Test of internal-conversion theory with a measurement in ^{111}Cd

TEXAS A&M PROGRAM TO MEASURE ICC
N. NICA

Internal Conversion Coefficients (ICC):

- **Big impact on quality of nuclear science**
- **Central for NSDD-USNDP and other nuclear data programs**
- **Intensely studied by theory and experiment**
- **Important result for nuclear data communities:**

The calculations including the atomic vacancy are now standard!

Internal Conversion:

- **Basic science:**
  - **Construction of nuclear level schemes**
  - **Total transition probabilities**
  - **Assignment of spins and parities**
- **Applications:**
  - **Medical**
  - **Pharmaceutical**
  - **Environmental**
- **Hundreds of measured values: 5-10% precision**
- **2002Ra45 study:**
  - **Systematic discrepancy: theory up to 2-3% larger than experiment** (for high multipolatities**)**
  - ***No benchmark experimental ICC values!***

2002RA45 survey ICC's theories and measurements

- **Theory:** **RHFS and RDF** (1989Ba84) **comparison**

  Exchange interaction, Finite size of nucleus, ***Hole treatment***

- **Experiment:**

  100 *E2*, *M3*, *E3*, *M4*, *E5* ICC values, 0.5%-6% precision,

  very few <1% precision!

- **Conclusions, Δ(exp:theory)%:**

  No hole*: +0.19(26)% *BEST!

  (bound and continuum states - SCF of neutral atom)

  ***Hole-SCF*: -0.94(24)%**

  (continuum - SCF of ion + hole (full relaxation of ion orbitals))

  ***Hole-FO*: -1.18(24)%**

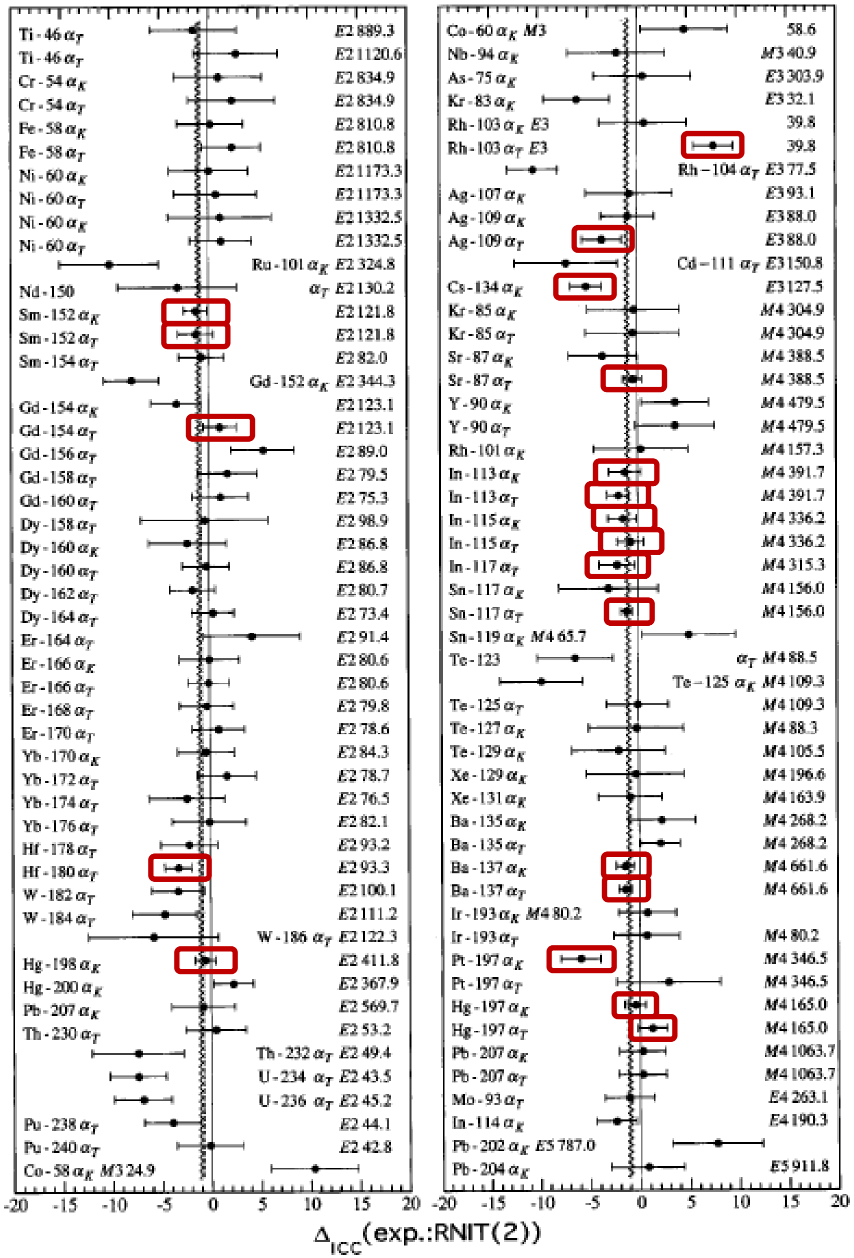
  (continuum - ion field from bound wave functions of neutral atom (no relaxation of ion orbitals))

  PHYSICAL ARGUMENT

  K-shell filling time vs. time to leave atom

  $\sim 10^{-15} - 10^{-17}$ s » $\sim 10^{-18}$ s

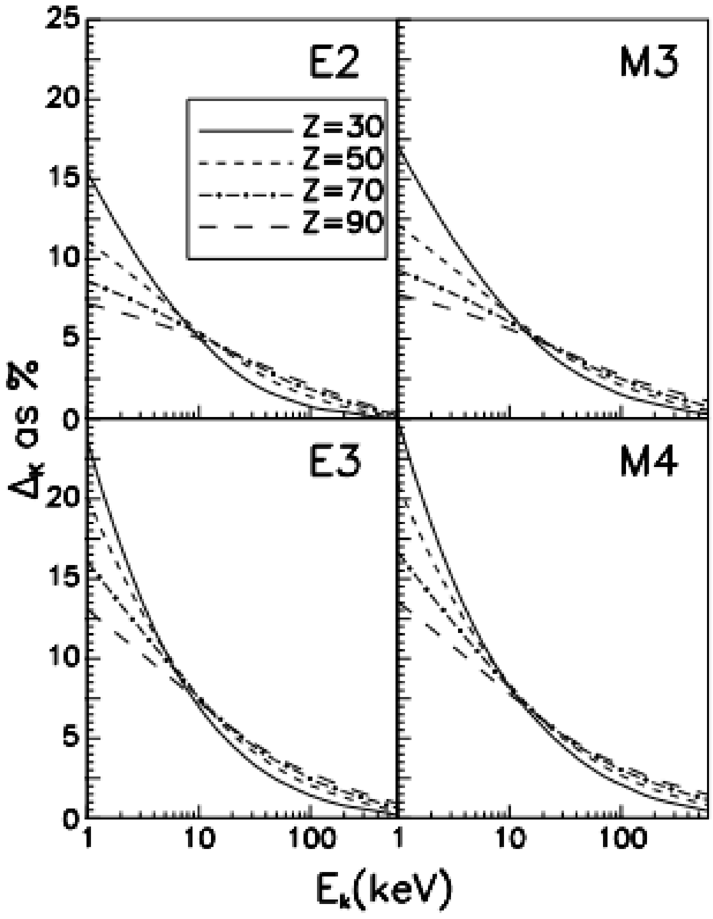
2002Ra45: 100 α_K(exp) cases compared with ‘hole FO’ calculations



2003 we started a program at Texas A&M University to measure benchmark ICC values, with the goal to provide a more precise and reliable data set, one particularly geared to addressing the atomic-vacancy issue.

1. ***Re-measure 'main set' of 100 cases***
2. ***Measure other cases***
3. ***Abnormal results***
4. ***High uncertainties***
5. ***Theory: Δ_K = 4-10%***
6. ***Experiment: about 1-2% precision***
7. ***Well spread on nuclear chart***

The difference Δ_K between α_K('hole') and α_K('no hole') (relative to α_K('hole')) as function of kinetic energy of converted electron E_K



KX to γ rays ratio method

- Single-transition level scheme (or dominated by a strong transition)
- Sources for n_{th} activation
  - Small selfabsorption (< 0.1%)
  - Dead time (< 5%)
  - Statistics (> 10^6 for γ or x-rays)
  - High spectrum purity
  - Minimize activation time (0.5 h)
- Impurity analysis - *essentially based on ENSDF*
  - Trace and correct impurity to 0.01% level
  - Use decay-curve analysis
  - Especially important for the K X-ray region
- Voigt-shape (Lorentzian) correction for X-rays
  - Done by simulation spectra, analyzed as the real spectra
- Coincidence summing correction (including angular correlation)

^{111m}Cd 150.8 keV, E3 transition

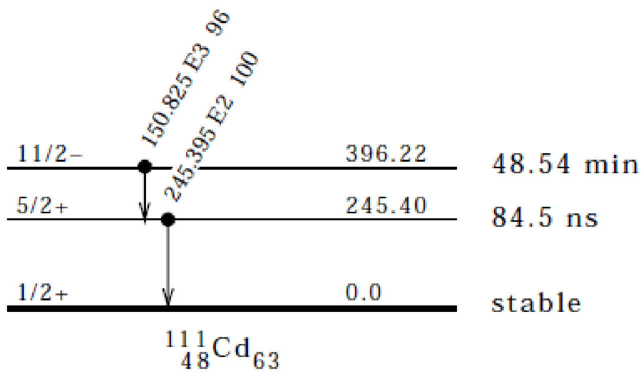
Suggested by 1984Ba84

- α(K)exp = 1.29 *11* (1987Ne05), %unc=8.5
- $\alpha(K)_{hole\_FO}$ = 1.450, $\alpha(K)_{no\_hole}$ = 1.425, Δ_K = 1.7%

^{111}Cd IT Decay (48.54 min)

Decay Scheme

Intensities: I(γ+ce) per
100 decays by this branch
%IT=100



- **Texas A&M precision ICC measurements by KX to γ rays ratio method:**

- **α_{K150} measurement:**

$$\alpha_{K150} = \frac{N_K}{N_{\gamma 150}} \cdot \frac{\varepsilon_{\gamma 150}}{\varepsilon_{K236}} \cdot \frac{1}{\omega_K} - \alpha_{K245} \cdot \frac{N_{\gamma 245}}{N_{\gamma 150}} \cdot \frac{\varepsilon_{\gamma 150}}{\varepsilon_{\gamma 245}}$$

- **Extended for α_{T150} measurement:**

$$(1+\alpha_{T150}) \cdot \frac{N_{\gamma 150}}{\varepsilon_{\gamma 150}} = (1+\alpha_{T245}) \cdot \frac{N_{\gamma 245}}{\varepsilon_{\gamma 245}}$$

  - N_K, N_γ **measured from *only one K-shell converted transition***
  - $\omega_K = 0.842(4)$ **from 1999SCZX (**compilation and fit**)**
  - **from** $\alpha_{K245} = 0.05326(17)$, $\alpha_{T245} = 0.06351(17)$

    (http://bricc.anu.edu.au, **2008KI07)**

Detection efficiency

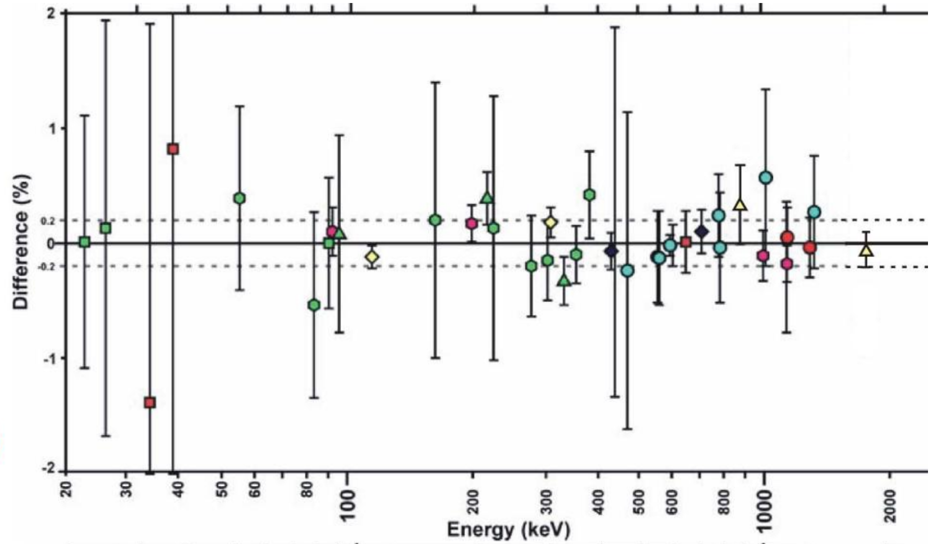
- **Very precise detection efficiency for ORTEC γ-X 280-cm^3 coaxial HPGe at standard distance of 151 mm:**
  - **0.2% , 50-1400 keV (2002HA61, 2003HE28)**
  - **0.4% , 1.4-3.5 MeV (2004HE34)**
  - **1% , 10-50 keV (KX rays domain)**

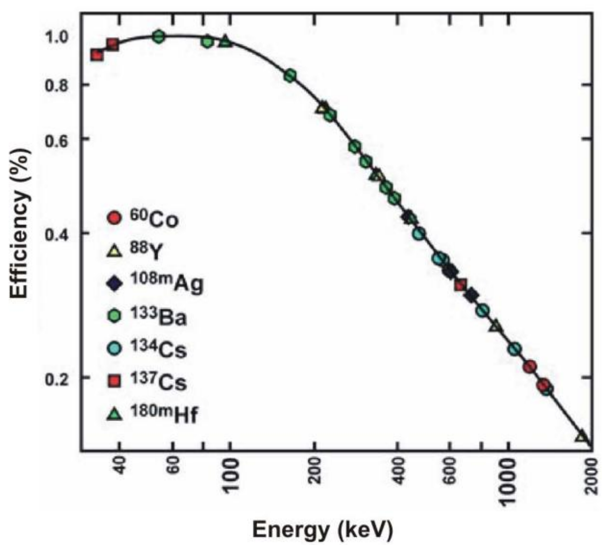
DETECTOR EFFICIENCY
50 keV < E_γ < 1.4 MeV

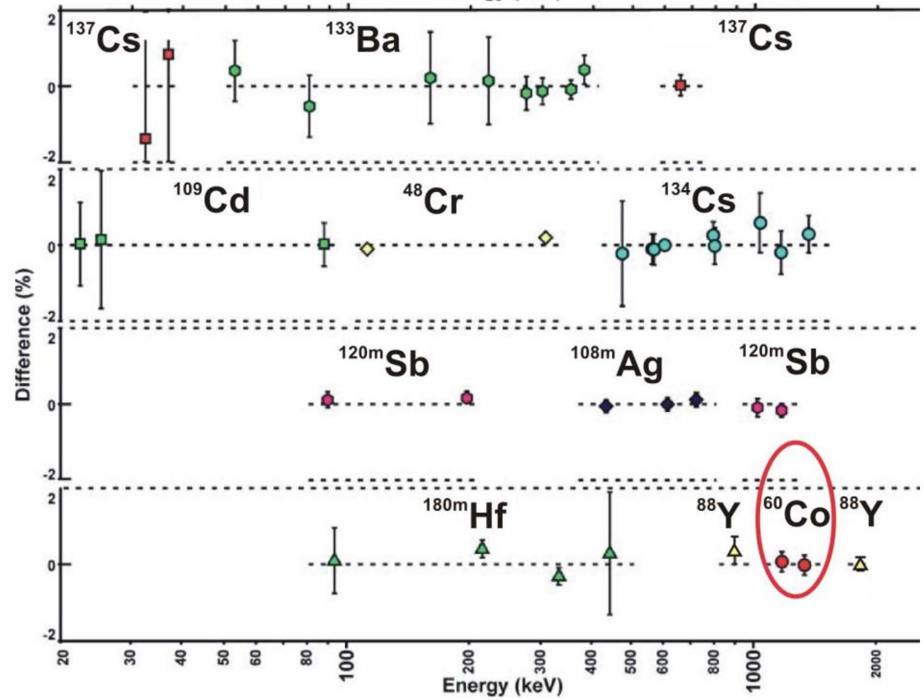
Coaxial 280-cc n-type Ge detector:

- Measured absolute efficiency (^{60}Co source from PTB with activity known to + 0.1%)
- Measured relative efficiency (9 sources)
- Calculated efficiencies with Monte Carlo (Integrated Tiger Series - CYLTRAN code)

0.2% uncertainty for the interval 50-1400 keV







Effect of scattering on the photo-peak efficiency (2007NI04)

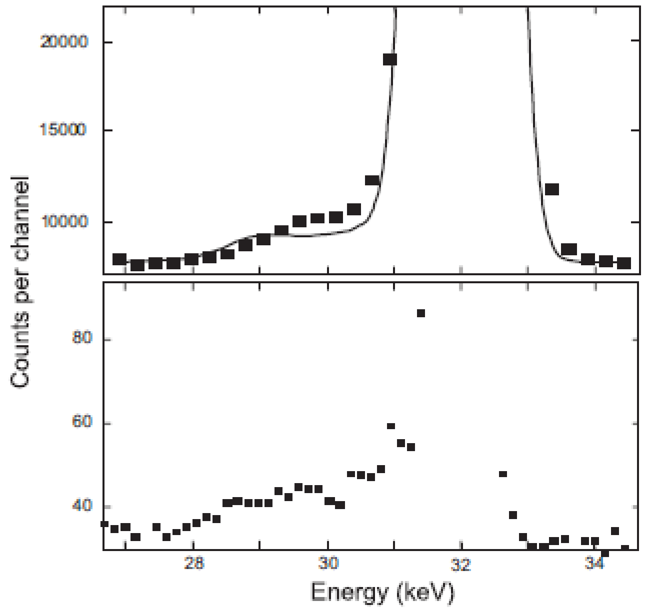
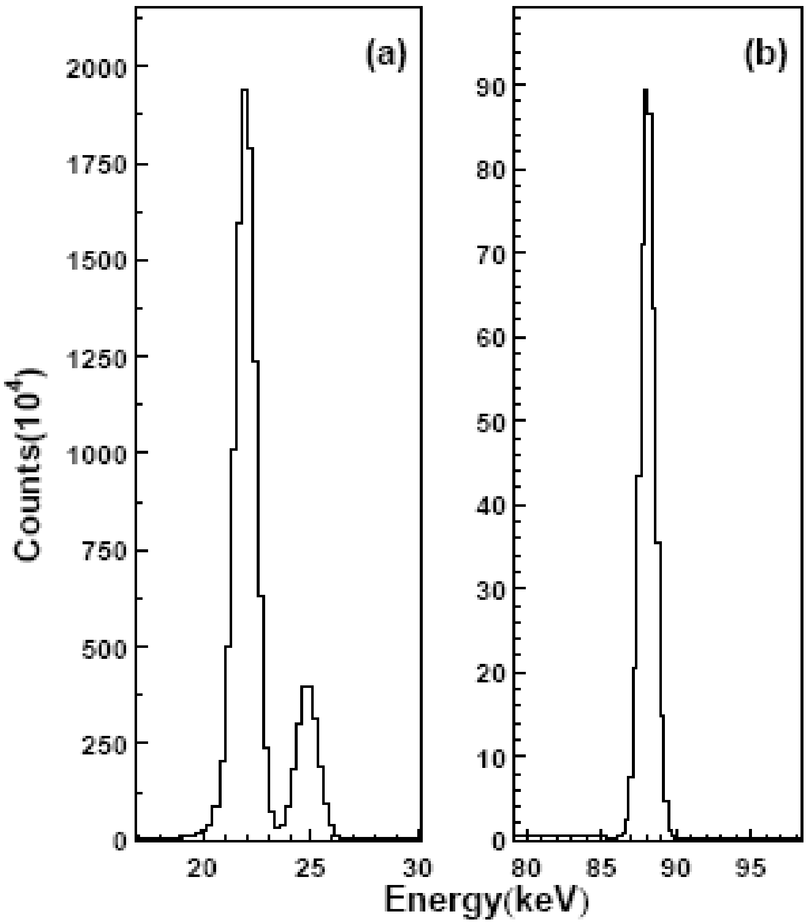


FIG. 5. The top panel shows an expanded region of the HPGe spectrum at the base of the barium K_α x-ray peak. The solid squares are the measured data from the ^{137}Cs source; the curve is the result of a Monte Carlo simulation. The bottom panel gives the same region of the ^{137}Cs spectrum as measured with a Si(Li) detector; the ordinate scale has been adjusted so that both panels display approximately the same fraction of the total K x-ray peak area.

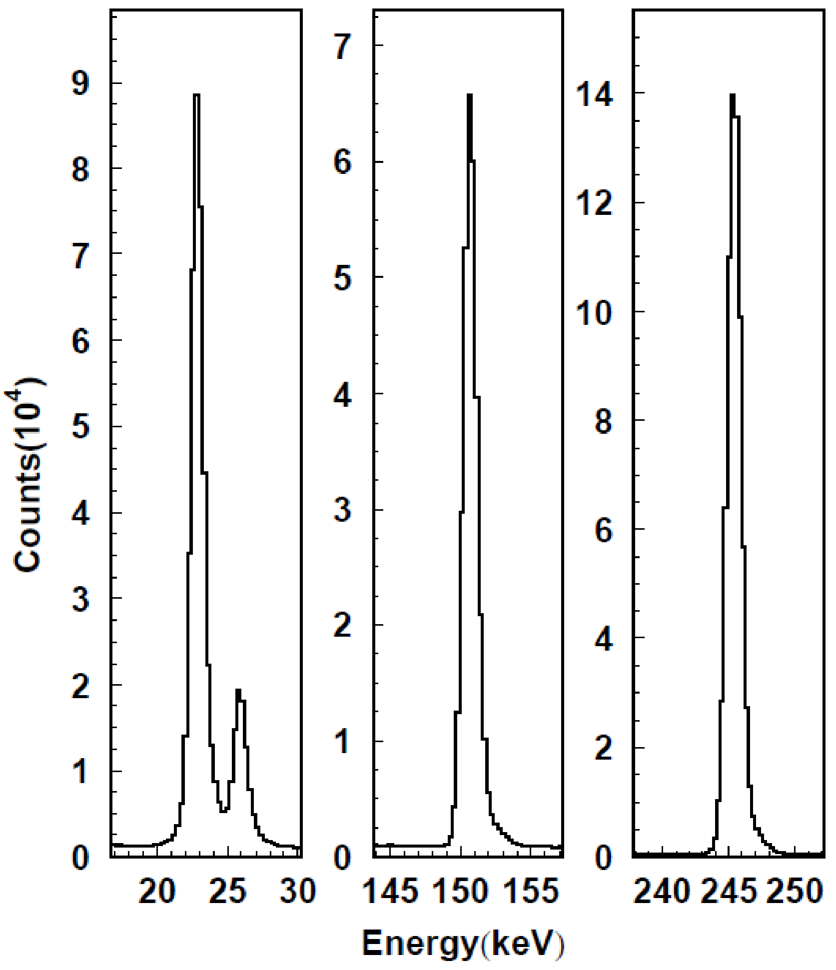
^{109}Cd Efficiency Calibration

22.6-keV AgKx & 88.0-keV E3 γ regions



^{111m}Cd Regions of interest

23.6-keV CdKx & 150.8-keV γ & 245.4-keV γ



- **Adopted efficiency:**

$$\left(\frac{\varepsilon_{\gamma 150}}{\varepsilon_{K23.6}}\right)_{^{111m}Cd} = \left(\frac{\varepsilon_{\gamma 88.0}}{\varepsilon_{K22.6}}\right)_{^{109}Ag,\exp} \times \left(\frac{\varepsilon_{\gamma 150}}{\varepsilon_{\gamma 88.0}}\right)_{Cyltran} \times \left(\frac{\varepsilon_{K22.6}}{\varepsilon_{K23.6}}\right)_{Cyltran}$$

$$\frac{\varepsilon_{\gamma 150}}{\varepsilon_{K23.6}} = 0.917(7)$$

$$\frac{\varepsilon_{\gamma 150}}{\varepsilon_{\gamma 245}} = 1.3123(14)$$

^{111m}Cd 150.8 keV, E3 transition - ICCs measurement

- ^{110}Cd 95.88% enriched (from 12.5% natural abundance), thin metal powder from *Trace Sciences International*.
- Impurities: ^{106}Cd (<0.01%), ^{108}Cd (<0.02%), ^{114}Cd (0.84%), ^{116}Cd (<0.16%).
- Backing: 10 µm Al foil (99.999%) from *GoodFellow*.
- Samples prepared by electro deposition by Dr. C. Folden III and Drd. T. Werke
- Samples: CdO, Φ=1.7 cm on 10 µm Al backing
  - S1: 0.99(2) mg, 0.53(1) µm
  - S2: 1.08(2) mg, 0.58(1) µm
- Neutron activation at Triga reactor @ TAMU, on both S1 and S2:
  - $\Phi = 7.5 \times 10^{12}$ n/(cm^{2}s)
  - $\alpha_{th} = 0.14(5)$ b
  - Samples activated 2 h (2 months apart)
  - Measured for 3 weeks

Impurity analysis

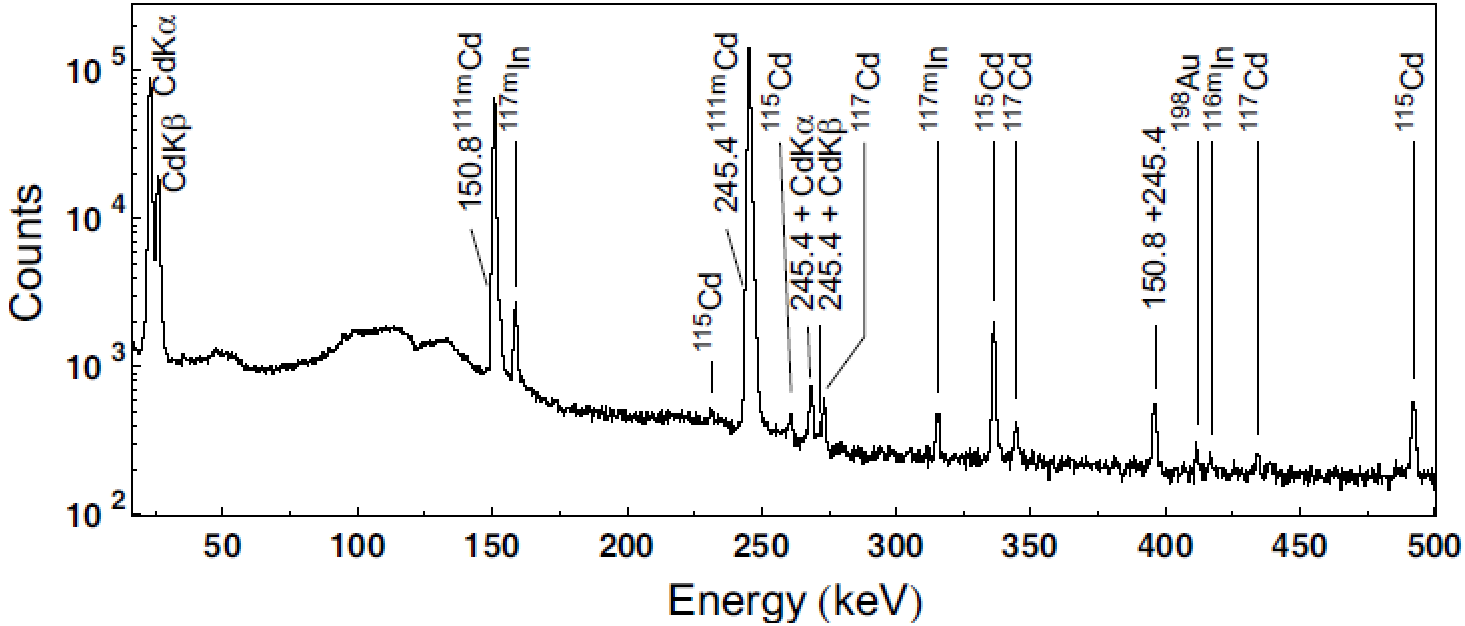


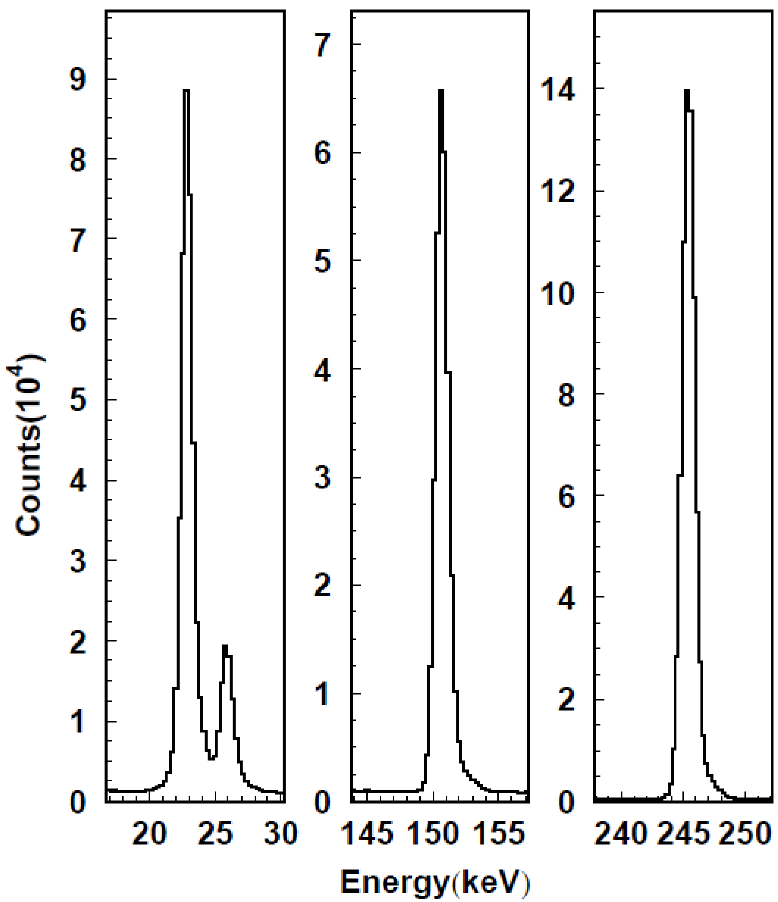
Table 1. The contributions of identified impurities that affect the cadmium *K* x-ray peaks.

Source	Contaminant	Contribution to spectrum (%)	
		S1	S2
^{115}Cd	In *K* x rays	1.81(8)	2.71(6)
^{117}Cd	In *K* x rays	0.113(12)	0.125(9)
^{117}In	Sn *K* x rays	0.18(3)	0.21(3)
^{117m}In	In+Sn *K* x rays	0.603(9)	0.484(5)
^{116m}In	In *K* x rays	0.010(2)	0.006(1)

Data analysis

Table 2. The total number of counts (or areas of the peaks) for ^{111m}Cd K x rays and the 150.8- and 245.4-keV γ rays, followed by corrections and the corrected area-ratios information required to extract the value of α_{K150}.

Quantity	Value	
	S1	S2
Cd ($K_\alpha + K_\beta$) x rays		
Total counts	$1.979(6)\times10^5$	$4.695(9)\times10^5$
Impurities	$-5.39(14)\times10^3$	$-1.66(3)\times10^4$
Lorentzian correction	+0.12(2)%	+0.12(2)%
Summing correction	+0.99(6)%	+0.99(6)%
Attenuation correction	+0.27(2)%	+0.29(2)%
Corrected counts, N_K	$1.952(6)\times10^5$	$4.593(10)\times10^5$
^{111}Cd 150.8-keV γ ray		
Total counts	$1.303(11)\times10^5$	$3.064(25)\times10^5$
Summing correction	+1.29(6)%	+1.29(6)%
Corrected counts, $N_{\gamma150}$	$1.320(12)\times10^5$	$3.104(25)\times10^5$
^{111}Cd 245.4-keV γ ray		
Total counts	$3.024(22)\times10^5$	$7.082(45)\times10^5$
Summing correction	+0.86(3)%	+0.86(3)%
Corrected counts, $N_{\gamma245}$	$3.050(22)\times10^5$	$7.143(45)\times10^5$
$N_K/N_{\gamma150}$	1.479(14)	1.480(12)
$N_{\gamma245}/N_{\gamma150}$	2.311(27)	2.301(24)



$$\frac{N_K}{N_{\gamma150}} = 1.479(10)$$

$$\frac{N_{\gamma245}}{N_{\gamma150}} = 2.395(7)$$

Results

Model	α_K	$\Delta(\%)$	α_T	$\Delta(\%)$
Experiment	1.449(18)		2.217(26)	
Theory:				
No vacancy	1.425(1)	+1.7(12)	2.257(1)	−1.8(12)
Vacancy, FO	1.451(1)	−0.1(12)	2.284(1)	−2.9(12)

α_T discrepancy:

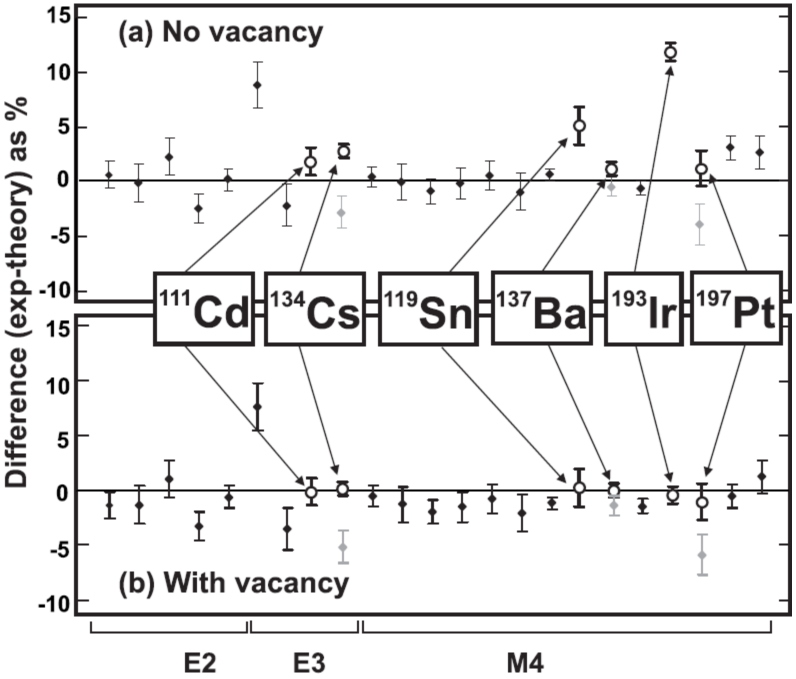
- 150.8-keV γ is hindered by 10^4 relative to its Weiskopf estimate.
- "Penetration" effects associated with the change from point-like to realistic finite-sized nucleus for transition electromagnetic potentials.
- ICCs *can thus become dependent on nuclear structure details and nuclear transition dynamics*.
- Under particular conditions it is possible for the penetration to be "hidden" by a cancellation that can affect one atomic shell but not the others (e.g. 1974KR01, for M1 transitions).
- Hypothetically this could also explain why in our case $\boldsymbol{\alpha_K}$ looks to be unaffected by penetration effects, while $\boldsymbol{\alpha_T}$ is significantly reduced.
- Despite the lack of direct support, ***penetration remains the best explanation for the discrepancy we observe here between experiment and theory for α_T.***

Current status of precision ICC measurements

Table 3. Comparison of the six measured α_K values with Dirac-Fock theoretical calculations

Parent	Transition Energy(keV)	Measured α_K	Calculated α_K No vacancy	Calculated α_K Vacancy
^{197m}Pt	346.5(2)	4.23(7)	4.191	4.276
^{193m}Ir	80.22(2)	103.0(8)	92.0	103.3
^{137m}Ba	661.659(3)	0.0915(5)	0.09068	0.09148
^{134m}Cs	127.502(3)	2.742(15)	2.677	2.741
^{119m}Sn	65.66(1)	1610(27)	1544	1618
^{111m}Cd	150.853(15)	1.449(18)	1.425	1.451
χ^2			219	0.68

Percentage difference between measured and calculated ICCs for the two Dirac-Fock calculations. The measured values include our published α_K values



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