Another interesting case of ICC measurement: the 88-keV, M4 transition in ^{127m}Te

TEXAS A&M PROGRAM TO MEASURE ICC

N. NICA

Internal Conversion Coefficients (ICC):

- **Big impact on quality of nuclear science**
- **Central for USNDP and other nuclear data programs**
- **Intensely studied by theory and experiment**
- **Important result: hole calculation now standard**
- ***Is the series of measurements complete?***
- ***Are there other critical cases to measure?***
- ***Overview of the scope and completeness of the method***

2002RA45 survey ICC's theories and measurements

- **Theory: RHFS and RDF 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

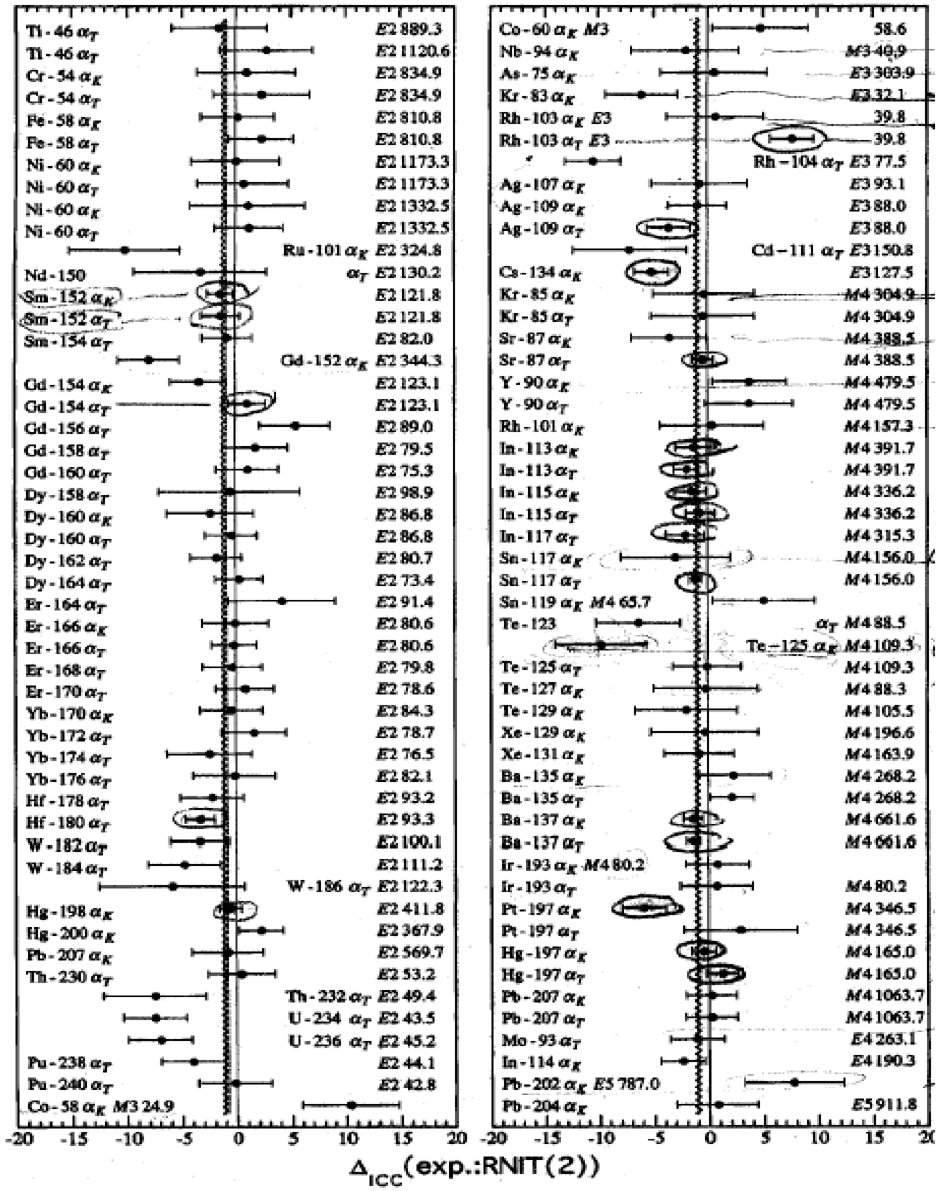
  (no relaxation of ion orbitals))

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



Texas A&M precision ICC measurements:

- **KX to γ rays ratio method**

$$\alpha_K \omega_K = \frac{N_K}{N_\gamma} \cdot \frac{\varepsilon_\gamma}{\varepsilon_K}$$

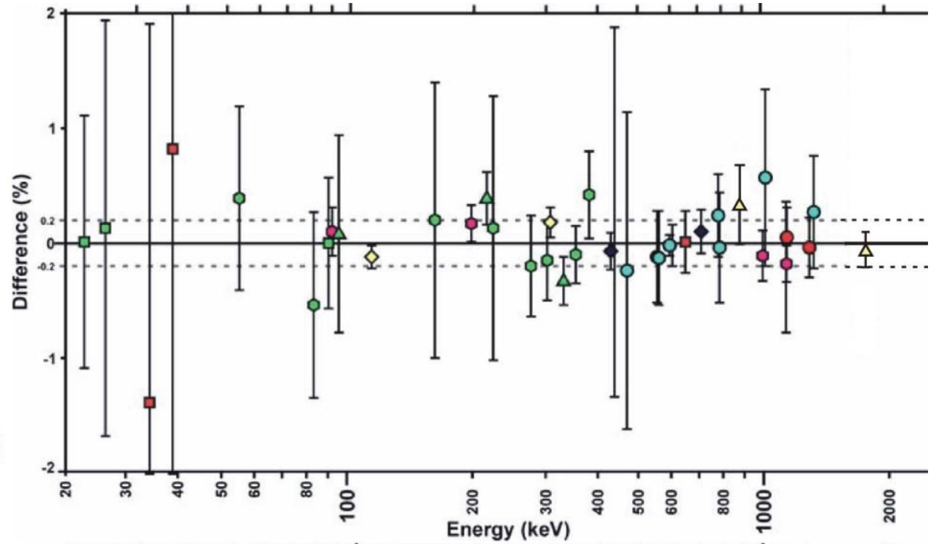
  - N_K, N_γ **measured from *only one K-shell converted transition***
  - ω_K **from 1999SCZX (**compilation and fit**)**

- **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)**

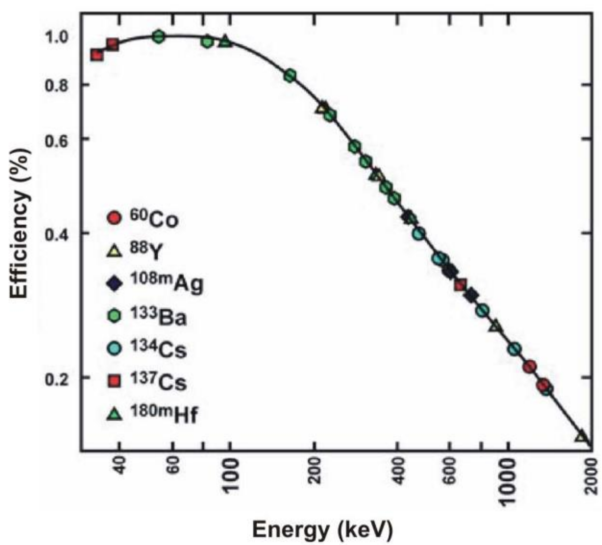
DETECTOR EFFICIENCY
50 keV < E$_\gamma$ < 1.4 MeV

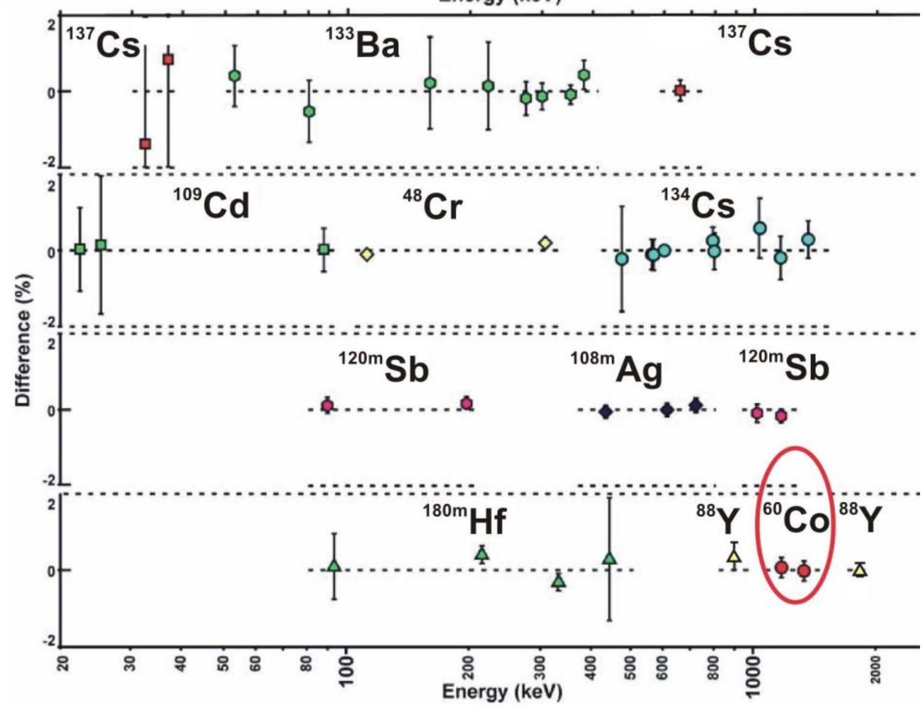
Coaxial 280-cc n-type Ge detector:

- 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



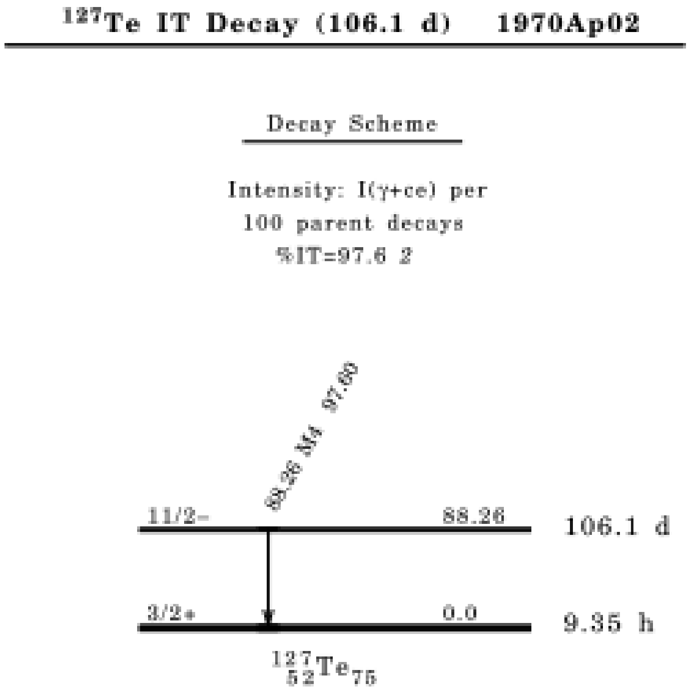


KX to γ rays ratio method

- 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

^{127m}Te 88.3 keV, M4 transition

- $\alpha(K)_{exp}$ = 484 *23* (1977So06), %unc=4.8
- $\alpha(K)_{hole\_FO}$ = 485, $\alpha(K)_{no\_hole}$ = 468

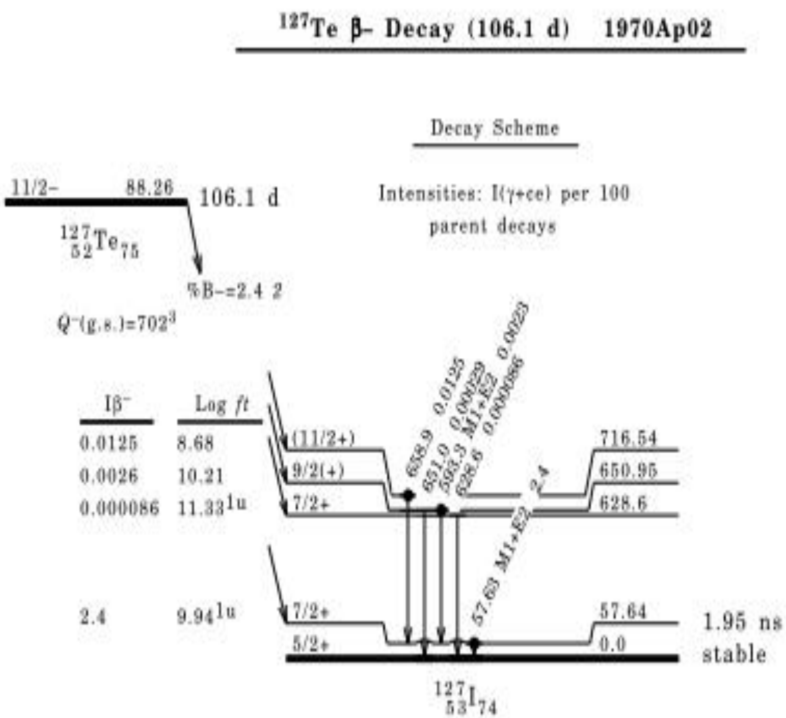


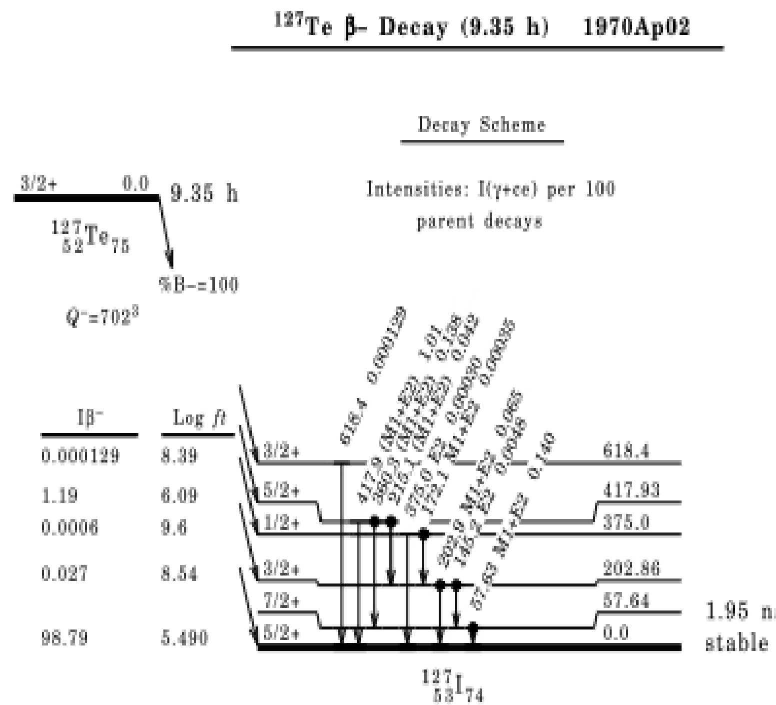
^{127m}Te 88.3 keV, M4 transition - α_K measurement

- ^{126}Te 98%+ enriched (from 19% natural abundance)
- Metal powder of 25(5) microns granularity
- Grinded at micron size
- Samples: 1.3 mg, disk of 1 cm diameter x 2.7-μm thick
- Sample consisted in three 1x1 inch, 1 mil-thick mylar foils stuck together; in middle one a disc of 1 cm diameter was cut and removed, and the hole filled with Te powder; then sealed with the other two mylar foils
- Neutron activation at Triga reactor @ TAMU,
  - $\Phi = 7.5 \times 10^{12}$ n/(cm^{2}s)
  - $\alpha_{th} = 0.135(23)$ b
  - Sample activated 24 h, then cooled down for 2 months
  - Measured for 3 weeks
- Measured with HPGe detector at 151 mm distance for three weeks

^{127m}Te Decay Modes

- 88.3-keV meta-stable state: IT, β^-
- ground state: β^-



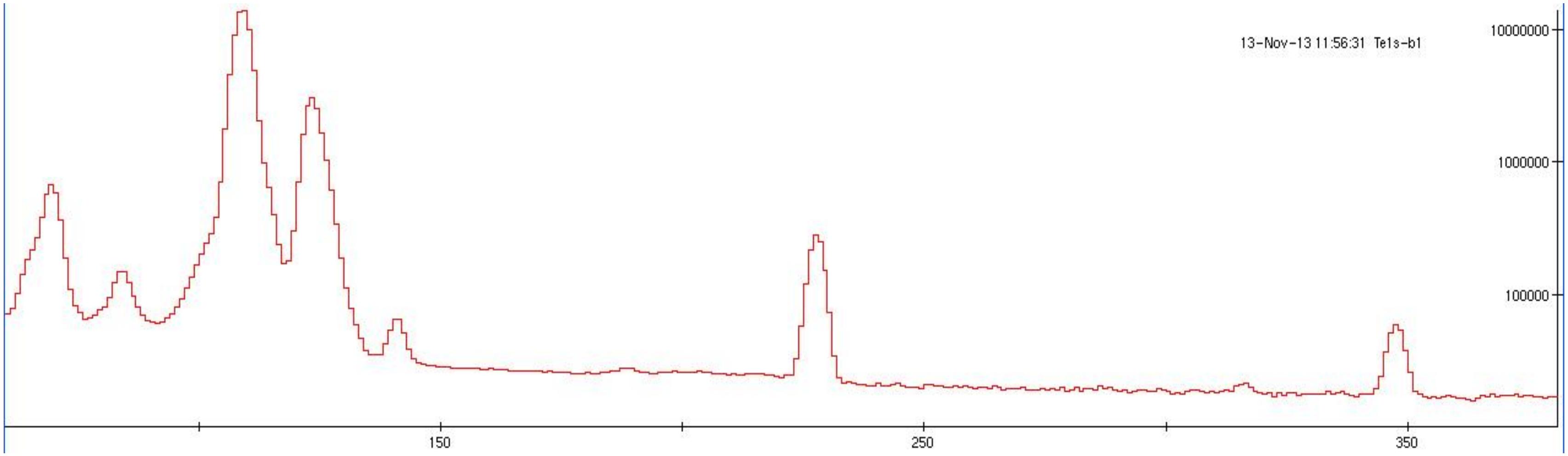


^{127m}Te 88.3 keV, M4 transition - α_K measurement

- Major difficulty:
  - Both the dummy mylar sample and the ^{126}Te sample were found rolled after activation.
  - The dummy was succesfully unrolled and fixed in between two thin mylar foils
  - However the ^{126}Te sample was getting friable and broke when unrolled
  - The partially unrolled sample was squeezed in between two mylar foils presumably with small loss of substance but with roughly a layer twice as thick as the initial one
  - A increase by factor of 1.5 for the relative attenuation of I(TeKx)/I(88γ) was adopted
  - One should normally repeat the run and get unspoiled source

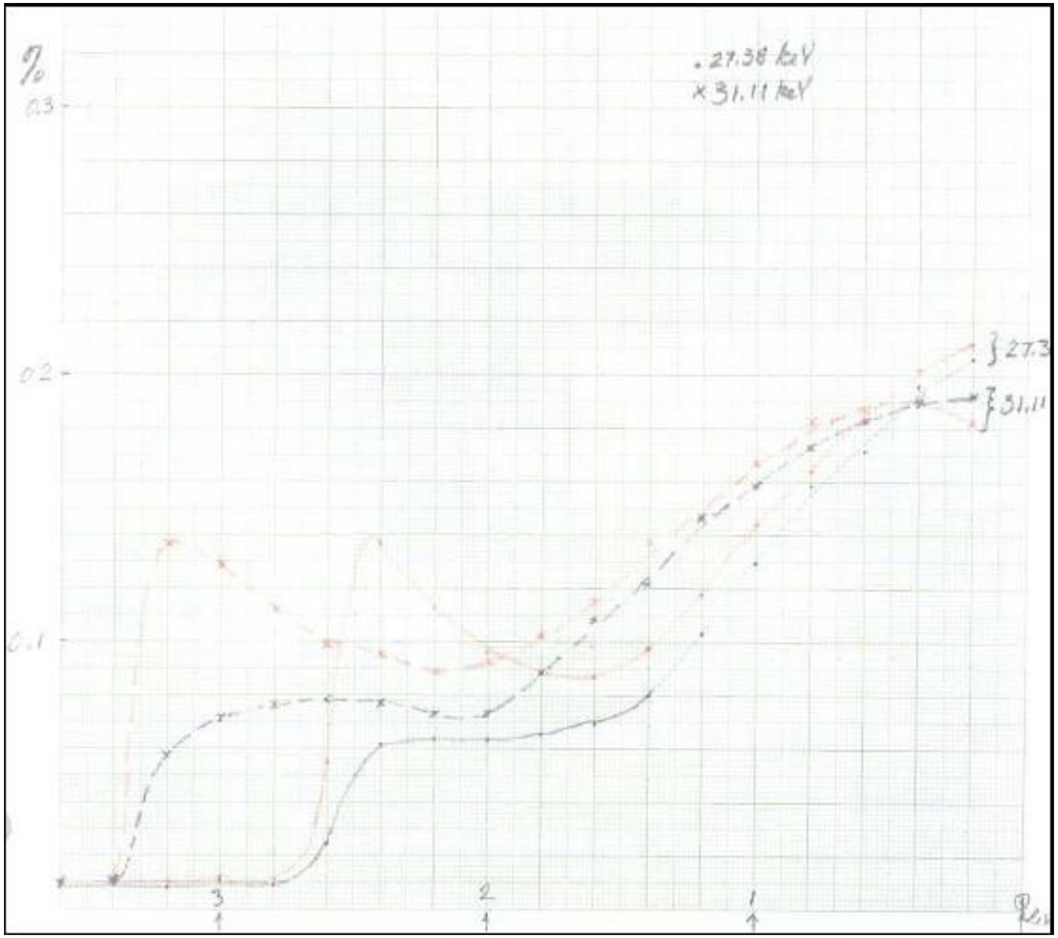
^{127m}Te 88.3 keV, M4 transition - α_K measurement

- **Second major difficulty: scattering affecting TeKx region**
  - **Rough estimate 4-5% effect**
  - **Correction: by simulation (Cyltran) and measurement (^{109}Cd)**



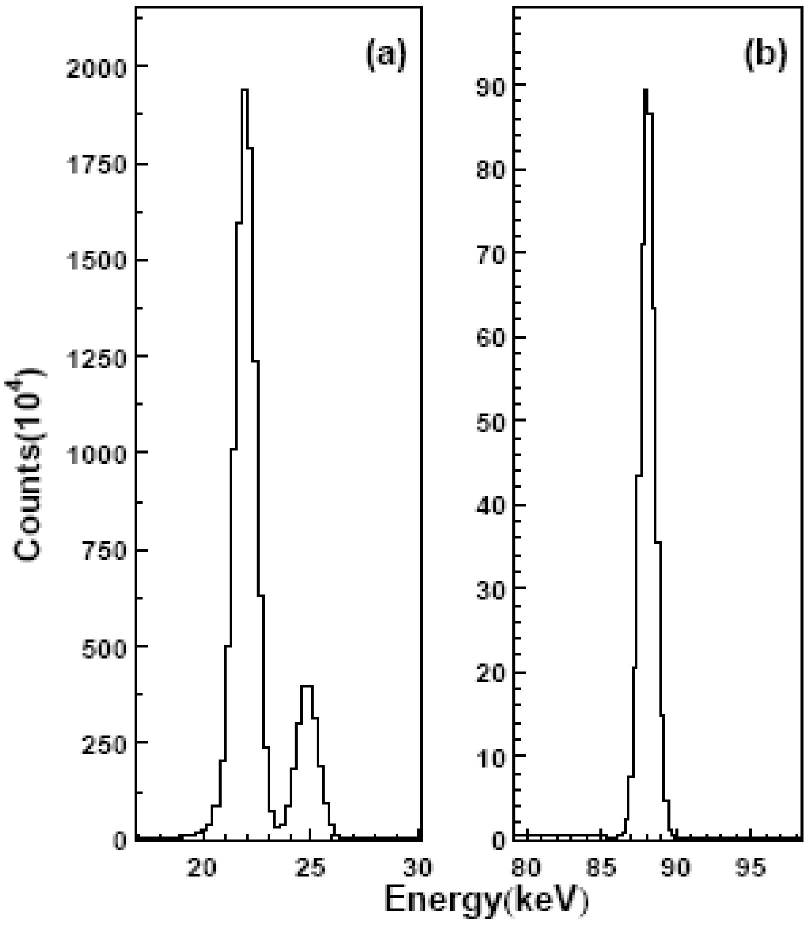
^{127m}Te 88.3 keV, M4 transition - αK measurement

Cytran simulation of scattering



^{109}Cd Efficiency Calibration

22.6-keV AgKx & 88.0-keV E3 γ regions



127mTe 88.3 keV, M4 transition - αK measurement

Impurity analysis

Impurity	Contribution to TeKx rays		Contribution to 88.3-keV γ	
^{127m}Te β^-	3.5%	0.6%		
^{125m}Te IT	2.63%	0.06%		
^{129m}Te β^-,IT	0.309%	0.012%		
^{127}Te β^-	0.226%	0.015%		
^{129}Te β^-	0.12%	0.05%		
^{123m}Te IT	0.104%	0.003%	0.081%	0.003%
^{131}I β^-	0.0374%	0.0009%		
^{121}Te e+β^+	0.0171%	0.0012%		
^{124}Sb β^-	0.0144%	0.0003%		
^{110m}Ag β^-	0.000366%	0.000011%		
^{110m}Ag IT	0.000121%	0.000003%		
Total	**7.0%**	**0.6%**	**0.081%**	**0.003%**

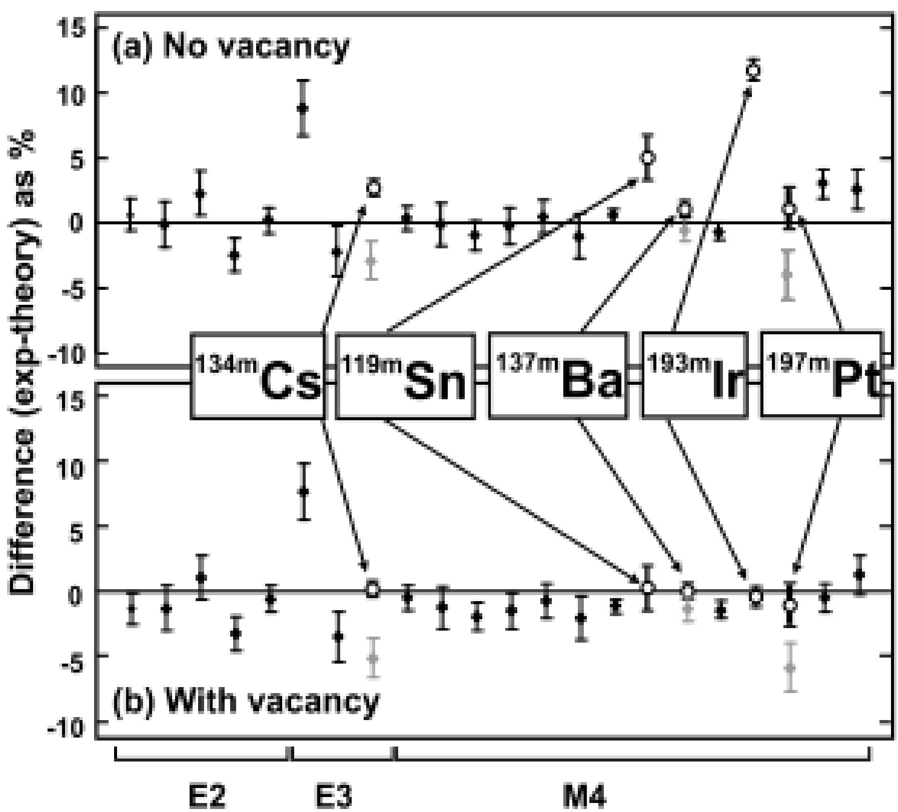
^{127m}Te 88.3 keV, M4 transition - αK measurement

Result (still preliminary) !

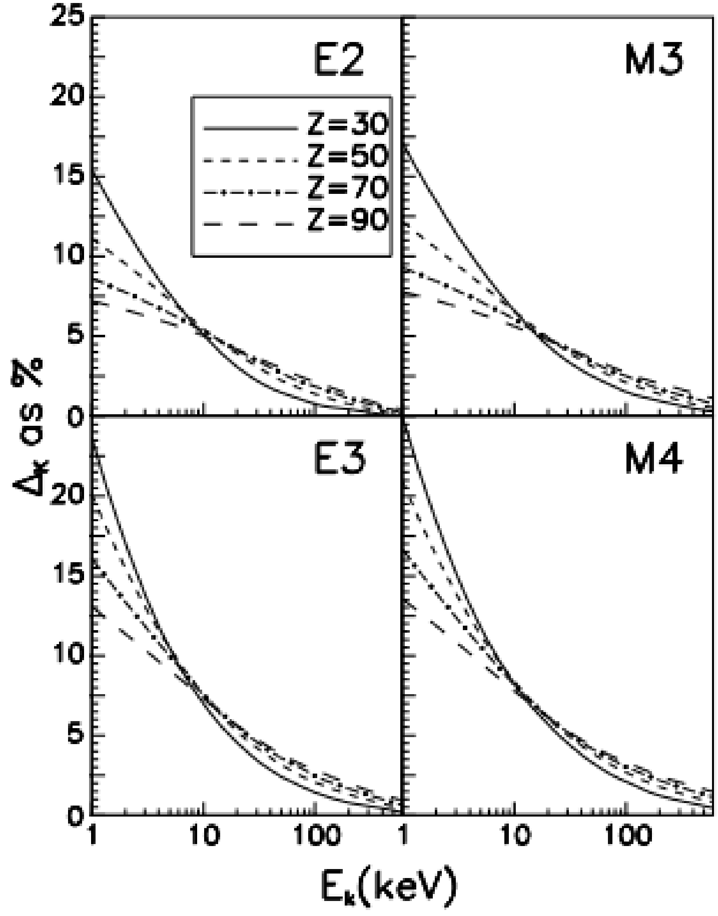
- α_K(exp) = **489 *7* (1.4%)**
- α_K(hole,FO)= 485; α_K(no-hole)= 468

Overview of the scope and completeness of the method

There is no criterion to reach the scope of comparison between ICC theories "with hole" and "no hole" except for measuring precisely as many relevant cases as practically possible



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



Systematic search for relevant α_K(exp) cases by I_{Kx}/I_γ ratio method

- Used NuDat to scan for all α_K cases of transitions having $\Delta_K > 5\%$
- Found 14 (E3), 9 (M3), 2 (E4), 8 (M4) in total 33 such cases ($\Delta_K = 5\% - 13\%$)
- Excluded 25 because the Kx rays from the IT transition can not be separated
- There are 8 favorable cases (provided one can find a suitable reaction to populate them)
  - 3 cases of $\Delta_K = 7\text{-}8\%$
  - 5 cases of $\Delta_K = 5\text{-}7\%$

NuDat search: E3 α_K cases of transitions having Δ_K > 5%

Nucleus	E_{level}(keV)	Jπ	$T_{1/2}$	E_γ(keV)	I_γ	γ mult.	γ conv. coeff.			
103RH	39.753 6	7/2+	56.114 m 9	39.755 6	100	E3	1403 20	135.1	127.3	5.8%
113AG	43.5 *1*	7/2+	68.7 s *16*	43.6 *2*	100	E3	1047	92.8	87.6	5.6%
115AG	41.16 *10*	7/2+	18.0 s *7*	41.1 *2*	100	E3	1.40E3 *5*	102.0	95.8	6.1%
116AG	47.90 *10*	(3+)	20 s *1*	47.9 *1*		E3	598 *11*	76.5	72.8	4.8%
117AG	**28.6 *2***	**(7/2+)**	**5.34 s *5***	**28.6 *2***	**100**	**E3**	**1.15E4 *6***	**60.7**	**52.7**	**13.2%**
131PR	152.4 *3*	(11/2-)	5.73 s *20*	64.8 *3*	100	E3	305	14.23	13.50	5.1%
158HO	**67.199 *10***	**2-**	**28 m *2***	**67.200 *10***	**100**	**E3**	**483**	**3.85**	**3.58**	**7.0%**
160HO	**59.98 *3***	**2-**	**5.02 h *5***	**59.98 *3***	**100**	**E3**	**940**	**1.91**	**1.71**	**10.5%**
171LU	**71.13 *8***	**1/2-**	**79 s *2***	**71.10 *9***	**100**	**E3**	**472**	**1.585**	**1.453**	**8.3%**
187AU	120.33 *14*	9/2(-)	2.3 s *1*	101.0 *2*	100	E3	120.4 *22*	0.925	0.874	5.5%
192AU	135.41 *25*	(5)+	29 ms	103.8 *3*		E3	103.3 *23*	0.977	0.926	5.2%
196AU	**84.656 *20***	**5+**	**8.1 s *2***	**84.66 *2***	**100**	**E3**	**327**	**0.290**	**0.260**	**10.3%**
195TL	**482.63 *17***	**9/2-**	**3.6 s *4***	**98.97 *12***	**100**	**E3**	**157.5**	**0.561**	**0.524**	**6.6%**
196BI	**271 *5***	**(10-)**	**240 s *3***	**102.0 *20***	**100**	**(E3)**	**155**	**0.388**	**0.361**	**7.0%**

NuDat search: M3 α_K cases of transitions having $\Delta_K > 5\%$

Nucleus	E_{level}(keV)	Jπ	$T_{1/2}$	E_γ(keV)	I_γ	γ mult.	γ conv. coeff.			
58CO	24.95 *6*	5+	9.10 h *9*	24.889 *21*	100	M3	2.52E3	1840	1754	4.7%
94NB	40.892 *12*	3+	6.263 m *4*	40.90 *5*	100	M3	1366	766	731	4.6%
96TC	34.23 *4*	4+	51.5 m *10*	34.20 *5*	100	M3	3.79E3	1694	1595	5.8%
100RH	**107.60 *20***	**(5+)**	**4.6 m *2***	**32.7 *2***	**0.11**	**[M3]**	**5.76E3 *20***	**2070**	**1930**	**6.8%**
104RH	**128.9679 *5***	**5+**	**4.34 m *3***	**31.866 *2***	**0.0279 *23***	**M3**	**6846**	**2236**	**2080**	**7.0%**
130I	**39.952 *1***	**2+**	**8.84 m *6***	**39.954 *2***	**100**	**M3**	**4.94E3**	**1154**	**1068**	**7.5%**
132LA	188.20 *11*	6-	24.3 m *5*	52.8 *1*	13.5 *10*	M3	1770	555	523	5.8%
144PR	59.03 *3*	3-	7.2 m *3*	59.03 *3*	100	M3	1258	408	387	5.1%
168HO	**≈59**	**(6+)**	**132 s 4**	**≈59**	**100**	**(M3)**	**2.41E3**	**335**	**308**	**8.1%**

NuDat search: E4 and M4 α_K cases of transitions having $\Delta_K > 5\%$

Nucleus	E_{level}(keV)	Jπ	$T_{1/2}$	E_γ(keV)	I_γ	γ mult.	γ conv. coeff.			
148PM	**137.9 *3***	**5-,6-**	**41.29 d *11***	**62.2 *5***		**E4**	**1.23E4**	**30.8**	**28.7**	**6.8%**
179W	221.91 *3*	1/2-	6.40 m *7*	101.6 *5*	0.0088 *8*	[E4]	1.32E3 *5*	4.09	3.88	5.1%
93NB	**30.77 *2***	**1/2-**	**16.12 y *12***	**30.77 *2***	**100**	**M4**	**1.693E5**	**26000**	**23900**	**8.1%**
95TC	38.91 *4*	1/2-	61 d *2*	38.9 *1*	100	M4	5.17E4 *11*	11580	10840	6.4%
108AG	**109.466 *7***	**6+**	**438 y *9***	**30.332 *8***	**100**	**M4**	**4.31E5**	**11130**	**9830**	**11.7%**
184RE	**188.0463 *17***	**8(+)**	**169 d *8***	**83.3067 *8***	**100 *4***	**M4**	**1.346E4**	**254**	**235**	**7.5%**
198AU	811.7 *15*	(12-)	2.272 d *16*	115.2 *15*	100	(M4)	2.49E3 *22*	185	176	4.9%
193HG	140.76 *5*	13/2(+)	11.8 h *2*	101.25 *4*	100	M4	6.06E3	170.4	159.5	6.4%
199HG	532.48 *10*	13/2+	42.67 m *9*	118.6	8.00E-05	M4	2310	167.8	159.5	4.9%
196TL	394.2 *5*	(7+)	1.41 h *2*	120.1 *3*	100	M4	2.30E3 *5*	155.5	147.7	5.0%

Most relevant candidates to conclude the α_K(exp) series: NuDat selection

1. ***$_{71}^{171m}$Lu, Δ_K=8.3%***

   71.1-keV E3, single IT γ , $T_{1/2}$=79 s, (p,n), (p,2n); α_K(exp)=3.0(10) (1965Bj01)

   ^{171}Lu g.s. ε, $T_{1/2}$=8.2 h, ($\lambda \times I_{Kx}$)(g.s./m.s.)=4.2(3)%

2. ***$_{53}^{130m}$I, Δ_K=7.5%***

   40.0-keV M3, single IT γ , $T_{1/2}$=8.8 m %IT=84%, (p,n), (n_{th},γ); no α_K(exp)

   ^{130}I g.s. β^-, $T_{1/2}$=12.4 h, ($\lambda \times I_{Kx}$)(g.s./m.s.)=0.100(4)%

   ^{130m}I %β^-=16, negligible Kx rays

3. ***$_{41}^{93m}$Nb, Δ_K=8.1%***

   30.8-keV M4, single IT γ, $T_{1/2}$=16.1 y, (p,n), (p,α), (^{3}He,d), (α,p), (α,d); α_K(exp)=25800(1500) (5.8%) (1965Bj01)

   NbKx rays: 16.5 – 19 keV (very low for HPGe detector)

Most relevant candidates to conclude the α_K(exp) series: 2002Ra45 selection

4. ***$_{50}^{117m}$Sn, Δ_K=2.1%, α_K(exp)=30.2(15), %unc=5.0%***

156.0-keV M4 IT γ, $T_{1/2}$=14.0 d, (n_{th},γ)

158.6 M1(+E2) γ, α_K(M1)/α_K(M4)=4.7%

5. ***$_{52}^{125m}$Te, Δ_K=3.2%, α_K(exp)=167(7) (2002Ra45), %unc=4.2%***

109.3-keV M4 IT γ, $T_{1/2}$=57.4 d, (n_{th},γ), *α_K(FO)=185, α_K(NH)=179*

30.5 M1+E2, δ=0.031(3) γ, α_K(M1+E2)/α_K(M4)=6.3%

6. ***$_{52}^{123m}$Te, Δ_K=3.7%, α_K(exp)=455(9) (in ENSDF; NOT in 2002Ra45), %unc=2.0%***

88.5-keV M4 IT γ, $T_{1/2}$=119.2 d, (n_{th},γ), *α_K(FO)=481, α_K(NH)=463*

159.0 M1+E2, δ=+0.062(6) γ, α_K(M1+E2)/α_K(M4)=0.03%

7. ***$_{52}^{129m}$Te, Δ_K=2.8%, α_K(exp)=213(10) (2002Ra45), %unc=4.7***

105.5-keV M4 γ, %IT=63(17), $T_{1/2}$=33.6 d, (n_{th},γ), *α_K(FO)=217, α_K(NH)=211*

also %β^-(m.s.)=17(17), I(Kx,m.s.β^-)/I(Kx,IT)«1

^{129}Te g.s. $T_{1/2}$=69.6 m, I(Kx,g.s.β^-)/I(Kx,IT)=0.51(14)%