Double K-shell ionization in the internal-conversion decay of $^{109}Ag^m$

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Double ionization of the atomic K shell accompanying the K-shell internal conversion of the 88.0-keV $E3$ transition of $^{109}Ag^m$ has been studied by recording coincidences between K x rays and $K\alpha$ x rays emitted when the double vacancies are filled. The probability per K-shell internal conversion that a double K-shell vacancy is formed, T_{KK}, was found to be $(1.53\pm 0.24)\times 10^{-4}$, and is about a factor of 5 smaller than a previous measurement. The energy shift, ΔE, of the $K\alpha$ "hypersatellite" x ray was measured to be (373 ± 75) eV.

[RADIOACTIVITY $^{109}Ag^m$; measured K x-ray—$K\alpha$ x-ray coin., deduced double K-shell ionization probability and $K\alpha$ "hypersatellite" x-ray energy shift.]

I. INTRODUCTION

In K-shell internal conversion, double ionization of the atomic K shell may occur when the unconverted K electron is either excited to an unoccupied bound state or completely ejected from the atom. This excitation or ejection can be produced by several separate processes. One process is a "shakeoff" type process similar to that found in β decay and is caused by the sudden disappearance of the electron-electron Coulomb interaction. A second process is the direct collision between the converted and unconverted K electrons. Other processes which can give rise to a doubly ionized K shell are higher-order electromagnetic transitions, both nuclear and "electronic" in nature. In the nuclear higher-order transition, the decay proceeds through a nuclear intermediate level with the internal conversion of both transitions. In the electronic decay mode the nucleus may transfer its energy to an orbital electron, which radiates a photon as it is ejected from the atom. This effect is commonly called the internal Compton effect. Double ionization of the K shell is then produced when the internal Compton photon itself is internally converted.

All of the above processes leave the atom in the same final state, characterized by a doubly ionized K shell. In atoms with large fluorescence yields the most probable mode of atomic deexcitation is the emission of two K x rays. Coincident detection of these x rays allows determination of the probability for the production of the double vacancy, although which of the different processes gives rise to the double vacancy can only be identified by studies of the ejected electron spectra.

Previously reported experiments have searched for either the electrons ejected or the x rays emitted in the double ionization processes. The most prominent of those performed in the former category have been studies of the 662-keV transition of $^{137}Ba^m$ by Ljubicic *et al.*[1] and Porter, Freedman, and Wagner.[2] Ljubicic *et al.* obtained a value of $(1.8\pm 0.5)\times 10^{-4}$ for the probability that two K electrons are ejected per K internal conversion, while Porter *et al.* set an upper limit of 2×10^{-4} "shakeoff" electrons emitted per K internal conversion. X-ray coincidence studies have been performed on the 164-keV transition of $^{131}Xe^m$ by Knauf, Sommer, and Klewe-Nebenius[3] and by Fischbeck, Abdulla, and Petry.[4] The results obtained in these studies for double K-shell ionization per K internal conversion were $(1.0\pm 0.2)\times 10^{-4}$ and $< 2\times 10^{-5}$, respectively. A measurement by Knauf and Sommer[5] gives a probability of $(7.4^{+0.5}_{-1.5})\times 10^{-4}$ for double K-shell ionization per K internal conversion in the 88.0-keV E3 transition of $^{109}Ag^m$, a value which is approximately 3 times greater than that reported for any other transition. For an excellent summary and bibliography of the experimental and theoretical aspects of these and related phenomena, the reader is referred to the recent review by Freedman.[6]

Briand *et al.*[7,8] have reported another method of detecting double K-shell vacancies. This method consists of searching for the K x-ray "hypersatellite" which would be emitted when a double K-shell vacancy is present. The hypersatellite is produced by an electron making a transition to a completely empty K shell with the essential absence of K-shell screening causing the x ray to be shifted to a higher energy. Detection of this hypersatellite then shows that a double vacancy had been formed.

In the present work double ionization of the K shell in the 88.0 keV transition of $^{109}Ag^m$ has been reexamined by recording $K\alpha$ x-ray–K x-ray coincidences between a Si(Li) x-ray detector and a NaI(Tl) detector. Although the Si(Li) detector used could not clearly resolve the hypersatellite x ray from the normal x ray (use of the word normal is meant to include the second x ray produced in filling the double vacancy which is actually a satellite x ray, owing to the $1s^{-1}2p^{-1}$ initial state, shifted by approximately 30 eV), computer analyses of the x-ray peak consistently brought out the hypersatellite and allowed its energy and intensity to be measured.

II. EXPERIMENTAL PROCEDURES

A. Sources and source mounting

Figure 1 shows the decay scheme[9] of ^{109}Cd and ^{109}Ag^m. Three ^{109}Cd sources with activities of 19, 41, and 23 nCi were used in the measurements. Sources were made weak to keep the fraction of accidental coincidences small. Each source was prepared by evaporating a drop of active solution onto thin Mylar backings (6 mg/cm^2, 6 mg/cm^2, and 1.7 mg/cm^2, respectively) which were mounted on a 1.6-mm thick brass plate having a 3.2-mm minimum diameter, 6.4-mm maximum diameter tapered hole. The brass plate was then placed between the detectors which were at an angle of 180° and in contact with the plate to give maximum geometrical coincidence efficiency.

For each source a Ge(Li) spectrum was recorded in order to find possible contaminants which could give rise to Ag $K\alpha$ x-ray–Ag K x ray coincidences. The main contaminant which could give rise to such coincidences would be the K internal conversion of both the 30.2- and 80-keV transitions in the decay of ^{108}Ag^m. A negligible upper limit of 1×10^{-7} coincidences per K conversion of ^{109}Ag^m was found for contaminants.

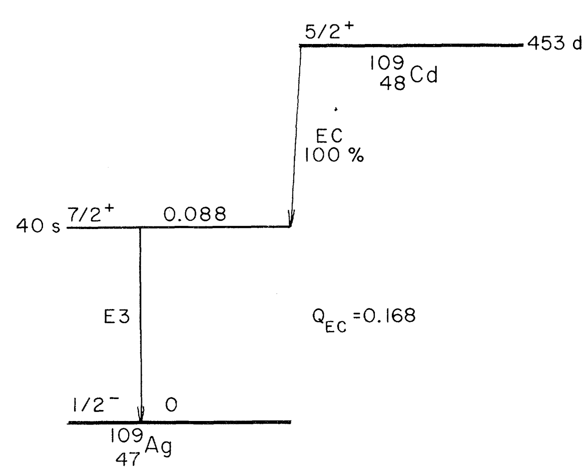

FIG. 1. Decay scheme of ^{109}Cd and ^{109}Ag^m (energies in MeV).

B. Detectors and coincidence system

An 8-mm diameter by 3-mm-thick ORTEC Si(Li) x-ray detector with a 0.25-mm-thick Be window was used in this work. Its full width at half maximum (FWHM) was approximately 600 eV for photons in the 20- to 50-keV region. Detection efficiencies were determined using sources whose decay rates were known to within 5%. Pulses from this detector and from a Harshaw 5.1×5.1-cm NaI(Tl) detector were analyzed in a fast-slow coincidence system. Fast-coincidence resolving times were electronically set at values between 17 and 60 nsec in an attempt to optimize the true coincidence spectra. For each resolving time used (corresponding to the different sources), the accidental coincidences per channel were calculated and subtracted to give the true coincidence spectra. The ratio of true to accidental coincidences varied between 4 to 1 and 8 to 1. The fast-circuit-coincidence efficiency was determined for each resolving time setting by using the slow coincidence circuit in the following manner. With a variable delay set at the maximum of a prompt curve, a coincidence measurement was made utilizing the fast-slow system and a ^{152}Eu source which gave a true fast coincidence rate, R_F. For this measurement, the energy gates spanned exactly the same photon regions as used in the ^{109}Ag^m coincidence measurements. Without changing either source or geometrical configuration, a slow coincidence measurement was performed in a similar way and the true slow-coincidence rate R_S determined. Since the resolving time for the slow-coincidence circuit was 1 μsec, the circuit efficiency for it was taken to be unity. The fast-coincidence-circuit efficiency was then simply given by R_F/R_S. Although the resolving time settings corresponded to coincidence efficiencies which differed by as much as a factor of 3 in these measurements, the consistency of the results support this method of determining the efficiencies. This same experimental system and this particular method for determining the coincidence efficiency has been described earlier[10] in similar measurements on double K-shell ionization accompanying electron capture.

C. Data recording

For a given coincidence measurement, pulses from the Si(Li) detector were recorded in one half of the memory of a Nuclear Data 512 channel analyzer. Since the time of each coincidence measurement varied from 13 to 20 days, Si(Li) single spectra were recorded periodically (minimum of 1 per day) in the other half of the memory throughout the measurement. These spectra were run in order to observe possible changes in peak position and width due to electronic drifts. A composite singles spectrum made up of a weighted sum of these single spectra was then compared to the (resultant) coincidence spectrum.

D. Evaluation of T_{KK}

All data analyses were performed on the $K\alpha$ x-ray peaks of the coincidence spectra recorded with the Si(Li) detector since the statistical accuracy on the $K\beta$ peaks was poor. The probability for double K-shell ionization per K conversion, T_{KK}, can be calculated from the coincidence count rate using

$$R_{K\alpha,K} = RT_K T_{KK} P\epsilon_1\epsilon_2\epsilon_C, \tag{1}$$

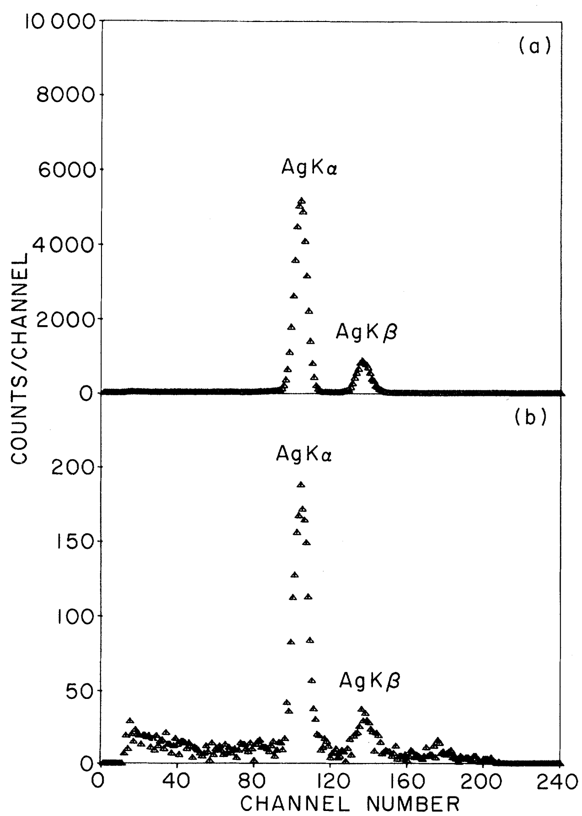

FIG. 2. (a) Si(Li) composite singles spectrum of ^{109}Cd and ^{109}Ag^m from 15 to 30 keV. (b) Si(Li) coincidence spectrum obtained with the NaI(Tl) detector gate set from 17 to 30 keV.

where

$R_{K\alpha,K}$ = coincidence rate due to double K vacancies for a $K\alpha$ x ray in the Si(Li) detector and a K x ray in the NaI(Tl) detector,

R = absolute decay rate of source,

T_K = probability per 88.0-keV transition for K internal conversion,

ϵ_1 = $K\alpha$ photopeak efficiency of Si(Li) detector, including solid angle,

ϵ_2 = K x-ray efficiency of NaI(Tl) detector, including solid angle, and

ϵ_C = coincidence circuit efficiency.

The factor P is the weighted sum of the probabilities that, given a double vacancy, a $K\alpha$ and K x ray will be emitted and detected in coincidence; i.e., two $K\alpha_1$ x rays, two $K\alpha_2$ x rays, a $K\alpha$ and a $K\beta'_2$ x ray, etc. In cases where each x ray is a $K\alpha$ x ray, the probability must be weighted by a factor of 2, since either x ray may be detected in either detector. Also incorporated into P is a modification of the usual K x ray relative intensities[9] to account for the specific vacancy left by the first transition. The fluorescence yield ω_K was taken to be 0.830 (Ref. 11) for both K-shell vacancies. The value of P for Ag is $1.65\omega_K^2$.

Using the NaI(Tl) K x-ray count rate

$$R_{\mathrm{NaI}} = R(A_K + T_K)\omega_K\epsilon_2, \tag{2}$$

where A_K is the probability per decay of ^{109}Cd for K capture, and multiplying by the total time of the measurement in Eq. (1) gives

$$N_{K\alpha,K} = \frac{N_{\mathrm{NaI}} T_K T_{KK} P\epsilon_1\epsilon_C}{(A_K + T_K)\omega_K}, \tag{3}$$

where $N_{K\alpha,K}$ and N_{NaI} refer to the total number of $K\alpha, K$ coincidences due to double vacancies and the total number of NaI(Tl) K x-ray gating pulses, respectively. N_{NaI} was determined by subtracting a small ($\simeq 7\%$) continuum from the NaI(Tl) singles spectrum to obtain a multiplicative factor which was applied to the scaled output of the NaI(Tl) single-channel analyzer.

III. RESULTS

Figure 2(a) shows a Si(Li) composite singles spectrum (weighted sum of singles spectra taken periodically throughout the measurement) for the decay of ^{109}Cd in the 15- to 30-keV Ag K x-ray energy region. This region was offset from zero by use of a biased amplifier. The Ag x rays are produced in both the K electron capture of ^{109}Cd and the K internal conversion of ^{109}Ag^m. Figure 2(b) shows a Si(Li) coincidence spectrum obtained with the NaI(Tl) detector gate set on the 17- to 30-keV energy region. The coincidence spectrum continuum is due to external bremsstrahlung photons produced in the absorption of the K internal conversion electrons and to internal Compton photons. Backscatter interactions involving the 88.0-keV γ ray cannot give rise to background in this region due to the presence of the brass plate between the detectors and the energy regions of the NaI(Tl) and Si(Li) gates.

Figure 3(a) shows the $K\alpha$ x-ray peaks of both the coincidence spectrum and the normalized composite singles spectrum. Background has been subtracted from both peaks. Figure 3(b) shows the Gaussian distributions fit with the computer program of Putnam *et al.*[12] to the peaks. The shift to higher energy and the broadening of the high energy side of the coincidence spectrum $K\alpha$ x-ray peak with respect to the composite singles spectrum $K\alpha$ x-ray peak is evidence of the high energy hypersatellite component in the coincidence spectrum peak. Coincidence spectra from all three measurements clearly exhibited this characteristic. The preence of the $K\alpha$ hypersatellite allowed the coincidence spectra $K\alpha$ x-ray peaks to be fitted with the sum of two Gaussian distributions representing the $K\alpha$ hypersatellite peak and the normal $K\alpha$ x-ray peak. This normal peak is composed of unshifted x rays in coincidence with external bremsstrahlung and internal Compton photons in the NaI(Tl) gating region and of $K\alpha$ satellite x rays in coincidence with $K\alpha$ hypersatellite x rays in the NaI(Tl) detector. Figure 4(a) shows the results of a computer fit and Fig. 4(b) shows the two Gaussian distribu-

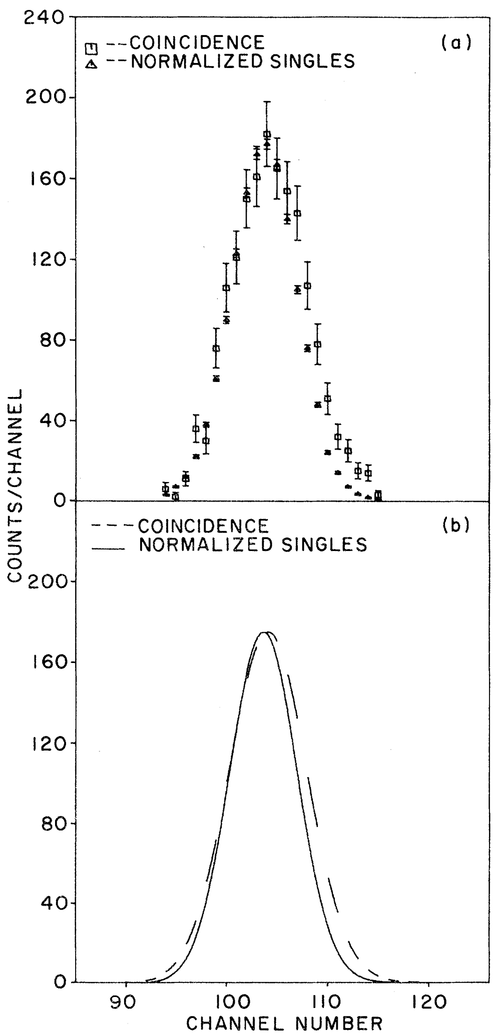

FIG. 3. (a) Si(Li) composite singles spectrum and coincidence spectrum $K\alpha$ x-ray peaks. The composite singles spectrum peak has been normalized to the height of the coincidence spectrum peak. (b) Gaussian distributions fitted to the two peaks.

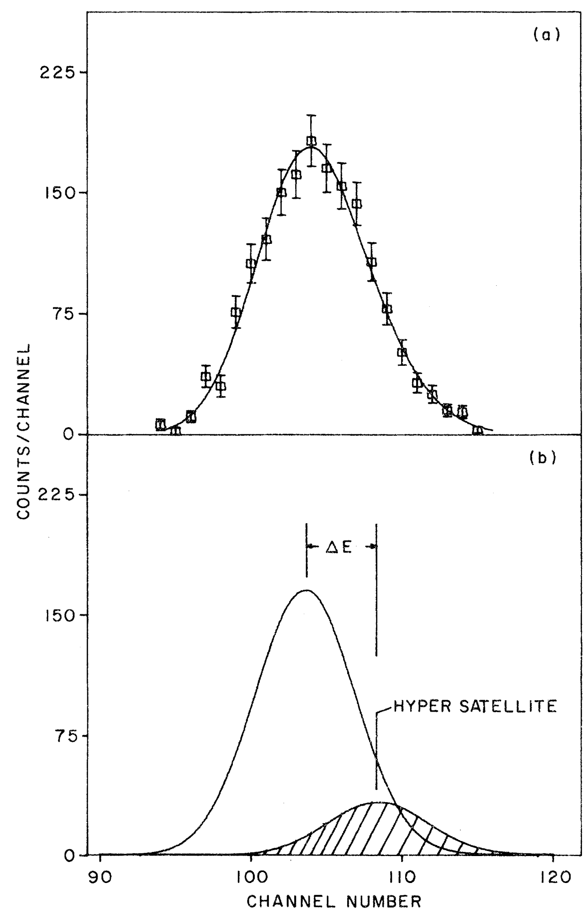

FIG. 4. (a) A two-Gaussian distribution fit to the Si(Li) coincidence spectrum $K\alpha$ x-ray peak. (b) The two-Gaussian distributions of which the fit of Fig. 4(a) is composed. The two distributions represent the normal and hypersatellite x-ray peaks.

tions of which the fit is composed. The energy shifts ΔE of the $K\alpha$ hypersatellite x ray with respect to the normal $K\alpha$ x ray found in each of the three coincidence measurements were 362, 340, and 417 eV, respectively. The average shift of (373 ± 75) eV is approximately 150 eV less than that which would be expected from a Z interpolation between shifts reported by Briand *et al.*[8] The reliability of the fitting procedure to isolate the hyperstatellite peak from a coincidence spectrum and hence determine its energy shift and intensity was tested on the $K\alpha$ and $K\beta'$ peaks in the composite singles spectra for all three coincidence measurements. The results of these tests showed average discrepancies of 15% between the energy differences obtained from the computer fits and the actual energy differences between the $K\alpha_2$ and $K\alpha_1$ x rays as well as between the $K\beta_1'$ and $K\beta_2'$ x rays. Similarly, 5% discrepancies between the fitted areas and the accepted relative intensities were obtained for the above x-ray peaks. The assigned uncertainty of 20% for the average energy shift of the hypersatellite x ray is intended to represent the best estimate of the standard deviation in fitting the unresolved distributions.

The probability for the double vacancy to be formed, T_{KK}, was determined by use of Eq. (3), where $N_{K\alpha,K}$, the total number of $K\alpha$ x rays due to double vacancies that were detected in the Si(Li) coincidence spectra, was determined in two ways. In the first method, $N_{K\alpha,K}$ was simply twice the number of x rays obtained by integration of the $K\alpha$ hypersatellite peaks. The factor of 2 accounts for coincidences in which the $K\alpha$ or $K\beta$ hypersatellite is detected in the NaI(Tl) and the succeeding $K\alpha$ is detected in the Si(Li) detector. The second method used to determine $N_{K\alpha,K}$ was independent of the first and consisted of reducing the Si(Li) coincidence spectra $K\alpha$ x-ray peaks to x rays due only to double vacancies, i.e., x rays in coincidence with external bremsstrahlung and internal Compton photons in the NaI(Tl) gating region were subtracted from the $K\alpha$ peak. This subtraction was done by first considering the materials surrounding the sources as solid targets for the 62.5-keV K internal conversion electrons and calculating the expected number of $K\alpha$ [Si(Li)]-external bremsstrahlung [NaI(Tl)] coincidences to be subtracted from the $K\alpha$ [Si(Li)] x-ray peaks. In the same manner the expected number of external bremsstrahlung [Si(Li)]-K x ray [NaI(Tl)] coincidences were calculated to reduce the coincidence continuum of Fig. 2(b) to photons produced only in the internal Compton process. This latter calculation allowed the determination of the probability for the internal Compton process in the 17- to 30-keV energy region which was needed to calculate the expected number of $K\alpha$ [Si(Li)]-internal Compton [NaI(Tl)] coincidences to subtract from the $K\alpha$ [Si(Li)] x-ray peaks. For this energy region an average probability of $(3.5 \pm 0.3) \times 10^{-4}$ internal Compton photons per K conversion was found which compares favorably with a value of 2.7×10^{-4} predicted by the theory of Iakobson (Ref. 13).

Using Eq. (3) and $N_{K\alpha,K}$ as determined by the above two methods, T_{KK} was determined for each of the three sources. These values are listed in Table I along with other experimental values necessary to evaluate T_{KK}. The principal uncertainties in the T_{KK} values are systematic ones due to the

TABLE I. Data used for the determination of T_{KK}. Symbols defined in text.

Source No.	1	2	3
$N_{K\alpha,K}(1)$ [a]	422 ± 36	2040 ± 121	943 ± 64
$N_{K\alpha,K}(2)$ [a]	614 ± 258	b	823 ± 312
$N_{K\alpha,K}$ [a]	425 ± 36	2040 ± 121	940 ± 64
N_{NaI}	$(2.41 \pm 0.02) \times 10^8$	$(4.62 \pm 0.04) \times 10^8$	$(2.21 \pm 0.02) \times 10^8$
ϵ_C	0.30 ± 0.03	0.70 ± 0.06	0.90 ± 0.08
ϵ_1	0.078 ± 0.008	c	c
T_K	0.43 ± 0.03 [d]	c	c
A_K	0.814 ± 0.002 [d]	c	c
T_{KK}	$(1.59 \pm 0.27) \times 10^{-4}$	$(1.71 \pm 0.27) \times 10^{-4}$	$(1.28 \pm 0.21) \times 10^{-4}$
T_{KK} (Average)		$(1.53 \pm 0.24) \times 10^{-4}$	

[a] $N_{K\alpha,K}(1)$ refers to the determination of $N_{K\alpha,K}$ in Eq. (3) by means of the hypersatellite analyses and $N_{K\alpha,K}(2)$ refers to the evaluation by subtracting the contributions due to external bremsstrahlung and internal Compton processes. $N_{K\alpha,K}$ is the weighted average of the two methods.

[b] The second method could not be applied to the measurements with this source because specific gating information had not been recorded.

[c] These values are the same as given for Source No. 1.

[d] Experimental result from Ref. 26.

coincidence and detection efficiencies and to the fitting procedure and are therefore not reduced when averaging the results from the three different sources. The average value of $(1.53\pm 0.24)\times 10^{-4}$ is a factor of 5 less than that measured by Knauf and Sommer.[5] It is worthwhile to note that even if all the $K\alpha$ x rays in the Si(Li) coincidence spectra were taken to be due to double K shell vacancies (i.e., coincidences with external bremsstrahlung and internal Compton photons included) the probability would still be a factor of 2 less than that measured by Knauf and Sommer.

IV. DISCUSSION

Although double K-shell ionization can also occur in the electron capture decay of ^{109}Cd, the theory of Intemann and Pollock[14] and of Intemann[15, 16], which has been shown[10,17] to be in agreement with experiments for K electron ejection with K capture, gives a probability of only 4.5×10^{-6} (Ref. 18) K-shell electrons ejected per K capture. Since Intemann expects the probability for K electron excitation to be small compared with that of K electron ejection[16], the above value would correspond to the probability per K capture for double K shell ionization. A recent theory by Mukoyama *et al.*,[19] however, argues that the probability for excitation is larger than that for ejection but the over-all probability for the production of double K-shell vacancies per K capture in this latter theory still appears to be less than 10^{-5}. Since these two values are about factors of 30 and 15 less than those determined in these measurements, contributions to the observed coincidence from electron capture were simply neglected.

A comparison can be made between the measured value of T_{KK} and existing theoretical estimates in each of the four processes, "shakeoff" (SO), direct collision (DC), double conversion or intermediate nuclear state (N), and internal conversion of the internal Compton radiation (ICE), discussed earlier. Considering the double vacancy to be produced by a shakeoff type process, Carlson *et al.*[20] have suggested that the probability for K shakeoff with K conversion would be related to K shakeoff in β decay by

$$T_{KK}(\mathrm{SO}) = T(\beta)[\Delta Z_{\mathrm{eff}}(\mathrm{IC})/\Delta Z_{\mathrm{eff}}(\beta)]^2, \qquad (4)$$

where $T(\beta)$ is the probability for K shakeoff in β decay and $\Delta Z_{\mathrm{eff}}(\mathrm{IC})$ and $\Delta Z_{\mathrm{eff}}(\beta)$ are the changes in effective charge seen by the electron in internal conversion and β decay, respectively. Using $T(\beta)$ given by Carlson *et al.*, $\Delta Z_{\mathrm{eff}}(\beta)=1$, and from Slater,[21] $\Delta Z_{\mathrm{eff}}(\mathrm{IC})=0.3$, gives

$$T_{KK}(\mathrm{SO}) = 4.0\times 10^{-5}.$$

This value is nearly a factor of 4 smaller than the experimental result. Carlson *et al.*, however, state that Slater's recipe can be particularly misleading for double K-shell vacancies but, based on their results for Kr, the $\Delta Z_{\mathrm{eff}}(\mathrm{IC})$ determined from the Hartree-Fock wave functions would lead to a $T_{KK}(\mathrm{SO})$ probability which is about a factor of 10 smaller than the experimentally measured value.

No formal theory for a direct collision process in internal conversion has been presented, but Feinberg[22] has estimated the relative probability of direct collision to shakeoff in β decay to be BE/E_0, where BE is the binding energy of the electron subsequently ejected and E_0 is the kinetic energy of the colliding electron. If this estimate is applied to K conversion, the ratio of BE/E_0 for the 88.0-keV transition of ^{109}Ag^m is 0.41. Applying this factor to the above shakeoff prediction yields

$$T_{KK}(\mathrm{DC}) = 1.6\times 10^{-5},$$

which is an order of magnitude smaller than experiment.

Although Eichler and Jacob,[23] Eichler,[24] and Grechukhin[25] have presented formal theories for two quantum transition intensities, it is very difficult to determine the probability for double conversion from either theory since all the intermediate states which may contribute to the process are not known. However, Eichler[24] has given the ratio of the differential (in energy) intensity of the double conversion process to the differential intensity of the double γ process to be

$$W_{KK}/W_{\gamma\gamma} = (\mu/2)\alpha_K(EL_1)\alpha_K(EL_2), \qquad (5)$$

where μ is a factor near unity, $\alpha_K(EL_i)$ is the K-shell conversion coefficient for a transition of energy equal to one half the energy of the single γ transition, and multipolarity EL_i. For an $E3$ transition the allowed two quanta will most probably be electric dipole and electric quadrupole so that Eq. (6) becomes

$$W_{KK}/W_{\gamma\gamma} = (\mu/2)\alpha_K(E1)\alpha_K(E2). \qquad (6)$$

This ratio of differential intensities can be changed to a ratio of probabilities quite easily to yield

$$T_{KK}(N)/T_{\gamma\gamma} = (\mu/2)\alpha_K(E1)\alpha_K(E2)/\alpha_K, \qquad (7)$$

where $T_{\gamma\gamma}$ is the probability per γ decay for a two γ process and α_K is the K conversion coefficient for the single transition ($\alpha_K = 11.0\pm 0.3$[26] for ^{109}Ag^m). The previous measurement by Knauf and Sommer[5] has given $T_{\gamma\gamma} \leqslant 1.9\times 10^{-5}$ for ^{109}Ag^m so that using $\alpha_K(E1)$ and $\alpha_K(E2)$ as given by Hager and Seltzer,[27] $T_{KK}(N)$ becomes

$$T_{KK}(N) \leqslant 1.7\times 10^{-5}.$$

TABLE II. Summary of experimental results and theoretical estimates for T_{KK} in the decay of $^{109}Ag^{m}$.

Experimental T_{KK}		Theoretical T_{KK} [b]			
This work	Previous work [a]	T_{KK}(SO)	T_{KK}(DC)	T_{KK}(N)	T_{KK}(ICE)
$(1.53 \pm 0.24)\times 10^{-4}$	$(7.4^{+0.5}_{-1.5})\times 10^{-4}$	4.0×10^{-5}	1.6×10^{-5}	$\leq 1.7\times 10^{-5}$	4.7×10^{-4}

[a] From experimental result in Ref. 5.
[b] SO, DC, N, and ICE refer to shakeoff, direct collision, nuclear intermediate state, and internal conversion of the internal Compton radiation, respectively. The manner in which these values were calculated is discussed and referenced in the text.

The upper limit for this value is a factor of 9 smaller than the experimentally determined value.

Listengarten[28] has proposed that the probability for the internal conversion of the internal Compton radiation is given by

$$T_{KK}(\mathrm{ICE}) = (4\alpha/3\pi)W_{BE}\int^{W-\mathrm{BE}} \frac{\alpha(E1,E)}{2}\,\frac{dE}{E}, \quad (8)$$

where W is the energy of the nuclear transition, BE is the K-shell binding energy and $\alpha(E1,E)$ is the K-shell internal conversion coefficient for electric dipole radiation of energy E. Applying Eq. (8) to the 88.0-keV transition of $^{109}Ag^{m}$, and using $\alpha(E1,E)$ as given by Hager and Seltzer, gives

$$T_{KK}(\mathrm{ICE}) = 4.7\times 10^{-4}.$$

This theoretical estimate is about a factor of 3 larger than the experimentally determined value.

Table II summarizes experimental results and theoretical estimates for T_{KK} in the 88.0-keV transition of $^{109}Ag^{m}$. While the value for T_{KK} determined in this investigation is a combination of all processes producing double K-shell vacancies, theoretical estimates indicate that internal conversion of the internal Compton radiation is the principal effect. However, as noted above and by Fischbeck, Abdulla, and Petry[4] for $^{131}Xe^{m}$, the values obtained using the Listengarten suggestion[28] are 3 to 5 times larger than experimentally measured values. To better understand the various processes occurring in the decay, more formal theoretical calculations as well as experimental spectrum shape studies of the ejected electrons are needed.

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