g=2.1728\pm0.0005$, $A^{59}=(54.0\pm0.2)\times10^{-4}$ cm^{-1}.

Using the usual formula $A=\gamma\beta\beta_N\langle1/r^3\rangle_{\mathrm{av}}$, and writing $\gamma=\mu/I$, we calculate the value of μ^{61} from

$$\mu^{61}=\frac{A^{61}}{A^{59}}\frac{I^{61}}{I^{59}}\mu^{59}R, \qquad (1)$$

where $I^{61}=\frac{3}{2}$, $I^{59}=\frac{7}{2}$ and R is the ratio $\langle1/r^3\rangle_{\mathrm{av}}(\mathrm{Co})/\langle1/r^3\rangle_{\mathrm{av}}(\mathrm{Ni})$. From the measured values of A, we find $\mu^{61}=0.31R$ nm.

To estimate a possible value for R we may calculate it for the case of V^{+2} and Cr^{+3} in MgO using the known values of the nuclear moments of V^{51} and Cr^{53}. The values of A are 74.3 and 16.2 ($\times10^{-4}$ cm^{-1}), respectively,[3] giving $R\approx0.98$, i.e., very close to unity. Thus, we estimate the nuclear moment of Ni^{61} to be (0.30 ± 0.02) nuclear magneton. The probable error is somewhat arbitrary.

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[3] J. W. Orton, *Reports on Progress in Physics* (The Physical Society, London, 1959), Vol. 22, p. 204.

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Decays of Rh^{106} and Ag^{106}

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The gamma-ray spectra of 30-sec Rh^{106} and 8.3-day Ag^{106}, which both decay to Pd^{106}, have been studied with scintillation spectrometers. Three gamma-gamma angular correlations have also been measured. The results are consistent with the following level scheme for Pd^{106}: 0.513(2+), 1.131(2+), 1.137(0+), 1.360 or 1.213, 1.563(2+), 1.73(2 or 3), 1.84, 1.88, 1.94(3− or 4+), 2.01, 2.052(4+), 2.09(3), 2.28, 2.305 (3 or 4), 2.352(4+), 2.46, 2.62, 2.764(5−), 2.87, and 3.08 Mev. The transition between the first and second 2+ levels was found to consist primarily of $E2$ radiation. The branching ratio obtained for the cascade to crossover gamma rays from the second 2+ level is 2.1 ± 0.3. This ratio combined with Coulomb excitation data of Stelson and McGowan gives a value of 1.0 ± 0.3 for the ratio $B(E2, 2'\rightarrow2)/B(E2, 2\rightarrow0)$.

I. INTRODUCTION

THIRTY-SECOND Rh^{106} decays by beta-ray emission to Pd^{106}, and 8.3-day Ag^{106} decays by orbital electron capture also to Pd^{106}. The spin and parity of Rh^{106} have been deduced as 1+ from the comparative half-lives of the beta-ray transitions to the 2+, 0.513-Mev level and 0+ ground state in Pd^{106}.[1] The spin of Ag^{106} has been measured by Ewbank *et al.*[2] as 6. Alburger and Toppel[3] from their investigation of the decays of Rh^{106} and Ag^{106} have proposed the energy level diagram given in Fig. 1. Most of the levels are shown as being populated by both Rh^{106} and Ag^{106}. This is rather surprising in view of the large difference in the spins of the two isotopes. Because of this unsatisfactory situation it was felt desirable to re-examine the decays of Rh^{106} and Ag^{106}.

The gamma rays of Rh^{106} given in Fig. 1 include all previously reported gamma rays[1,4,5] with the exception of a 2.28-Mev gamma ray observed by Kahn and Lyon.[5]

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* Supported in part by U. S. Atomic Energy Commission with Purdue Research Foundation.

[1] D. E. Alburger, Phys. Rev. **88**, 339 (1952).

[2] W. B. Ewbank, W. A. Nierenberg, H. A. Shugart, and H. B. Silsbee, Phys. Rev. **110**, 595 (1958).

[3] D. E. Alburger and B. J. Toppel, Phys. Rev. **100**, 1357 (1955).

[4] J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 1081 (1953).

[5] B. Kahn and W. S. Lyon, Phys. Rev. **92**, 902 (1953).

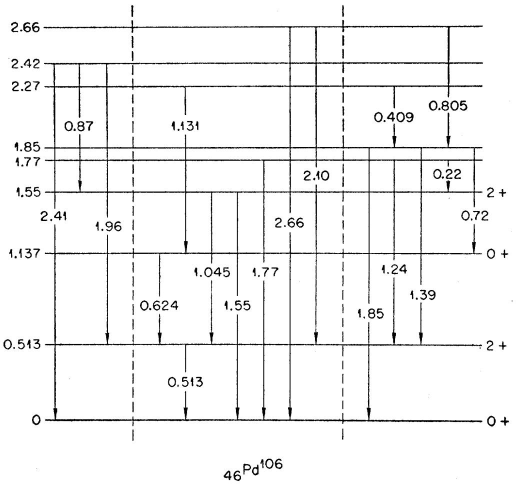

FIG. 1. Levels and transitions in Pd^{106} proposed by Alburger and Toppel (see footnote 3). In the center between dashed lines are transitions common to both Rh^{106} and Ag^{106}. To the left are transitions observed only in Rh^{106} decay and to the right those observed only in Ag^{106} decay.

Klema and McGowan[6] have established the spin of the 1.55-Mev level as 2 from their measurement of the angular correlation function for the 1.045-0.513-Mev gamma-ray cascade. The correlation functions obtained by Arfken, Klema, and McGowan,[7] by Kraushaar and Goldhaber,[4] and by Klema and McGowan[6] for the 0.624-0.513-Mev cascade are in best agreement with the assignment of spin 0 for the 1.137-Mev level; however, in all cases there is a discrepancy between the experimental function and the theoretical function for a 0-2-0 spin sequence. From the comparative half-lives of the beta-ray transitions which populate the 1.137- and 1.55-Mev levels,[1] these levels are expected to have even parity.

Studies by other investigators[8,9,10] of the decay of Ag^{106} confirm the gamma rays given in Fig. 1 except those with energies of 1.39, 2.10, and 2.66 Mev. Horen and Bosch[10] have found an additional gamma ray with an energy of 2.250 Mev. In a recent paper Bendel[11] has reported that Ag^{106} decays largely to a level in Pd^{106} at 2.78 Mev.

Coulomb excitation studies of Pd^{106} provide additional evidence for the 2+, 0.513-Mev level.[12] More recent Coulomb excitation measurements have revealed a previously unreported 1.120-Mev level with spin and parity of 2+.[13]

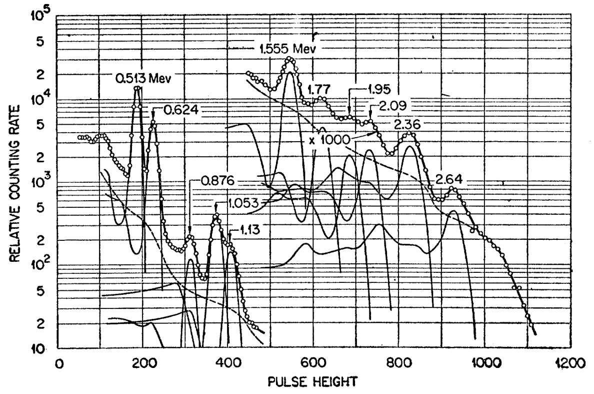

FIG. 2. Rh^{106} singles gamma-ray spectrum.

In the present work the singles and coincidence gamma-ray spectra of Rh^{106} and Ag^{106} have been investigated. Gamma-gamma angular correlation measurements have been made on gamma rays of Ag^{106}. Energy level diagrams consistent with the data have been proposed.[14]

II. EXPERIMENTAL PROCEDURE AND RESULTS

The gamma-ray spectra were studied with scintillation spectrometers. The detectors were 3 in.×3 in. NaI crystals which were mounted on 6363 DuMont photomultiplier tubes. The resolution of each detector was 8% for the 662-kev gamma-ray peak in Cs^{137}. The data were taken with a twenty-channel pulse-height analyzer. For the investigation of the coincidence spectra a fast-slow coincidence circuit with a resolving time 2τ of 0.17 μsec was employed.

A. Rh^{106} Gamma-Ray Spectra

The Rh^{106} source material used in this study was in an equilibrium condition with 1-yr Ru^{106}. Ru^{106} decays to Rh^{106} by the emission of a 39-kev beta-ray group[15] and thus does not affect gamma-ray measurements. The singles spectrum of Rh^{106} was observed with a source-to-detector distance of 14 cm. One-half inch of Lucite was placed between the detector and source to absorb the beta rays. This spectrum is given in Fig. 2. The spectrum was decomposed into eleven gamma rays and a continuum. The spectral distributions for the gamma rays, as illustrated in Fig. 2, were deduced from the spectra of Na^{24}, Y^{88}, Na^{22}, Zn^{65}, Mn^{54}, Cs^{137}, and Be^7. Gamma rays of these activities were also used as standards for energy calibration. We determined the intensities of the Rh^{106} gamma rays by measuring the area under each full-energy peak and by correcting for the total intrinsic efficiency and peak-to-total ratio of the crystal, for absorption, and for gamma-ray summing

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[6] E. D. Klema and F. K. McGowan, Phys. Rev. **92**, 1469 (1953).

[7] G. B. Arfken, E. D. Klema, and F. K. McGowan, Phys. Rev. **86**, 413 (1952).

[8] J. Y. Mei, C. M. Huddleston, and A. C. G. Mitchell, Phys. Rev. **79**, 1010 (1950).

[9] R. W. Hayward, Phys. Rev. **85**, 760 (1952).

[10] D. J. Horen and H. E. Bosch, Bull. Am. Phys. Soc. 4, 373 (1959) and private communication.

[11] W. L. Bendel, Bull. Am. Phys. Soc. 4, 426 (1959).

[12] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).

[13] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. **2**, 267 (1957).

[14] A brief account of some of these measurements was presented at the 1959 Washington meeting of the American Physical Society [R. L. Robinson, F. K. McGowan, and W. G. Smith, Bull. Am. Phys. Soc. 4, 279 (1959)].

[15] H. M. Agnew, Phys. Rev. **77**, 655 (1950).

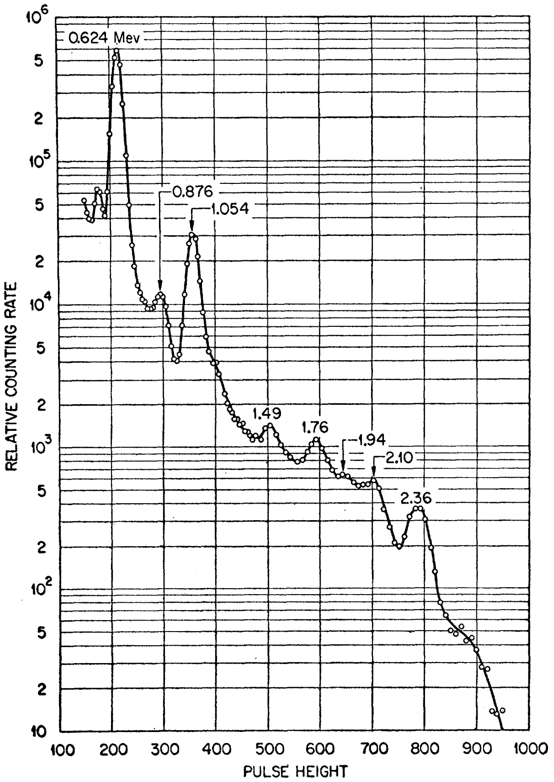

FIG. 3. Rh^{106} gamma-ray spectrum in coincidence with the 0.513-Mev gamma ray.

in the crystal. The intensities, which are normalized to a value of 100 for the intensity of the 0.513-Mev gamma ray, are listed in Table I. The continuum represented by a dotted line in Fig. 2 is due primarily to bremsstrahlung produced by electrons from the high-energy, beta-ray groups. Such a large continuum contributes to the uncertainty of the gamma-ray intensities (particularly those at high energies) and may obscure completely some weak gamma rays.

TABLE I. Rh^{106} gamma-ray energies and relative intensities. Intensities for gamma rays in the singles spectra are given for source-to-detector distances of 14 and 40 cm.

	Relative intensity			
	Singles spectra		Coincidence spectra	
E_γ(Mev)	14 cm	40 cm	0.513 Mev	0.624 Mev
0.513±0.005	100±4	100±4		53±4
0.624±0.005	51±3	53±3	49±4	
0.71 ±0.02				0.17±0.08
0.876±0.009	1.8±0.2	1.9±0.2	1.1±0.1	1.3±0.1
1.053±0.010	6.8±0.4	6.9±0.4	6.4±0.6	
1.13 ±0.01	2.4±0.3	2.3±0.3	<0.3	<0.2
1.49 ±0.02			0.16±0.04	
1.555±0.015	0.63±0.05	0.65±0.05		
1.77 ±0.02	0.19±0.03		0.20±0.03	
1.95 ±0.03	0.10±0.02		0.07±0.03	0.020±0.003
2.09 ±0.03	0.13±0.02		0.16±0.04	
2.36 ±0.03	0.17±0.02		0.20±0.03	
2.64 ±0.04	0.03±0.01			

As a large fraction of the peak at 1.13 Mev in Fig. 2 is a sum peak of the intense 0.513- and 0.624-Mev gamma rays, the spectrum was also observed for a source-to-detector distance of 40 cm. In this spectrum the sum peak is relatively smaller. (The 0.513-0.624-Mev gamma-ray sum peak would decrease approximately as the fourth power of the source-to-detector distance, whereas the 1.13-Mev peak resulting from a gamma ray of that energy would decrease approximately with the square of the distance.) The intensities of the lower energy gamma rays were determined from this spectrum. They are included in Table I. The values for the 1.13-Mev gamma-ray intensity obtained in the two runs are in good agreement. The average value is similar to that given by Kahn and Lyon,[5] but it is larger than the value of 0.8 given as an upper limit by Alburger and Toppel.[3]

The gamma-ray spectra which were measured in coincidence with the 0.513- and 0.624-Mev gamma rays are shown in Figs. 3 and 4. The distance between the source and each detector was 5 cm. The coincidence spectra reveal peaks which are not observed in the singles spectrum at 0.71 and 1.49 Mev. There is also some indication of an ~1.2-Mev gamma ray in coincidence with both the 0.513- and 0.624-Mev gamma rays. The intensities of the gamma rays found in these spectra are given in Table I. A correction for angular correlation between the coincidence gamma rays has been applied where the correlation function was known. A correction has

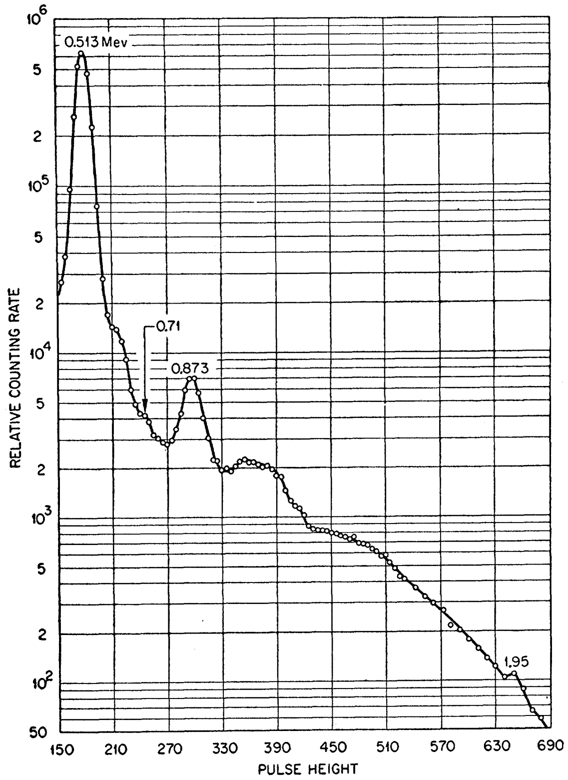

FIG. 4. Rh^{106} gamma-ray spectrum in coincidence with the 0.624-Mev gamma ray.

also been made for coincidences with pulses which gated the multichannel but were not produced by gamma rays in the full-energy peak of interest. Such pulses were produced by higher energy gamma rays which were Compton scattered in the crystal and by bremsstrahlung.

An energy level diagram for Pd^{106} which incorporates the results tabulated in Table I is shown in Fig. 5. The position given for the 1.13-Mev gamma ray is the only one compatible with our data. The intensity of a gamma ray of approximately this energy which originates at the 2.28-Mev level, as suggested by Kahn and Lyon[5] and by Alburger and Toppel,[3] is less than 0.3. Since the 1.137-Mev level is known to have spin and parity of 0+,[1,6] the 1.13-Mev gamma ray does not originate at this level (emission of a single $E0$ transition is strictly forbidden). The level from which the 1.13-Mev gamma ray originates is probably the same as the 2+, 1.120-Mev level which was found to be Coulomb excited.[13] Population of this level by the decay of Rh^{106} explains the difference observed between the experimental correlation function for the 0.624-0.513-Mev cascade[6] and the theoretical correlation function for a 0-2-0 sequence.

The drop in the observed intensity of the 0.876-Mev gamma ray between the singles and coincidence spectra indicates that it populates the 1.13-Mev level rather than the 1.137-Mev level. It was not possible from our data to determine at which of the two levels the 0.71- and 1.95-Mev gamma rays terminate.

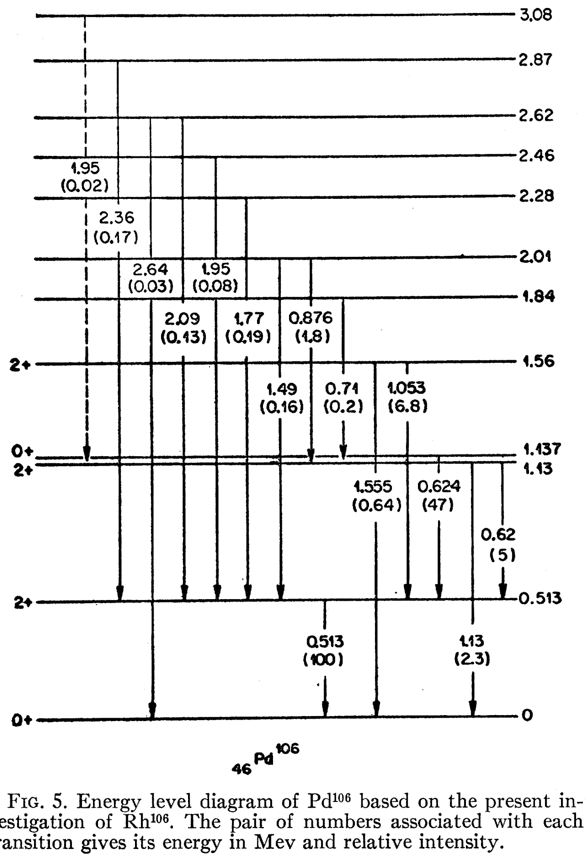

FIG. 5. Energy level diagram of Pd^{106} based on the present investigation of Rh^{106}. The pair of numbers associated with each transition gives its energy in Mev and relative intensity.

The values for the 1.95-Mev gamma-ray intensity obtained in the singles and coincidence spectra suggest that there are two gamma rays of approximately this energy. The less certain of the two is shown as a dotted line which originates at the 3.08-Mev level in Fig. 5.

It was not possible to resolve the full-energy peaks of the 0.62- and 0.624-Mev gamma rays which originate at the 1.13- and 1.137-Mev levels, respectively. (The intensity for the 0.624-Mev gamma ray given in Table I includes that of the weaker 0.62-Mev gamma ray.) However, an estimation of their relative intensities can be made from the angular correlation function determined by Klema and McGowan[6] for the 0.624-0.513-Mev gamma-ray cascade. If the 0.62-Mev gamma ray is assumed to be a pure $E2$ transition, their angular correlation function is obtained with the addition of 90.6% of the theoretical correlation function for a 0-2-0 spin sequence and 9.4% of the theoretical correlation function for a 2-2-0 spin sequence. This gives values of 4.9 ± 1.3 and 47 ± 3 for the 0.62- and 0.624-Mev gamma-ray intensities, respectively.

B. Ag^{106} Gamma-Ray Spectra

Ag^{106} was produced in the Purdue University cyclotron by an (α,n) reaction on rhodium metal foil, 0.002 inch thick. The energy of the alpha particles was ~15 Mev. Care was taken to remain below the 16.2-Mev threshold of the reaction Rh$^{103}(\alpha,2n)$Ag^{105}.[16] The bombarded foil was heated in molten Na$_2$O$_2$. The rhodium did not dissolve appreciably; however, ~10% of the Ag^{106} produced was removed from the foil. Silver carrier was added and the AgCl was precipitated. The AgCl was dissolved in concentrated NH$_4$OH and a Fe(OH)$_3$ scavenge was made. Palladium and cadmium holdback carriers were added and the AgCl was precipitated again. The Fe(OH)$_3$ scavenge and the AgCl precipitation were repeated. The AgCl was metathesized to Ag$_2$O by adding

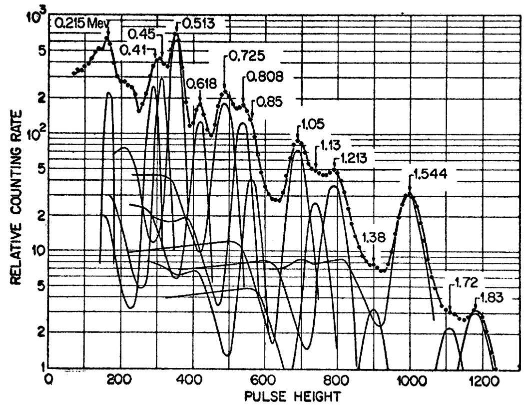

FIG. 6. Ag^{106} singles gamma-ray spectrum.

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[16] H. L. Bradt and D. J. Tendam, Phys. Rev. **72**, 1117 (1947).

TABLE II. Ag^{106} gamma-ray energies and relative intensities.

E_γ (Mev)	Singles spectrum	0.215[a]	0.513	0.618	0.725	0.81[c]	1.050	1.21[c]	1.54[c]	1.83[a]
	Relative intensity									
		Spectra in coincidence with gamma rays of energies (Mev):								
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		62±5	21±3	13±5[b]	13±3	23±3	14±3	10±2	Yes
0.456±0.007		Yes								
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	70±7		71±7		9±2					
0.725±0.007								(1.8±1.4)	17±2	
0.739±0.012							15±3		2±1	
0.751±0.012				4±2		⩽2				
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		25±2		16±2					
1.56 ±0.02								0.3±0.2		
1.58 ±0.02		Yes								
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.

NaOH. The Ag$_2$O was dissolved in concentrated HNO$_3$ for the preparation of sources.

The singles spectrum of Ag^{106} was observed for a source-to-detector distance of 14 cm. This spectrum is shown in Fig. 6. A second measurement of the spectrum was made with the same source three weeks later. All gamma rays were found to decay with the half-life characteristic of Ag^{106}. The half-life obtained from these measurements is 8.4±0.2 days. There was no evidence of any 40-day Ag^{105} impurity.

The singles spectrum was decomposed and intensities were determined in the same manner as described for the singles spectrum of Rh^{106}. The peaks at 0.725, 1.213, and 1.544 Mev all appear too wide to be the peak of a single gamma ray. The gamma-ray intensities are given in Table II. They are normalized to a value of 100 for the intensity of the 0.513-Mev gamma ray. The 2.10- and 2.63-Mev gamma rays which were reported by Alburger and Toppel[3] were not observed. The intensity of the 2.250-Mev gamma ray found by Horen and Bosch[10] is compatible with the upper limit that is given in Table II for the intensity of any gamma ray of energy greater than 1.9 Mev.

The gamma-ray spectra obtained in coincidence with the 0.513-, 0.618-, 0.725-, 0.81-, 1.050-, 1.21-, and 1.54-Mev gamma rays are illustrated in Figs. 7 and 8. The distance between the source and each detector was 5 cm except for the spectrum in coincidence with the 0.618-Mev gamma ray. For this spectrum the distances between the source and the two detectors were 5 and 14 cm. The spectra were decomposed and the intensities determined. Intensities which are normalized to a value of 100 for the 0.513-Mev gamma ray are given in Table II. Corrections have been made for coincidences with gamma rays which were not in the full-energy peak of interest. This explains why no intensities are included in Table II for some peaks which appear in the coincidence spectra in Figs. 7 and 8. Parts of the spectra in coincidence with the 0.215- and the 1.83-Mev gamma rays were also investigated. The presence of a coincidence gamma ray is denoted by a "yes" in Table II. A study of the coincidence spectra reveals that the peaks at 0.725, 0.808, 1.213, and 1.544 Mev in the singles spectrum are each the result of two or more gamma rays. The presence of two gamma rays with energies of ~1.21 Mev has previously been established by Alburger and Toppel.[3] They found internal conversion electron lines which corresponded to 1.205- and 1.225-Mev transitions.

An energy level diagram compatible with most of the results tabulated in Table II is given in Fig. 9. Intensity values in parentheses in Table II should be zero if the energy level diagram is complete. In every case it has been necessary to apply large corrections to these values. The resulting values are small and have large errors. A value of zero for each of these intensities is thus not in poor agreement with our data.

The 0.513-, 1.131-, and 1.563-Mev levels in Fig. 9 are probably the same as those populated by Rh^{106}. Failure to observe the 1.73-Mev gamma ray in coincidence with the 0.513-Mev gamma ray indicates it is a ground-state transition and thus a level is placed at 1.73 Mev. The presence of the 1.94-Mev level is inferred from the coincidences found between the 0.81-Mev gamma ray and the 0.618- and 1.13-Mev gamma rays. The weak 0.751-Mev gamma ray observed in coincidence with the 0.618-Mev gamma ray has been tentatively suggested as deexciting a level at 1.88 Mev. However, our data does not eliminate the possibility that the 0.751-Mev gamma-ray terminates instead at the 1.94-Mev level.

From the spectra in coincidence with the 0.513-, 0.725-, and 1.54-Mev gamma rays, the 0.725-, 1.537-, and 0.513-Mev gamma rays are known to be in cascade. The 0.725-Mev gamma ray is placed highest in the cascade in order to be compatible with the coincidence found between it and the 1.73-Mev gamma ray. This ordering of the triple cascade leads to the proposed levels in Fig. 9 at 2.052 and 2.764 Mev. The energy of the 0.31-Mev gamma ray, which is detected in the spectrum in coincidence with the 0.725-Mev gamma ray, agrees with the energy separation of the 1.73- and 2.052-Mev levels. Additional evidence is given for this position of the 0.31-Mev transition by the similarity of the 0.31- and 1.73-Mev gamma-ray intensities observed in coincidence with the 0.725-Mev gamma ray. Since the 0.700- and 0.847-Mev gamma rays also have similar intensities in the spectrum in coincidence with the 0.725-Mev gamma ray, and since their sum energy is approximately that of the 1.537-Mev gamma ray, they are given as cascade gamma rays which parallel the 1.537-Mev gamma ray. The energy of their intermediate level is 1.213 or 1.360 Mev.

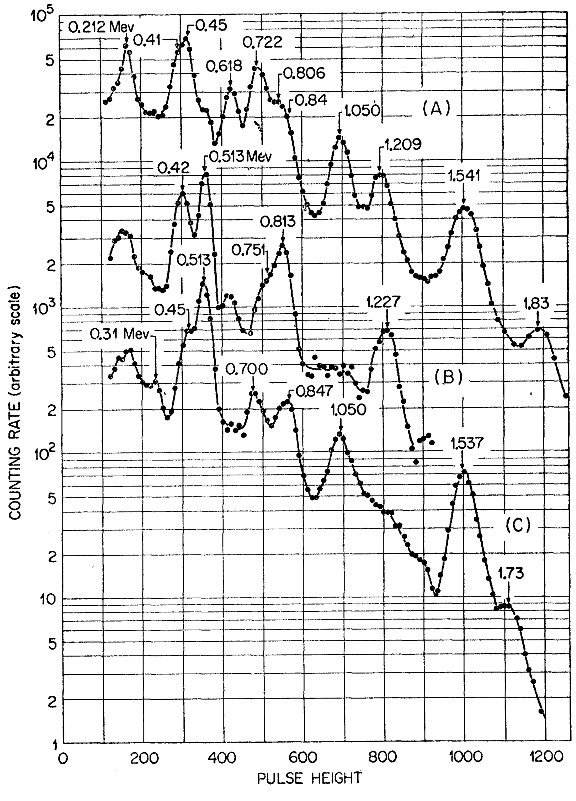

FIG. 7. Ag^{106} gamma-ray spectra in coincidence with the (A) 0.513-, (B) 0.618-, and (C) 0.725-Mev gamma rays.

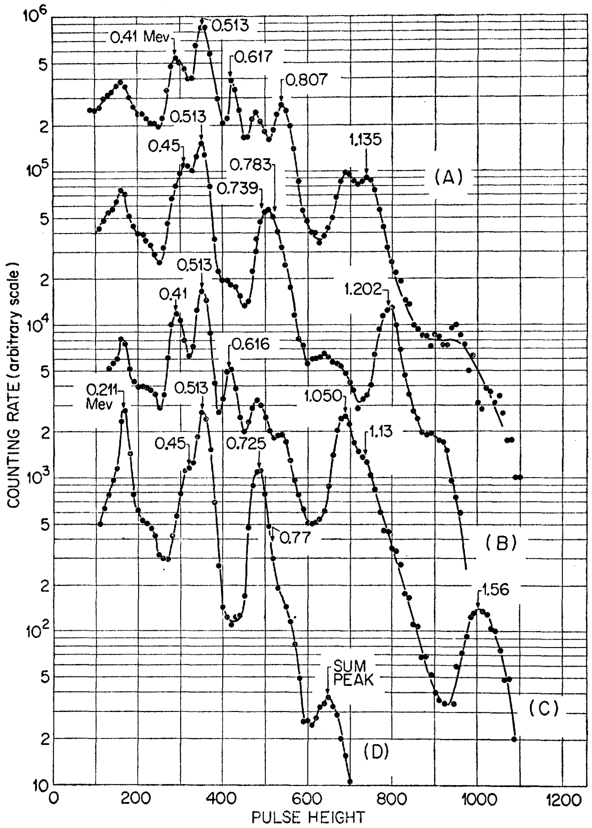

FIG. 8. Ag^{106} gamma-ray spectra in coincidence with the (A) 0.81-, (B) 1.050-, (C) 1.21-, and (D) 1.54-Mev gamma rays.

The 0.456-, 0.513-, and 1.58-Mev gamma rays are in coincidence with the 0.215-Mev gamma ray. The sum of the energies of these four gamma rays is 2.76 Mev, which is the energy of a level already proposed. This suggests that the four gamma rays are in cascade. The order given in Fig. 9 for the cascade establishes levels at 2.09 and 2.305 Mev. This order is selected because coincidence between the 1.050- and 0.739-Mev gamma rays also indicates the presence of a level at 2.30 Mev.

Placement of a level at 2.352 Mev is based on the coincidences found between the 0.513- and 1.83-Mev gamma rays, between the 0.618- and 1.227-Mev gamma rays, and between the 1.050- and 0.783-Mev gamma rays. The 2.764-Mev level is confirmed by the coincidences found between the 1.83- and 0.410-Mev gamma rays, between the 1.050- and 1.202-Mev gamma rays, and between the 0.81- and 0.81-Mev gamma rays.

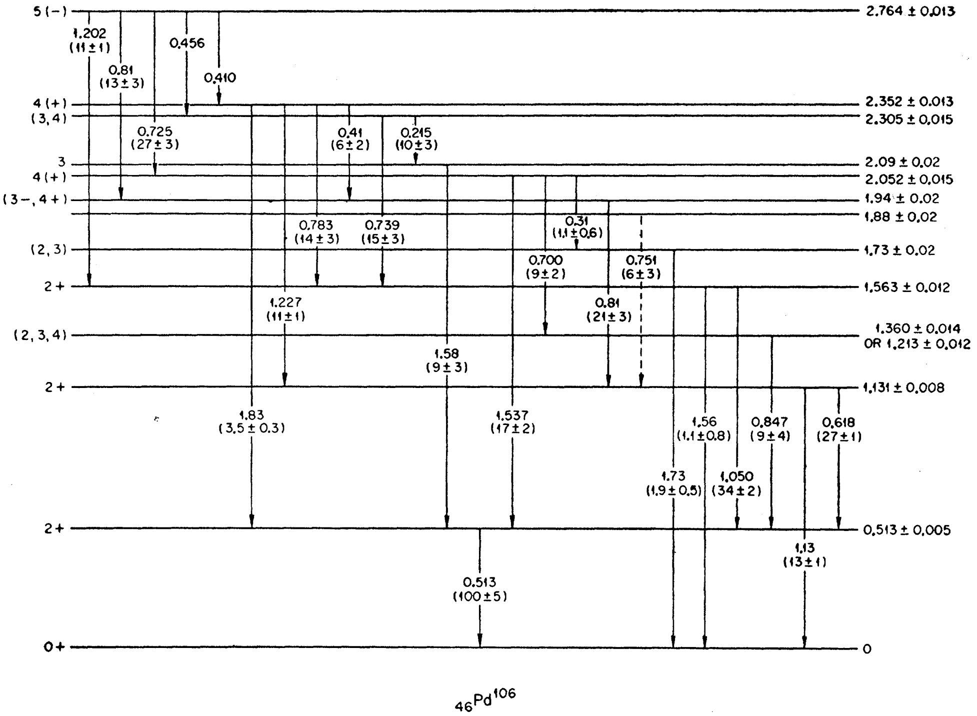

FIG. 9. Energy level diagram of Pd^{106} based on the present investigation of Ag^{106}. The pair of numbers associated with each transition gives its energy in Mev and relative intensity. Less certain spin and parity assignments are enclosed in parentheses.

The 1.38-Mev gamma ray is not included in the energy level diagram. Although its energy agrees within errors with the energy separation of the 1.360-Mev level and ground state, of the 2.764- and 1.360-Mev levels, and of the 1.88- and 0.513-Mev levels, its position cannot be assigned with any certainty on the basis of our results.

The 0.847-Mev gamma-ray intensity given in Fig. 9 is compatible with the value obtained for it from the spectrum in coincidence with the 0.725-Mev gamma ray; however, the intensity does not agree with the value obtained from the singles spectrum and the spectrum in coincidence with the 0.513-Mev gamma ray. The discrepancy may arise from the presence of another gamma ray of approximately this energy; for example, a transition between the 2.764- and 1.88-Mev levels would have an energy of 0.88 Mev. Such a transition with an intensity of $\leqslant 2$ would not be in disagreement with any of our data.

For the 0.513-, 1.131-, 1.360-, 1.563-, 1.73-, 1.94-, 2.052-, and 2.09-Mev levels, the total intensity of gamma rays terminating at each of these levels agrees within the errors with the total intensity of gamma rays originating at these levels. Although the intensities of the individual gamma rays between 0.40 and 0.50 Mev could not be determined, their total intensity is 61 ± 5. If the 0.410- and 0.456-Mev transitions, which are given in Fig. 9 as de-exciting the 2.764-Mev level, account for the larger part of this intensity, the 2.352- and 2.305-Mev levels are fed predominantly by gamma rays. It thus appears that Ag^{106} decays primarily to the 2.764-Mev level. This has also been suggested by Bendel.[11] The log *ft* value obtained for this decay is 5.0 if the disintegration energy of 3.1 Mev as determined by Enns[17] is used. This comparative half-life is characteristic of an allowed transition (spin change of 0 or 1 and no change in parity).

C. Ag^{106} Gamma-Gamma Angular Correlations

For the Ag^{106} gamma-gamma angular correlation measurements the source consisted of ~ 50 microliters of $AgNO_3$ solution. The solution was contained in a cylindrical fluorothene holder. The source was 15 cm from each detector. Data were taken every 10° between 90° and 180° or between 270° and 180°. A least-squares fit of the data was made to the function $W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$ on an IBM 704. The results were then corrected for the finite angular resolution of the detectors.[18]

To obtain the correlation for the 0.618-0.513-Mev cascade, we first observed a region of the spectrum which included the 0.618-Mev gamma ray in coincidence with gamma rays of energies around 0.513 Mev. However, this measurement included coincidences with gamma rays not in the 0.513-Mev full-energy peak. To eliminate these coincidences the same region of the spectrum was observed in coincidence with gamma rays of energies

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[17] T. Enns, Phys. Rev. **56**, 872 (1939).

[18] M. E. Rose, Phys. Rev. **91**, 610 (1953).

TABLE III. Angular correlation of the 0.618–0.513-Mev cascade.

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
$4(Q)2(Q)0$		$+0.102$	$+0.009$

TABLE IV. 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

around 0.56 Mev. The number of counts in the 0.618-Mev peak in the two coincidence spectra were determined for each angle and subtracted. The experimental angular correlation coefficients for the 0.618-0.513-Mev cascade are given in Table III. Also given in Table III are the theoretical correlation coefficients which occur for different spin values of the 1.131-Mev level. For spins 1, 2, and 3 the value of the mixing ratio δ is chosen to give the best agreement between the theoretical and experimental coefficients. [δ^2 is the ratio of the intensity of the $(L+1)$-pole radiation to the intensity of the L-pole radiation.] The experimental coefficients are consistent only with the theoretical coefficients for the spin sequence $2(D+Q)2(Q)0$ with $\delta=30$, in the notation of Biedenharn and Rose.[19] From the errors given for the A_2 coefficient, the approximate limits on the mixing ratio of the 0.618-Mev transition are 15 and infinity. This transition thus consists of >99.5% E2 radiation.

The angular correlation coefficients for the 0.725-1.537-Mev cascade are given in Table IV. This cascade has been proposed as originating at the 2.764-Mev level and terminating at the 2+, 0.513-Mev level. Since the 2.764-Mev level appears to be populated by an allowed transition from Ag^{106} which has spin 6,[2] its spin is 5, 6, or 7. The theoretical correlation coefficients for functions compatible with these spins are given in Table IV. Only dipole and quadrupole radiations were considered for the lower transition in the cascade. For higher multipoles the anisotropy would probably be appreciably attenuated by extra-nuclear effects. The experimental coefficients are in best agreement with the theoretical coefficients for a spin sequence $5(11\%\,D+89\%\,Q)4(Q)2$. However, the theoretical coefficients of the sequences $5(84\%\,D+16\%\,Q)4(Q)2$, $6(0)3(88\%\,D+12\%\,Q)2$, and $6(0)3(32\%\,D+68\%\,Q)2$ and the experimental coefficients are in sufficient agreement that these sequences should also be considered as possibilities.

The composite angular correlation function for the 1.537–0.513- and 1.58–0.513-Mev cascades was found to be

$$W(\theta)=1-(0.27\pm0.03)P_2(\cos\theta)-(0.01\pm0.04)P_4(\cos\theta).$$

The 1.537–0.513-Mev cascade probably has the sequence $4(Q)2(Q)0$. (The argument for a spin 4 assignment to the 2.052-Mev level is presented in Sec. III.) The theoretical correlation function for this sequence is $W(\theta)=1+0.102P_2(\cos\theta)+0.009P_4(\cos\theta)$. With the assumption that the contributions of the 1.58–0.513- and 1.537–0.513-Mev cascades to the composite correlation function were in proportion to the intensities of the 1.58- and 1.537-Mev gamma rays, the correlation function for the 1.58–0.513-Mev cascade was determined. The coefficients obtained for this correlation function are compared with the theoretical coefficients for the most likely sequences in Table V. The coefficients for the sequence $3(41\%\,D+59\%\,Q)2(Q)0$ agree best with the experimental results.

III. DISCUSSION

Comparison of the energy level diagrams in Figs. 5 and 9 indicates only the levels in Pd^{106} at 0.513, 1.13, and 1.56 Mev are populated by both 30-sec Rh^{106} and 8.3-day Ag^{106}. Because of the large difference in the spins of Rh^{106} and Ag^{106}, it is not surprising that so few levels are excited by both isotopes.

Values of the intensities and comparative half-lives for the beta-ray groups of Rh^{106} are given in Table VI. The values for the ground-state group are those reported by Alburger.[1] For the other groups the values are those expected if our proposed decay scheme is correct. The comparative half-lives are all characteristic of allowed or once-forbidden, nonunique transitions. Since the ground-state spin of Rh^{106} is 1,[1] each level given in Fig. 5 is expected to have a spin of 0, 1, or 2.

Estimates of the K-shell internal conversion coefficients have been made for transitions of Ag^{106} for which Alburger and Toppel[3] have given relative internal conversion electron intensities. The coefficients which resulted from the combination of their intensities with our gamma-ray intensities were normalized to the pure $E2$ theoretical coefficient for the 0.513-Mev transition. [The theoretical value of 4.86×10^{-3} is higher than the

TABLE V. 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

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[19] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

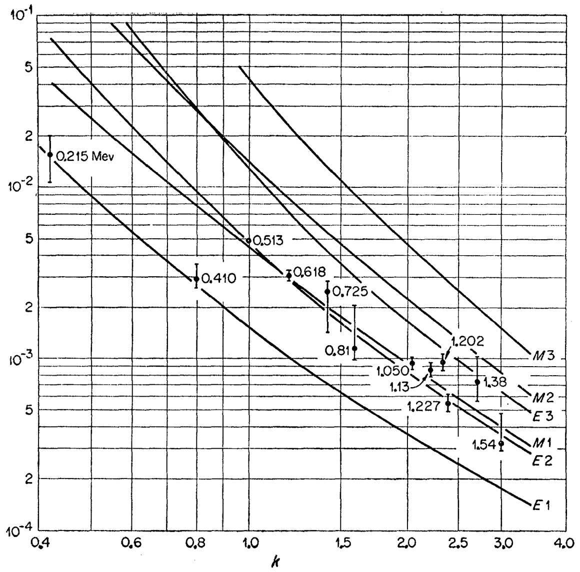

FIG. 10. Comparison of K-shell internal conversion coefficients for transitions in Pd^{106} to the theoretical coefficients for $Z=46$. k is the gamma-ray energy in units of m_0c^2.

experimental value of $(3.5\pm1.0)\times10^{-3}$ as determined by Alburger[1] in his investigation of Rh^{106}.] These experimental coefficients are compared with the theoretical coefficients[20,21] in Fig. 10. The flags on the experimental points do not include the errors in the internal conversion electron intensities. These errors are probably similar in magnitude to those of the gamma-ray intensities. For the coefficients of the 0.410-, 0.81-, and 1.54-Mev transitions, the intensities for the composite gamma-ray peaks at these energies are used. The coefficients will be increased if instead the intensity of only one gamma ray is used for each coefficient. If the internal conversion electron intensity given for the 0.725-Mev transition contains also the intensity of the 0.739-Mev transition, the coefficient for the 0.725-Mev transition will be smaller. For these four transitions of energies 0.410, 0.725, 0.81, and 1.54 Mev, the error flags given in Fig. 10 are extended to include the possible alternatives.

From these internal conversion coefficients and from the information obtained in the present study of Ag^{106}, spin and parity assignments have been suggested for levels in Pd^{106} which are populated by the decay of Ag^{106}. These are given in Fig. 9. The 0.513-, 1.131-, and 1.563-Mev levels are probably the same levels as populated by Rh^{106} and thus each has spin and parity of 2+. The internal conversion coefficients for the 0.618- and 1.050-Mev transitions are compatible with these assignments. The angular correlation function obtained for the 0.618–0.513-Mev cascade confirms the spin given for the 1.131-Mev level.

TABLE VI. Intensities and comparative half-lives of the Rh^{106} beta-ray groups.

Terminating level (Mev)	Relative intensity	Log ft
0	68	5.2
0.513	12.6	5.7
1.13	1.7	6.2
1.137	14.6	5.2
1.56	2.3	5.7
1.84	0.06	7.0
2.01	0.61	5.8
2.28	0.059	6.4
2.46	0.025	6.6
2.62	0.050	6.0
2.87	0.053	5.5
3.08	0.006	5.8

The log ft value (5.0) of the transition which populates the 2.764-Mev level and the angular correlation function of the 0.725–1.537-Mev cascade suggest that the 2.764-Mev level has spin 5; however, they also allow a spin assignment of 6. This assignment is eliminated by the presence of the 1.202-Mev transition between the 2.764-Mev and the 2+, 1.563-Mev levels. A transition between levels of spins 6 and 2 would not compete with the other transitions which de-excite the 2.764-Mev level. As the internal conversion coefficient for the 1.202-Mev transition agrees better with the theoretical curve for $E3$ radiation than with the curve for $M3$ radiation, odd parity is proposed for the 2.764-Mev level. If this is correct, the parity of 8.3-day Ag^{106} is also odd.

With the spin for the 2.764-Mev level established as 5, the angular correlation function for the 0.725–1.537-Mev is consistent only with spin 4 for the 2.052-Mev level. Dipole radiation is excluded for the 1.537-Mev transition since it takes place between levels of spins 2 and 4. With this limitation the conversion coefficient of this transition indicates its character is $E2$. Thus even parity is assigned to the 2.052-Mev level. The 0.725-Mev gamma ray must be an $E1$-$M2$ transition in order to be compatible with the spin and parity assignments of the 2.052- and 2.764-Mev levels. The best fit between the experimental correlation function for the 0.725–1.537-Mev cascade and the theoretical correlation function is that for which the 0.725-Mev transition consists of 11% dipole radiation and 89% quadrupole radiation (see Table IV). A somewhat poorer but acceptable fit is obtained with 84% dipole radiation and 16% quadrupole radiation. The best fit has an unusually large amount of $M2$ to $E1$ radiation. In both cases the $E1$ transition probability would have to be less than that obtained for a single-particle transition.[22] For either dipole-quadrupole mixture of the 0.725-Mev transition the internal conversion coefficient agrees

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[20] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

[21] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57ICC KI, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

[22] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), Chap. XII.

better with an $M1$-$E2$ mixture than with an $E1$-$M2$ mixture. We have no explanation for this inconsistency.

On the basis of the correlation function obtained for the 1.58–0.513-Mev cascade, spin 3 is assigned to the 2.09-Mev level. The internal conversion coefficient of the 0.215-Mev transition, which terminates at this level, indicates its character is $E1$. It then follows that the spin of the 2.305-Mev level is either 2, 3, or 4. The parity of this level is opposite that of the 2.09-Mev level. The presence of the intense 0.456-Mev transition between the 2.305-Mev level and the spin 5, 2.764-Mev level makes spin 2 unlikely for the 2.305-Mev level.

Our coincidence spectra suggest that the 0.31-, 0.700-, 0.81-, and 0.847-Mev gamma rays are limited to dipole and quadrupole radiations. Transitions of higher multipole radiations would not be expected to give coincidence counts because of their longer half-lives. Spins compatible with these radiations are 2, 3, and 4 for the 1.360-Mev level; 2, 3, 4, 5, and 6 for the 1.73-Mev level; and 0, 1, 2, 3, and 4 for the 1.94-Mev level. A ground-state transition from the 1.73-Mev level rules out spins 4, 5, and 6 for this level. A spin assignment of 0, 1, or 2 for the 1.94-Mev level is eliminated by the presence of the intense 0.81-Mev gamma ray which de-excites the spin 5, 2.764-Mev level. For either spin 3 or 4 for the 1.94-Mev level, one of the 0.81-Mev gamma rays must be a pure quadrupole transition. This fact coupled with the composite internal conversion coefficient obtained for the two 0.81-Mev transitions suggests one is predominantly an $E1$ transition and the other is an $E2$ transition. The spin and parity of the 1.94-Mev level are then either $3-$ or $4+$.

The conversion coefficient of the 0.410-Mev transition indicates it consists primarily of $E1$ radiation. The 2.352-Mev level thus is expected to have even parity and spin of 4, 5, or 6. The internal conversion coefficient of the 1.227-Mev transition is compatible only with the $4+$ assignment.

From Ag^{106} the branching ratio of the cascade to crossover gamma rays from the second $2+$ level is 2.09 ± 0.25. This value was also determined indirectly in our study of Rh^{106}. It was found to be 2.1 ± 0.6. This branching ratio combined with Coulomb excitation data of Stelson and McGowan[13] gives a value of 1.0 ± 0.3 for the ratio $B(E2,2'\rightarrow2)/B(E2,2\rightarrow0)$, where $B(E2,2'\rightarrow2)$ and $B(E2,2\rightarrow0)$ are the reduced $E2$ transition probabilities of the transitions between the second and first $2+$ levels and between the first $2+$ level and ground state, respectively. The $B(M1)$ for the 0.618-Mev transition is $\leqslant 1.54\times10^{-4}(e\hbar/2mc)^2$. Corrections for double $E2$ excitation and angular correlation effects have been applied to the Coulomb excitation data. However, no correction has been made for the interference between direct and double $E2$ excitation of the second $2+$ level. This interference term could change the value by as much as 30%. Several models, which have been proposed for even-even nuclei in the medium-weight region, predict the value of the $B(E2,2'\rightarrow2)/B(E2,2\rightarrow0)$ ratio. If the first and second $2+$ levels arise from quadrupole vibrations of spherical nuclei, the value predicted for this ratio is 2.[23] From the axially asymmetric nuclear model proposed by Davydov and Filippov,[24] the predicted value is 1.1. This is for $\gamma=26.5°$ where γ is a measure of the axial asymmetry of the nucleus and is determined from the ratio of the energies of the second and first $2+$ levels. A model proposed by Raz[25] in which he considers the results when a weak or intermediate surface interaction is added to the typical two-particle interaction, gives a value of 0 to a maximum of about 1 for this ratio.

From the angular correlation function obtained for the 0.618–0.513-Mev cascade, the transition between the second and first $2+$ levels was found to consist of greater than 99.5% $E2$ radiation. This predominance of $E2$ radiation is typical of nuclei in this region and is consistent with the proposed models.

The presence of a $4+$ level near the $2+$, 1.13-Mev level, as predicted by the models of Scharff-Goldhaber and Weneser[26] and of Raz,[25] was not observed. However, it is possible that such a level is populated by Ag^{106} but is so near in energy to the $2+$, 1.13-Mev level that the gamma rays from the two levels cannot be resolved. In order to be compatible with the angular correlation function obtained for the 0.618–0.513-Mev cascade, the excitation of a possible $4+$ level is less than 13% of the excitation of the $2+$ level. The presence of a $0+$ level near the second $2+$ level is predicted only by the pure vibrational model of Scharff-Goldhaber and Weneser.[26]

The model proposed by Davydov and Filippov[24] predicts several higher energy levels. From their model with $\gamma=26.5°$ the next two levels are at 1.41 and 1.64 Mev with spins and parities of $4+$ and $3+$, respectively. These levels could correspond to the experimental 1.360- and 1.73-Mev levels.

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[23] G. Scharff-Goldhaber, *Proceedings of the University of Pittsburgh Conference on Nuclear Structure, 1957*, edited by S. Meshkov (University of Pittsburgh and Office of Ordnance Research, U. S. Army, 1957).

[24] A. S. Davydov and G. F. Filippov, Nuclear Phys. **8**, 237 (1958).

[25] B. J. Raz, Phys. Rev. **114**, 1116 (1959).

[26] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).