K-Conversion Coefficients of Transitions in In^{114} and Cd^{114}

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The K-conversion coefficients of the 192 keV isomeric transition in In^{114} and the 556 and 722 keV transitions in Cd^{114} have been measured for the first time by means of a high resolution double focusing β-ray spectrometer, using the internal-external conversion method. The results obtained are:

$$\alpha_K\,(192\text{ keV}-In^{114}) = 2.3653 \pm 0.3075\,,$$

in excellent agreement with the theoretical value 2.4638 for pure E4 transition calculated by Sliv and Band, and

$$\alpha_K\,(556\text{ keV}-Cd^{114}) = 0.00419 \pm 0.00046\,,$$
$$\alpha_K\,(722\text{ keV}-Cd^{114}) = 0.00207 \pm 0.00025\,,$$

both results in excellent agreement with the theoretical values for pure electric quadrupole radiation 0.00432 and 0.00218 respectively computed by Sliv and Band. These data confirm the essentially pure E4 character of the $5+ \rightarrow 1+$, 192 keV transition in In^{114} and the pure E2 character of the $4+ \rightarrow 2+$, 722 keV and $2+ \rightarrow 0+$, 556 keV transitions in Cd^{114}. The conversion coefficient measurements reported here in Cd^{114} and In^{114} ($Z=48$ and 49) and in earlier studies ($Z=22-28$ and 56) indicate that E2-conversion coefficients in the Z region below 60 are in good agreement with theory.

According to McGowan and Stelson [1] several E2-conversion coefficients of transitions between lowest $2+$ states and $0+$ ground states in even rare earth nuclei are rather larger than theoretical values. The energies of these transitions are often lower than 100 keV. The experimental errors in the reported values are considerable. Certain deviations from theory have also been reported [2] for E2-conversion coefficients of $2+ \rightarrow 0+$ transitions in isotopes with mass numbers around 200 where the energies of interest are in the region $300 \rightarrow 400$ keV. These discrepancies prompted a careful systematic study of E2 conversion coefficients as a function of Z to search for possible nuclear structure effects. The results on E2 K-internal conversion coefficients reported by Hamilton et al. [3] have indicated good agreement between experimental and theoretical values in the low Z region, $(22-28)$, agreement within about 5% for Z about 80; and disagreements up to 20% both higher and lower than theory in the deformed nuclear region [4, 5]. In Gd^{152} just outside the deformed nuclear region, there is evidence that the experimental α_K values are $5-10\%$ lower than theory [3, 6]. In Ba^{134}, α_K and α_L of the $2+ \rightarrow 0+$ E2 transitions were found to agree with theory [6]. The work reported on here is the completion of studies in the intermediate Z region in In^{114} and Cd^{114} from the decay of In^{114m}.

1. In^{114m} Decay Scheme

The nuclide In^{114} has a 50-day isomeric state 192 keV above its 72-sec ground state, see Fig. 1. The latter decays by an allowed β^- transition ($\log ft = 4.44$) to the ground state of Sn^{114} ($I=0+$). On this basis an angular momentum quantum number of $I=1$ and even parity has been assigned to the In^{114} ground state. The isomeric transition from the 50-day state to the 72-sec state is an E4 transition (concluded from K/L conversion ratios) and therefore, an angular momentum of 5 (even parity) was suggested for the 50-day state [7]. This angular

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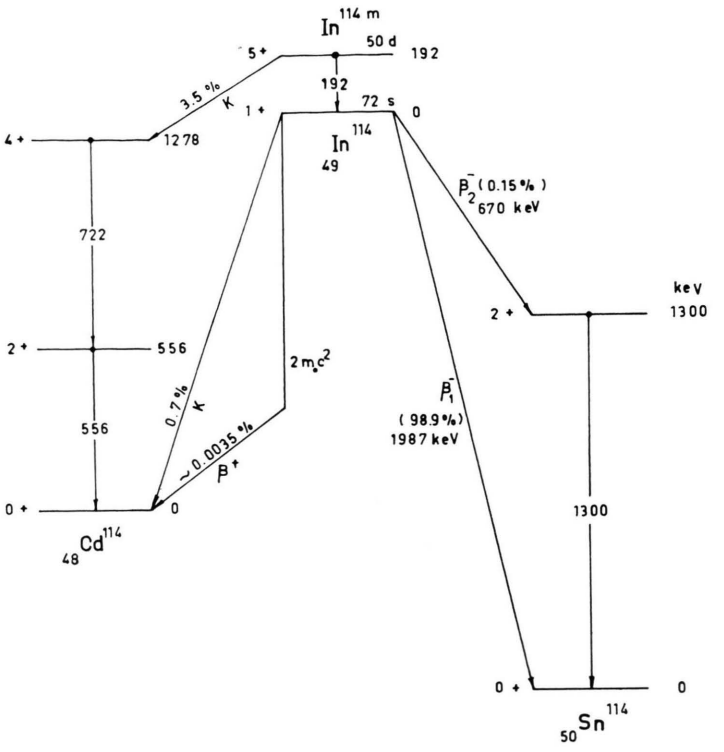

Fig. 1. In^{114m} decay scheme.

momentum assignment has been confirmed by a direct measurement using the atomic beam magnetic resonance method [8]. The 72-sec ground state decays by β^+ emission and K capture to the ground state of Cd^{114} and was also assumed to decay by K capture to the second 1.28 MeV excited state of cadmium-114 [9, 10]. Hence an angular momentum quantum number of 1 or 2 was indicated for this state. An angular momentum assignment of 0 was ruled out on the basis of the interpretation of a weak 1.28 MeV γ ray as a direct transition from this state to the $I=0$ ground state of Cd^{114}. The ft value (log $ft=3.4$) of the K transition from the 72-sec ground state to the second excited Cd^{114} level indicated a superallowed transition, which appeared to be very unlikely in this case. It was thus hypothesized [7] that this K decay originates from the 50-day isomeric state of In^{114}, requiring an angular momentum quantum number of 4 or 5 for the second excited state of Cd^{114}.

A 0.722 MeV − 0.556 MeV γ-γ cascade was known to proceed from this second excited state [9, 11] and the γ-γ directional correlation was measured in an attempt to find the angular momentum of the second excited state of Cd^{114}. With this information the In^{114} state from which the K decay originates could be determined. The first directional correlation experiments [7] were consistent with an angular momentum assignment of 4, 2, 0 to the second excited, first excited and ground states respectively, and thus indicated that the K decay indeed originated from the 50-day In^{114} state with $I=5$ rather than from the 72-sec ground state with $I=1$. The ft value of this K decay was characteristic of a first forbidden transition, and therefore an assignment of odd parity to the second excited state of Cd^{114} was made. These assignments, however, caused a serious discrepancy between the expected and the observed intensity of the 1.28 MeV-γ radiation, if the interpretation of this radiation as a cross-over transition was to be maintained.

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In view of this difficulty several groups performed additional directional correlation experiments [12, 13]. All of these measurements seemed to suggest an angular momentum assignment of 2-2-0 with the assumption of a mixed 96% dipole − 4% quadrupole γ transition from the second excited state. This assignment was consistent with the intensity of the cross-over transition and strongly favored the conclusion that the electron capture takes place in the 72-sec ground state of In^{114}. Apparent discrepancies between the experimental and the theoretical 2-2-0 directional correlation function were attributed to the effects of competing cascades whose existence was reported by JOHNS et al. [13, 14], but which did not reappear in other measurements performed in the same laboratory [15].

Polarization directional correlation measurements, however, furnished decisive evidence for the (4+) (2+) (0+) assignments [16]. BRAZOS and STEFFEN [17] remeasured the directional correlation of the 0.722 MeV − 0.556 MeV cascade with the use of differential pulse height selection in order to eliminate the effect of possible competing cascades. Their results agreed very well with the 4-2-0 spin assignments, and moreover, did not support the findings of DAUBIN and HAMILTON [18] that there existed a strong extranuclear influence on this γ-γ cascade.

Confirmation of these angular momentum assignments was furnished by experiments [19, 20] on the 72-sec In^{114} ground state which revealed that no excited state of Cd^{114} is involved in the 72-sec K capture decay. The apparent discrepancy in the intensity of the cross-over transition was resolved by GRODZINS and MOTZ [19] whose coincidence experiments revealed that the high-energy γ transition, which was formerly interpreted as due to the cross-over, is emitted by an excited state of Sn^{114} following a low intensity β^- transition from the 72-sec In^{114}. These conclusions were also arrived at independently by JOHNS et al. [15].

In order to determine the parities of the Cd^{114} levels and, possibly, to give further support to the 4-2-0 assignment, the K-conversion coefficients of the 556 keV and 722 keV transitions have been measured absolutely for the first time by the internal-external conversion method, using an iron-yoke double focusing β-ray spectrometer. Also the same technique was used to measure, for the first time, the K-conversion coefficient of the 192 keV transition de-exciting the 192 keV isomeric state in In^{114} which decays with a 50-day half-life. The internal-external conversion method has been developed [21] since 1959 for the measurements of absolute values of internal conversion coefficients. The method is attractive because of simple experimental technique and general applicability, regardless of the complexity of the particular decay.

2. Experimental Procedures

The measurements were performed by a 22.5 cm radius, iron-yoke, double-focusing β-ray spectrometer *. The detector employed in the present studies was a GEIGER–MÜLLER counter with a 2.1 mg /cm² mica end-window. A uranium converter 3 mg /cm² (5×30 mm²) was used. The converter foil was obtained from the same supply [22] that was prepared in Stockholm for similar studies.

2.1. Internal conversion coefficients

The internal-external conversion method was used and is described elsewhere [21]. The K-shell internal conversion coefficient denoted by α_K is found from:

$$\alpha_K = \frac{(A_{in})_K}{(A_{ex})_K} \tau_K f_K S d b c$$

where $(A_{in})_K$ is the intensity of the K-internal conversion line, $(A_{ex})_K$ the intensity of the external

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* β-ray spectrometer type БПП-2 (Moscow, 1957).
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photoelectric conversion line from the K shell of the converter, τ_K the photoelectric cross section for the K shell, f_K the correction which accounts for the anisotropical distribution of the photoelectrons emitted from the K shell, S the ratio of the external and internal sources strength, d the thickness of the converter in mg/cm^2, b a dimension factor (2.531×10^{-6} atoms $\times$ cm^2/barns $\times$ mg for uranium), and finally c is a correction factor to account for differences in transmission of the spectrometer for the external and internal conversion sources.

HULTBERG [21b] has developed the procedure of calculating the f-factors from the measured angular distributions for various source geometries. For a rectangular source and converter, which is the most useful geometry for measurements with a magnetic spectrometer of a double focusing type, the following expression is obtained,

$$f = \frac{2/\pi \int_0^{\Theta_2} J(\Theta+\Delta)\ \mathrm{tg}\,\Theta \left[\arcsin \frac{\mathrm{tg}\,\Theta_0}{\mathrm{tg}\,\Theta} - \arccos \frac{\mathrm{tg}\,\Theta_0}{\mathrm{tg}\,\Theta}\right] \exp\left(\frac{-\mu g}{\cos\Theta}\right) \mathrm{d}\Theta}{\int_0^{\pi} J(\Theta) \sin\Theta\, \mathrm{d}\Theta}$$

where J is the appropriate photoelectric angular distribution function. For definition of the various angular symbols the reader is referred to ref. [21b]. f may be calculated for each energy and shell for which angular distributions are known. The denominator of f is an integral over the angles used in the experiment and is a function of the given experimental set-up (i. e. source to converter distance, source and converter sizes, etc.).

A computation of the f-factors, for 13 γ energies from 159 to 5000 keV according to the geometry used in the present measurements, has been worked out by HULTBERG ** as a programme on the electronic computer BESK at Stockholm. The photoelectric cross section τ_K was taken from the calculations by HULTBERG et al. [23]. They are corrected to any order in α_z but neglect the effect of screening. The correction for the latter effect is rather small for the K shell and can partially be corrected for. The uncertainties in τ_K and f_K are taken to be 6% and 5% respectively, in accordance with refs. [21, 24].

2.2. *Source preparation*

The In^{114m} target was produced by thermal neutron bombardment of spectroscopically pure (99.99%) indium metal with 49.8% In^{113} in the UAR reactor at Inchass. The neutron flux was about 10^{13} neutrons/cm^2 ·sec for the internal-conversion studies, indium metal was uniformally sputtered on aluminium foil of thickness about 1 mg/cm^2. The sputtered material was distributed in a rectangular form of dimensions 0.2×2 cm^2. The thickness of the material deposited was estimated to be 100 μg/cm^2.

For the external-conversion measurements, rectangular indium sources were used with dimensions 4 mm width by 29 mm length and thickness 0.12 mm. In the measurements the sources were embeded between β-absorbing copper sheets with a wall thickness of 1 mm. The resulting "sandwich" was then mounted closely behind the uranium converter. The measurements were started after 5 days from the end of the irradiation to avoid completely any contributions from the decay of In^{114} ($T_{1/2} = 1.2$ min), In^{116m} ($T_{1/2} = 53.99$ min) and In^{116} ($T_{1/2} = 13$ sec) produced from (n,γ) reaction.

2.3. *Measurements*

The internal-external conversion method for the experimental determination of internal conversion coefficients is based on a straightforward measurement of the rates of emission of internal conversion electrons and γ rays belonging to the same transition. The ratio of these rates defines the internal conversion coefficient.

The K photoelectrons were measured for the 192 keV transition in In^{114} and the 556 and 722 keV transitions in Cd^{114} to determine their γ intensities. Each conversion line was measured several times. The data were recorded over a sufficiently large energy range around the conversion lines in order to determine accurately the background under the peaks. Examples of the K-photoconversion lines of the 192, 556 and 722 keV-γ rays are shown in the lower parts of Figs. 2 – 4.

** We express our sincere gratitude to Dr. S. HULTBERG for making his programme available for us.

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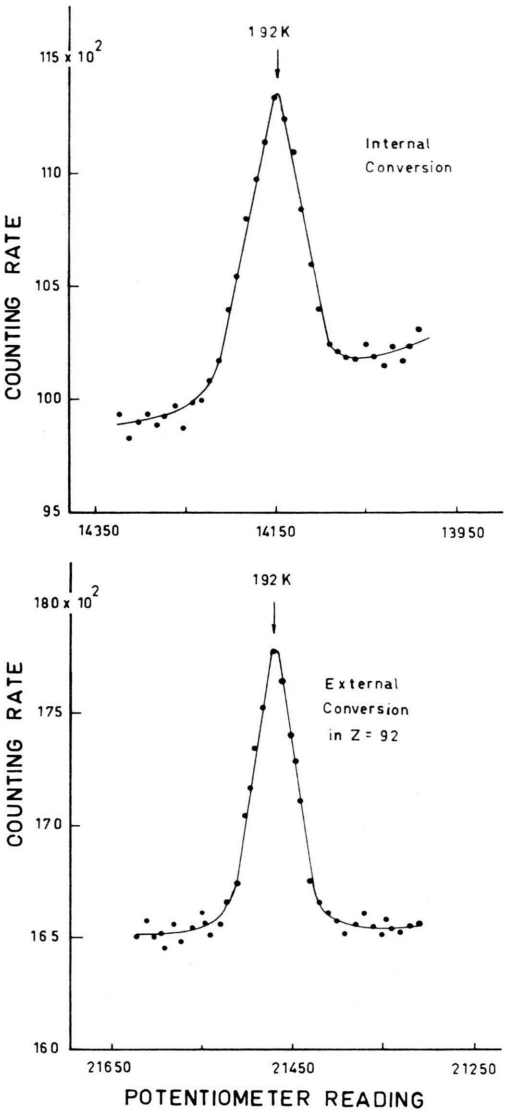

Fig. 2. K-internal conversion line and K-external conversion line, from uranium, of the 192 keV transition in In^{114}.

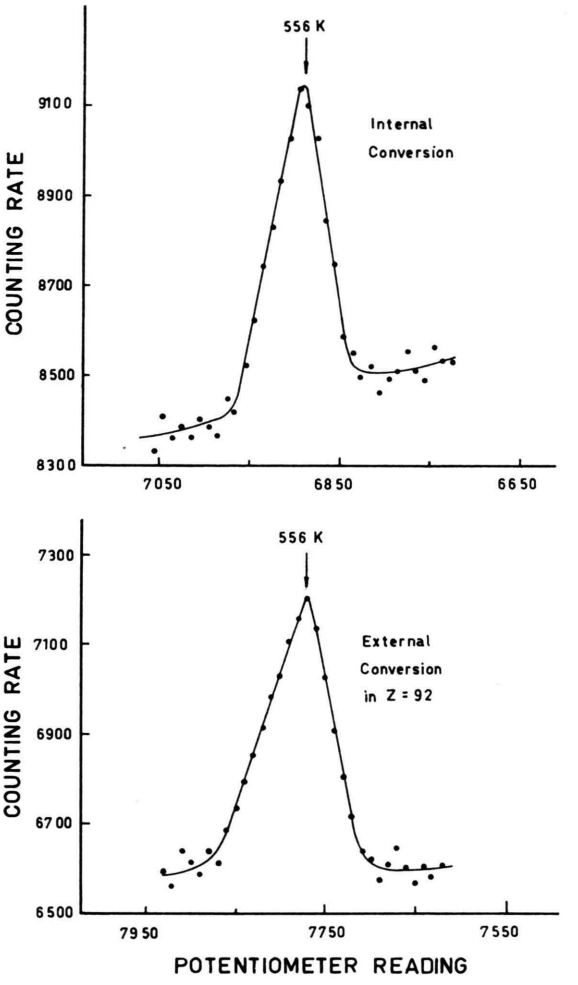

Fig. 3. K-internal conversion line and K-external conversion line, from uranium, of the 556 keV transition in Cd^{114}.

The emission of photoelectrons from the converter is not isotropic, and in order to reduce scattering effects the external conversion process must then take place in very thin layers of material. The photon intensity from a converter of uniform density is proportional to the total cross section τ_x (for the particular atomic shell and transition energy) and to a factor f, which depends on the character of the appropriate photoelectric angular distribution and on the details of the experimental arrangement of the γ-ray source and the photoelectric converter inside the spectrometer. According to HULTBERG [21b], the intensity of a γ ray can be expressed as:

$$I_\gamma = C \frac{A_\gamma}{f \tau},$$

where C is a constant depending on the converter thickness, source strength and the instrumental transmission factor and A_γ the measured intensity of a photoline taken as the area under the photo-conversion peak after normalizing to the unit momentum interval.

The K-shell internal conversion line of the 192 keV transition in In^{114} as well as the K-shell internal conversion lines of the 556 and 722 keV transitions in Cd^{114} were measured, as given in the upper parts of Figs. 2 – 4. Each conversion line was measured several times. The intensities of the electron lines

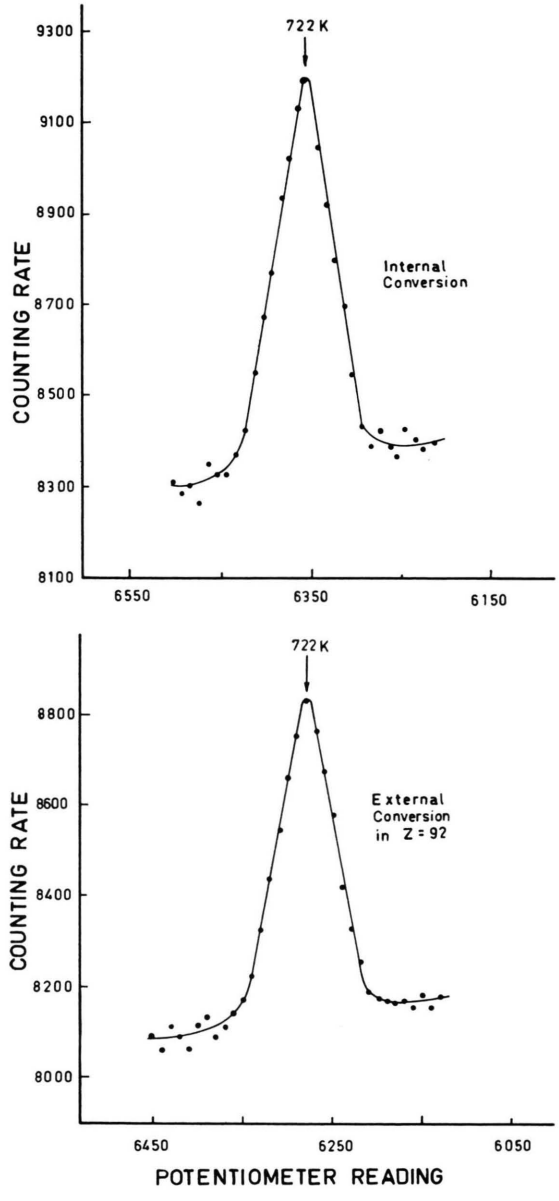

Fig. 4. K-internal conversion line and K-external conversion line, from uranium, of the 722 keV transition in Cd^{114}.

were determined by integrating the areas of peaks on an N/p versus p plot (p is the momentum). The standard error of these intensities is believed to be $\cong 4$ percent for the intense lines and more than 10 percent for the weaker lines. The conversion electron intensity results were corrected for the absorption in the mica counter window. The internal and external conversion line areas for each transition were averaged and the ratio A_{in}/A_{ex} of the averages was formed. Since both sets of intensities were obtained by means of the same instrument, some kinds of systematic error tend to vanish when a ratio is taken. The data were also decay corrected. The largest uncertainty in these measurements is in the determination of the areas of the K-external conversion line. An uncertainty of about 12 percent was estimated for the weakest line.

3. Results and Discussion

The results obtained for the K-internal conversion coefficients of the 192 keV transition in In^{114} and the 556 and 722 keV transitions in Cd^{114} by the internal-external conversion method are:

$$\alpha_K(192) = 2.3653 \pm 0.3075 ,$$
$$\alpha_K(556) = 0.00419 \pm 0.00046 ,$$
$$\alpha_K(722) = 0.00207 \pm 0.00025 .$$

The results are given in Table 1 together with the theoretical values calculated by Sliv and Band [25]. It is shown that the 192 keV transition in In^{114} has a pure E4 character, while both the 556 and 722 keV transitions in Cd^{114} have pure electric quadrupole character.

Nucleus	Transition energy in keV	Theoretical K-internal conversion coefficients as computed by Sliv and Band [25]								Experimental K-internal conversion coefficient α_K	Multipolarity
		E1	E2	E3	E4	M1	M2	M3	M4		
In^{114}	192	0.02409	0.12735	0.57280	2.46380	0.07396	0.43251	2.20290	12.727	2.3653 ± 0.3075	E4
Cd^{114}	556	0.00147	0.00432	0.01127	0.02864	0.00452	0.01396	0.03767	0.21184	0.00419 ± 0.00046	E2
	722	0.00082	0.00218	0.00507	0.01143	0.00244	0.00668	0.01596	0.07798	0.00207 ± 0.00025	E2

Table 1. Theoretical and experimental K-internal conversion coefficients of the 192 keV transition in In^{114} and the 556 and 722 keV transitions in Cd^{114}.

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Author	Experimental K/L ratio	Theoretical K/L ratio [25]		Multipolarity of 192 keV transition
		value	multipolarity	
Lawson et al. [26]	1.0 ± 0.1	8.8242	E1	E4
Boehm et al. [9]	1.1 ± 0.1	6.3367	E2	
Shipinel et al. [27]	1.16	3.1262	E3	
Steffen [28]	1.10 ± 0.05	1.4983 [34a]	E4	
Kelly [29]	1.30 ± 0.05	8.6573	M1	
Graves et al. [30]	1.18	7.2011	M2	
Kelman et al. [31]	1.32 ± 0.02	5.3498	M3	
Grabowski et al. [32]	1.16 ± 0.05	4.2592	M4	
Daniel et al. [33]	1.25 ± 0.03			

Table 2. Deduction of the multipolarity of the 192 keV transition in In^{114} from K/L ratios. Theoretical K/L ratio for various possible multipolarities are given.

3.1. The 192 keV transition in In^{114}

This transition is the de-excitation of the 192 keV isomeric state which decays with a 50-days half-life. Previous measurements of the K/L ratio confirmed that this transition is of E4 character, see Table 2. The $K/(L+M+N)$ conversion ratio of this isomeric transition was measured by Daniel and Panussi [35] to be 1.00 ± 0.02, and by Daniel and Lührs [33] to be 0.99 ± 0.03 in agreement with the theoretical value $K/(L+M+N) = 0.8$ for E4 character calculated by Rose [34b] and using the measured conversion ratio $M/N = 4.6 \pm 0.2$ by Kelman et al. [31]. Our value for $\alpha_K(192) = 2.3653 \pm 0.3075$, gives a definite evidence for E4 character for this transition. Grabowski et al. [32] showed experimentally that the 192 keV isomeric state in In^{114} might alternatively decay by two-quantum emission since it may proceed by enhanced E2 transitions. Considering that the 192 keV E4 transition is strongly retarded, their results showed [32] that the relative probability for two-quantum decay is less than 3×10^{-5}, a value which is lower by one order of magnitude than the conservative theoretical estimate and 3000 times lower than the estimate obtained assuming reasonable enhanced E2 transition probabilities.

3.2. The 556 and 722 keV transitions in Cd^{114}

The 722 keV and 556 keV-γ radiations originate [17] mainly from the 50-day isomeric state of In^{114} and the second excited state of Cd^{114}. The measured values of $\alpha_K(556) = 0.00419 \pm 0.00046$ and $\alpha_K(722) = 0.00207 \pm 0.00025$ agree perfectly with the theoretical values 0.00432 and 0.00218 respectively, for E2 character as computed by Sliv and Band [25]. Since the ground state of Cd^{114} has spin and parity $0+$, as is the case for even-even nuclei, then the spin and parity of the 556 keV first ecxited state are $2+$ and those of the 1278 keV second excited state are $4+$. Our results derived from internal conversion measurement support previous conclusions obtained by Brazos et al. [16] from the directional correlation and the polarization directional correlation experiments that all three states involved in the Cd^{114} cascade have the same parity, and furthermore, strongly favour the $(4^+) - E2 \rightarrow (2^+) - E2 \rightarrow (0^+)$ assignment. The possible assignment $2 - M1 + E2 \rightarrow 2 - M2 \rightarrow 0$ proposed [17] from polarization directional correlation was excluded on the basis of life time considerations, since the life time of the first excited Cd^{114} state,

$$\tau_N \leqq 2.3 \times 10^{-10} \text{ sec } [36],$$

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is too short to be compatible with an M2 transition [37] by several orders of magnitude. The conversion coefficients measurements reported here in Cd^{114} and In^{114} ($Z=48$ and 49) and in earlier results by FREY et al. [38], HAMILTON et al. [3, 39–41] and LU et al. [6] for $Z=22-28$ and 56 indicate that E2-conversion coefficients in the Z region below 60 are in good agreement with theory.

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Messung der Druckverbreiterung von Linien der 2. Lyman-Serie des Heliumions

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In einer gepulsten Kapillarentladung wird ein Heliumplasma hoher Elekronendichte ($n_e=2$ bis $4\cdot10^{18}$ cm^{-3}) und Temperatur ($T=50\,000-55\,000$ °K) erzeugt. Die Plasmadaten werden aus Messungen der Linienbreite sowie des Intensitätsverhältnisses Linie/Kontinuum der He II-Linie 4686 Å bestimmt. Mit Hilfe dieser Daten werden aus den gemessenen Profilen die normierten Profile der im Vakuumultravioletten liegenden He II-Linien bei $\lambda=1640$, 1215 und 1085 Å ermittelt. Wegen der guten Reproduzierbarkeit und der hohen Dichte des emittierenden Plasmas eignet sich die Lichtquelle als Strahlungsnormal bei 1640 Å.

Die Elektronendichte in einem Plasma kann aus den Profilen von Spektrallinien, deren STARK-Verbreiterungsparameter bekannt sind, einfach und schnell bestimmt werden. Bei Plasmen hoher Elektronendichte sind solche Messungen meist nur im vakuum-ultravioletten Spektralbereich möglich, weil die Linien im langwelligeren Teil des Spektrums nicht mehr aus dem Kontinuum herausragen. Da Helium ein oft benutztes Indikatorgas ist, wurden die bisher unbekannten Profile der drei ersten Linien der 2. LYMAN-Serie des Heliumions, die zwischen 900 und 1700 Å liegen, experimentell bestimmt.

Dazu war es notwendig, eine Lichtquelle zu entwickeln, die sehr reproduzierbar ein heißes Helium-Plasma großer Dichte erzeugte und die mit hoher Wiederholfrequenz betrieben werden konnte.

Lichtquelle und Meßmethode

Das als Lichtquelle dienende Plasma wurde in einer Kapillarlampe (Abb. 1) durch einen Rechteckimpuls von 8,5 kAmp Stromstärke und 2,5 μs Dauer erzeugt. Die Schaltung des als Stromquelle benutzten Kettenleiters zeigt Abb. 2. Bei dem verwendeten Fülldruck von120 Torr Helium war der Widerstand der Entladung so hoch, daß 80% der gespeicherten Energie dem Entladungsplasma in Form von JOULEscher Wärme zugeführt wurde. Die Kapillare von 3 mm Innendurchmesser und 125 mm Länge bestand aus gesintertem Aluminiumoxid (Degussit Al 23), ihr Ende befand sich 115 mm vor dem Eintrittsspalt eines Seya-Namioka-Vakuummonochromators ($f=1$ m, Gitter mit 1200 Strichen/mm). Zwischen Lampe und Spalt befand sich ein 0,2 mm dickes LiF-Fenster (Fa. E. Leitz, Wetzlar), das unerwünschte Strahlung aus Wellenlängenbereichen unterhalb 1040 Å ausfilterte. Photographisch aufgenommene Spektren der Entladung zeigten nur wenige Verunreinigungs-Linien, die bei der Auswertung nicht störten.

Da die Lichtemission während einer Entladung stark variierte, erfolgte die quantitative Untersuchung photoelektrisch. Bei fester Wellenlängeneinstellung des Monochromators wurde mit Sekundärelektronenvervielfacher (RCA 6810 A) und Zweistrahloszillograph (Tektronix 551) der emit-