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Decay of Ag^{110m}

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The gamma rays from Ag^{110m} were studied in magnetic spectrometers. Twenty-two electron lines corresponding to 14 gamma transitions were observed. These gamma rays were arranged in a plausible decay scheme. Directional correlation measurements were carried out on six gamma cascades in Cd^{110} resulting in spin assignments for 4 levels and multipolarity assignments for the strong gamma transitions.

INTRODUCTION

THE decay of Ag^{110m} (253 days) has been the subject of numerous investigations.[1-7] The presently accepted decay scheme, which was first proposed by Siegbahn,[1] is shown in Fig. 1. In addition to the gamma rays shown in Fig. 1, five weak transitions have been found in internal conversion work. These are at approximately 575 kev,[7] 618 kev,[2,6,7] 740 kev,[2] 1480 kev,[2,7] and 1560 kev.[8]

The 656-kev transition has been definitely established as $E2$ by conversion coefficient measurements[1,7] and Coulomb excitation results.[9,10] Therefore the first excited state in Cd^{110} has a spin of $2+$.

The two high-energy beta transitions of 2.86 and 2.12 Mev are of allowed type requiring a $1+$ assignment for the ground state of Ag^{110}. Antoneva *et al.*[2] have reported an additional weak beta transition at about 1.4 Mev but no confirmation of this has been made. Using the measured beta branching ratios,[2] approximate log *ft* values for the low-energy beta transitions can be found from Moszkowski's graphs.[11] This analysis gives a log *ft* value of 8.4 for the 530-kev beta and 5.6 for the 87-kev beta. These values indicate that the 530-kev beta transition is first forbidden while the 87-kev beta transition is allowed.

The spin of Ag^{110m} has been measured as 6 by Ewbank *et al.*[12] using an atomic beam method. Measurements of the K/L ratio for the 116-kev transition and lifetime considerations indicate that the 116-kev transition is of $M4$ character. Since there is a spin difference of 5 between the Ag^{110m} level and the ground state of Ag^{110}, there may be a low-energy dipole transition in cascade with the 116-kev transition,[13] somewhat similar to the case of Cs^{134m}.[14]

The ground state of Ag^{110} most certainly is formed from a configuration with the odd proton in a $g_{9/2}$ state and the odd neutron in a $g_{7/2}$ state. The $1+$ assignment is then in agreement with Nordheim's strong coupling rule. The isomeric state probably results from the odd proton in a $g_{9/2}$ state and the odd neutron in a $d_{5/2}$ state giving even parity for the spin 6 level.

Gamma-gamma directional correlation measurements on five cascades in Cd^{110} have been reported by Knipper.[15] The results are shown in Table II. Knipper based his interpretation on the Siegbahn decay scheme and a spin of $5-$ for Ag^{110m}. He assigned spins and parities of 3 or 4 to the 1415-kev level, $4+$ to the 1541-kev level, $4+$, $5+$, or $6+$ to the 2476-kev level, and $5-$ to the 2920-kev level, with the 1389-kev transition consisting of $E1+M2$ radiation, the 935-kev transition $M1$ or $E2$, the 885-kev transition $E2+M3$, and the 1516- and 759-kev transitions both mixtures with their

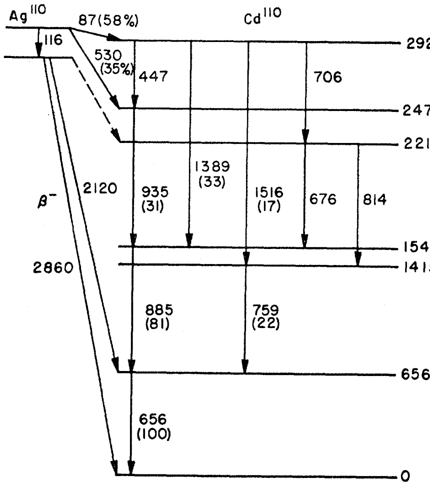

FIG. 1. Decay scheme of Ag^{110m} proposed by Siegbahn. All energies are in kev.

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character depending on whether the spin of the 1415-kev level is 3 or 4.

The investigation described in this paper consists of precise energy measurements of the gamma rays in the decay of Ag^{110m} and angular correlation measurements on six gamma cascades in Cd^{110}. A revised decay scheme is proposed.

GAMMA-RAY ENERGY MEASUREMENTS

The source material was obtained from Oak Ridge and was in the form of $AgNO_3$ in HNO_3. The source was studied in 180° permanent magnet spectrometers employing photographic detection (resolution$\sim$0.1%). A total of 22 electron lines was observed. These corresponded to 14 gamma transitions. The energies and interpretation of the electron lines are listed in Table I.

All of the observed transitions can be placed in a decay scheme in a consistent manner if one assumes that the 764-kev transition precedes the 1504-kev transition. This scheme is shown in Fig. 2. The 1504-kev gamma ray is known to be in coincidence with both the 764-kev and 657-kev gamma rays but the order of the 1504- and 764-kev transitions has never been definitely established. Further evidence for the inverted order of these transitions is found in the angular correlation measurements which are discussed in the following sections.

The energy sum of the 657- and 814-kev gammas is close to the 1473-kev gamma and therefore a level is placed at 1473 kev. The existence of a state in Cd^{110} at this energy has been verified by Stelson and McGowan[16] by means of Coulomb excitation. The 1473-kev level must then necessarily have a spin of 2 and positive parity. The 1560-kev transition observed by Dzhelepov *et al.*[8] would fit between the levels at 657 and 2219 kev and the 1400-kev beta transition reported by Antoneva[2] would be the expected transition between the 1+ Ag^{110} level and the 2+ level at 1473 kev in Cd^{110}.

In Fig. 2, the spins listed beside the Cd^{110} levels and the multipolarity of the gamma rays are those determined by the angular correlation measurements. The beta energies are those of Antoneva *et al.*[2]

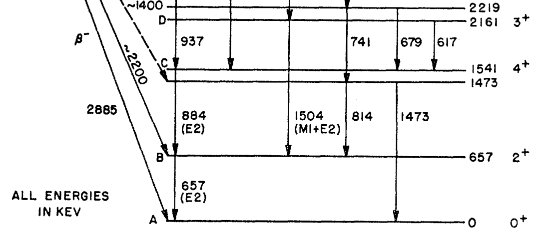

FIG. 2. Revised decay scheme of Ag^{110m}.

RESULTS OF DIRECTIONAL CORRELATION MEASUREMENTS

The correlation measurements were carried out with a conventional fast-slow coincidence circuit having an effective resolving time of 1×10^{-8} sec.[17] The scintillation counters consisted of 2 in.$\times$2 in. NaI(Tl) crystals mounted on RCA type 6342 photomultipliers. The counters were shielded frontally by $\frac{3}{16}$ in. of aluminum. Lateral lead shielding was employed in some measurements to eliminate coincidences due to scattering.

The liquid source was contained in a cylindrically-shaped Lucite holder, $\frac{1}{8}$ inch in diameter and $\frac{3}{8}$ inch in length. In all correlation measurements the source was centrally mounted at a distance of 10 cm from the front face of each crystal. The data were taken in the double-quadrant sequence at intervals of 15°, running 5 minutes at each angle. The real coincidence rates were normalized by dividing by the single counting rates, and after all data for a given angle were combined, a least-squares fit was made to the function

TABLE I. Conversion electron energies in kev and their interpretation. The energies are accurate to about 0.2%.

Electron energy	Interpretation	Energy sum	Electron energy	Interpretation	Energy sum
91.2	K^1	116.7	787.6	K^9	814
113.4	L^1	116.8	814	L^9	817
116.2	M^1	116.6	857.6	K^{10}	884
420.0	K^2	447	879	L^{10}	883
590.2	K^3	617	910.4	K^{11}	937
630.7	K^4	657	932	L^{11}	936
652.6	L^4	656	1355.8	K^{12}	1383
and	K^5	679	1379	L^{12}	1383
678.7	K^6	705	1446.7	K^{13}	1473
714.3	K^7	741	1476.9	K^{14}	1504
737.2	K^8	764	1494	L^{14}	1498
760.8	L^8	764			

$$W'(\theta)=A_0'+A_2'P_2(\cos\theta)+A_4'P_4(\cos\theta),$$

where P_k is the Legendre polynomial of order k. The annihilation radiation method[18] was used to correct for the effect of finite angular resolution, giving the normalized coefficients A_2 and A_4.

The scintillation spectrum is shown in Fig. 3. The arrows and letters refer to discriminator settings used for various correlations.

For the 1383−884 kev cascade the differential discriminators were set at positions *a* and *b* as shown in Fig. 3. With these settings there is no interference from any other cascades. The corrected correlation function shows an asymmetry of about 39% negative and is given by

$$W(\theta)=1-(0.308\pm0.013)P_2+(0.009\pm0.020)P_4.$$

The 937−884 kev correlation cannot be obtained

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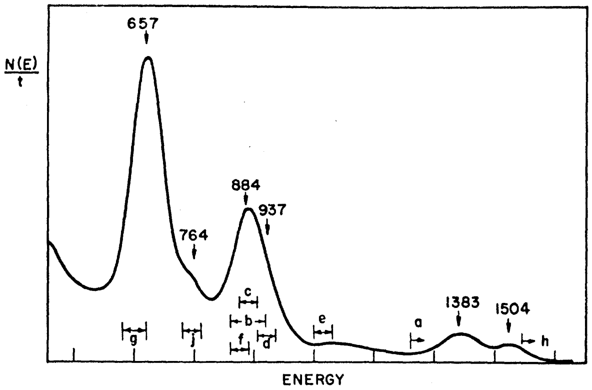

FIG. 3. Scintillation spectrum of Ag^{110m}. Letters and arrows refer to discriminator settings used in the correlation measurements.

without interference from the 1383−884 kev cascade. Since the interfering correlation has a large asymmetry it can appreciably alter the true 937−884 kev correlation. However, a fairly accurate subtraction process was carried out in this case. The correlation was run with the discriminators set at positions *c* and *d*, and background correlations were run with the discriminators set first at positions *c* and *e* and then at *d* and *e*. After proper normalization, the background correlation was subtracted point for point from the total correlation. Since some uncertainty was introduced here, a ±10% error was assigned to the background rate before subtraction. The background amounted to approximately 25% of the total coincidence rate. After correction for finite geometry the correlation function is given by

$$W(\theta)=1+(0.150\pm0.027)P_2-(0.006\pm0.036)P_4.$$

For the 884−657 kev correlation the discriminators were set at positions *f* and *g*. It was estimated that about 10 to 15% of the total coincidence counts were due to interfering correlations, but no correction could be made for this interference. The 884−657 kev correlation function is given by

$$W(\theta)=1+(0.073\pm0.014)P_2+(0.009\pm0.020)P_4.$$

The 1504−657 kev and 764−1504 kev correlations are complicated by the fact that the 657- and 764-kev peaks are not resolved by the scintillation counter and the 1504- and 1383-kev peaks are only partially resolved. With the discriminators set at positions *h* and *j*, the measured correlation function was mainly composed of the 764−1504 kev correlation but contained some interference from the 1504−657 correlation. The result was

$$W_A(\theta)=1-(0.202\pm0.021)P_2-(0.006\pm0.030)P_4.$$

With the discriminators set at positions *h* and *g*, the correlation function was composed mainly of the 1504−657 kev correlation but contained interference from the 764−1504 kev correlation. For these settings the result was

$$W_B(\theta)=1-(0.328\pm0.023)P_2-(0.022\pm0.031)P_4.$$

If W_1 is the true 764−1504 kev correlation function and W_2 is the true 1504−657 correlation function, then W_1 and W_2 are given in terms of the observed functions W_A and W_B by

$$W_1=[(1-X_B)W_A-(1-X_A)W_B]/(X_A-X_B),$$
$$W_2=(X_AW_B-X_BW_A)/(X_A-X_B),$$

where X_A and X_B are the fractions of W_A and W_B which are composed of the 764−1504 kev correlation. An estimate of the quantities X_A and X_B was obtained graphically. The values found were $X_A=0.85$ and $X_B=0.32$. Since uncertainty is introduced here it was considered reasonable to assign maximum errors of ±0.10 to X_A and X_B. The result for the 764−1504 kev correlation was

$$W_1(\theta)=1-(0.17_{-0.10}^{+0.05})P_2-(0.002_{-0.066}^{+0.035})P_4.$$

The result for the 1504−657 kev correlation was

$$W_2(\theta)=1-(0.40_{-0.07}^{+0.13})P_2-(0.03_{-0.04}^{+0.09})P_4.$$

The coefficients here are the values found for $X_A=0.85$ and $X_B=0.32$ and the errors quoted for the coefficients correspond to the maximum errors assigned to X_A and X_B.

In an attempt to gain information on the 1383−657 kev correlation, a correlation was run with the discriminators set at positions *a* and *g*. This correlation consisted mainly of a composite of the 1504−657 kev and 1383−657 kev correlations. It showed an asymmetry of 40% negative and a negligible value for the coefficient of the P_4 term. It was estimated that about 45% of the coincidences were due to the 1383−657 kev correlation and about 25% were due to the 1504−657 kev correlation. Other interfering cascades were the 764−1504 (~10%) and the 1383−884 (~20%). Assuming these estimates for the interference it was concluded that the 1383−657 kev correlation has an asymmetry of about 40% negative (with negligible P_4 contribution). One can definitely say that the asymmetry is greater than 25% negative.

The results of the directional correlation measurements are listed in Table II together with the results published by Knipper.[15]

INTERPRETATION OF CORRELATION DATA

The Cd^{110} levels pertinent to the correlation data are designated by letters in Fig. 2 and henceforth will be referred to by these letters. Since the spin of Ag^{110m} is known to be 6, the possible spin values considered for levels *E* and *F* are 4, 5, and 6. No crossover transitions from levels *C* and *D* occur to the ground state of Cd^{110}, and no beta transitions leading to these states have

TABLE II. Directional correlation results for Ag^{110m}.

Correlation	Results of Knipper A_2	A_4	Results of this investigation A_2	A_4
1383−884	-0.288 ± 0.012	-0.018 ± 0.014	-0.308 ± 0.013	$+0.009\pm0.020$
937−884	$+0.14\pm0.03$	-0.02 ± 0.03	$+0.150\pm0.027$	-0.006 ± 0.036
884−657			$+0.073\pm0.014$	$+0.009\pm0.020$
1383−657	-0.37 ± 0.05	$+0.06\pm0.06$	Asymmetry $\sim -40\%$ (A_4 small)	
1504−657	-0.34 ± 0.07	-0.12 ± 0.09	$-(0.40_{-0.07}^{+0.13})$	$-(0.03_{-0.04}^{+0.09})$
764−1504	-0.16 ± 0.02	$+0.01\pm0.03$	$-(0.17_{-0.10}^{+0.05})$	$-(0.002_{-0.066}^{+0.035})$

been observed. Therefore no spin lower than 2 or higher than 4 is considered for levels C and D.

Since the 1383−884 kev correlation is free of interference from other cascades it is the logical correlation with which to begin the interpretation. Considering pure transitions only, no combination of the possible spins for levels B, C, and F is consistent with the data. If one considers dipole-quadrupole mixtures in one or both of the transitions, three sequences are compatible with the data. These are $5(D,Q)4(Q)2$, $6(0)3(D,Q)2$, and $4(D,Q)3(D,Q)2$. Even though the 1383−657 kev and 884−657 kev correlations are not too accurate due to interference, the results of these correlations are sufficient to eliminate the sequences $6(0)3(D,Q)2$ and $4(D,Q)3(D,Q)2$ as possibilities for the 1383−884 kev cascade.

The discrepancy between the experimental coefficients for the 884−657 kev cascade and the theoretical coefficients $A_2=0.1020$ and $A_4=0.0091$ for a $4(Q)2(Q)0$ sequence is not too great and can easily be explained by interfering correlations. The 1383−657 kev correlation results are in good agreement with the spin sequence of $5(D,Q)4(Q)2(Q)0$. For this sequence the 1383−657 kev correlation should be identical with the 1383−884 kev correlation, and the experimental data agree with this.

Therefore, $5(D,Q)4(Q)2(Q)0$ is the only sequence of spins for levels F, C, B, and A, respectively, which simultaneously satisfies the results of the 1383−884 kev, 884−657 kev, and 1383−657 kev correlations. With this sequence the 1383−884 kev correlation data require the 1383-kev gamma transition to be a mixture of $(13.5\pm1.5)\%$ quadrupole and $(86.5\mp1.5)\%$ dipole radiation ($\delta>0$). Since the spin and parity of Ag^{110m} are 6 and +, respectively, and the 87-kev beta transition is allowed, level F must have positive parity. An assignment of positive parity to level C would be in agreement with the fact that no beta transition to this level has been observed and the empirical fact that in even-even nuclei, low-lying levels with even spin normally have even parity. In addition this would require the 1383-kev transition to be an $M1-E2$ mixture which is more likely than an $E1-M2$ mixture. Therefore, assignments of 5+ and 4+ are made to the 2924-kev and 1541-kev levels, respectively, with the 884-kev gamma being pure $E2$ and the 1384-kev gamma being a mixture of $(13.5\pm1.5)\%$ $E2$ and $(86.5\mp1.5)\%$ $M1$ radiation ($\delta>0$).

Since the spins of levels C and B have been established as 4 and 2, the spin combinations to be considered for the 937−884 kev correlation are 6-4-2, 5-4-2, and 4-4-2. The theoretical coefficients for a pure $6(Q)4(Q)2$ sequence are $A_2=0.1020$ and $A_4=0.0091$, and for a pure $4(D)4(Q)2$ sequence they are $A_2=0.1965$ and $A_4=0$. Neither of these sequences is quite consistent with the experimental values of $A_2=0.150\pm0.027$ and $A_4=-0.006\pm0.036$ for the 937−884 kev correlation, but they are both close enough to warrant consideration as possibilities. They cannot be ruled out on the basis of the correlation data alone because the subtraction process introduces uncertainties in the data. A pure $5(D)4(Q)2$ sequence can definitely be discarded since it would require a negative A_2. If dipole-quadrupole mixtures are considered, both the $4(D,Q)4(Q)2$ and $5(D,Q)4(Q)2$ sequences are compatible with the data. With a spin of 4 for level E, the 937-kev transition would be a mixture of $(98.0\pm1.8)\%$ dipole and $(2.0\mp1.8)\%$ quadrupole ($\delta<0$) and with a spin of 5 for level E, it would be a mixture of $(86\pm4)\%$ dipole and $(14\mp4)\%$ quadrupole radiation ($\delta<0$).

Since the beta-decay data indicate that the 520-kev transition is first forbidden or unique first forbidden, level E must have negative parity. A 5− assignment then requires an $E1-M2$ mixture ($\sim14\%$ $M2$) for the 937-kev gamma. This is unlikely, and therefore a spin of 5 for level E is not probable. An assignment of 4− requires almost pure $E1$ radiation for the 937-kev transition while an assignment of 6− requires $M2$ radiation. These are the most likely possibilities.

The 1504−657 kev and 764−1504 kev correlations are not too accurate because of interfering correlations. However, some information about level D can be obtained from them since the spins of all the other states involved in these correlations have been determined. Considering spins of 2, 3, or 4 for level D, it is found that only a $3(D,Q)2(Q)0$ sequence will explain the 1504−657 kev correlation data. Spins of 2 and 4 can definitely be ruled out. One should thus be able to explain the 764−1504 kev results by a $5(Q)3(D,Q)2$ sequence with a mixture in the 1504-kev gamma which is consistent with the result obtained from the 1504−657 kev correlation. This is not the case, but the interference from the highly negative 1383−657 and 1383−884 kev correlations could account for the discrepancy. If it is conceded that this is possible, a spin of 3 for level D is consistent with the data. This requires a mixture of about 10% quadrupole and 90% dipole radiation in the 1504-kev transition.

If the 1504- and 764-kev transitions are reversed in order as shown in Fig. 1, the sequences which must be considered for the 1504−657 kev correlation are $5(0)2(D,Q)2(Q)0$, $5(Q)3(D,Q)2(Q)0$, and $5(D,Q)4(Q)2(Q)0$. Neither of the first two sequences can give a negative asymmetry greater than 6% no matter what the mixing parameter. From the experimental data it is certain that the 1504−657 kev correlation must have a large negative asymmetry and these sequences can be ruled out. If the spin sequence were $5(D,Q)4(Q)2(Q)0$, the correlation function for the 1504−657 kev cascade would have to be identical with the 1504−764 kev correlation. The data are not in agreement with this, and any interference which might be present due to the interfering cascades cannot possibly explain the discrepancy. Since the 1504−764 kev and 1504−657 kev correlations are not at all in agreement with any reasonable spin sequences if the 1504-kev gamma precedes the 764-kev gamma, it is apparent that the data favor the new ordering of these transitions.

In the interpretation of the 1504−657 kev and 764−1504 kev correlations, the possibility of both the 764- and 1504-kev gammas being mixed multipoles was not considered. This would require a quadrupole-octupole mixture in one gamma transition. Relative intensity considerations and conversion coefficient data[8] tend to rule out this possibility. Therefore it is concluded that the 764-kev gamma is $E2$ and the 1504-kev gamma is an $M1-E2$ mixture ($\sim 10\%$ $E2$) with the 2160-kev level having a spin of 3 and positive parity.

DISCUSSION

The revised decay scheme is in better agreement with the systematics of medium weight even-even nuclei in the region around Cd^{110}. In the old decay scheme the second excited state occurs at 1421 kev and would necessarily have a spin of 3 or 4. This is not in agreement with the systematics of nuclei in this region since they all have a 2+ second excited state. In the new scheme, the spin of the second excited state is 2+.

From Coulomb excitation of Cd^{110}, Stelson and McGowan[16,19] found that the $E2$ transition probability for the 657-kev transition is 32 times the single-particle estimate, and the $E2$ transition probability for the 1473-kev transition is 0.88 times the single-particle value. These results together with the fact that the ratio of the energy of the second excited state to that of the first excited state is 2.24 indicate that the low-lying levels in Cd^{110} follow the near-harmonic vibrational level structure. The 2+ and 4+ states at 1473 and 1541 kev could then be members of the expected close-lying triplet of states of the type 0+, 2+, and 4+.

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