Double K-shell vacancy creation in the decay of ^{109}Pd and ^{109}Cd

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The probability P_{KK}(IC) of double K-shell vacancy creation per K internal conversion of the 88 keV $E3$ transition in the decay of $^{109}Ag^m$ has been determined by means of a $K\alpha$-x-ray–K-x-ray coincidence experiment on ^{109}Pd: $P_{KK}(\text{IC}) = (13.0 \pm 1.1) \times 10^{-5}$. From P_{KK}(IC) and a similar experiment on ^{109}Cd the probability P_{KK}(EC) of double K-shell vacancy production per K-electron capture decay of ^{109}Cd has been determined as well: $P_{KK}(\text{EC}) = (1.02 \pm 0.36) \times 10^{-5}$. The energy shift of the hypersatellite Ag $K\alpha_1^H$-x-ray line was found to be 532 ± 6 eV.

RADIOACTIVITY ^{109}Pd and ^{109}Cd; measured $K\alpha$-x-ray–K-x-ray coincidences, deduced double K-shell vacancy production probabilities of 88 keV $E3$ transition and EC decay, and hypersatellite $K\alpha_1$-x-ray shift.

I. INTRODUCTION

Recently we reported a value for the probability of double K-shell vacancy creation per K internal conversion of the 88 keV $E3$ transition in the decay of $^{109}Ag^m$ (Ref. 1): $P_{KK}(\text{IC}) = (2.8 \pm 0.7) \times 10^{-5}$. This result was obtained from an experiment on ^{109}Cd ($t_{1/2} = 464d$) in which coincidences were measured between Ag K-x rays and hypersatellite Ag $K\alpha^H$-x rays. In the evaluation of the data we had to take into account the probability of double K-shell vacancy creation per K-electron-capture decay of ^{109}Cd to $^{109}Ag^m$, P_{KK}(EC). Since P_{KK}(EC) has not yet been determined experimentally, we used a theoretical value. However, the correctness of the theory has not yet been established and therefore this procedure is not satisfactory.

In an experiment on ^{109}Pd ($t_{1/2} = 13.46h$) the above sketched problem does not arise and therefore we determined P_{KK}(IC) from an experiment on this isotope.

Furthermore, we repeated the measurements on ^{109}Cd. The reason for this is that we discovered a systematic error in the previous experiment.[1] The coincidence efficiency was found to have changed with time in such a way that the efficiency for the Ag K-x-ray–$K\alpha^H$-x-ray coincidences had become lower than the efficiency for the Te K-x-ray–$K\alpha$-x-ray coincidences by means of which the experimental set-up was calibrated. The difference could be removed by warming up the intrinsic-Ge detector for approximately 24 hours and subsequently cooling it down again. An explanation is probably found in a surface effect of the detector, i.e., in an increase with time of the number of trapping centers near the surface, in consequence of which the rise time of the pulses from radiation detected close to the surface increases relatively to the rise time of the pulses from radiation which is detected deeper in the detector. Then, in the used slow-rise-time reject mode of the constant-fraction discriminator more Ag K-x-ray pulses than Te K-x-ray pulses are rejected.

The intrinsic-Ge detector was replaced by a new one which, up till now, did not show the above described effect in the energy range of interest.

From the ^{109}Cd data and P_{KK}(IC) obtained from the experiment on ^{109}Pd we also found P_{KK}(EC).

II. METHOD OF MEASUREMENT

The experiments have been performed by means of a 25 mm^2 intrinsic-Ge x-ray detector of Princeton Gamma-Tech and a 40 mm diam NaI(Tl) x-ray detector. A coincidence circuit was employed with a time window of 50 ns. The coincidence spectrum, the accidental-coincidence spectrum, and the singles spectrum were recorded simultaneously by means of a routing system. In addition we recorded the NaI(Tl) spectrum and the time spectrum. The data were handled by means of a PDP 11/10 computer.

The ^{109}Pd activity was obtained from neutron bombardment of ^{108}Pd (enrichment 99%) for 4 hours at a neutron flux of $10^{13} \text{cm}^{-2} \text{s}^{-1}$; the ^{109}Cd was commercially available carrier free ^{109}Cd with a specific activity of more than 50 μCi/μg Cd. All sources were prepared by evaporation of a drop of active solution onto Scotch tape. The sources were sandwiched between the two detectors placed at 180°. In order to prevent the detection of electrons arising from double K-shell vacancy production, Auger electrons, and conversion electrons, Al foils, 0.3 mm thick, were placed on either side of a source.

From the decay schemes[2] we find for the relation between N_c the number of Ag $K\alpha^H$-x-ray counts in the coincidence spectrum recorded with the Ge detector, and N_{NaI}, the number of Ag K-x-ray counts in a gate set on the K-x rays recorded with the NaI(Tl) dectector, for the case of ^{109}Pd,

$$N_c/(\epsilon N_{\mathrm{NaI}}) = \alpha^H \omega_K^H P_{KK}(\mathrm{IC}), \quad (1)$$

and for the case of ^{109}Cd,

$$N_c/(\epsilon N_{\mathrm{NaI}}) = \alpha^H \omega_K^H[(0.34 \pm 0.01)P_{KK}(\mathrm{IC}) + (0.66 \mp 0.01)P_{KK}(\mathrm{EC})]. \quad (2)$$

ϵ is the product of the coincidence efficiency, the detection efficiency, and the solid angle of the Ge detector; α^H is the $K\alpha^H$ fraction of all the K^H-x rays and ω_K^H is the fluorescence yield for the K^H-x rays. In the derivation of these formulas it was assumed that the fluorescence yield ω_K^S of K^S-x rays (satellite K-x rays emitted by an atom that has initially one K and one L vacancy) and ω_K of diagram K-x rays are identical. The uncertainties in the numerical factors in formula (2) are due to the uncertainty in the intensities of the decay processes.

Before and after each measurement on ^{109}Pd or ^{109}Cd the instrumental constant ϵ has been determined by means of a ^{125}Te^m source ($t_{1/2} = 58d$). The tellurium activity was obtained from neutron bombardment of ^{124}Te (enrichment 96%) for 12 days at a neutron flux of 2.5×10^{14} cm^{-2} s^{-1}. The tellurium source was also sandwiched between Al foils, 0.3 mm thick, and placed between the detectors in a position identical to the one in which the ^{109}Pd or ^{109}Cd source was placed. ϵ was determined from the intensity of the Te $K\alpha$-x-ray coincidences $N_{c\alpha}$ ($E = 27.4$ keV), the Te $K\beta$-x-ray coincidences $N_{c\beta}$ ($E = 31.0$ keV), and the 35 keV γ-ray coincidences $N_{c\gamma}$. The applied formulas, derived from the decay scheme,[3] are for the $K\alpha$-x rays

$$\epsilon = 2.28\, N_{c\alpha}/N_{\mathrm{NaI}}, \quad (3)$$

for the $K\beta$-x rays

$$\epsilon = 10.1\, N_{c\beta}/N_{\mathrm{NaI}}, \quad (4)$$

and for the 35 keV γ rays

$$\epsilon = 39\, N_{c\gamma}/N_{\mathrm{NaI}}. \quad (5)$$

N_{NaI} is the sum of the number of Te K-x-ray counts and the number of 35 keV γ-ray counts in a gate set on the corresponding part of the spectrum recorded with the NaI(Tl) detector. The uncertainty in the coefficients in the formulas is 3% due to the uncertainty in the intensities of the transitions. In formulas (3) and (4) the fluorescence yield, $\omega_K = 0.875 \pm 0.028$ (Ref. 4), does also contribute to the uncertainty. However, this value has been obtained from a fit of a smooth curve to all available ω_K values, and ω_K for the Ag K-x rays is also obtained from this fit. As a consequence of this the latter ω_K value will have approximately the same systematic error as ω_K for Te K-x rays. Then, in applying formulas (1)–(4), the errors cancel. For this reason the error in ω_K is not taken into account. If we apply formula (5) the advantage of cancellation does not occur. Because of this and because of the poorer statistics ($N_{c\alpha} \simeq 17N_{c\gamma}$) we use ϵ as obtained from formula (5) only as a rough test of the independence of ϵ of the energy.

Before we apply ϵ as obtained from formulas (3) and (4) to formulas (1) and (2), some corrections have to be made. In order to take into account the difference in absorption in the Al foil between the Ag $K\alpha^H$-x rays (22.6 keV) and, respectively, the Te $K\alpha$-x rays ($E = 27.4$ keV) and $K\beta$-x rays ($E = 31.0$ keV) we applied corrections of, respectively, 11% and 14%. In the case of formula (5) the correction was 16%. Furthermore, corrections have been applied for the difference in detection efficiency of the radiation in the Ge detector. These corrections were 2%, 3%, and 4%, respectively.

The three values obtained from formulas (3)–(5) are in good agreement with each other. We find $\epsilon = (20.3 \pm 1.2) \times 10^{-3}$. The error is a standard deviation which takes into account the uncertainty in the coefficients in formulas (3) and (4) which amounts 3%, the uncertainty in the above-mentioned corrections (3%), the uncertainty due to the statistics and the positioning of the source between the detectors (3%) and the uncertainty due to a correction of (20 ± 3)% applied to N_{NaI} in formulas (3)–(5) in order to take into account summation effects in the NaI(Tl) crystal.

Calibrations have been performed with different tellurium sources, varying in strength from approximately 1 to 100 nCi, which corresponds to counting rates in the Ge and NaI(Tl) detector varying from, respectively, $\simeq 10$ to $\simeq 10^3$ s^{-1} and $\simeq 10^2$ to 10^4 s^{-1}. ϵ did not vary significantly within this range. The ^{109}Pd, ^{109}Cd, and ^{97}Ru (see below) sources used in the experiments were chosen to have counting rates in the center of the above-mentioned range.

In view of the problems with the intrinsic-Ge detector, mentioned in the Introduction, we also performed a calibration at an energy below the energy of the Ag $K\alpha^H$-x rays. We used a ^{97}Ru source ($t_{1/2} = 2.9d$). The activity was obtained by neutron bombardment of natural Ru for 3 days at a neutron flux of 2.5×10^{14} cm^{-2} s^{-1}. The source was also sandwiched between Al foils, 0.3 mm thick, and placed between the detectors in a position identical to the one of the other sources.

For the number of Tc $K\alpha$-x-ray coincidences ($E = 18.3$ keV) in the Ge detector we find from the decay scheme[5]

$$\epsilon = 24.0\, N_{c\alpha}/N_{\mathrm{NaI}} \qquad (6)$$

and for the number of Tc $K\beta$-x-ray coincidences ($E = 20.6$ keV) we find

$$\epsilon = 122 N_{c\beta}/N_{\mathrm{NaI}} \qquad (7)$$

in which N_{NaI} is the sum of the number of $K\alpha$-x-ray counts and $K\beta$-x-ray counts recorded with the NaI(Tl) detector. The uncertainty in the coefficients is about 5% due to the uncertainty in the intensities of the transitions. As in the case of ^{125}Te^{m} the uncertainty due to the fluorescence yield ($\omega_K = 0.779 \pm 0.032$) is left out of consideration. In order to find N_{NaI} a correction of 13% had to be applied for the Compton background under the K-x-ray photopeak, and a correction of ≈35% to subtract the Rh K-x-rays due to the decay of ^{103}Ru which is also present in the source. For summation effects in the NaI(Tl) crystal a correction of 10% was applied to N_{NaI}. To find N_c we had to subtract 39% of the intensity of the K-x-ray peaks in the coincidence spectrum to correct for the contribution due to coincidences with the Compton background under the K-x-ray photopeak in the NaI(Tl) spectrum. Before we can apply ϵ, as obtained from formulas (6) and (7), to formulas (1) or (2) we have to correct for the difference in absorption in the Al foil between the Ag $K\alpha^H$-x rays and the Tc $K\alpha$ and $K\beta$-x rays. The corrections are, respectively, 14% and 2.5%. For the difference in detection efficiency we applied corrections of, respectively, 2.5% and 1%. Owing to all these corrections we arrive at an accuracy of 10% in ϵ as obtained from ^{97}Ru. From the Tc $K\alpha$-x rays we find $\epsilon = (20.7 \pm 2.1) \times 10^{-3}$; from the Tc $K\beta$-x rays we find $\epsilon = (22.8 \pm 2.3) \times 10^{-3}$. These values are in good agreement with the above-mentioned value of $\epsilon = (20.3 \pm 1.2) \times 10^{-3}$ as obtained from ^{125}Te^{m}. The conclusion seems justified that ϵ is independent of the x-ray energy within the energy region of interest. Because of the better accuracy and the possibility of calibrations before and after each measurement on ^{109}Cd or ^{109}Pd as a consequence of the long lifetime, we used the ^{125}Te^{m} results for the calibrations.

Once $N_c/(\epsilon N_{\mathrm{NaI}})$ has been determined, we have to know $\alpha^H \omega_K^H$ in order to find P_{KK}(IC) [see formula (1)]. It has been pointed out by Åberg *et al.*[6] that in the case of low and intermediate Z the intensity ratio of the $K\alpha_1^H$ and the $K\alpha_2^H$-x-ray transition is considerably smaller than the ratio for the corresponding diagram lines. In the case of Ag the ratio is 1.30 for the hypersatellite lines[6] as against 1.89 for the diagram lines.[4] If we make the assumption that only the $K\alpha_1^H$-x-ray transition is suppressed we find $\alpha^H \omega_K^H = 0.63$ as against $\alpha\omega_K = 0.685$ for diagram lines.[4] No information is available on whether other transitions are suppressed or not. If some of them are we arrive at a higher value of $\alpha^H \omega_K^H$, probably somewhere in between 0.63 and 0.685. Therefore we used $\alpha^H \omega_K^H = 0.66 \pm 0.03$.

III. RESULTS

A. ^{109}Pd

On ^{109}Pd five measurements have been performed, each of which took five days. Per measurement we used five sources, i.e., one per day. The five sources were prepared in advance with increasing source strength to compensate for the decay. Before and after each measurement a calibration was performed by means of ^{125}Te^{m}. The measurements on ^{109}Pd have been performed alternately with measurements on ^{109}Cd and other isotopes. The measurements have been spread out over a period of a year. Figure 1(a) shows the coincidence spectrum of the Ag $K\alpha$-x-ray complex, recorded with the Ge detector in one of the measurements. The height of the subtracted background was 82 ± 4 counts per channel. The background is due to (1) external

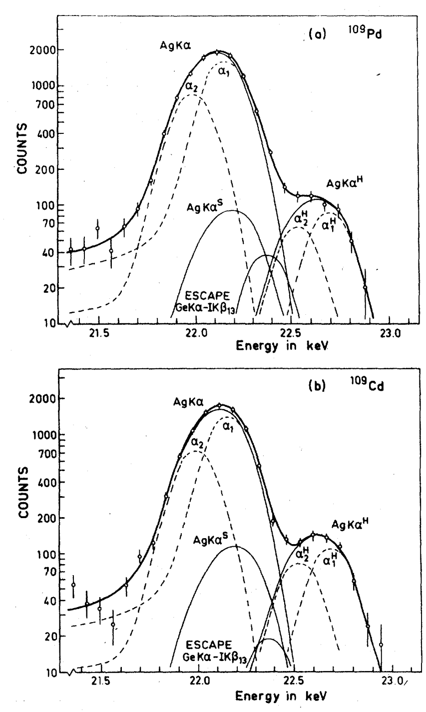

FIG. 1. Ge coincidence spectrum of the Ag $K\alpha$-x-ray region. (a) As obtained from ^{109}Pd and (b) as obtained from ^{109}Cd.

bremsstrahlung due to K-conversion electrons of the 88 keV transition, (2) internal Compton photons of the 88 keV transition, (3) β^- particles emitted in transitions in which shakeoff takes place from the K shell, and (4) β^- particles and γ rays from transitions in which levels are involved with an energy higher than 88 keV; these types of radiation are all coincident with Ag $K\alpha$-x rays detected in the NaI(Tl) detector.

If the above-mentioned types of radiation (1)–(4) are detected in the NaI(Tl) detector an Ag $K\alpha$-x-ray line shows up in the coincidence spectrum recorded with the Ge detector; 80% of the intensity of the diagram line in Fig. 1(a) is due to these coincidences. The remaining 20% is due to accidental coincidences which have not been subtracted.

The satellite Ag $K\alpha^S$ line in Fig. 1(a) is due to coincidences with Ag $K\alpha^H$-x rays detected in the NaI(Tl) crystal. The intensity of the $K\alpha^S$ line is 0.83 times the intensity of the $K\alpha^H$ line. This is the $K\alpha^S$-x-ray fraction of all the K^S-x rays. It has been assumed that this fraction is identical to that of diagram lines. For the energy shift we used 70 eV.[7] For simplicity we assumed that the satellite line due to coincidences with $K\beta^H$-x rays has the energy of the diagram line.

The escape peak in Fig. 1(a) arises from Ge $K\alpha$-x-ray escape when I $K\beta_{13}$-x-rays are detected, which themselves are due to escape from the NaI(Tl) crystal when 88 keV γ rays or β^- particles are detected. The intensity of the escape peak is obtained from the intensity of the I $K\beta_{13}$ line and the intensity ratio known from the $^{125}Te^m$ spectrum.

In the unfolding procedure we used the Ag $K\alpha$-x-ray line from the singles spectrum for the diagram and the satellite line. For the escape peak the shape of the I $K\beta_{13}$-x-ray line has been used. The hypersatellite line has been constructed by means of the $K\alpha_1$ and $K\alpha_2$-x-ray lines as obtained from the unfolding of the diagram line (assuming an intensity ration of 1.89). For the hypersatellite line we used the intensity ratio of 1.30, and we assumed that the energy shift is the same for the two components. In order to get an impression of the influence of the intensity ratio on the spectrum analysis we also did an analysis in which we used the diagram-line shape for the $K\alpha^H$ line. In the latter case the obtained intensity of the $K\alpha^H$ line was only ~2.5% higher. In consequence we judged the inaccuracy in the intensity of the $K\alpha^H$ line due to the inaccuracy in the intensity ratio negligibly small. The measured energy difference $E(K\alpha_1^H) - E(K\alpha_1)$ was about 12 eV lower.

The results of the five measurements are in excellent agreement: $N_c/(\epsilon N_{NaI}) = (8.6 \pm 0.7) \times 10^{-5}$, $(8.7 \pm 0.7) \times 10^{-5}$, $(9.5 \pm 0.8) \times 10^{-5}$, $(8.2 \pm 0.7) \times 10^{-5}$, and $(8.1 \pm 0.6) \times 10^{-5}$. The errors are standard deviations due to counting statistics. The average value is given in Table I. Using formula (1) with $\alpha^H \omega_K^H = 0.66 \pm 0.03$, and including an inaccuracy of 5% due to the calibration by means of $^{125}Te^m$, we find the value of P_{KK}(IC) presented in Table I. The energy differences are in good agreement as well: $E(K\alpha_1^H) - E(K\alpha_1) = 515 \pm 25$, 515 ± 25, 551 ± 25, 519 ± 25, and 554 ± 25 eV, respectively. The average value is also presented in Table I.

B. ^{109}Cd

The measurements on ^{109}Cd have been performed on sources of different strength and for different periods of time. Figure 1(b) shows the coincidence spectrum of the Ag $K\alpha$-x-ray complex of one of the measurements. The height of the subtracted background was 46 ± 2 counts per channel. This background is due to the radiations (1) and (2) mentioned in the explanation of the background in the case of ^{109}Pd. The diagram line in Fig. 1(b) is for 45% due to the nonsubtracted accidental coincidences. The remaining 55% is due to coincidences with the above-mentioned radiations (1) and (2) detected in the NaI(Tl) crystal. In the case of ^{109}Cd the escape peak is somewhat lower than in the case of ^{109}Pd; in the latter case the I escape lines are for a large fraction due to β^- particles. The spectrum analysis has been performed in the same way as described for ^{109}Pd.

We give the average results of the measurements performed in five periods following the five measurements on ^{109}Pd. The results are in good agreement (measuring time in parentheses): $N_c/(\epsilon N_{NaI}) = (3.46 \pm 0.20) \times 10^{-5}(13d)$, $(3.37 \pm 0.12) \times 10^{-5}(30d)$, $(3.37 \pm 0.12) \times 10^{-5}(45d)$, $(3.34 \pm 0.13) \times 10^{-5}(22d)$, and $(3.33 \pm 0.22) \times 10^{-5}(10d)$. The average value is presented in Table I. The energy shifts are $E(K\alpha_1^H) - E(K\alpha_1) = 530 \pm 18$, 524 ± 12, 535 ± 10, 536 ± 12, and 538 ± 18 eV, respectively. The average value is presented in Table I as well.

In order to obtain P_{KK}(EC) we rewrite formula (2) and find by means of formula (1):

$$P_{KK}(\text{EC}) = \frac{[N_c/(\epsilon N_{NaI})]_{Cd} - (0.34 \mp 0.01)[N_c/(\epsilon N_{NaI})]_{Pd}}{(0.66 \pm 0.01)\alpha^H \omega_K^H} . \quad (8)$$

From the values in the second column in Table I and $\alpha^H \omega_K^H = 0.66 \pm 0.03$ we find the value of P_{KK}(EC) presented in the fourth column in Table I.

IV. DISCUSSION

A. P_{KK}(IC)

In Table II we compare the present experimental value of P_{KK}(IC) with the theoretical probabilities

TABLE I. Experimental results.

	$\frac{N_c}{\epsilon N_{\mathrm{NaI}}} \times 10^5$	$P_{KK}(\mathrm{IC}) \times 10^5$	$P_{KK}(\mathrm{EC}) \times 10^5$	$E(K\alpha_1{}^H) - E(K\alpha_1)$ (eV)
^{109}Pd	8.6 ± 0.4	13.0 ± 1.1		531 ± 12
^{109}Cd	3.37 ± 0.07		1.02 ± 0.36	532 ± 6

of double K-shell vacancy creation by different processes: shakeoff (SO), direct collision (DC), double internal conversion (DIC), and internal conversion of internal Compton effect (ICIC).

A review of the shaking process during various nuclear events has been given by Freedman.[8] In the case of internal conversion, calculations of the shakeoff probability $P_{KK}(\mathrm{SO})$ have been performed by Mukoyama and Shimizu.[9] They used a one- and two-step relativistic overlap theory. Theoretical values for the shakeup probability are not available. Calculations on electron capture decay show that there the contribution of shakeup is considerable.[10] Consequently, a significant contribution of shakeup in internal conversion cannot be excluded *a priori*.

For internal conversion the direct-collision process has not been treated theoretically. In the case of β^- decay Feinberg[11] estimated the relative probability of direct collision and shakeoff to be equal to the ratio of the K binding energy and the decay energy. Application of Feinberg's estimate to internal conversion gives only a rough order of magnitude. From $P_{KK}(\mathrm{SO}) = 0.9 \times 10^{-5}$ we find $P_{KK}(\mathrm{DC}) \simeq 0.4 \times 10^{-5}$ and from $P_{KK}(\mathrm{SO}) = 7.4 \times 10^{-5}$ we obtain $P_{KK}(\mathrm{DC}) \simeq 3 \times 10^{-5}$.

Nagy *et al.*[12] evaluated Eichler's theory of double internal conversion[13] for the case of $^{109}\mathrm{Ag}^m$. The result is $P_{KK}(\mathrm{DIC}) \leqslant 1.7 \times 10^{-5}$.

Internal conversion of internal Compton effect has been treated theoretically by Listengarten.[14] Evaluation by Nagy *et al.*[12] for $^{109}\mathrm{Ag}^m$ results in a probability of $P_{KK}(\mathrm{ICIC}) = 47 \times 10^{-5}$, i.e., a value which is precluded by the experimental result.

The questions of whether the calculations using the one-step theory do predict the experimental shaking probability correctly and whether the two-step calculations can constitute an adequate approximation cannot be answered as long as the ICIC theory has not been revised.

B. P_{KK}(EC)

As expected, the present result of the experiment on ^{109}Cd, $N_c/(\epsilon N_{\mathrm{NaI}}) = (3.37 \pm 0.07) \times 10^{-5}$, is considerably higher than the value we reported before.[1] The value of the energy shift of the $K\alpha_1^H$ line is in excellent agreement with the value obtained from the experiment on ^{109}Pd (see Table I) and with the value of 532 ± 12 eV reported previously.[1] The average is $E(K\alpha_1^H) - E(K\alpha_1) = 532 \pm 6$ eV. The assignment of a smaller error would be incorrect since a systematic error due to (1) the inaccuracy in the ratio $K\alpha_1^H/K\alpha_2^H$ and (2) the assumption in the spectrum analysis that the energy shift of the $K\alpha_1^H$ and the $K\alpha_2^H$ line is the same (the actual difference is about 8 eV[15]) starts to contribute significantly. The present result is in agreement with the value of about 540 eV, expected on the basis of our results on $^{114}\mathrm{In}^m$.[15]

Comparison of $N_c/(\epsilon N_{\mathrm{NaI}})$ with the corresponding value obtained from the data of Nagy *et al.*,[12] $N_c/(\epsilon N_{\mathrm{NaI}}) = (3.43 \pm 0.54) \times 10^{-5}$, shows good agreement. This good agreement is somewhat unexpected considering the value of 373 ± 75 eV which Nagy *et al.* reported for the energy shift of the

TABLE II. Comparison of the present experimental value of P_{KK}(IC) with theory ($P_{KK} \times 10^5$).

Experimental P_{KK}(IC)	P_{KK}(SO) [b] one step	P_{KK}(SO) [b] two step	Theoretical [a] P_{KK}(DC) [c]	P_{KK}(DIC) [d]	P_{KK}(ICIC) [e]
13.0 ± 1.1	0.92	7.4	$\simeq 0.4/3$	$\leqslant 1.7$	47

[a] SO, DC, DIC, and ICIC refer to shakeoff, direct collision, double internal conversion, and internal conversion of internal Compton effect, respectively.
[b] Reference 9.
[c] Reference 11.
[d] Reference 13.
[e] Reference 14.

TABLE III. Comparison of the present experimental value of P_{KK}(EC) with theory ($P_{KK} \times 10^5$).

Experimental P_{KK}(EC)	P_{KK}(SO + SU) [b]	Theoretical [a] P_{KK}(SO) [c]	P_{KK}(SO) [d]
1.02 ± 0.36	3.47	1.2	1.4

[a] SO and SU refer to shakeoff and shakeup, respectively.
[b] Reference 9.
[c] Reference 10.
[d] Reference 17.

$K\alpha^H$ line.

Before comparing P_{KK}(EC) with theory we make a few remarks on the experimental method. As can be seen from formula (8), P_{KK}(EC) is very sensitive to a systematic error in only one of the two $N_c/(\epsilon N_{NaI})$ terms. For example, an increase of $[N_c/(\epsilon N_{NaI})]_{Cd}$ with 10% results in an increase of P_{KK}(EC) to 1.80×10^{-5}. If, on the contrary, systematic errors of the same magnitude occur in both terms in formula (8) the influence on P_{KK}(EC) is small. A 10% increase in both terms results in an increase of P_{KK}(EC) with only 0.11×10^{-5} to 1.13×10^{-5}. We have attempted to make systematic errors, if present, equal in both terms by performing the measurements alternately, and applying identical procedures in the data handling.

In Table III we compare the present P_{KK}(EC) value with theory. A review of the shaking process in electron capture has been given by Bambynek *et al.*[16] The value in the second column in Table III is the only one calculated directly.[9] This value takes into account both shakeoff (SO) and shakeup (SU). The other two theoretical values have been obtained from an interpolation of predictions for other isotopes.[10,17] These values take into account shakeoff only. The difference between the values in columns two and three gives the shakeup probability.

Good agreement does exist between the experimental value and the predictions in columns three and four. The value in the second column seems definitely to be too high. It is not possible to decide on whether this discrepancy is due to an overestimation of shakeup alone, or to an overestimation of shakeup as well as shakeoff. In the latter case the agreement between experiment and the theoretical values in columns three and four is only accidental.

Discrepancies between the theory of Mukoyama *et al.*[10] and experiment have been observed in experiments on other isotopes as well.[18,19] However, these discrepancies are not as strong as in the present case. It may be that we do observe here that the shaking probability is relatively lower near threshold. In the case of ^{109}Cd the ratio of the transition energy and the energy required to produce two K-shell vacancies is approximately 2, versus approximately 3.5 or more for the other isotopes studied so far.

In view of the above-mentioned sensitivity of the present result to systematic errors, more experimental evidence is required on shaking near threshold in EC, in order to establish whether the observed strong discrepancy is real.

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