150.8 keV, $E3$ transition in $^{111}Cd^m$ and comparison of experimental and theoretical high multipole order internal conversion coefficients

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$^{111}Cd^m$ was excited by (γ,γ') reactions with bremsstrahlung of a 4.5 MeV linear electron accelerator, and the K and total internal conversion coefficients of the 150.8 keV, $E3$ transition were measured. The obtained values are $\alpha_K^{151}=1.29\pm0.11$, $\alpha_T^{151}=1.98\pm0.05$ (68% confidence level). These values deviate from the theory by more than 10%, but less strongly than was reported very recently. Several experimental internal conversion coefficient values of high multipole transitions with better than 5% accuracy are compared with the theory, and definite discrepancies are observed.

I. INTRODUCTION

The internal conversion coefficients (ICC's) calculated by Hager and Seltzer[1] are considered to be systematically 2—3 % higher for high multipole electromagnetic transitions than the experimental values.[2] However, recently discrepancies greater than 10% were reported for several $E3$, $E4$, and $M4$ transitions.[3–9] If these discrepancies really exist, more careful recalculation of ICC's is required.

Since the appearance of the fundamental work of Raman *et al.*,[2] many new ICC determinations have been performed, in view of which it seemed worthwhile to review again the available high multipole ICC's. On the other hand, in an endeavor to refine our preliminary result,[5] we remeasured the total ICC of the 150.8 keV $E3$ transition[10] in $^{111}Cd^m$, where the largest anomaly was observed[3,4] as well as the K conversion coefficient of the same transition. Utilizing the simple level scheme of $^{111}Cd^m$, we took advantage of the intensity balance method and the XPG (x-ray and γ-ray counting) method.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

The decay scheme of $^{111}Cd^m$ shown in Fig. 1 is well established. Energy and spin data are taken from Ref. 10; the half-life data are from Ref. 11. The total ICC of the 150.8 keV transition was obtained by the well known intensity balance method using the expression

$$N_\gamma^{151}(1+\alpha_T^{151})=N_\gamma^{245}(1+\alpha_T^{245}) , \quad (1)$$

where the N_γ are the respective γ intensities corrected for detector efficiency, sum peak loss, and attenuation, while the α_T are the relevant total ICC's. As far as α_T^{245} is concerned, on one hand it is small and on the other the theoretical ICC's for $E2$ transitions are known to be in good agreement with the experimental ones, so we may take the α_T^{245} value of Hager and Seltzer,[1] which is 0.064. If this is substituted in Eq. (1) only α_T^{151} remains unknown.

The K conversion coefficient was determined by means of the XPG method according to the expression

$$\frac{N_{KX}}{\omega_K}-N_\gamma^{245}\alpha_K^{245}=N_\gamma^{151}\alpha_K^{151} , \quad (2)$$

where the α_K are the respective K conversion coefficients, N_{KX} is the K x-ray intensity, and ω_K is the K fluorescence yield. ω_K was taken to be 0.840 ± 0.029 from Ref. 12; α_K^{245} is 0.0535, from Ref. 1.

High purity natural Cd foils of 0.16 mm thickness were irradiated by bremsstrahlung of the LPR4 linear electron accelerator of the Institute of Isotopes, Budapest. The 4.5 MeV electron beam was converted to photons by a 1.8 mm thick tungsten target. The beam intensity was 16 μA. Irradiation times varied between 1.0 and 2.5 h.

γ-ray spectra were recorded by an Ortec HPGe (HP denotes high purity) detector of 0.55 cm^3, a shielded Ge(Li) detector of 35 cm^3, and two multichannel analyzers. Measurement times varied from 2000 to 10 000 s. Counts of six samples recorded by the HPGe detector were summed and are shown in Fig. 2. Spectra of 12 samples taken by the Ge(Li) detector were independently evaluated. Peak areas were fitted by the HYPERMET[13] and

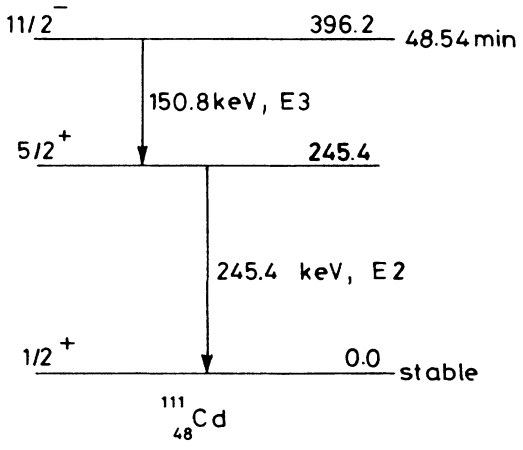


FIG. 1. Decay scheme of $^{111}Cd^m$. Energy, spin, and multipolarity data are from Ref. 10; half-life data are from Ref. 11.

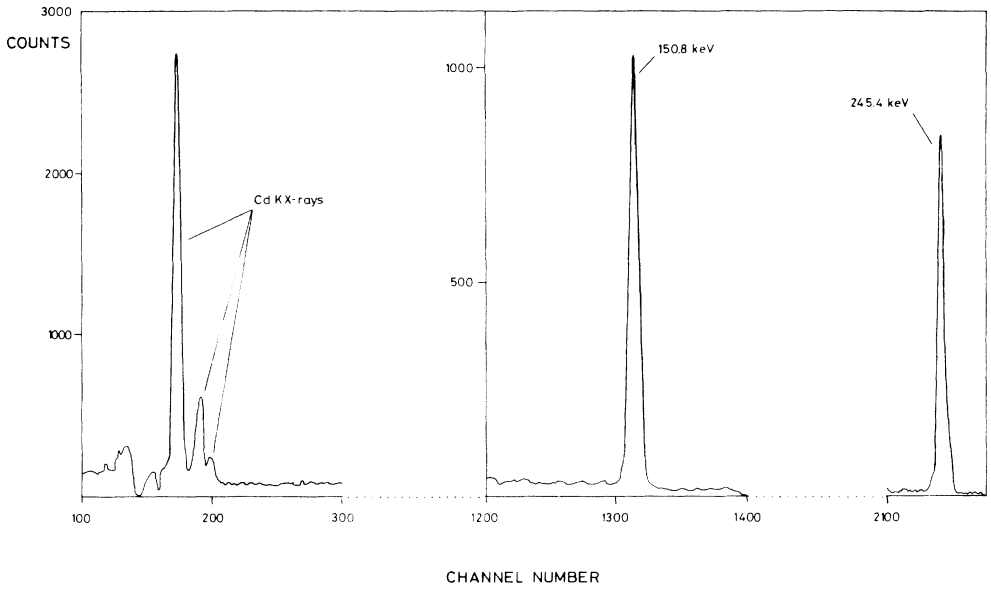


FIG. 2. Spectrum of $^{111}Cd^m$ recorded by 0.55 cm^3 Ortec HPGe detector. The spectrum is the sum of counts from six samples. Total counting time: 3×10^4 s.

the OTHER[14] code, and were then corrected for detector efficiency, sum peak loss and sample self-attenuation. Efficiency was determined with standard ^{57}Co, ^{133}Ba, ^{144}Ce, ^{152}Eu, and ^{241}Am sources. The attenuation correction factors for the γ rays were calculated in the exponential approximation:

$$F_i=[1-\exp(-\mu_i d)]/\mu_i d \ ,$$

where the F_i are the correction factors, the μ_i are the total attenuation cross sections taken from Ref. 15, and d is the sample thickness. For the x-rays,

$$F_i=1/\mu_i d \ ,$$

in accordance with the infinitely thick sample approximation.

III. RESULTS

In the case of Ge(Li) measurements the weighted average of the (245.4 keV)/(150.8 keV) peak area ratios were calculated. Substituting this value in Eq. (1), $\alpha_T^{151}=1.97\pm0.07$ was obtained. From the HPGe spectrum $\alpha_T^{151}=1.99\pm0.10$. Our final result is $\alpha_T^{151}=1.98\ \pm0.05$ (68% confidence level), which is (13.9 ± 2.2)% smaller than the theoretical value of 2.30 due to Hager and Seltzer[1] and Dragoun *et al.*,[16] but definitely higher than the extremely low value of Suryanarayama *et al.*[3,4]

Our α_K^{151} value obtained from Eq. (2) is 1.29 ± 0.11 (68% confidence level), which is 11.5% smaller than the theoretical value of 1.458.[1] Although the standard deviation of our result is relatively high, partly because of the 3.5% uncertainty of ω_K^{12}, a definite discrepancy is observable between experiment and theory.

IV. DISCUSSION

Extensive comparison of third and fourth order ICC's with theoretical ones is shown in Figs. 3 and 4. This comparison involves 55 experimental values: 16, 1, 2, and 36 for $E3$, $M3$, $E4$, and $M4$ transitions, respectively. All experimental ICC values with better than 5% accuracy are shown, except where more than two ICC's satisfy the criterion. In these cases, only the two best values are indicated, except the α_T values of $^{125}Te^m$ and $^{137}Ba^m$, where the discussion required the indication of three values. Six experimental values are also shown, where the accuracies are slightly worse than 5%, but the discrepancies are larger than the standard deviations. In the case of the 381.0 keV, $M4$ transition in $^{87}Y^m$, α_T^{381} was calculated from the $\alpha_T^{381}/\alpha_T^{388}=1.135$ value reported by Sakai *et al.*[31] and from the α_T^{388} value of Goodier *et al.*[30] α_T^{388} stands for the total ICC of the 388.4 keV, $M4$ transition in $^{87}Sr^m$.

The greater data sample allows more definite conclusions than were possible in Ref. 2. It is striking that 25 of the 38 fourth order ICC's have discrepancies between 2% and 5% (see Fig. 4). This strong trend suggests the revision of the values falling outside that band. Of the 13, nine have an uncertainty larger than 3%, so these are among the less accurate measurements.

The most contradictory results are at the 109.3 keV transition in $^{125}Te^m$, where the low α_T of Mukherjee *et al.*[7] has a discrepancy of 16.9%, which is much greater than that of α_K. It means that the outer shell contributions have to dominate the α_T discrepancy. However, taking into account that α_K gives more than 50% of α_T, some of the outer shell contributions have to have a discrepancy of more than 30%, which does not seem too

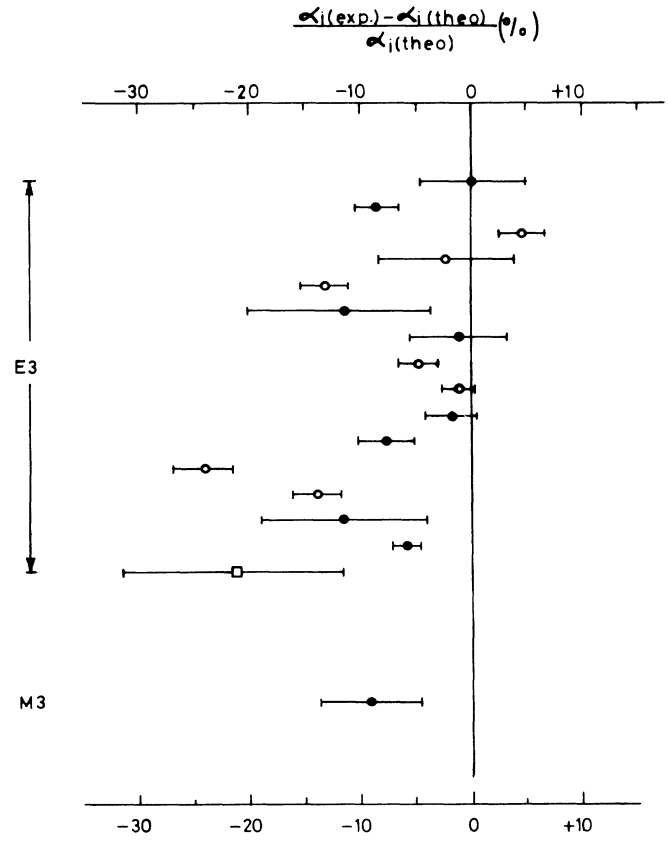
likely. On the other hand, the α_T values of Coursol,[40] 354 ± 12, and of Soni *et al.*,[41] 357 ± 11, having only 3.3% and 2.5% discrepancies, respectively, also makes the $\alpha_T=304\pm17$ value of Mukherjee *et al.*[7] questionable.

Also problematic is the case of $^{137}Ba^m$, where very accurately quoted but controversial experimental results exist.[44–46] We have modified the values of Behrens and Christmas[44] in accordance with the critical remarks of Hansen;[26] Hansen's remarks led to a decrease in the discrepancy but have not resolved the contradiction. For a detailed discussion of the α's of $^{137}Ba^m$, see Ref. 26. More precise ICC determinations for $^{137}Ba^m$ and for nuclides with discrepancies of more than 5% or less than 2% would be necessary, as well as an extension of the investigations to further nuclides. Even so, for the fourth order ICC's a decisive trend is observable.

The picture is not so clear for the third order ICC's (see Fig. 3). There is not a band with a width of some percent in which the greatest number of the points would fall. Ten of the 17 values show a discrepancy greater than 5%, so one cannot exclude the existence of higher anomalies, as opposed to the fourth order ICC's. Nevertheless, we should mention that the four largest discrepancies originate from measurements carried out at the same laboratory,[3,4,6,8,9] which might indicate that there is some systematic error.

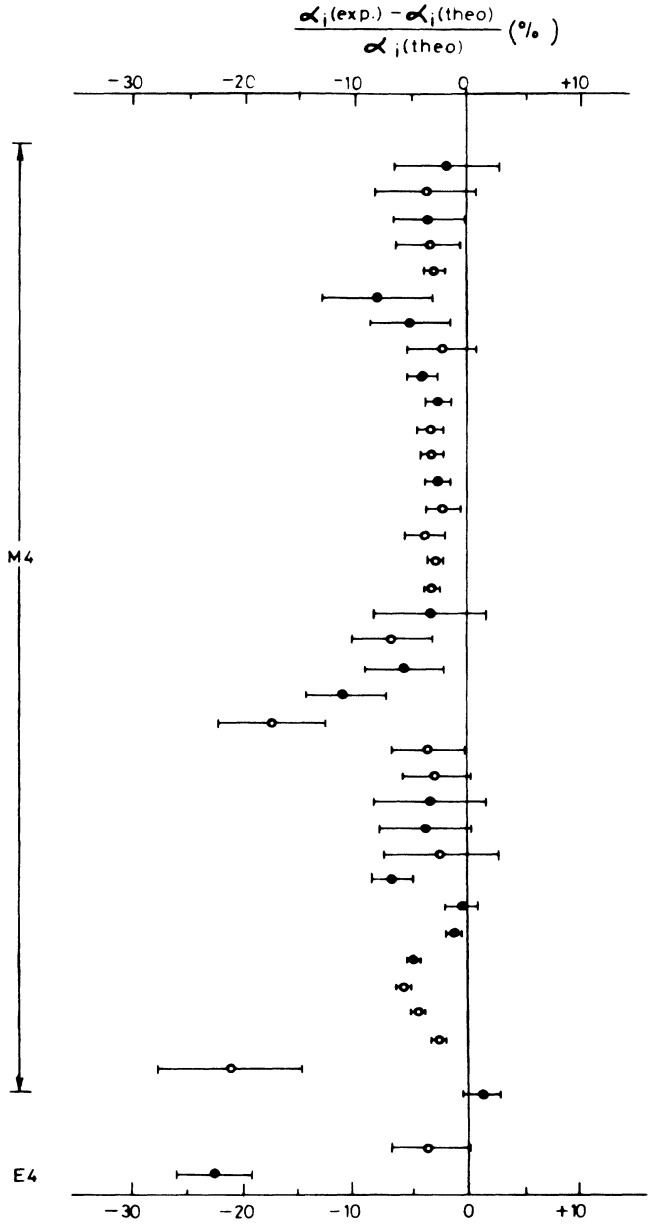
As far as the third order ICC's are concerned, a large uncertainty is observable. It is striking that where we could indicate two results (for $^{103}Rh^m$, $^{109}Ag^m$, and $^{111}Cd^m$), the values were contradictory in each case. The total ICC of the 88.0 keV transition of $^{109}Ag^m$ reported by Leutz *et al.*[25] was modified as suggested by Hansen.[26] The $\alpha_T=1430\pm89$ value of Vaninbroukx *et al.*[19] for the 39.75 keV transition of $^{103}Rh^m$, which does not satisfy the criterion (having an uncertainty slightly higher than 5%), was indicated to show an α_T value with negative discrepancy in addition to the more accurately quoted but very high value of Czock *et al.*[18] The α_T value of Lu[49] for the 150.8 keV transition of $^{111}Cd^m$ with an extremely low uncertainty was rejected.

In spite of our remarks, it is clear that the theoretical calculations of Hager and Seltzer[1] are not in full agreement with the experiments. There is no agreement with the other theoretical calculations,[24,50–53] which give re-



Nucleus	γ-energy (keV)	α_i(exp)	Ref.	α_i(theo)
$^{75}As^m$	303.9	0.0472(23)	17	0.0471
$^{103}Rh^m$	39.75	127(3)	18	139.4
		1531(30)		1432
		1430(89)	19	
$^{104}Rh^m$	77.5	39(1)	4,20	44.9
$^{101}Ag^m$	176.2	0.69(7)	21	0.788
$^{107}Ag^m$	93.1	9.3(4)	22	9.39
$^{109}Ag^m$	88.03	25.4(5)	23	26.7
		26.4(4)	24	
		11.4(3)		11.6
		10.7(3)	25,26	
$^{111}Cd^m$	150.8	1.76(8)	3,4	2.30
		1.985)	Present	
		1.29(11)		1.46
$^{134}Cs^m$	127.4	2.60(4)	27	2.76
$^{191}Ir^m$	41.9	1370 9(1900)	8	17440
$^{94}Nb^m$	40.9	710(37)	4,20	781

FIG. 3. Comparison of accurately measured $E3$ and $M3$ internal conversion coefficients and theoretical values. The theoretical ICC's are from Refs. 1 and 16. Open circles, solid circles, and open squares indicate the total, the K, and the L conversion coefficients, respectively.



Nucleus	γ energy (keV)	α_i (exp.)	Ref.	α_i (theo)
$^{85}Kr^m$	304.9	0.432(20)	28	0.439
		0.509(24)		0.527
$^{87}Sr^m$	388.4	0.177(6)	29	0.183
		0.211(6)		0.218
		0.212(2)	30	
$^{87}Y^m$	381.0	0.201(10)	31,30	0.218
$^{90}Y^m$	479.5	0.00856(29)	32	0.00901
		0.00102(34)		0.00125
$^{113}In^m$	391.7	0.431(7)	33	0.448
		0.437(7)	34	
		0.540(7)		0.557
		0.541(6)	35	
$^{115}In^m$	336.2	0.843(12)	36	0.866
		1.073(14)		1.094
$^{117}In^m$	315.0	1.414(25)	37	1.465
$^{117}Sn^m$	156.0	46.58(15)		47.8
		46.40(25)	2	
$^{119}Sn^m$	65.66	1610(82)	38	1660
$^{123}Te^m$	88.5	1076(42)	39	1152
$^{125}Te^m$	109.3	178.9(66)	40	189
		169(7)	7	
		304(17)		366
		354(12)	40	
		357(11)		
$^{127}Te^m$	88.26	484(23)	41	497
$^{129}Te^m$	105.5	213(10)		222
$^{129}Xe^m$	196.6	13.61(67)	40	13.9
$^{131}Xe^m$	163.9	30.1(6)	42	32.2
		32.1(4)	43	
$^{137}Ba^m$	661.6	0.0916(4)	44	0.0926
		0.0883(4)		
		0.1086(5)	45,26	
		0.1100(6)	46	0.11148
		0.1121(5)	44	
$^{197}Hg^m$	165.0	2.75(19)	9	3.48
$^{207}Pb^m$	1063.6	0.0986(30)	47	0.097
$^{93}Mo^m$	263.1	0.688(24)	48	0.711
$^{114}In^m$	190.3	2.00(9)	6	2.584

FIG. 4. Comparison of accurately measured $M4$ and $E4$ internal conversion coefficients and theoretical values. The theoretical ICC's are from Refs. 1 and 16. Open and solid circles indicate the total and the K conversion coefficients, respectively.

sults very close to those of Hager and Seltzer.[1] In view of the lack of unanimity, highly accurate investigations are needed to test the theory of high multipole order ICC's.

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