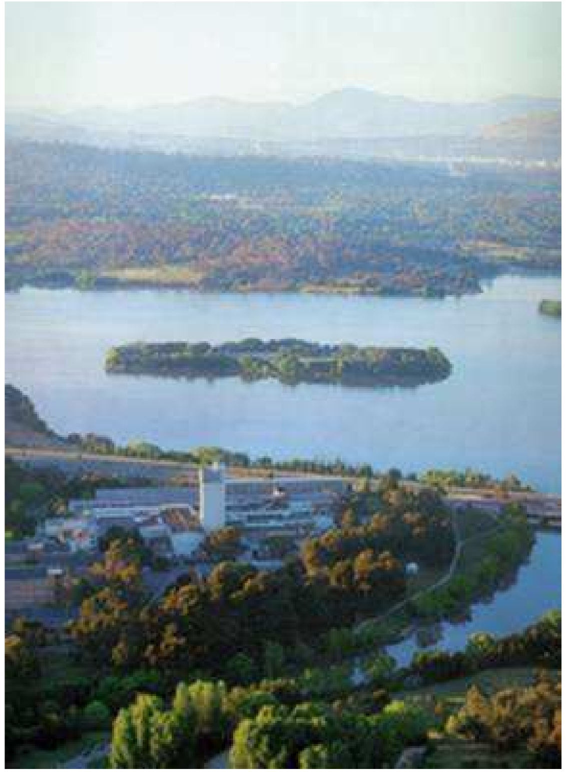
Experimental techniques to deduce J^π



T. Kibédi

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Canberra, Australia

Workshop on
"Nuclear Structure and Decay Data:
Theory and Evaluation"
Trieste, Italy, 2006

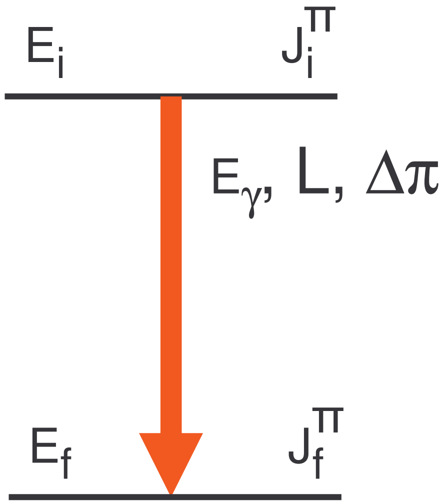
Outline:

<u>Lecture I:</u> ***Experimental techniques to deduce J^{π} from***

- ***Angular distributions and correlations***
- ***Directional Correlations from Oriented nuclei (DCO)***
- ***Gamma-ray linear polarizations***
- ***Internal conversion coefficients***

<u>Lecture II:</u> ***New developments in characterizing nuclei using separators***

Electromagnetic Decay and Nuclear Structure



Multipolarity known

ΔJ may not be unique

$\Delta\pi$ unique

Energetics of γ-decay:

$$E_i = E_f + E_\gamma + T_r$$

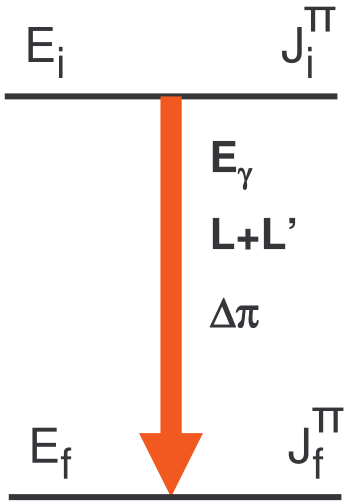
$$0 = p_R + p_\gamma$$

where $T_R = (p_R)^2/2M$; usually $T_R/E_\gamma \sim 10^{-5}$

Angular momentum and parity selection rules & multipolarities

$\lvert J_i - J_f\rvert \le L \le \lvert J_i + J_f\rvert$	$L \neq 0$
$\Delta\pi$ = no	M1, E2, M3, E4, …
$\Delta\pi$ = yes	E1, M2, E3, M4, …
$\lvert J_i - J_f\rvert \le L \le \lvert J_i + J_f\rvert$	$L \neq 0$
$\Delta\pi$ = unknown	D, Q, O, H, ...
$J_i = J_f$	$L = 0$
$\Delta\pi$ = no;	E0

More on EM transitions



Mixed multipolarity & Mixing ratio

$$\delta(\pi`L`/\pi L) = I_\gamma(\pi`L`) \; / \; I_\gamma(\pi L)$$

$$I\gamma = I\gamma(\pi L) + I\gamma(\pi' L')$$

Or in terms of transition probability

$$\lambda_\gamma = \lambda_\gamma(\pi L) + \lambda_\gamma(\pi' L')$$

Total transition probability

$$\lambda_T = \lambda_\gamma + \lambda_{CE} + \lambda_\pi + \lambda_{\gamma\gamma} + \ldots$$

λ_{CE} – conversion electrons, K,L1,L2… shells

λ_π – electron-positron pair production; $E_\gamma > 2\ m_oc^2$

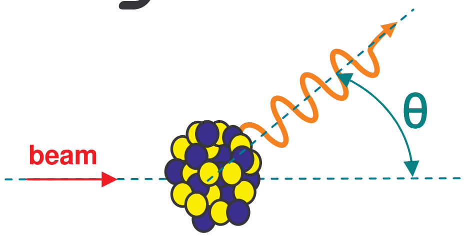
$\lambda_{\gamma\gamma}$ – 2 photon emission; very rare (10^{-5})

Determining transition multipolarity

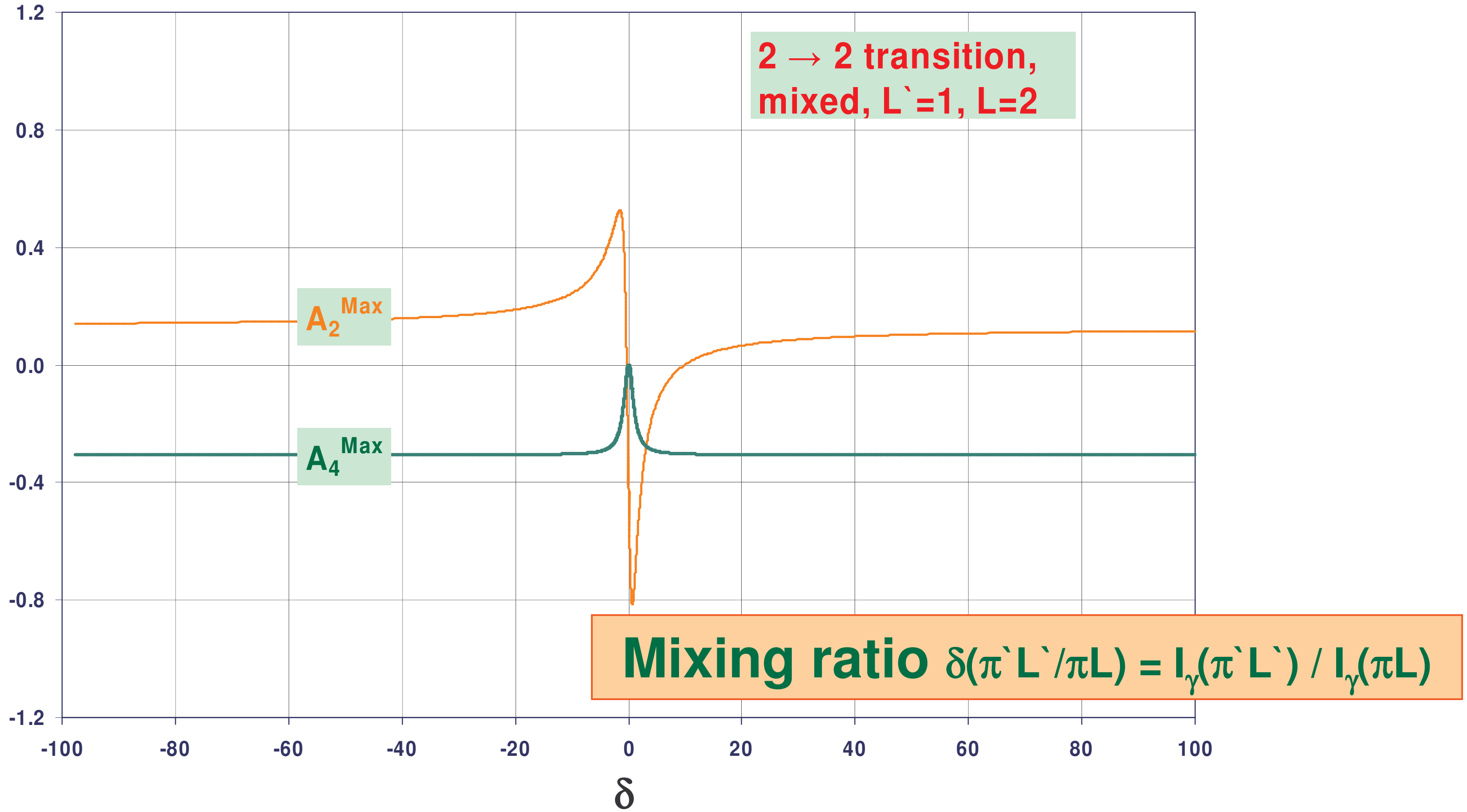
➢ **Gamma-rays**	Angular distribution with spins oriented Angular correlations Polarization effects
➢ **Conversion electrons**	Electron conversion coefficients E0 (L=0) transitions
➢ **Electron positron pairs**	Pair conversion coefficients

NATURAM PRIMUM COGNOSCERE RERUM

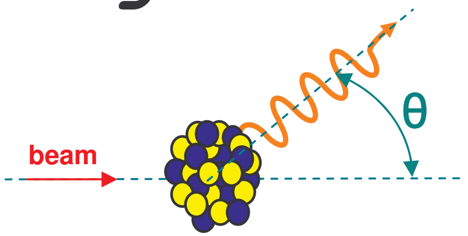
Angular distributions of Gamma-rays



$$W(\theta) = 1 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$$



Angular distributions of Gamma-rays



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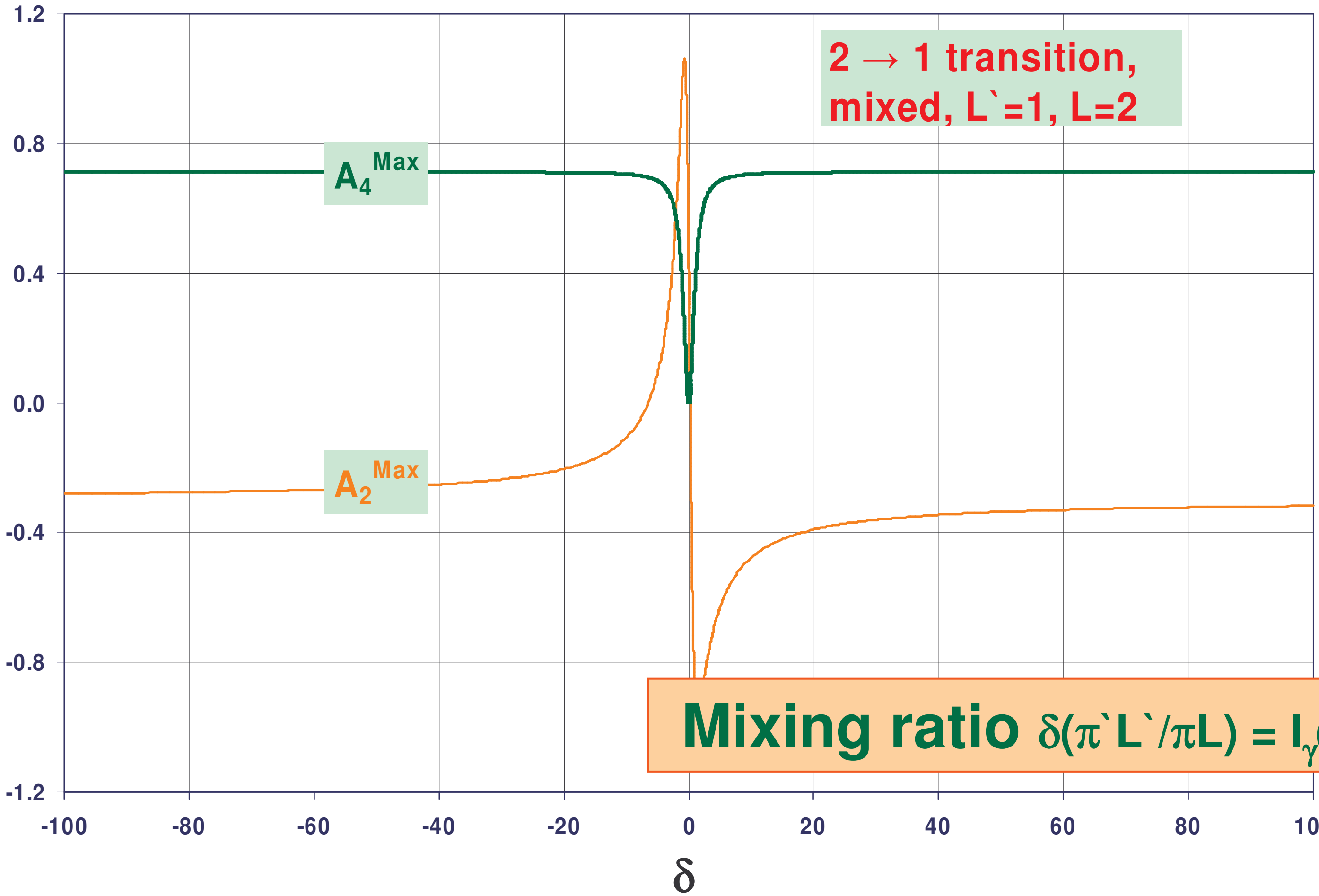


Mixing ratio $\delta(\pi`L`/\pi L) = I_\gamma(\pi`L`) / I_\gamma(\pi L)$

Angular distributions of Gamma-rays

$$W(\theta) = 1 + A_{22} P_2(\cos\theta) + A_{44} P_4(\cos\theta)$$

Attenuation due to relaxation of nuclear orientation

$$0 \le A_{kk} \le A_k^{\max}(J_i, J_f, L); k = 2,4...$$

$$A_k^{\max}(J_i, J_f, L) = \frac{F_k(LLJ_fJ_i) + 2\delta \times F_k(LL+1J_fJ_i) + \delta^2 \times F_k(L+1L+1J_fJ_i)}{1+\delta^2}$$

*For **$F_k(LL`J_fJ_i)$** see E. Der Mateosian and A.W. Sunyar, ADNDT 13 (1974) 407*

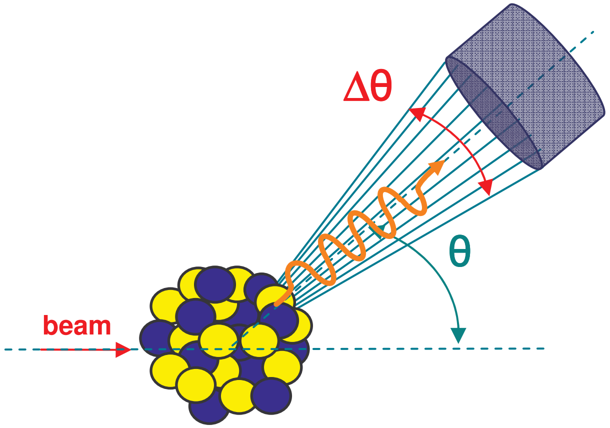
$$A_{kk} = B_k(J_i) \times A_k^{\max}(J_i, J_f, L)$$

Nuclear orientation can be achieved

- **by interaction of external fields (E,B) with the static moments of the nuclei at low temperatures**
- **by nuclear reaction**

Attenuation of angular distributions

Detector finite size (Δθ): solid angle attenuation



Beam defines a symmetry axis

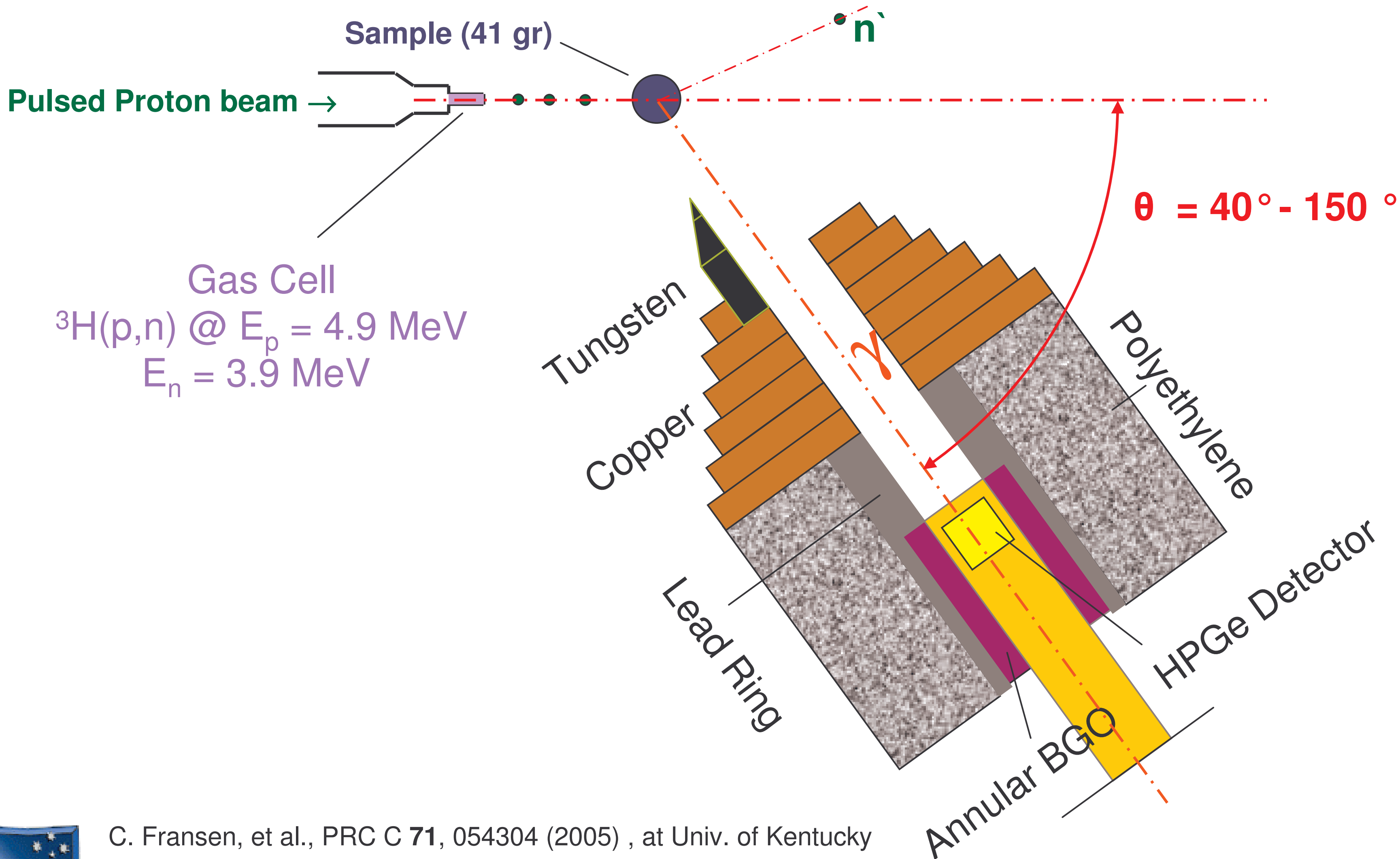
$$W(\theta) = 1 + \Sigma_{k=2,4} Q_k \times B_k(J_i) \times A_k^{\max}(J_i, J_f, L, \delta)$$

where $B_k(J)$ is the statistical tensor

$$B_k(J_i) = \sum_{m=-J_i}^{+1} (-1)^{J_i+m} \sqrt{(2k+1)(2J_i+1)} \times \begin{pmatrix} J_i & J_i & k \\ -m & m & 0 \end{pmatrix} \times \underbrace{\frac{Exp(-m^2/2\sigma^2)}{\sum_{m=-1}^{J_i} Exp(-m^2/2\sigma^2)}}_{\text{Approximation with Gaussian distribution}}$$

Approximation with Gaussian distribution

Angular distributions of Gamma-rays (n,n`) reaction on ^{92}Zr



C. Fransen, et al., PRC C **71**, 054304 (2005) , at Univ. of Kentucky

Figure courtesy of S.W. Yates

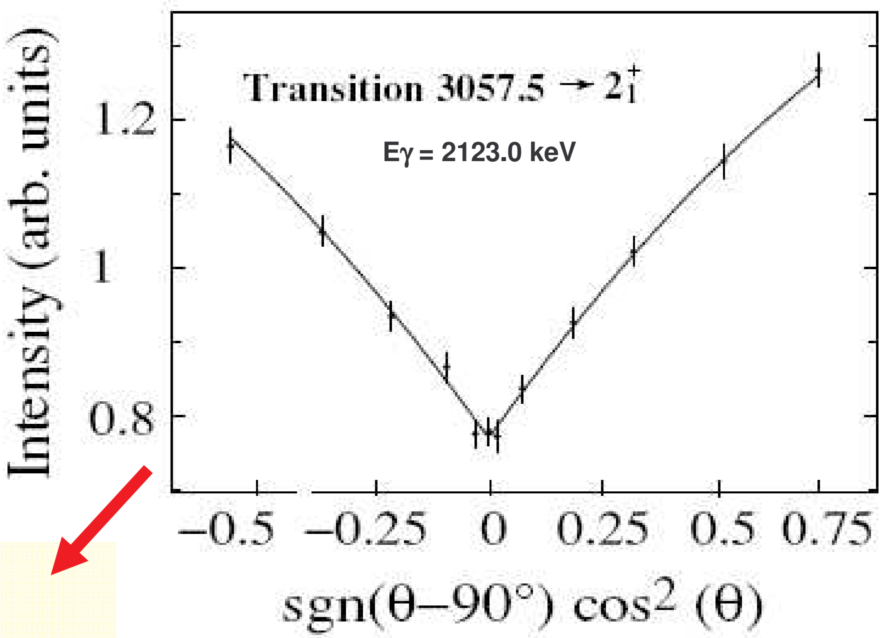
Angular distributions of Gamma-rays

^{92}Zr(n,n`) reaction

12 angles and

12 hours / angle

γ-spectrometer at 1.4 m



C. Fransen, et al., PRC C **71**, 054304 (2005), at Univ. of Kentucky

Fit to data

$$W(\theta) = A_0 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$$

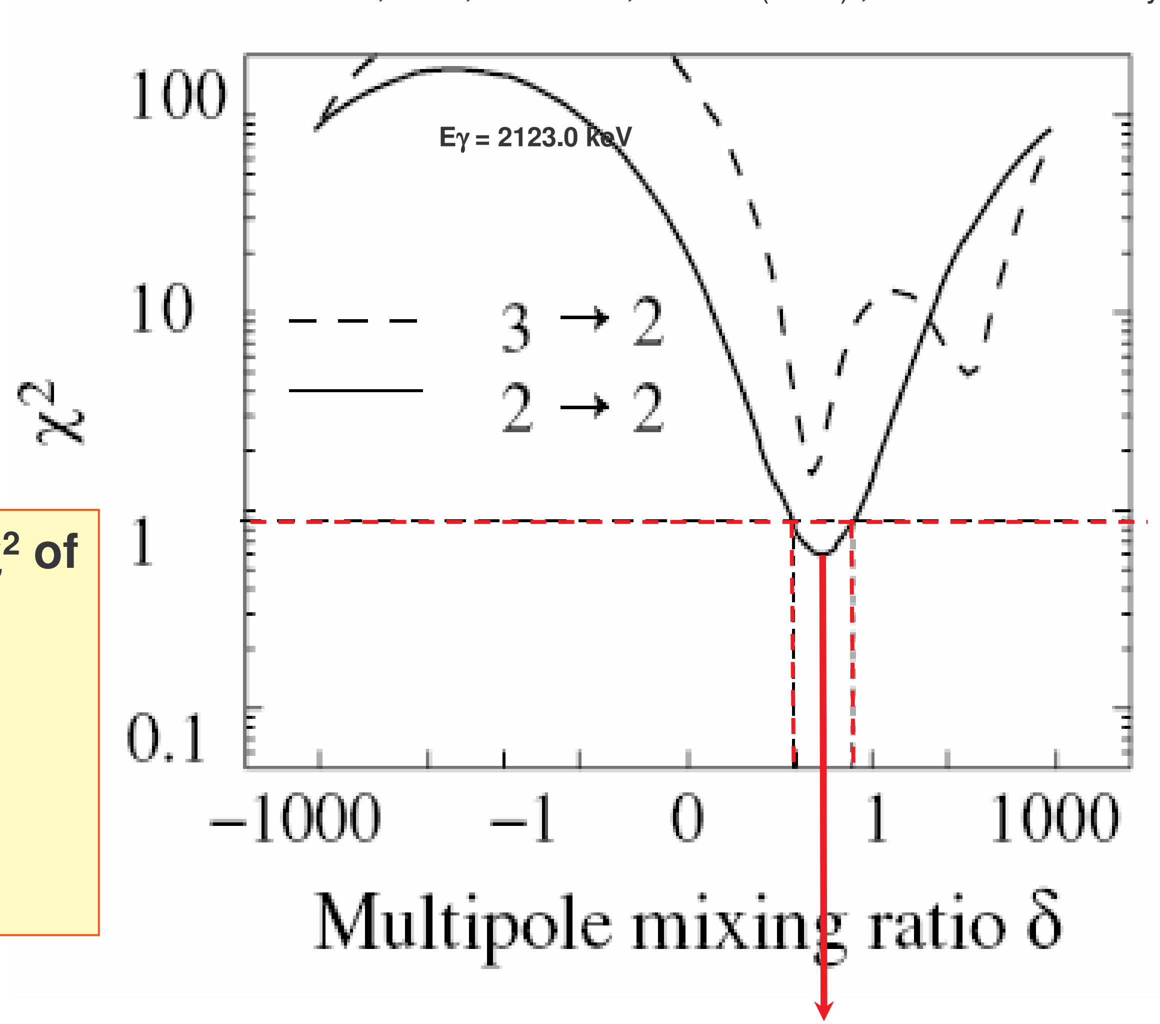
Deduced $A_2 = A_{22}/A_0$

$A_4 = A_{44}/A_0$

Typical values	A_2	A_4
ΔJ=2 (stretched quadrupole)	**+0.3**	**-0.1**
ΔJ=1 (stretched dipole)	**-0.2**	**0**
ΔJ=1, D+Q	**+0.5 to -0.8**	**>0**

Angular distributions – mixing ratio

C. Fransen, et al., PRC C **71**, 054304 (2005) , at Univ. of Kentucky



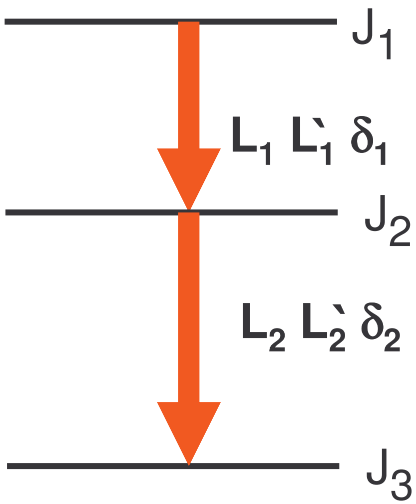
Mixing ratio, δ deduced from χ^2 of

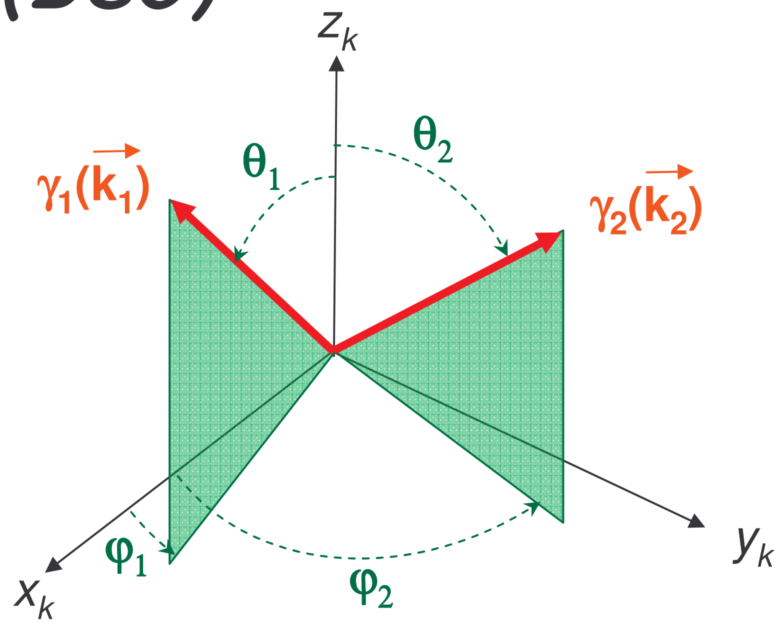
$$\frac{W_{\exp}(\theta)}{W_{calc}(\theta)}$$ **as a function of δ**

But no information on Electric or Magnetic character E1+M2 or M1+E2

δ= 0.69(16) (D+Q)

Directional Correlations from Oriented nuclei (DCO)





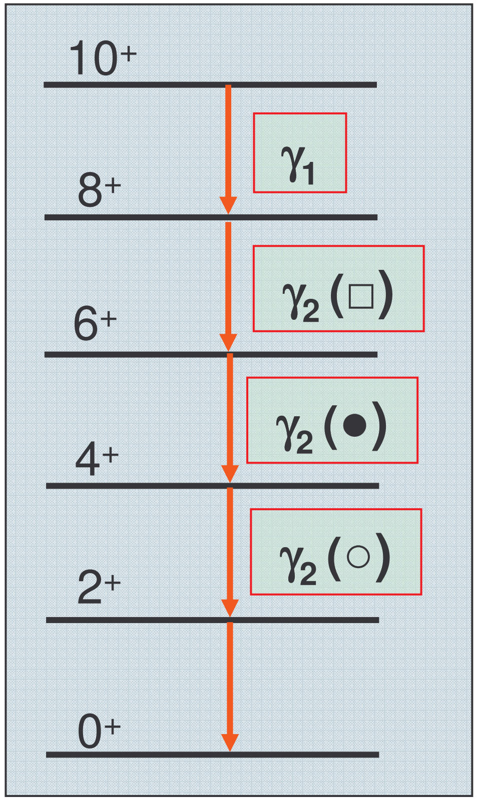
For a $J_1 \rightarrow J_2 \rightarrow J_3$ cascade *(see A.E. Stuchbery, Nucl. Phys.* ***A723*** *(2003) 69)*

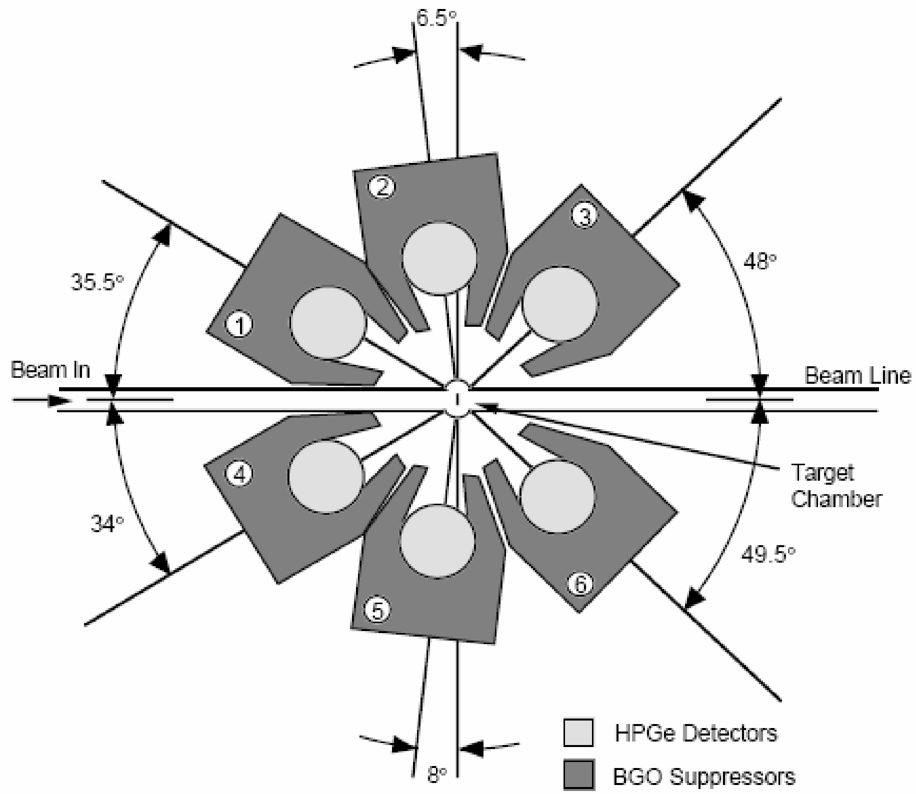
$$W(\theta_1,\varphi_1,\theta_2,\varphi_2) = \sum_{k,q,k_1,q_1,k_2,q_2} \rho_{k_1 q_1}(J_1)(-1)^{k_1+q_1}\sqrt{(2k+1)(2k_1+1)}\begin{pmatrix} k_1 & k & k_2 \\ -q_1 & q & q_2 \end{pmatrix}$$
$$\times A_k^{k_2 k_1}(\delta_{\gamma 12} L L' J_2 J_1) Q_k(E_{\gamma 12}) D_{q0}^{k*}(\varphi_1,\theta_1,0)$$
$$\times A_{k2}(\delta_{\gamma 23} L L' J_3 J_2) Q_{k_2}(E_{\gamma 23}) D_{q_2 0}^{k_2 *}(\varphi_2,\theta_2,0)$$

Directional Correlations from Oriented nuclei (DCO) – example

^{184}Pt from ^{nat}Gd + ^{29}Si @ 145 MeV CAESAR array (ANU)

M.P. Robinson et al., Phys. Lett B530 (2002) 74





Directional Correlations from Oriented nuclei (DCO) - example

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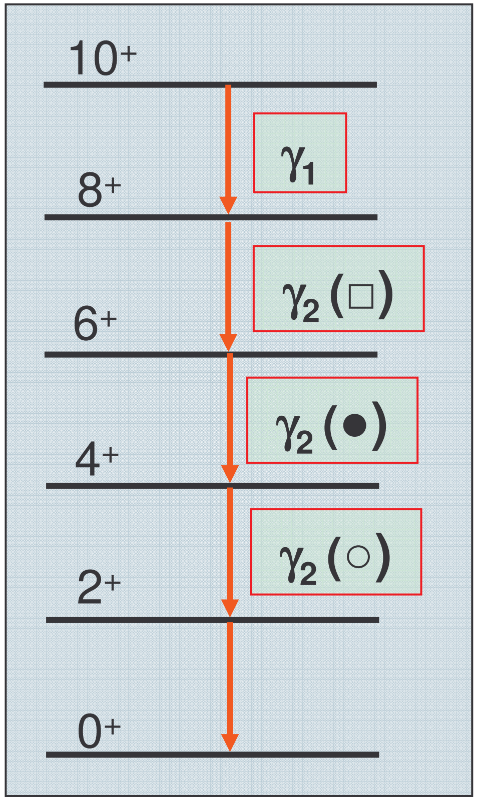
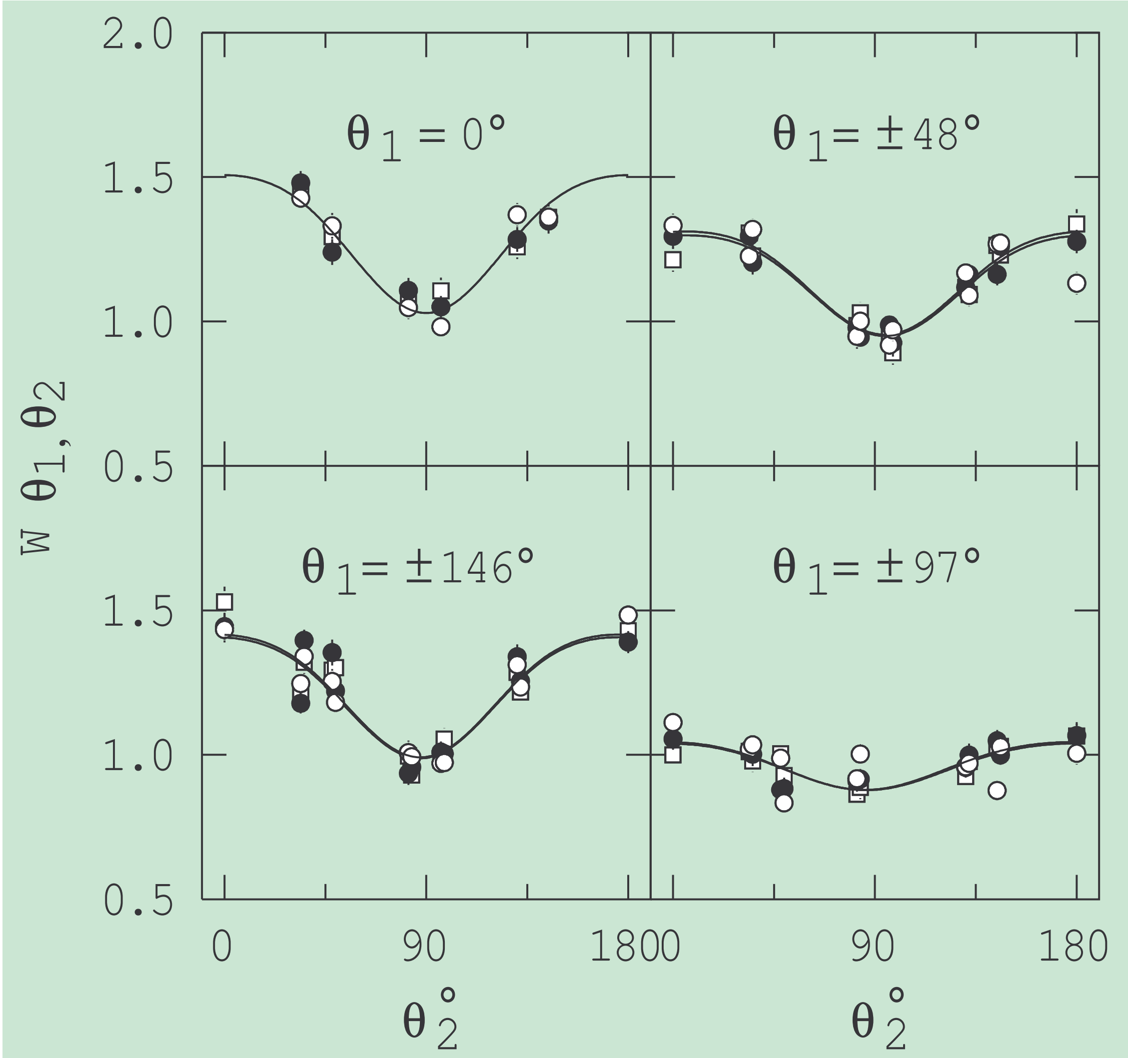
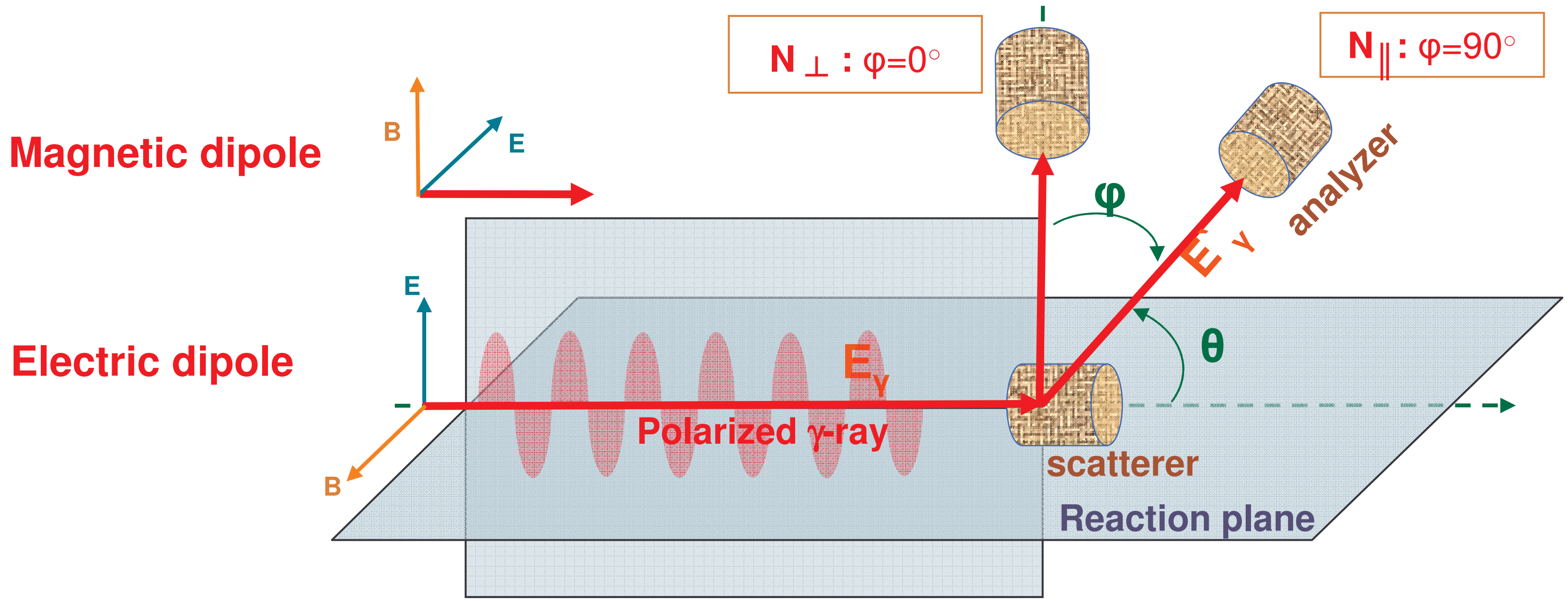
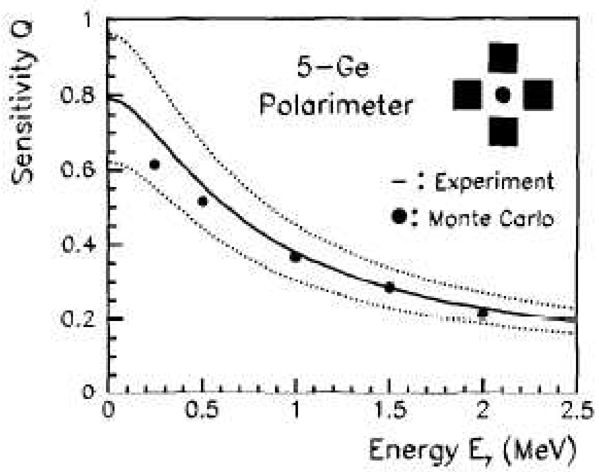




Gamma-ray linear polarization

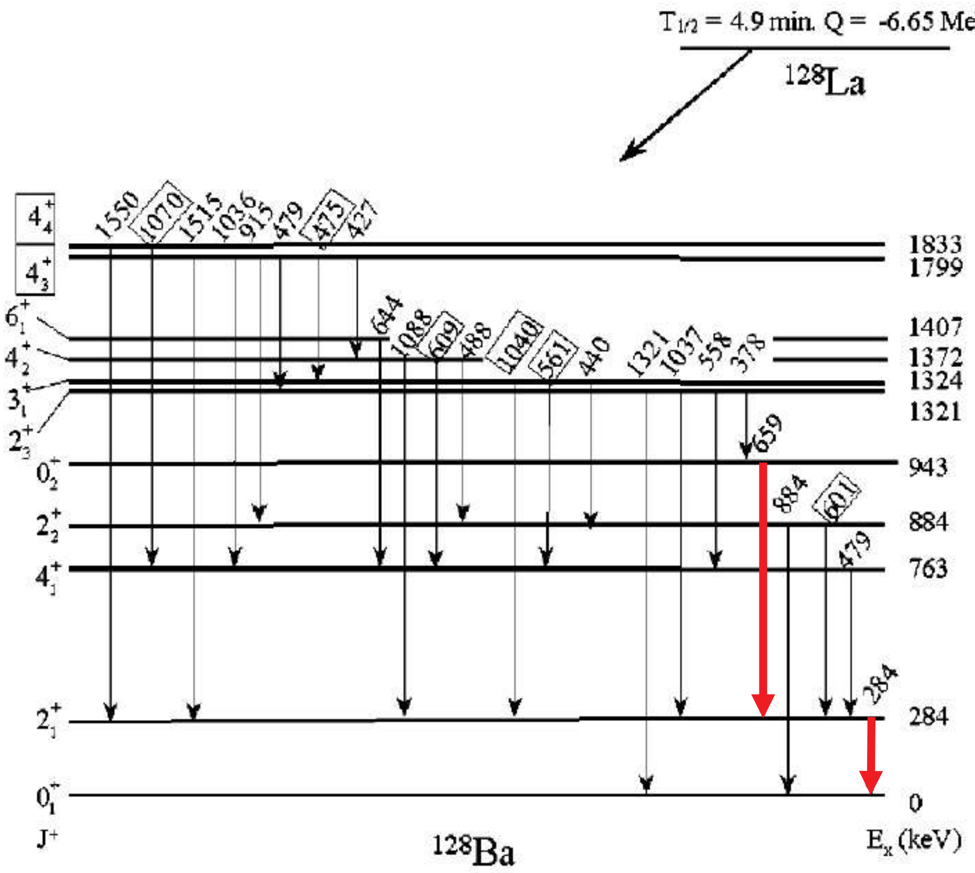




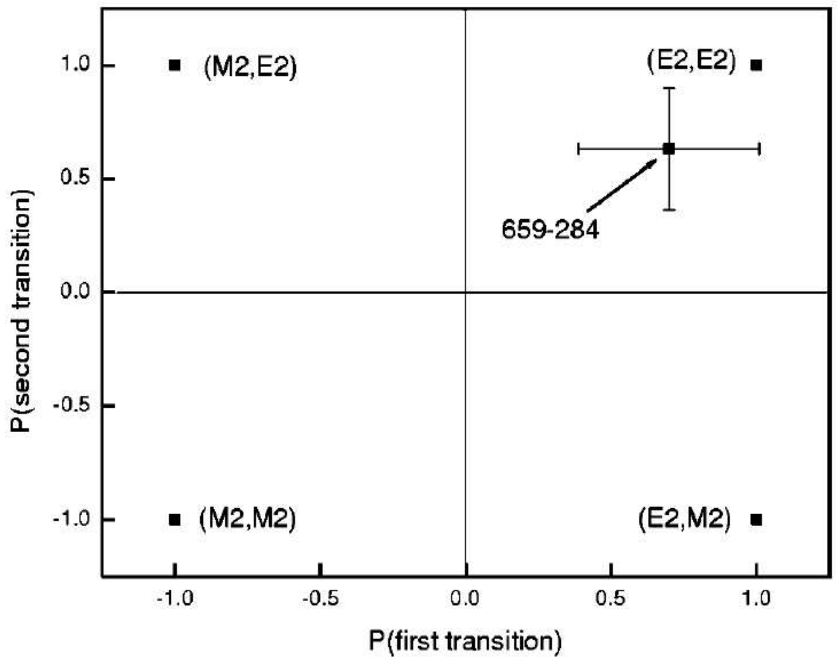
L.M. Garcia-Raffi, et al. NIM ***A391*** *(1997) 461*

Compton-scattering	$E_{\gamma'} = \dfrac{E_\gamma}{1+\alpha(1-\cos\theta)}$ with $\alpha = \dfrac{E_\gamma}{m_\circ c^2}$
Klein-Nishina formula	$\dfrac{d\sigma}{d\Omega} = \dfrac{1}{2} r_\circ^2 \dfrac{E_{\gamma'}^2}{E_\gamma^2}\left(\dfrac{E_{\gamma'}}{E_\gamma} - \dfrac{E_\gamma}{E_{\gamma'}} - 2\sin^2\theta\cos^2\varphi\right)$
Polarization	$P = A / Q$
Asymmetry	$A = (N_\perp - N_\parallel) / (N_\perp + N_\parallel)$
Polarization sensitivity	Q

Gamma-ray linear polarization – example

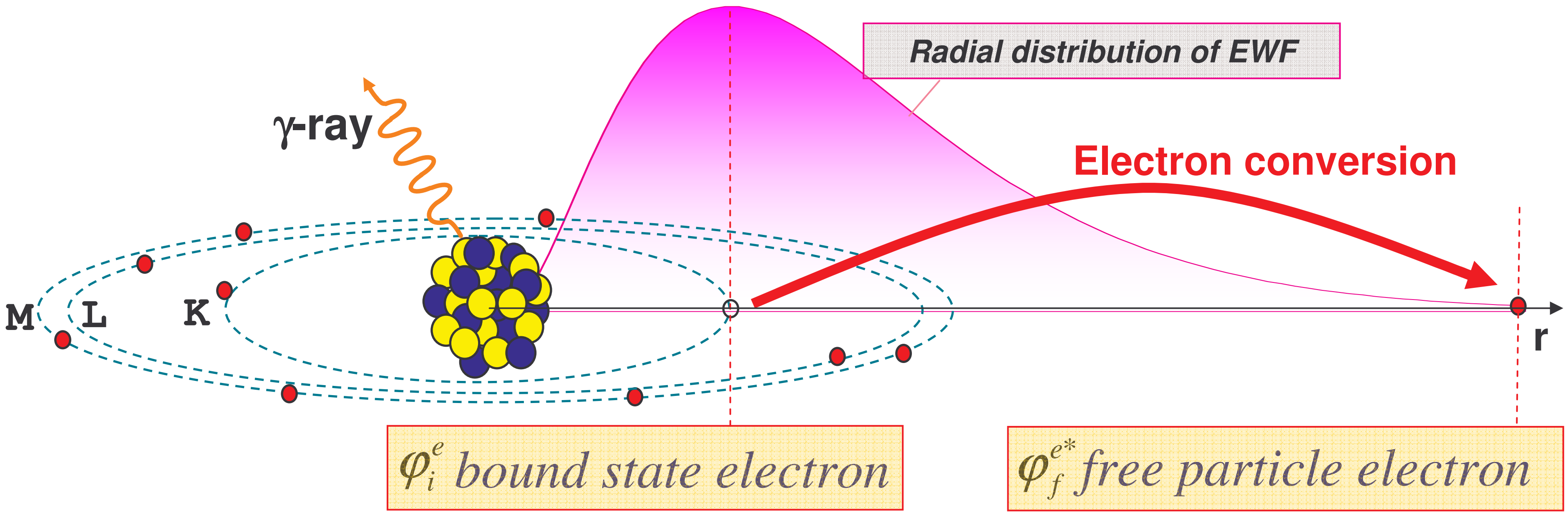


659–284 keV, $0_2 \rightarrow 2_1 \rightarrow 0_1$



A. Wolf, *et al. Phys. Rev.* C **66**, 024323 (2002)

Conversion electrons (CE)



Energetics of CE-decay (i=K, L, M,….)

$E_i = E_f + E_{ce,i} + E_{BE,i} + \cancel{T_r}$

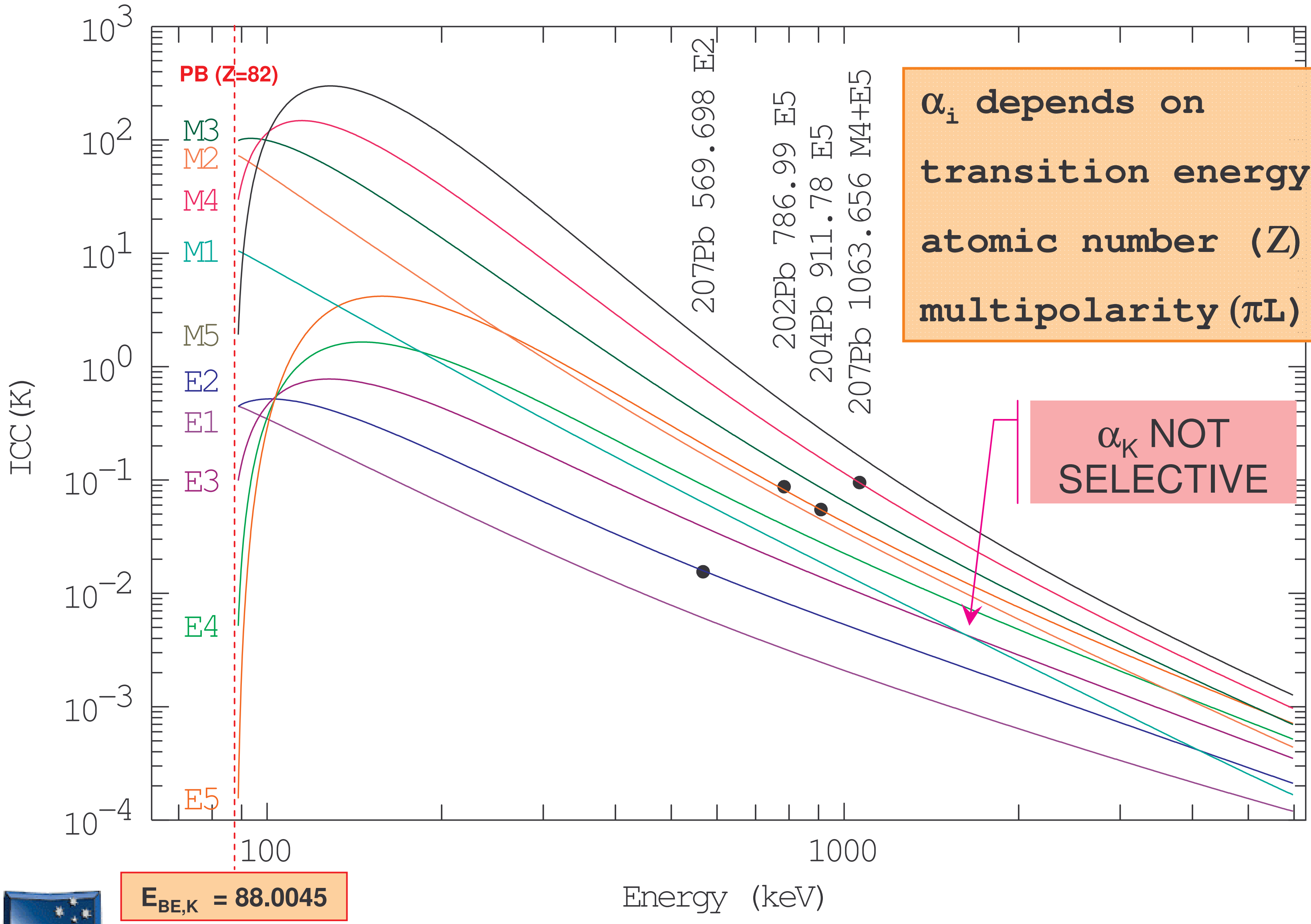
γ- and CE-decays are independent; transition probability (λ ~ Intensity)

$$\lambda_T = \lambda_\gamma + \lambda_{CE} = \lambda_\gamma + \lambda_K + \lambda_L + \lambda_M \ldots\ldots$$

Conversion coefficient

$$\alpha_i = \lambda_{CE,i} / \lambda_\gamma$$

Sensitivity to multipolarity



α_i depends on transition energy ($E\gamma$), atomic number (Z) and multipolarity (πL)

The physics of conversion coefficients

$$\alpha_K \equiv \frac{\lambda_{e,K}}{\lambda_\gamma}$$

$$\lambda_e = \frac{2\pi}{\hbar}\left|m_{fi}\right|^2 \frac{d\rho}{dE}$$ *Fermi's golden rule*

Density of final electron state (continuum)

$$m_{fi} = \psi_f^{N*} \quad \varphi_f^{e*} \quad F_{\ell,m} \quad \psi_i^N \quad \varphi_i^e$$

Nuclear

Electron

Multipolar source

Same for γ and CE

φ_i^e *bound state electron*

φ_f^{e*} *free particle electron*

Theoretical Conversion Coefficients

Current tabulations:

- **Hager and Seltzer** (1968)

  Relativistic Hartree-Fock-Slater, WITH Hole, NO dynamic effect

  Z=30-103; K, L, M only; limited energy range

- **Rösel-Fries-Pauli** (1978)

  Relativistic Hartree-Fock-Slater, NO Hole, NO dynamic effect

  Z=30-104; All shells; wider energy range

- **Band-Trzhaskovskaya** (1978)

  Relativistic Hartree-Fock-Slater, WITH Hole, WITH dynamic effect

  Z=10-104; K, L, M; wider energy range

- **Band-Trzhaskovskaya-Nestor-Tikkanen-Raman** (2002)

  Relativistic Dirac-Fock, NO Hole, WITH dynamic effect

  Z=10-126; ALL shells; wider energy range

- **BrIcc** (2005)

  Relativistic Dirac-Fock, With Hole, WITH dynamic effect

  Z=10-95; ALL shells; improved accuracy

Higher order and atomic effects

- Atomic many body correlations: factor ~2 for $E_{kin}(ce) < 1$ keV (BrIcc single particle approximation)
- Partially filled valence shell: non-spherical atomic field
- Shake effect: increases ICC
- Resonance Internal conversion: $E_{kin}(ce) \approx BE$
- Binding energy unc.: <0.5% for $E_{kin}(ce) > 10$ keV
- Chemical effects: <<1%
- Penetration:
  n s1/2 shells (K, L1, M1,..); M1, M2, M3.. multipolarities
  For M1 transition:
  0.01% (Z=10)
  ~15% (Z=112)

Mixed multipolarity and E0 transitions

$$\delta^2 = \frac{I_\gamma(E2)}{I_\gamma(M1)} \qquad \alpha^{M1/E2} = \frac{\alpha_{M1} + \delta^2 \alpha_{E2}}{1+\delta^2}$$

In some cases the mixing ratio can be deduced

$$\delta^2 = \frac{\alpha_{M1} - \alpha^{\exp}}{\alpha^{\exp} - \alpha_{E2}}$$

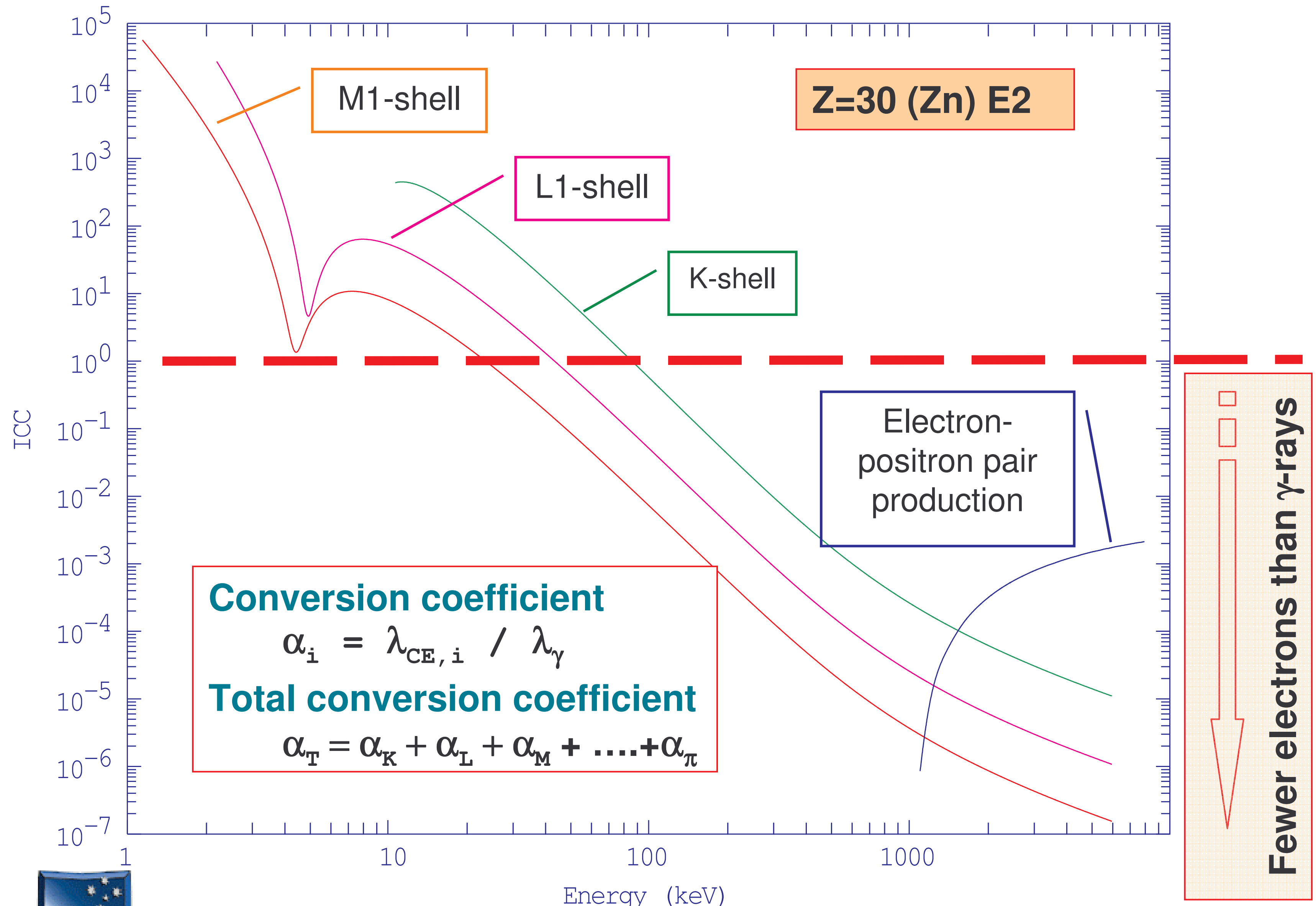
E0 transitions – pure penetration effect; no γ-rays ($I_\gamma=0$)

$$\alpha = \frac{I_{CE}}{I_\gamma} = \infty$$

- **Pure E0 transition: $0^+ \rightarrow 0^+$ or $0^- \rightarrow 0^-$**
- **$J \rightarrow J$ ($J\neq 0$) transitions can be mixed E0+E2+M1**

$$\alpha = \frac{I_{CE}(E0) + I_{CE}(E2) + I_{CE}(M1)}{I_\gamma(E2) \quad + I_\gamma(M1)}$$

More on conversion coefficients



Conversion coefficient

$$\alpha_i = \lambda_{CE,i} / \lambda_\gamma$$

Total conversion coefficient

$$\alpha_T = \alpha_K + \alpha_L + \alpha_M + \dots + \alpha_\pi$$

Measuring conversion coefficients – methods

- NPG: normalization of relative CE ($I_{CE,i}$) and γ (I_γ) intensities via intensities of one (or more) transition with known α

$$\alpha_i = \frac{I_{CE,i}}{I_\gamma} \times \left[\frac{I_\gamma^*}{I_{CE}^*} \times \alpha^* \right]_{KNOWN}$$

- CEL: Coulomb excitation and lifetime measurement

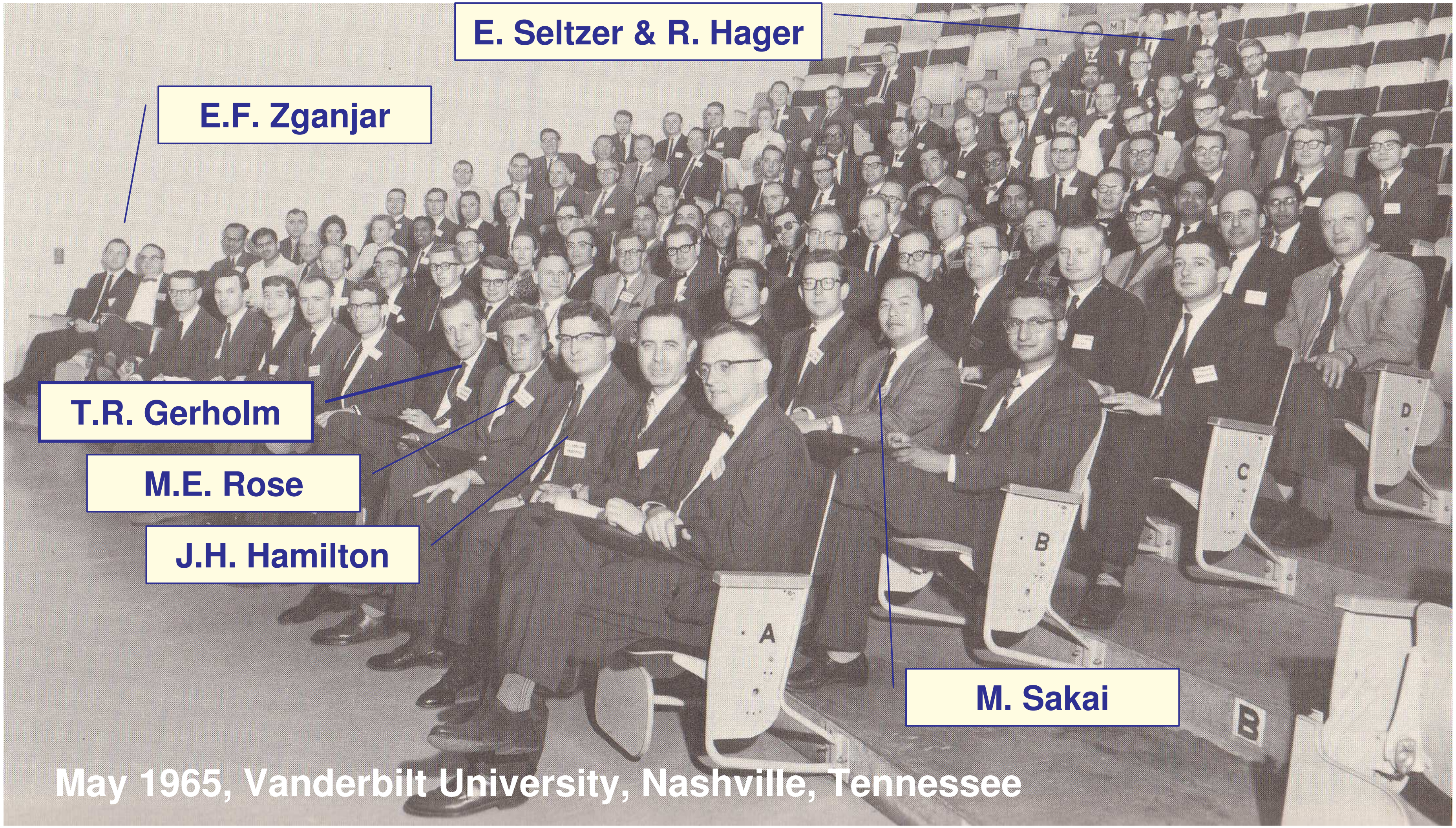
$$\alpha_T = \frac{2.829 \times 10^{11} \times E_\gamma^{-5}(keV)}{B(E2)\uparrow(e^2b^2) \times T_{1/2}(ns)} - 1$$

- XPG: intensity ratio of K X-rays to γ-rays with K-fluorescent yield, ω_K

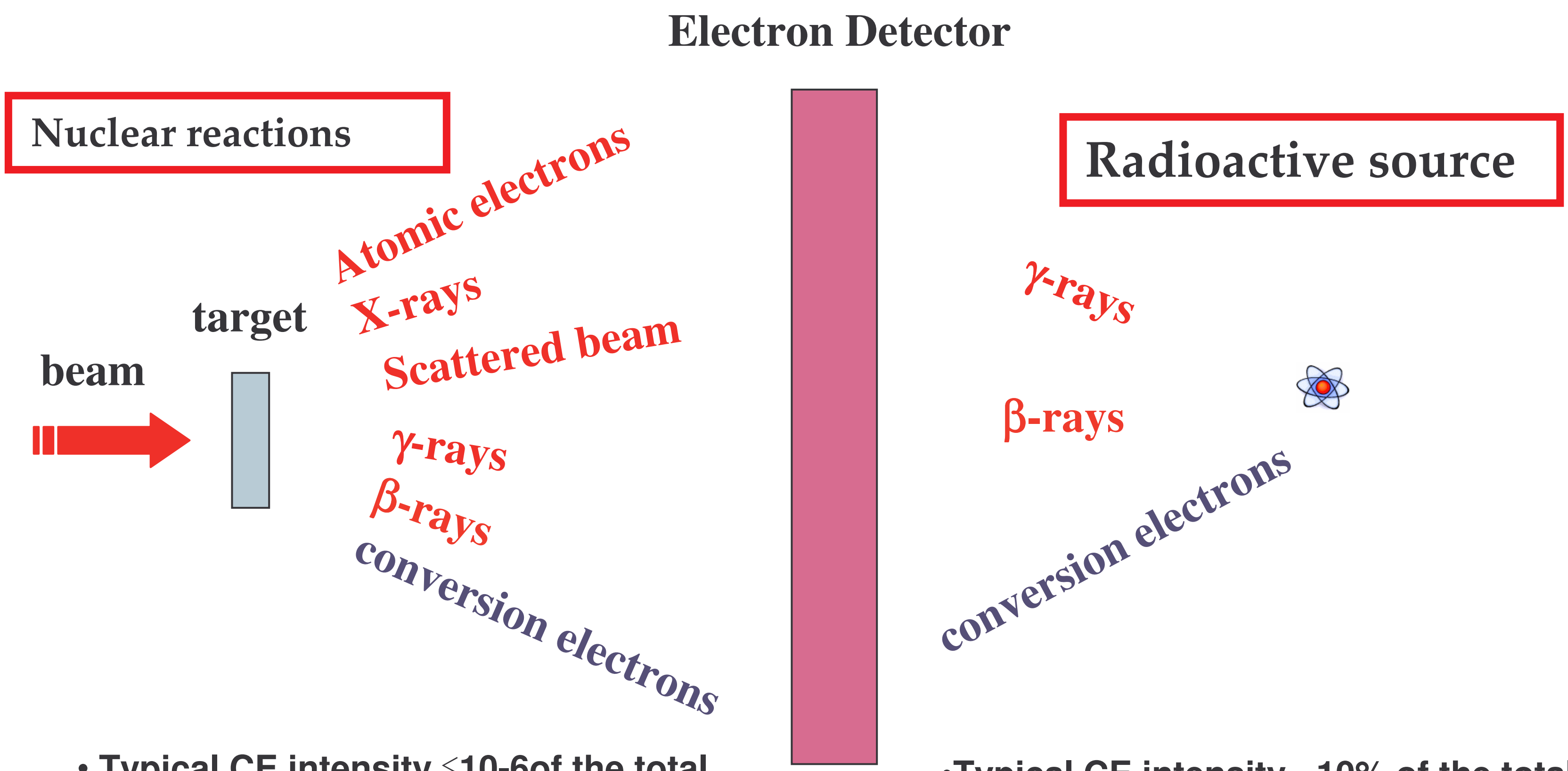
$$\alpha_K = \frac{I_{KX}}{I_\gamma} \times \frac{1}{\omega_K}$$

And many more, see Hamilton`s book

Internal Conversion Process – The Pioneers



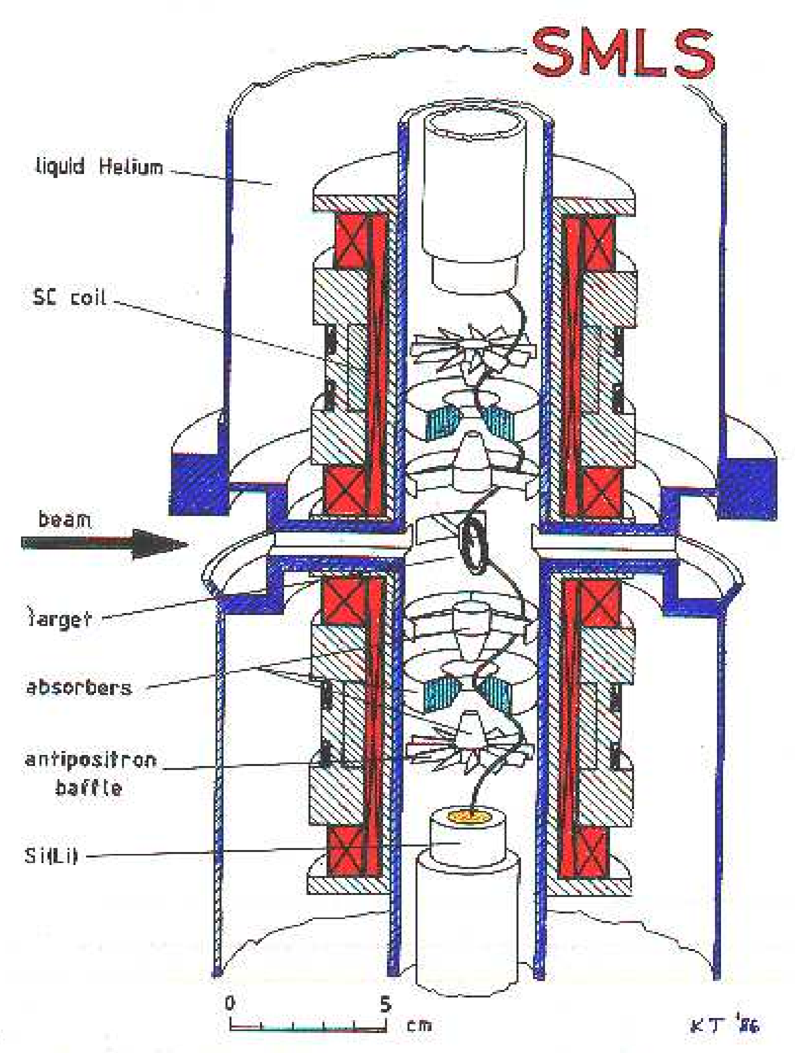
Direct ICC measurements



- Typical CE intensity $\lesssim 10^{-6}$of the total *(scattered beam excluded)*
- *Energy resolution affected by absorption in target; FWHM for a Si(Li): 3-5 keV*
- *Angular distribution of conversion electrons – usually neglected(?)*
- *Typical* $\Delta\alpha/\alpha$ ~10–20%

- Typical CE intensity ~10% of the total
- Thin source, better energy resolution; *FWHM for a Si(Li): 1.6-2.5 keV*
- *No/attenuated angular distribution*
- *Typical* $\Delta\alpha/\alpha$~*5-10%*

Basic electron transporters

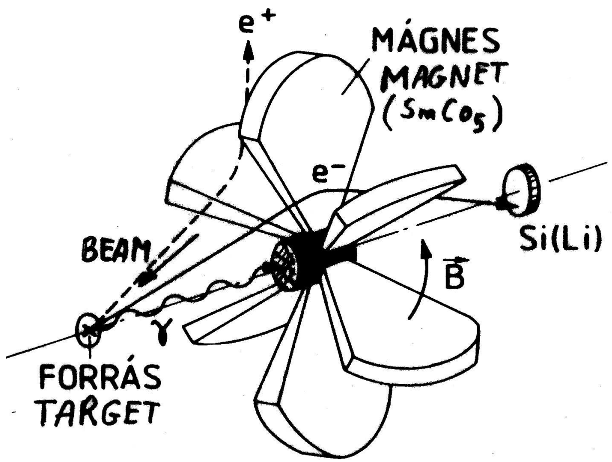


Superconducting solenoid

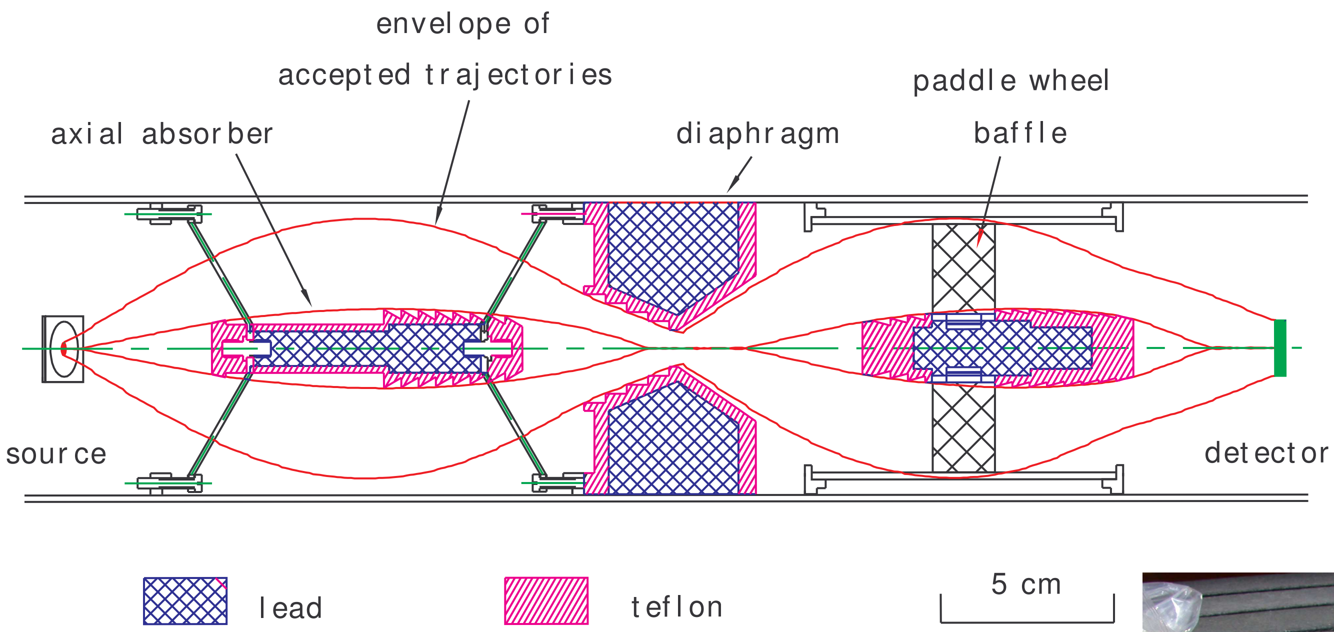
- Broad-range mode – 100 keV up to a few MeV
- Lens mode – finite transmitted momentum bandwidth ($\Delta p/p$~15-25%) – high peak-to-total ratio

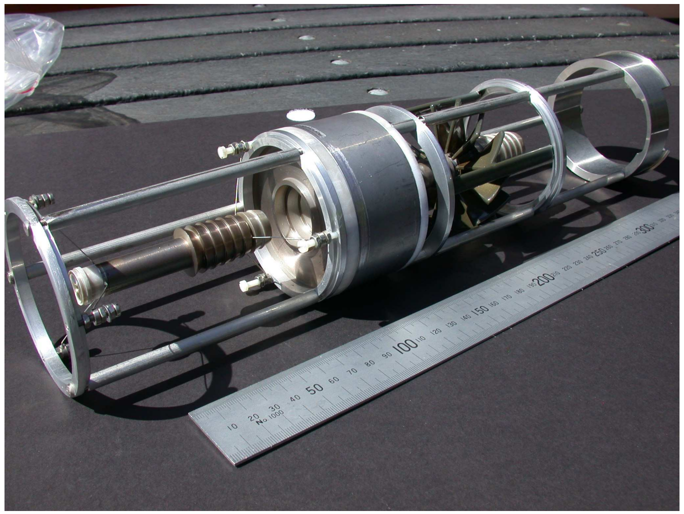
Mini-orange (looks like a peeled orange)

- transmission > 20%
- small size and portability, but poorer quality



ANU Superconducting Solenoid Spectrometer

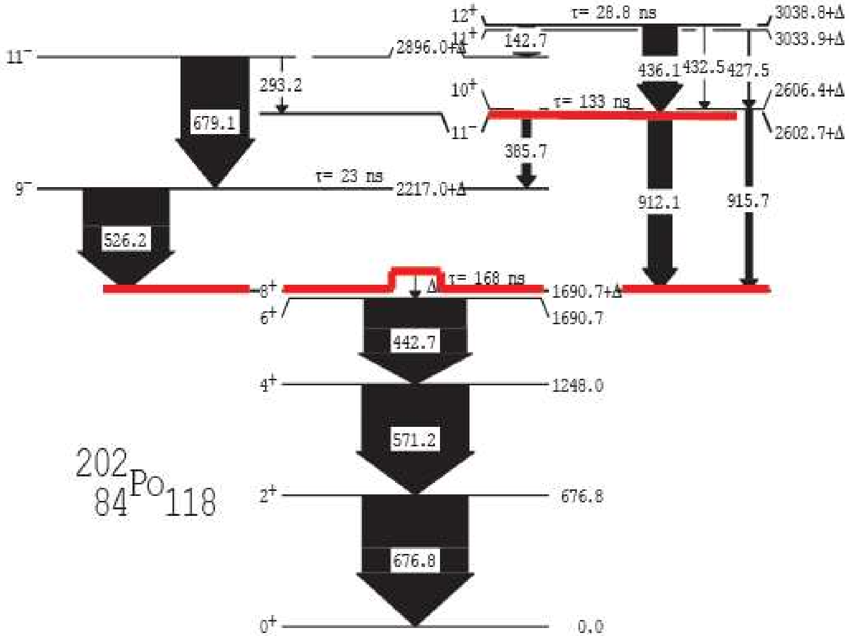


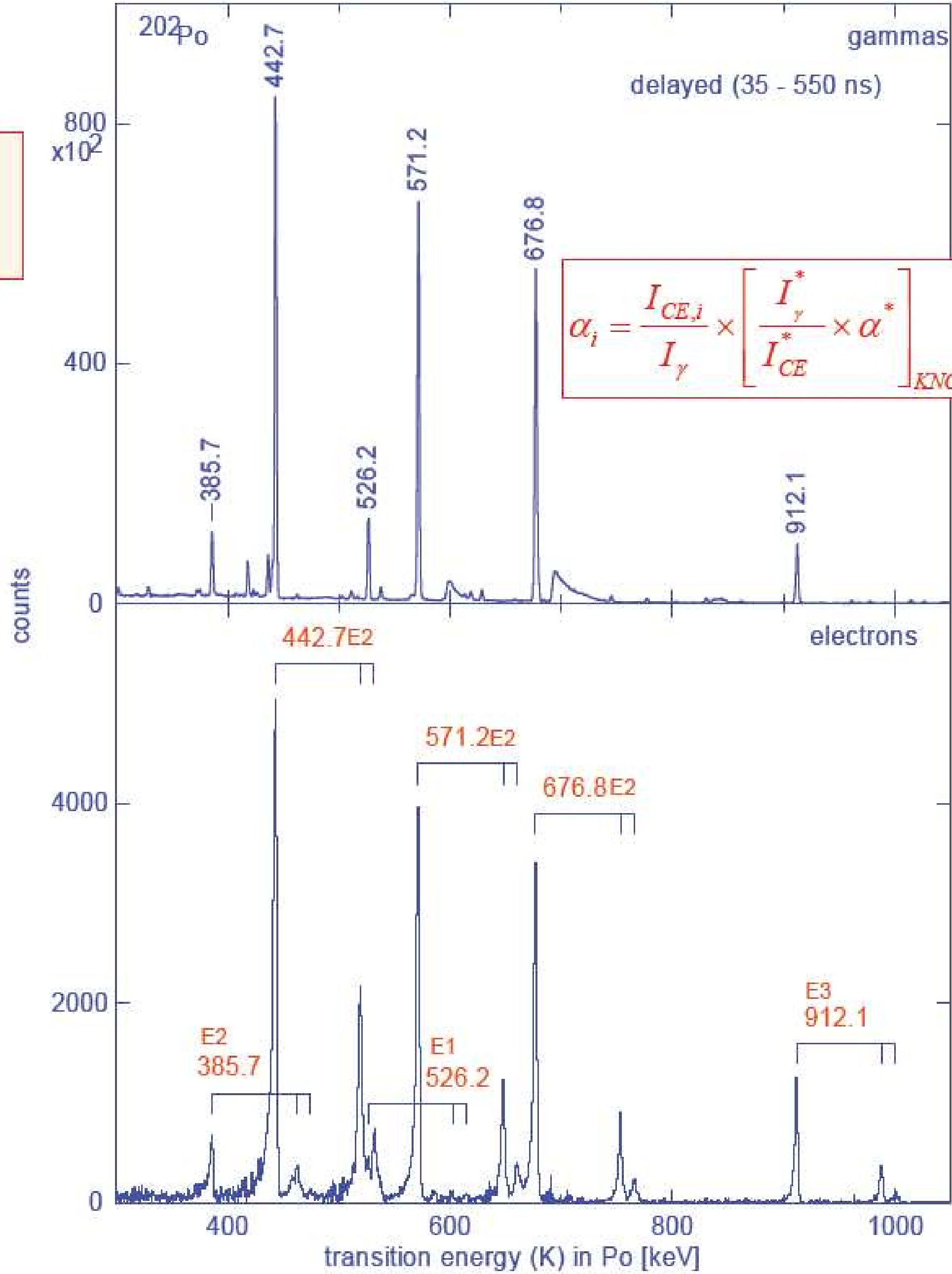


Super-e Lens (ANU)

$^{194}Pt(^{12}C,4n)^{202}Po$ @ 76 MeV

Pulsed beams (~1 ns) with 1.7 μs separation

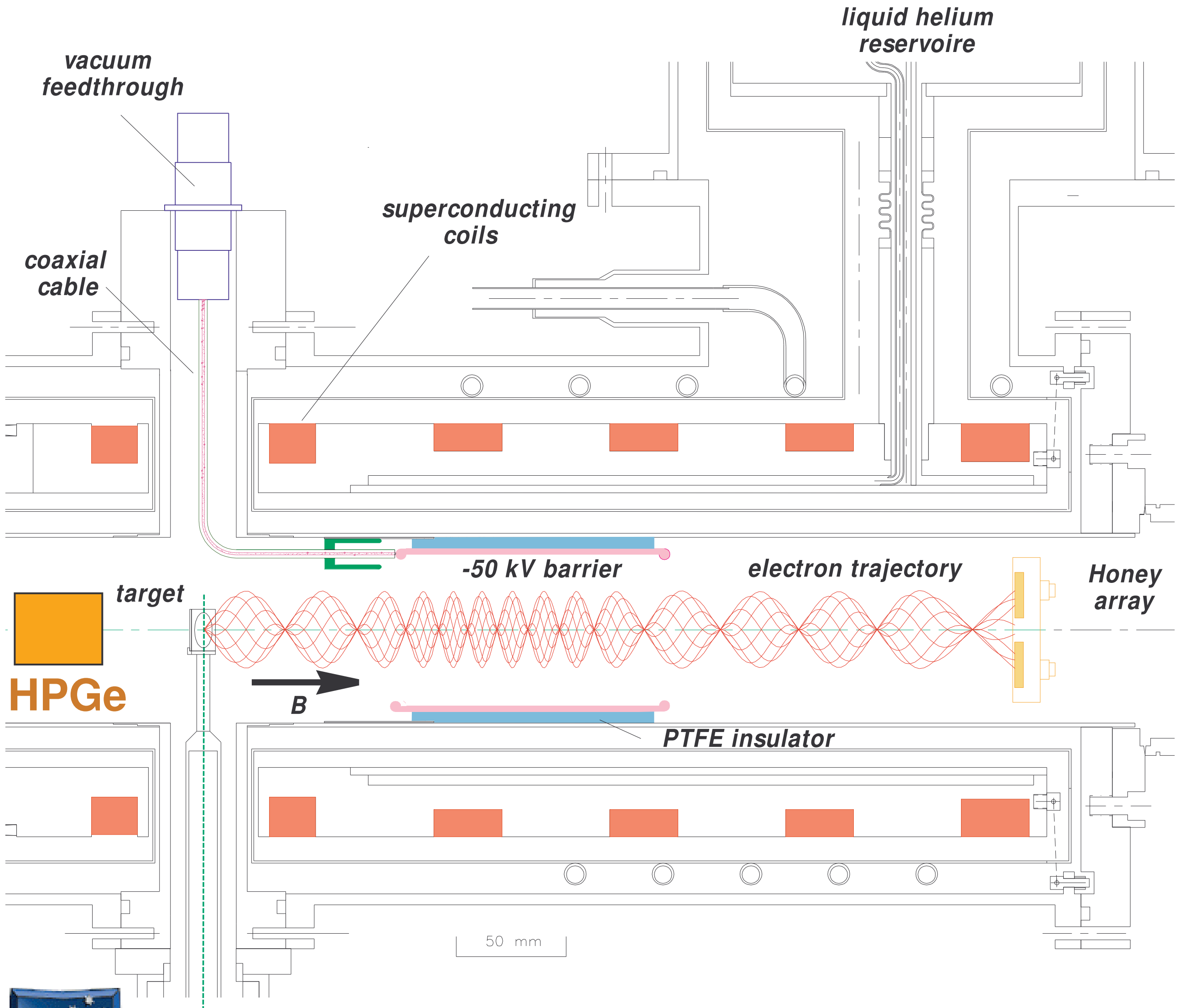




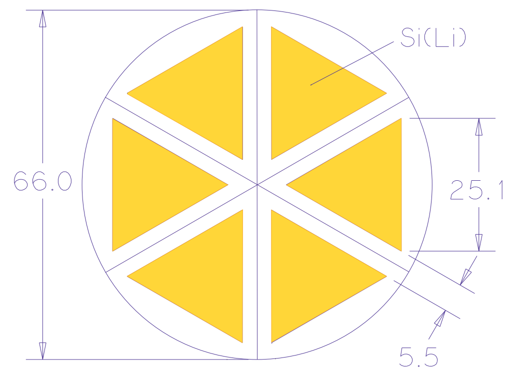
$$\alpha_i = \frac{I_{CE,i}}{I_\gamma} \times \left[\frac{I^*_\gamma}{I^*_{CE}} \times \alpha^* \right]_{KNOWN}$$

T. Kibèdi, NSDD Workshop, Trieste 2006

Super-e Honey (ANU)

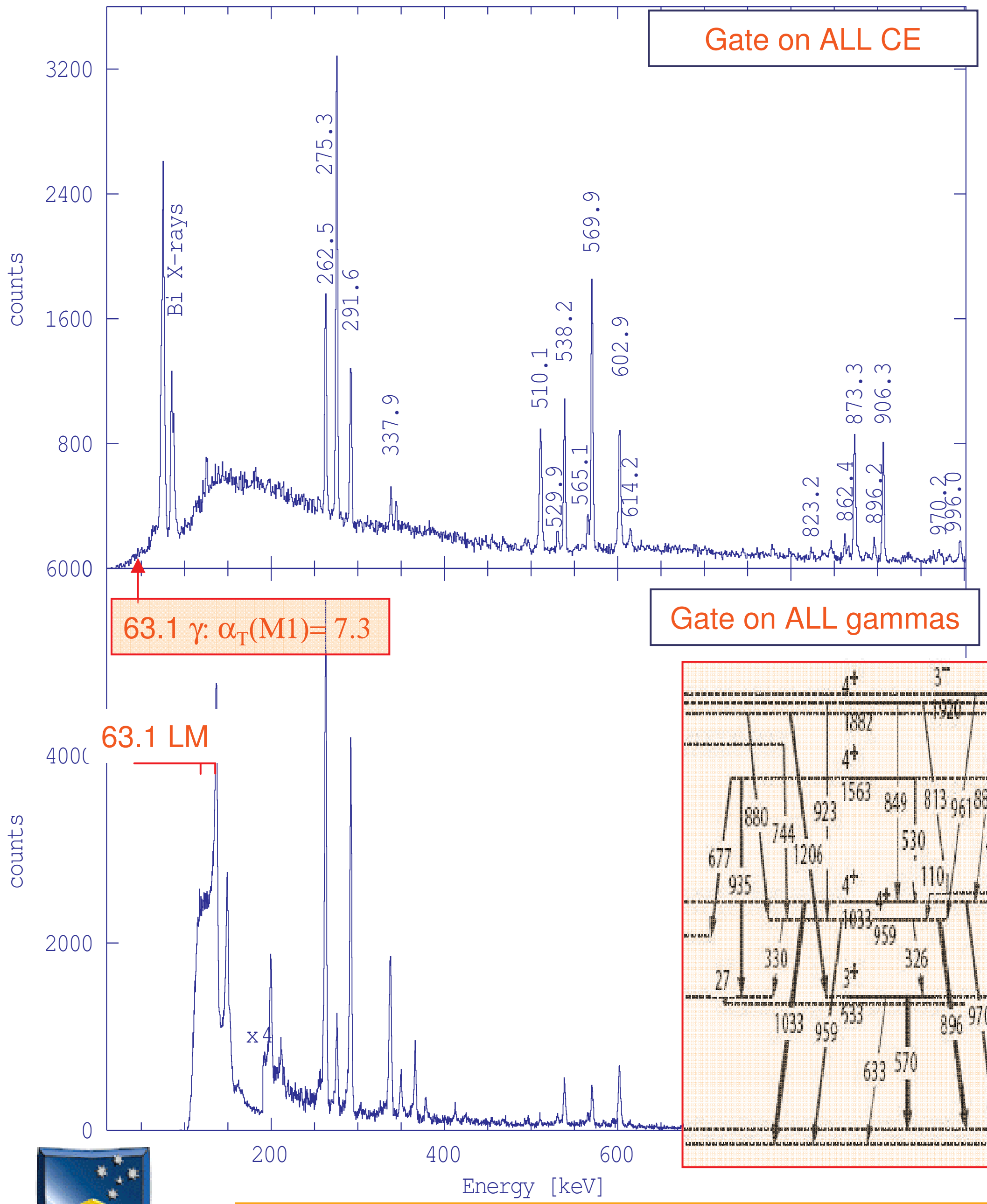


Electrons from atomic collisions are the major difficulty in low energy CE spectroscopy using ion induced reactions



eeγ coincidences

Super-e Honey (ANU)
eeγ coincidences

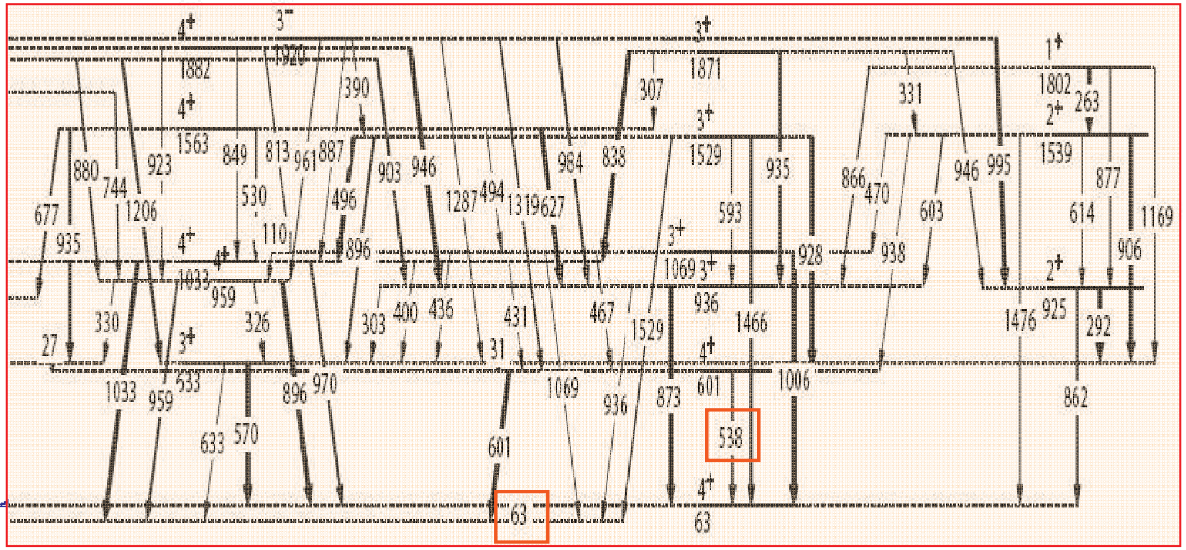


$^{208}Pb(p,n)^{208}Bi$ @ 9 MeV

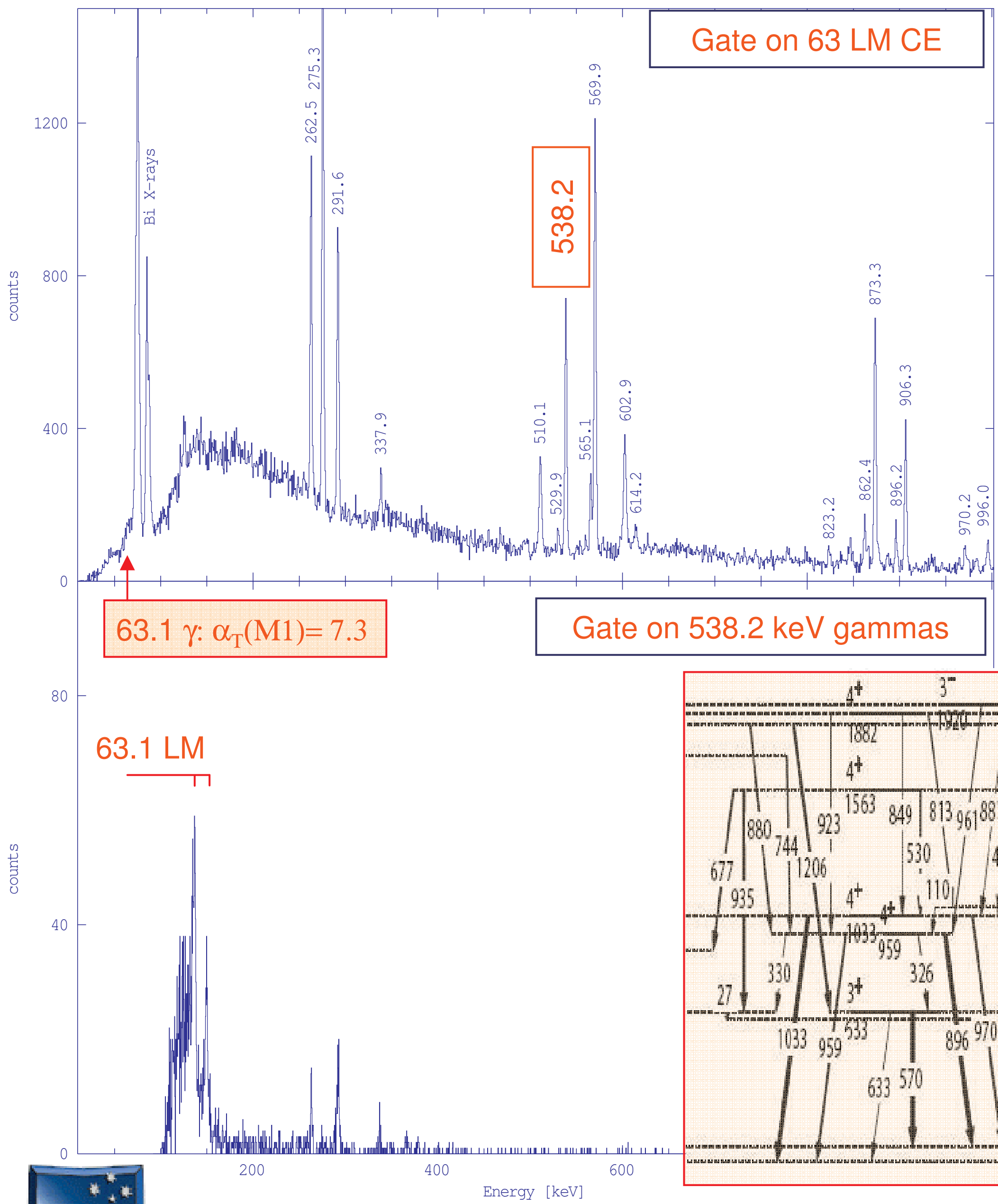
H. Meier et al. (to be published)

E_γ=63.1 keV transition not visible in gamma spectra.

No K conversion; BE_K=90.5 keV



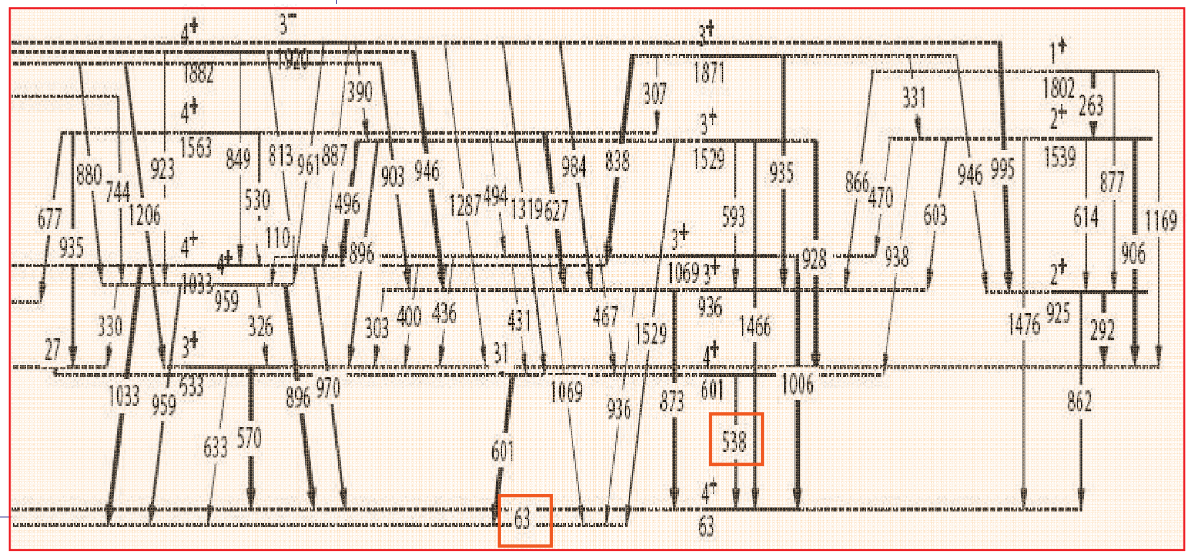
Super-e Honey (ANU)
eeγ coincidences



$^{208}Pb(p,n)^{208}Bi$ @ 9 MeV

H. Meier et al. (to be published)

Sample coincidence gates



ICC from total intensity balances – example 1

In out-of-beam (or decay) coincidence data

$$I_{\gamma_{in}}^{tot} = I_{\gamma_{in}} \times (1+\alpha_{in}^{tot}) \equiv I_{\gamma_{out}}^{tot} = I_{\gamma_{out}} \times (1+\alpha_{out}^{tot})$$

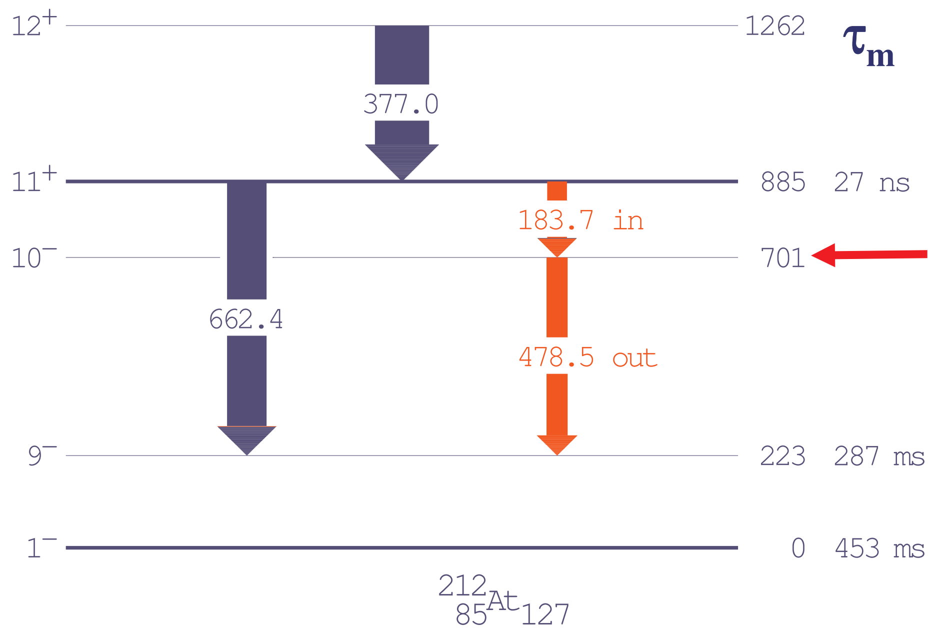
$$\alpha_{in}^{tot} \equiv (I_{\gamma_{out}} / I_{\gamma_{in}}) \times (1+\alpha_{out}^{tot}) - 1$$

$$\alpha_{out}^{tot}(478.5, M1) = 0.166$$

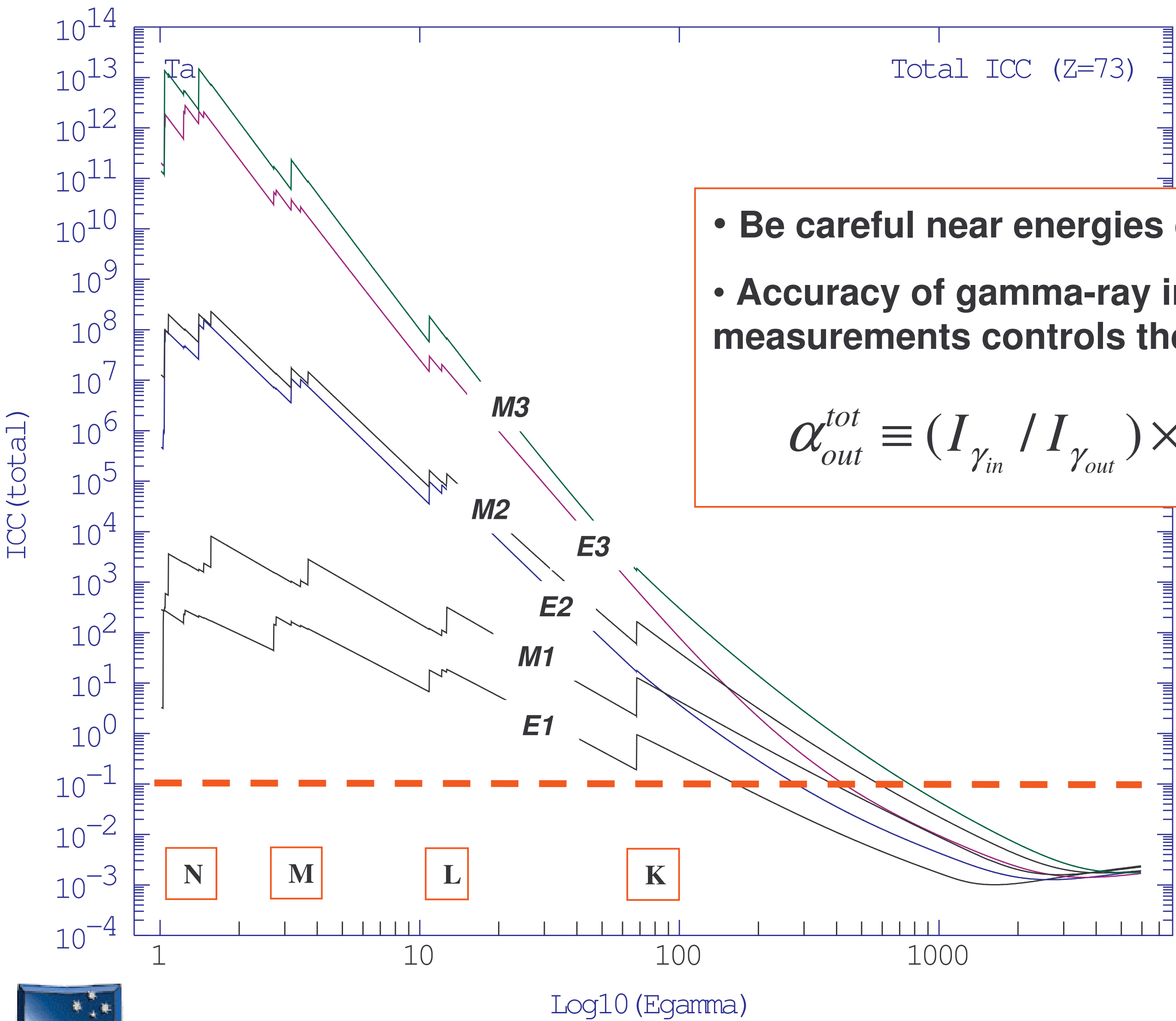
$\alpha_{in}^{tot}(183.7) = 0.23(5)$ $E1: 0.103$ $M1: 2.15$ $E2: 0.674$ $M2: 10.7$

E1(+M2)

S. Bayer, et al., Nucl. Phys. A650, 3 (1999)



ICC from total intensity balances – when to use



- **Be careful near energies close to shell binding**
- **Accuracy of gamma-ray intensity measurements controls the range of its use**

$$\alpha_{out}^{tot} \equiv (I_{\gamma_{in}} / I_{\gamma_{out}}) \times (1 + \alpha_{in}^{tot}) - 1$$

$\delta I_\gamma / I_\gamma \sim 10\%$

ICC from total intensity balances – example 2

In-beam: only when gating from "above"

$$I^{tot}_{\gamma_{in}} = I_{\gamma_{in}} \times (1+\alpha^{tot}_{in}) \equiv I^{tot}_{\gamma_{out}} = I_{\gamma_{out}} \times (1+\alpha^{tot}_{out})$$

$$I^{tot}_{\gamma_{out}} = I^{tot}_{\gamma_{in}} + I_{sf}$$

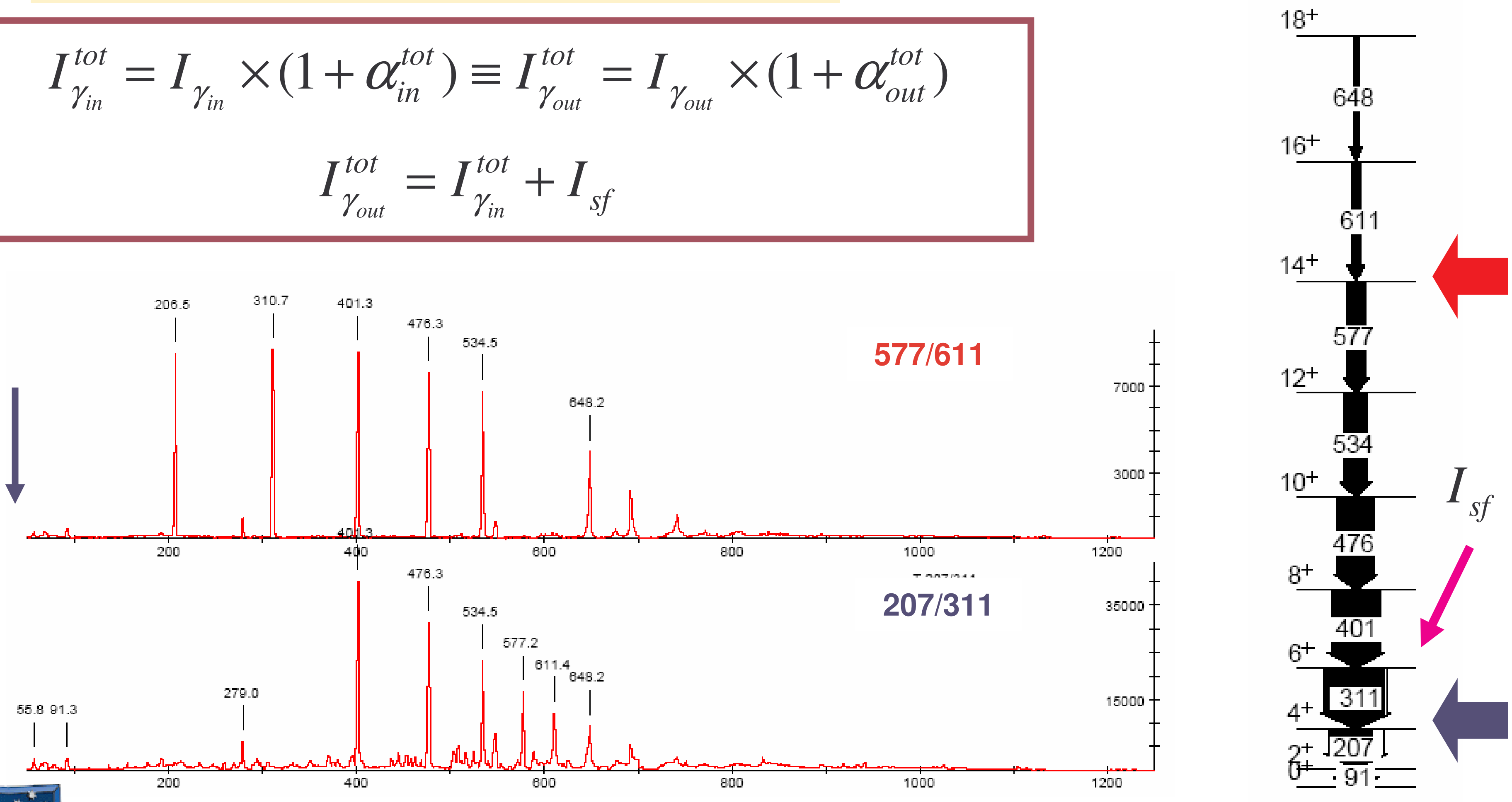
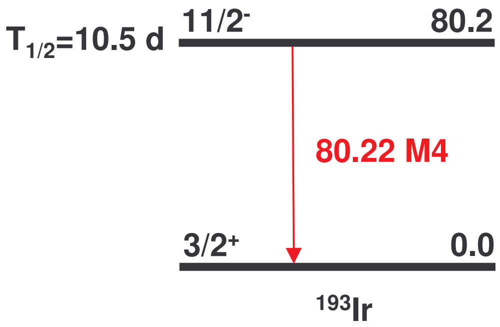


Figure courtesy of F.G. Kondev (ANL)

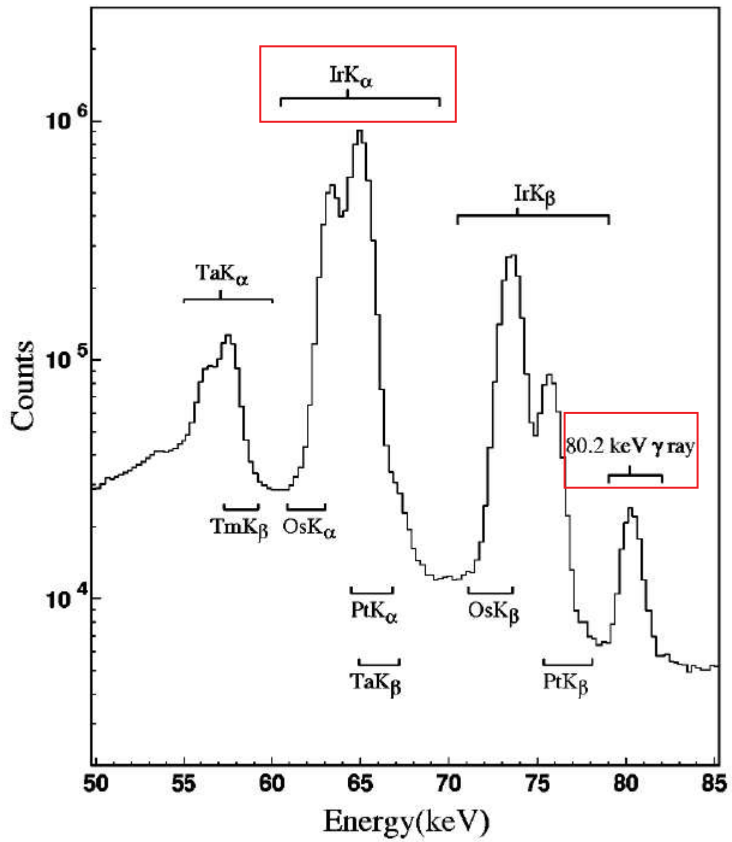
ICC from intensity ratio of K X-rays to γ-rays – ^{193m}Ir



$$\alpha_K = \frac{N_{KX}}{N_\gamma} \times \frac{\varepsilon_\gamma}{\varepsilon_{KX}} \times \frac{1}{\omega_K}$$

Looks simple but….

- **source preparation (purity)**
- **efficiency (ε) calibration**
- **coincidence summing**
- **etc.**



N. Nica, et al., Phys. Rev. ***C 70****, 054305 (2004)*

Determined: α_K = 103.8(8)

Note: α_T = 21333(373)

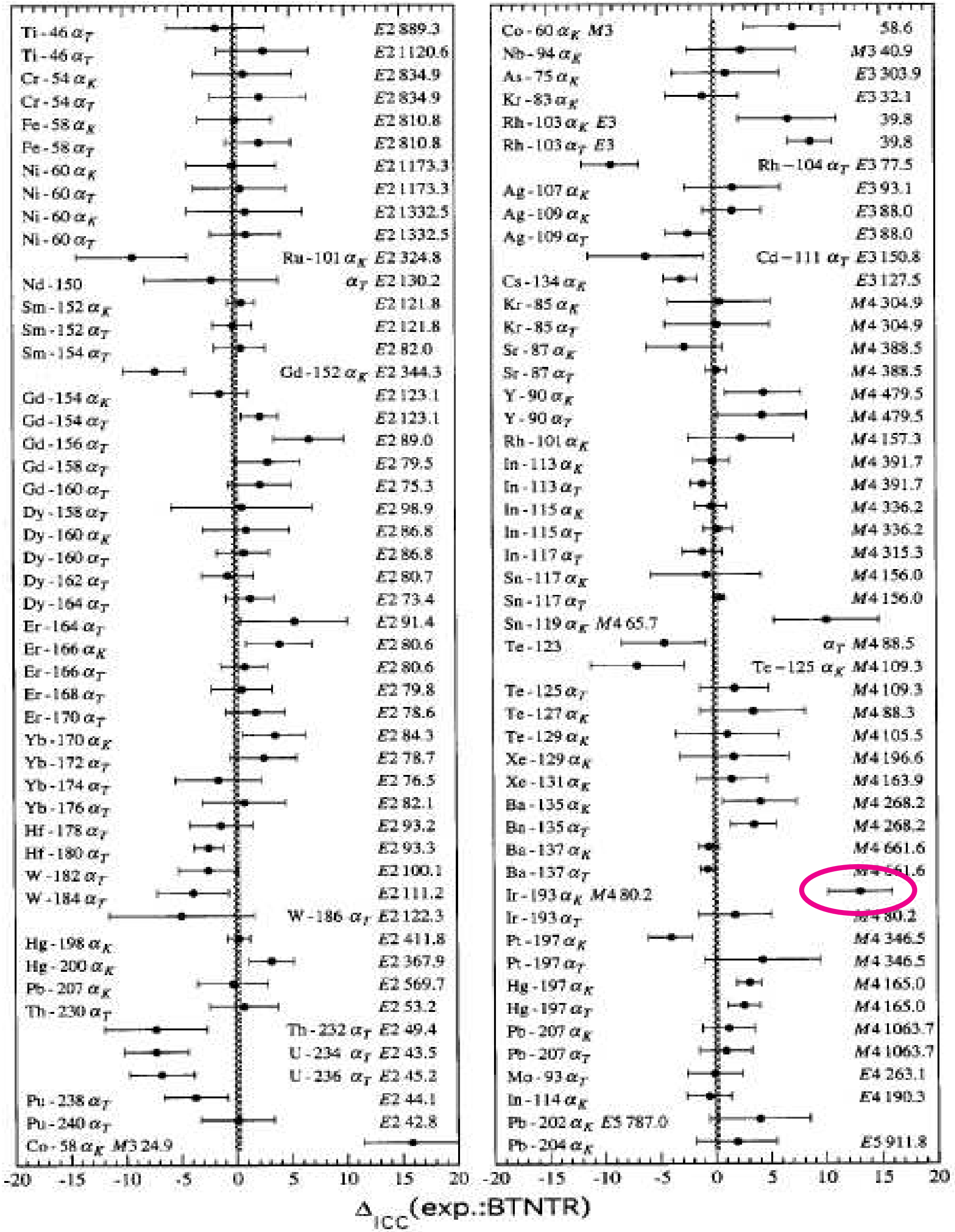
Raman et al. *(2002)*

“How good are the internal conversion coefficients now?”

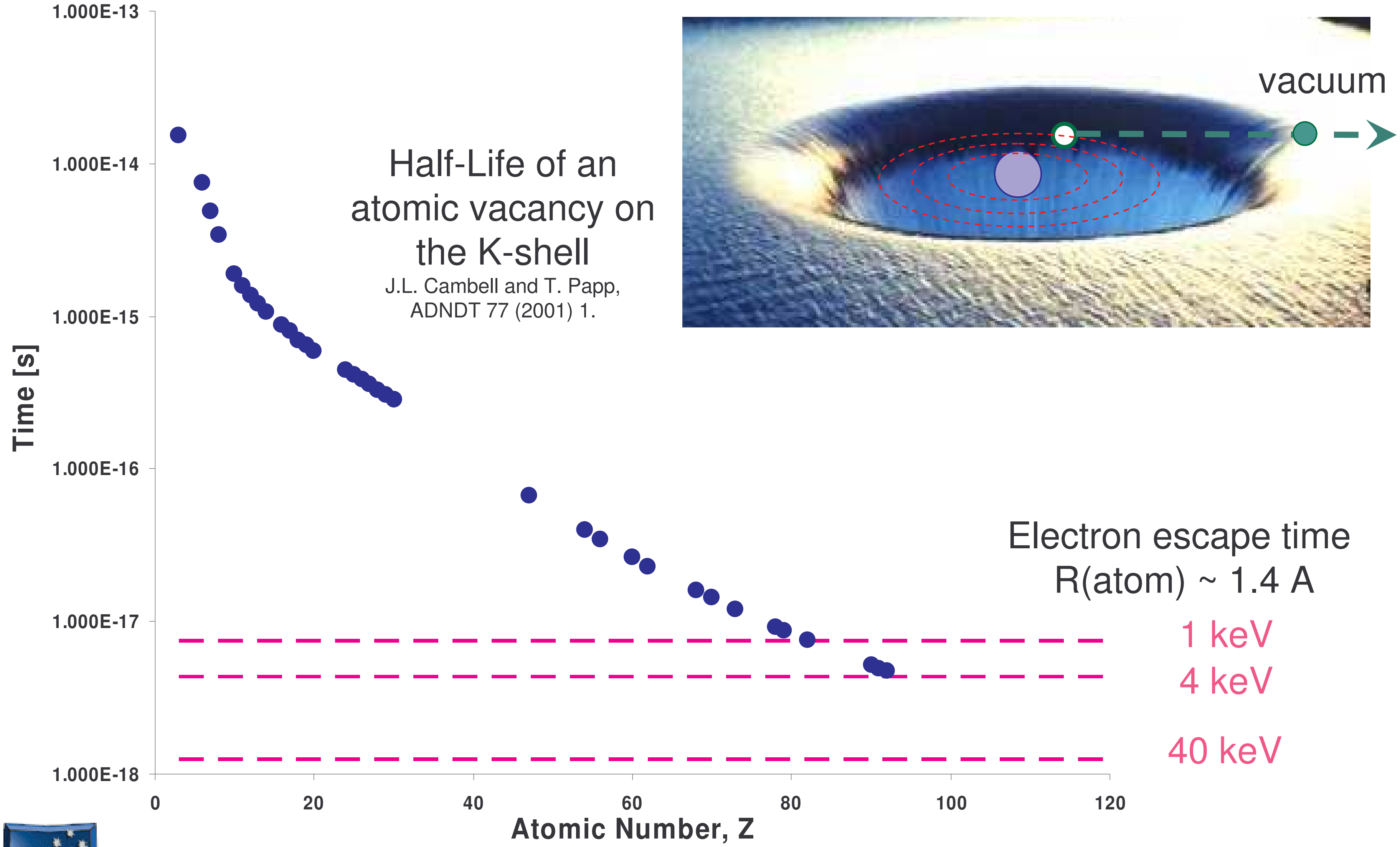
- **100 experimental ICC**
- **Deviation of ICC**

$$\Delta ICC(Exp:Theory) = \frac{[Icc(Exp) - Icc(Theory)]}{Icc(Theory)} \times 100$$

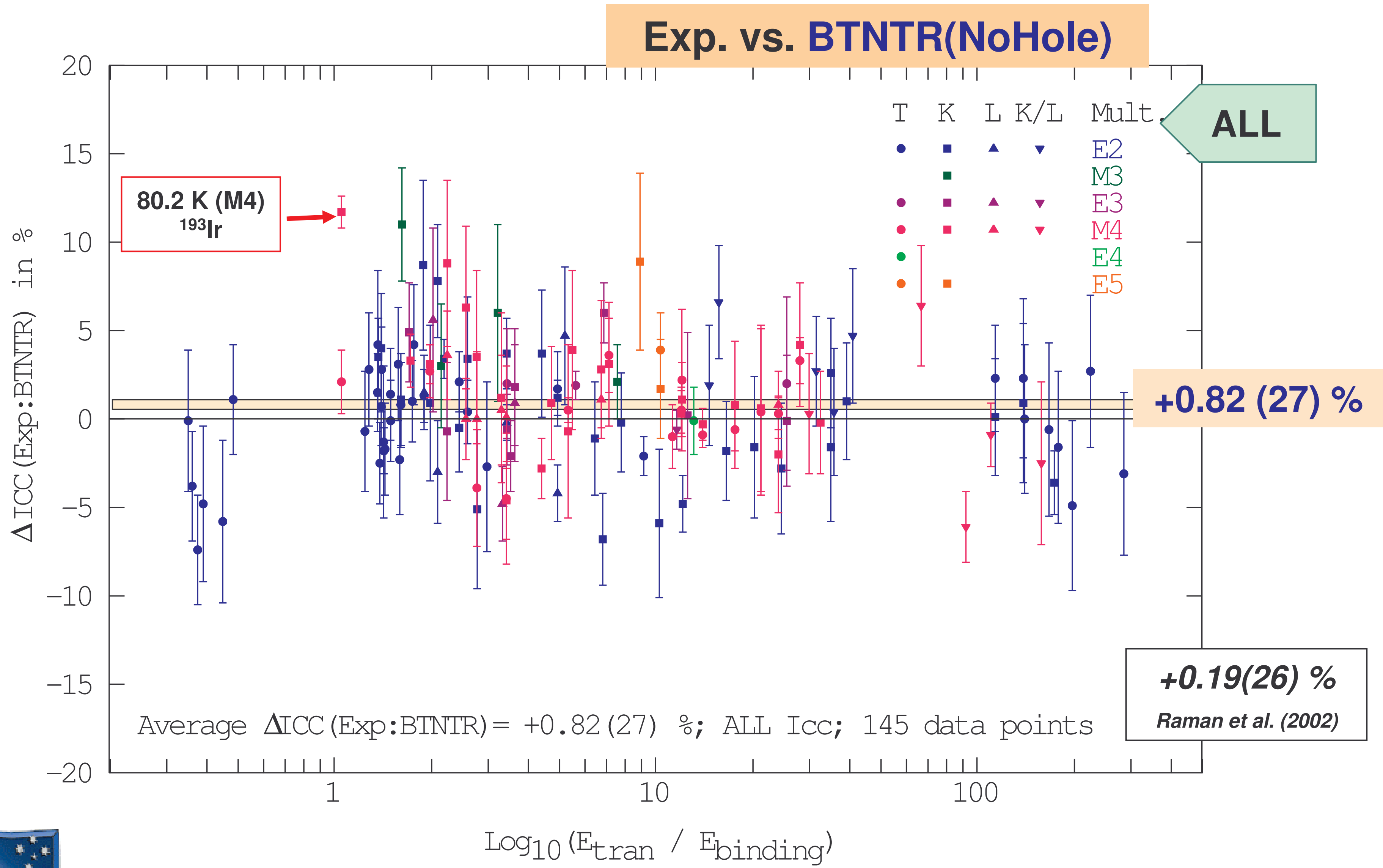
Hager-Seltzer:	**-3.01(24)%**
Rössel et al:	-2.71(24)%
BTNTR **NO Hole**	+0.19(26)%
RNIT(1) **With Hole**	-0.94(24)%
RNIT(2) **With Hole**	-1.18(24)%



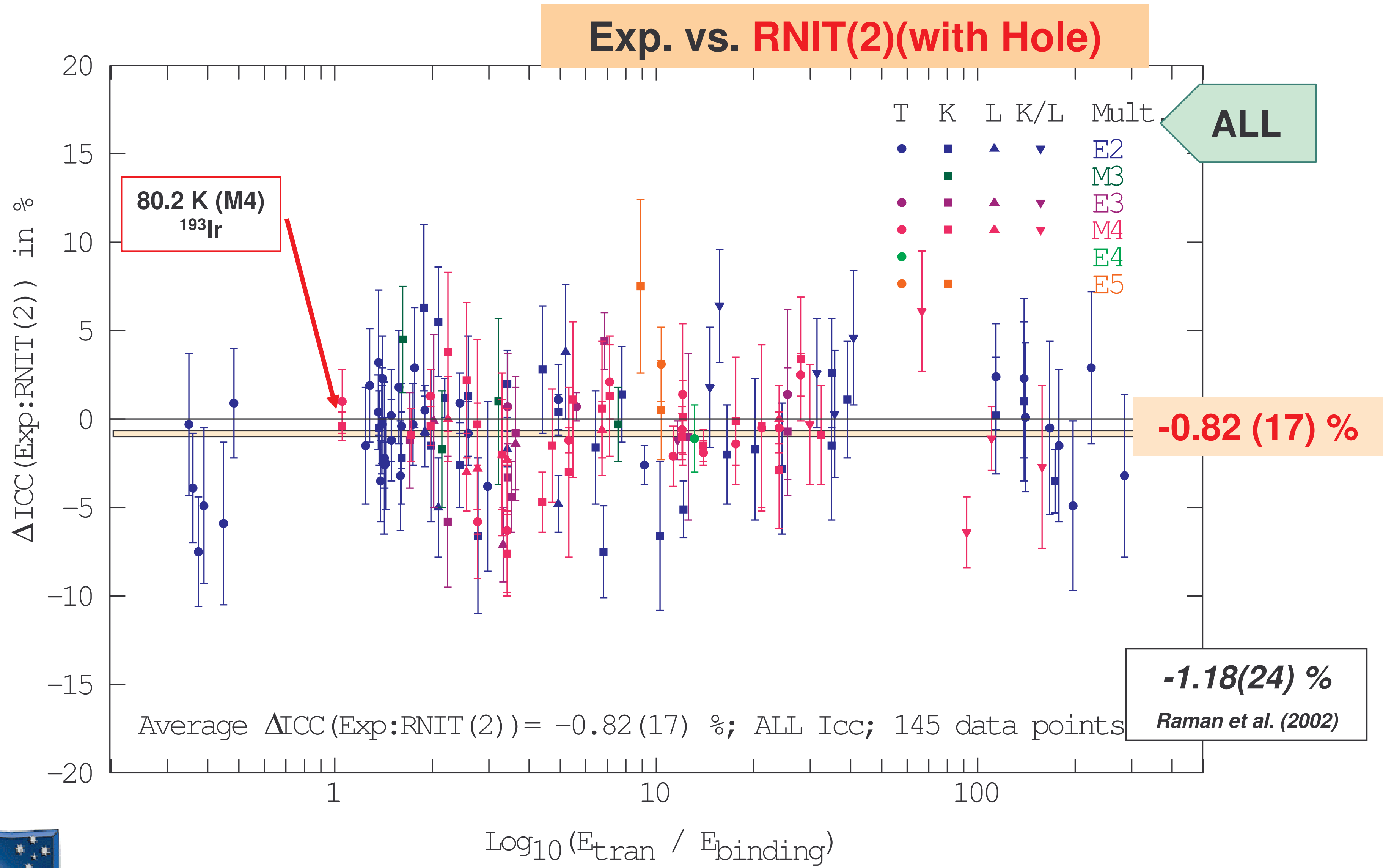
Can we ignore the atomic vacancies?



How good are the internal conversion coefficients now?



How good are the internal conversion coefficients now?



Acknowledgements

G.D. Dracoulis , G.J. Lane, P. Nieminen, H. Maier (ANU)
F.G. Kondev (ANL)
T.W. Burrows (NNDC)
P.E. Garrett (*University of Guelph and TRIUMF)*
S.W. Yates (Univ. of Kentucky)
P. Greenlees (University of Jyväskylä)
P.M. Walker (Surrey)

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