TRIUMF

Internal Conversion Electron Spectroscopy at TRIUMF-ISAC

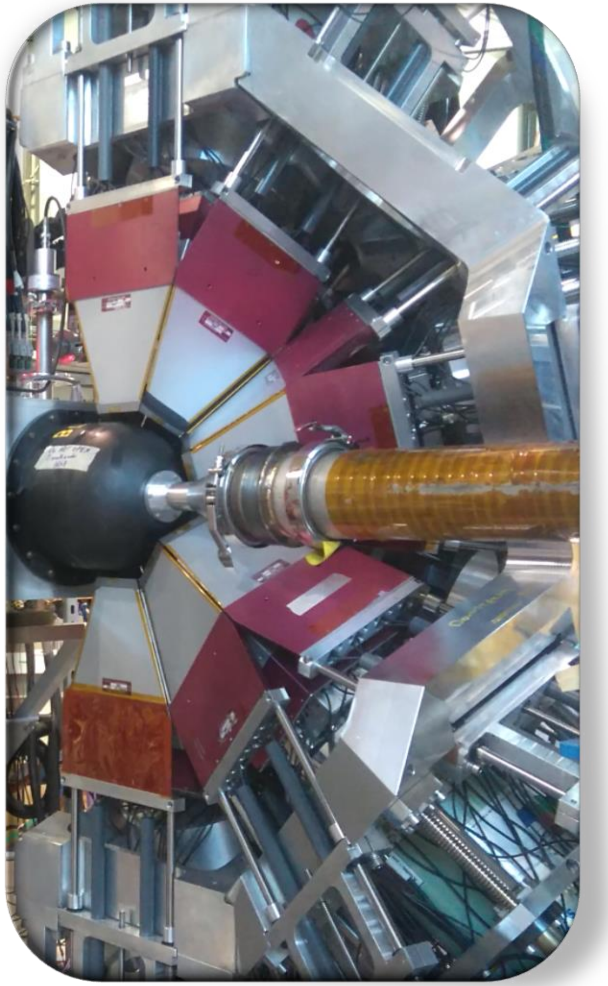
James Smallcombe

Discovery, accelerated

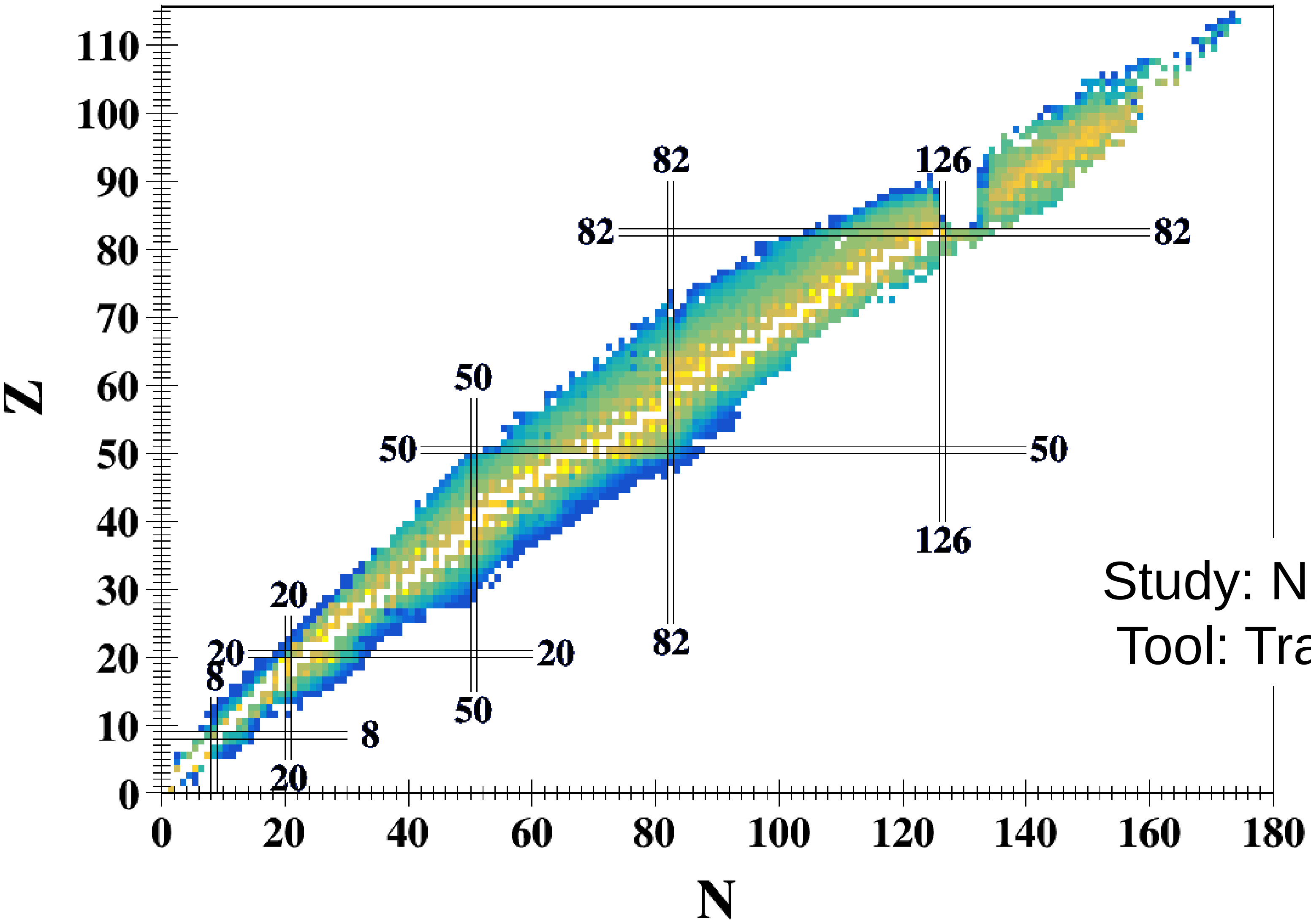
2018-02-14

Internal Conversion Electron Spectroscopy at TRIUMF-ISAC

- Motivation - Electromagnetic Transitions in Nuclei
- Internal Conversion Process
- Electron Spectroscopy at TRIUMF
  - TIGRESS & SPICE
    - $^{110}_{46}\mathrm{Pd}_{64}$ – K Goodness
    - $^{70}_{34}\mathrm{Se}_{36}$ – Shape Coexistence
  - GRIFFIN & PACES
    - $^{72}_{32}\mathrm{Ge}_{40}$ – Shape Mixing
    - $^{198}_{81}\mathrm{Tl}_{117}$ – ICC Mulipolarities



Nuclear Structure – Many Body Nuclear Problem



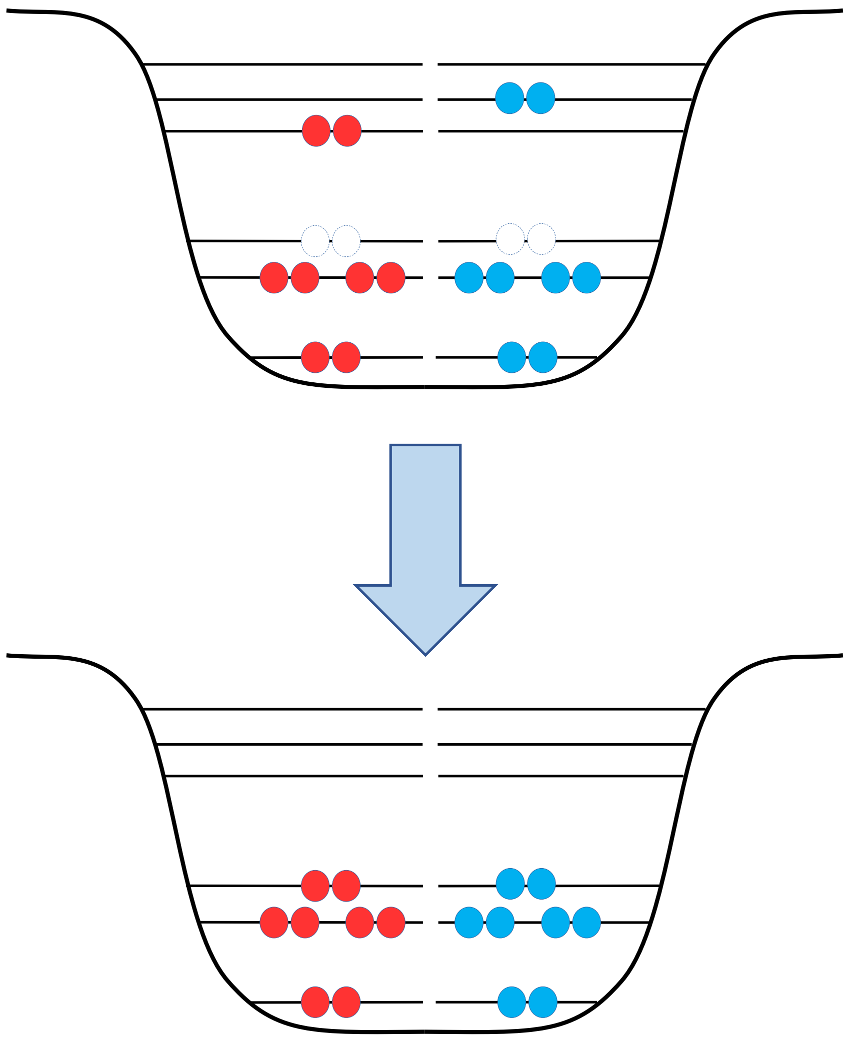
Open questions:
- Magicity
- Nucleon configurations
- Single particle vs collective
- Deformation

Study: Nuclear states
Tool: Transitions between states

Nuclear De-excitation

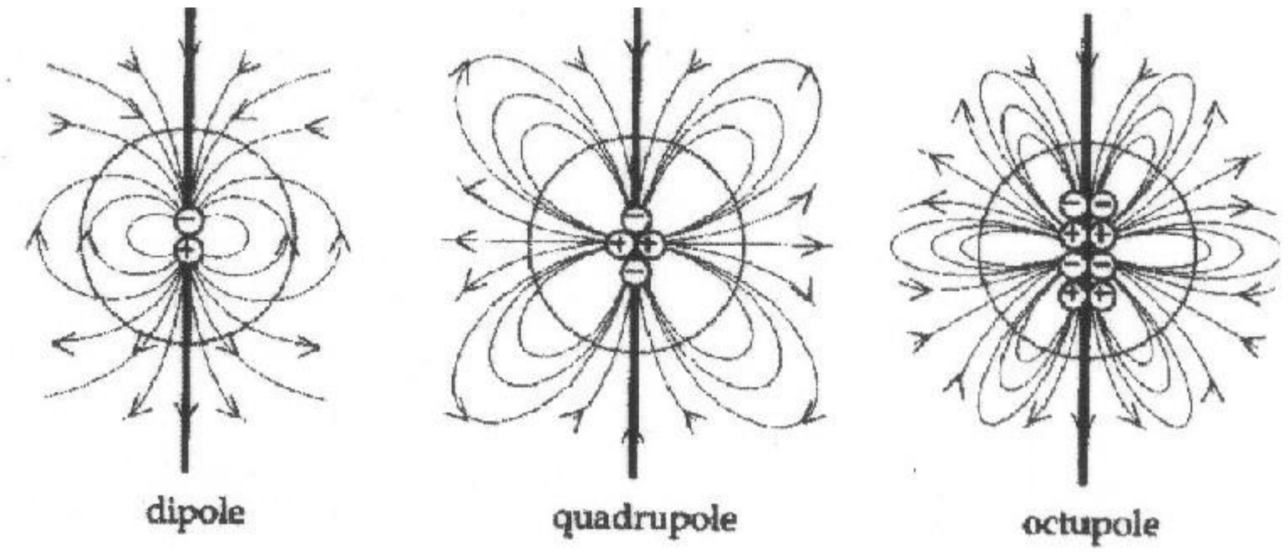
$$\langle \Psi_f | \hat{O} | \Psi_i \rangle$$

- Nucleons reconfigure
- Become more bound
- Energy released



Multipole Radiation Field

- "Moving" charges induces EM field
- Released energy goes into field
- Strength of field ∝ Transition energy (ΔE) & $\langle \Psi_f | \hat{O} | \Psi_i \rangle$
- Field shape ∝ Transition angular momentum (ΔL)



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- Field shape ∝ Transition angular momentum (ΔL)

For EM, operator well understood

Matrix element extracts nuclear wavefunction information.

Transition strength gives wavefunction insight

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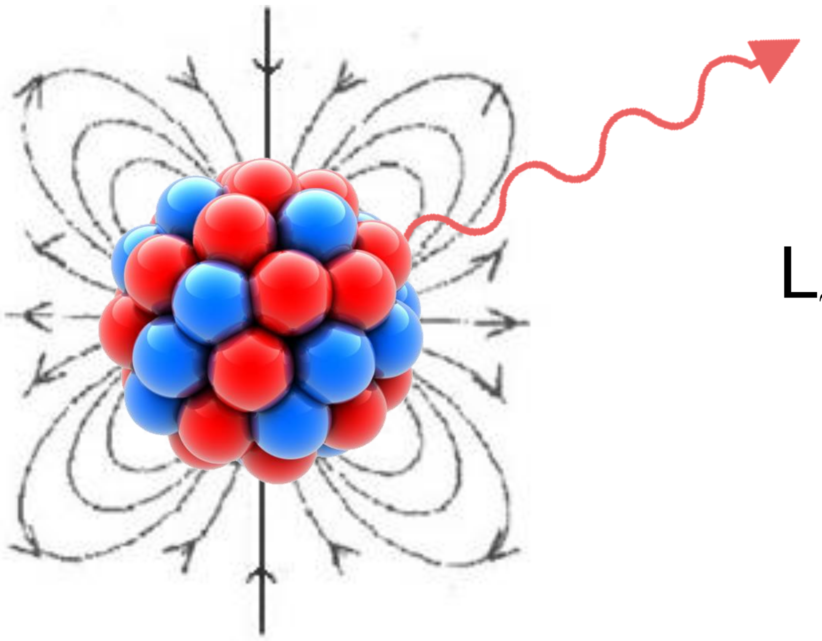
Gamma rays (γ rays)

*Most common, other possibilities

- Field propagates away from the nucleus
- Interacts with the universe, quantised as photon (γ ray)*



E_γ = Transition energy

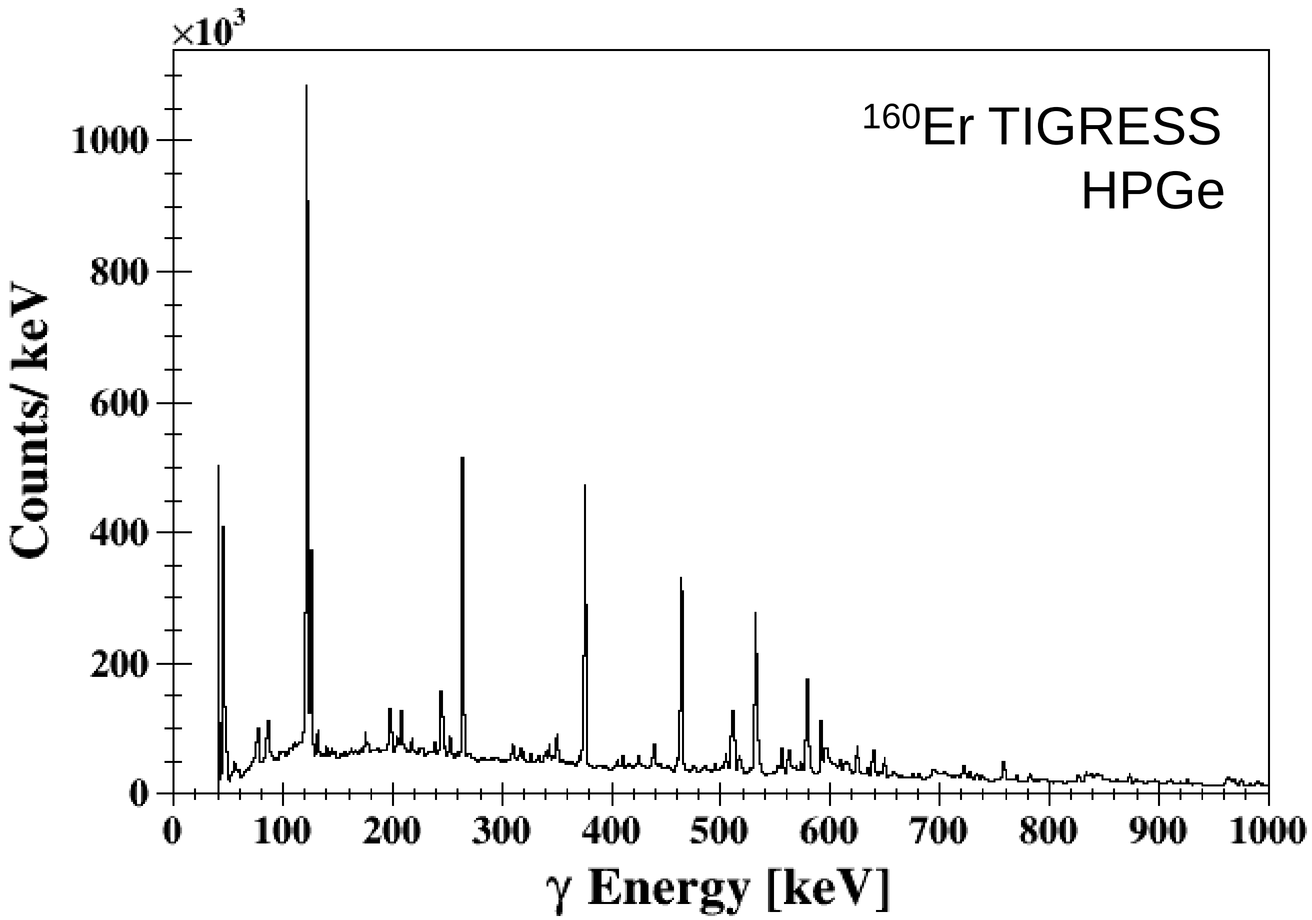
L_γ = Transition angular momentum

$$\tau_\gamma = 1 / \lambda$$

(Lifetime$_\gamma$ = 1 / transition probability)

Experimental Measurement of γ rays

- Measure **energy**, **spatial** and **time** distribution of ensemble.

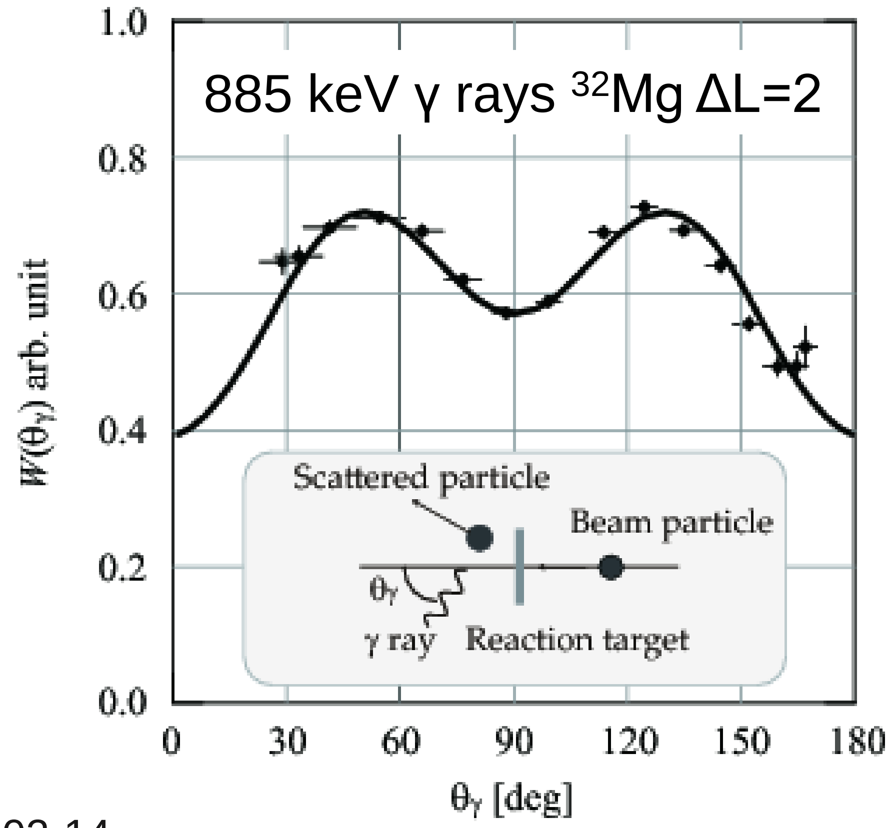


Discovery, accelerated

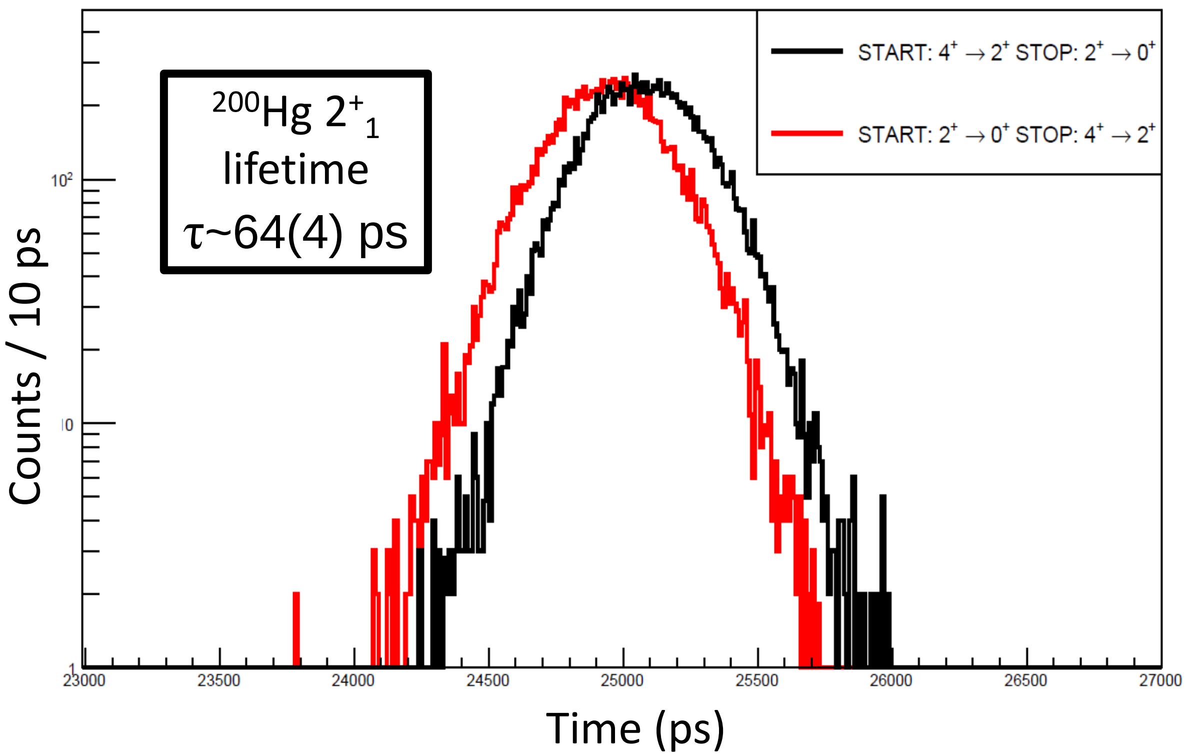
Experimental Measurement of γ rays

- Measure **energy**, **spatial** and **time** distribution of ensemble.

S. Takeuchi et al. Nucl. Instrum. Meth. A763 (2014) 596-603



B.Olaizola, M. Bowry *et al.* TRIUMF April 2017



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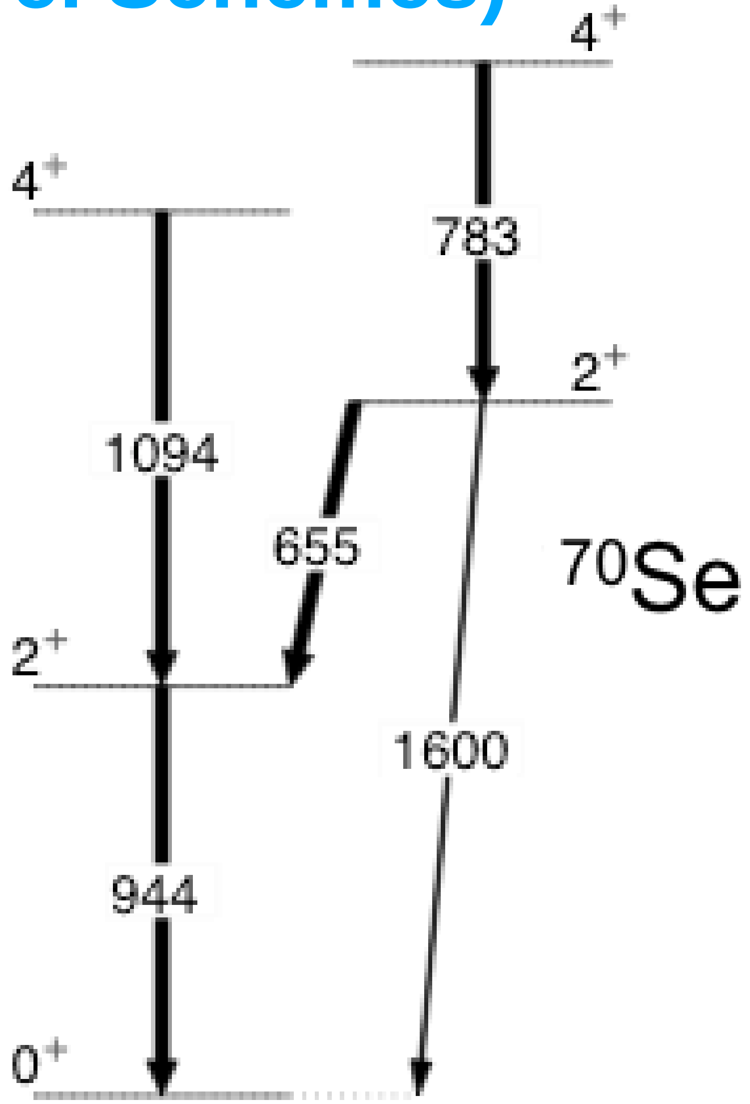
Constructing Nuclei (Nuclear Level Schemes)

We can combine information and determine properties of successive nuclear states:

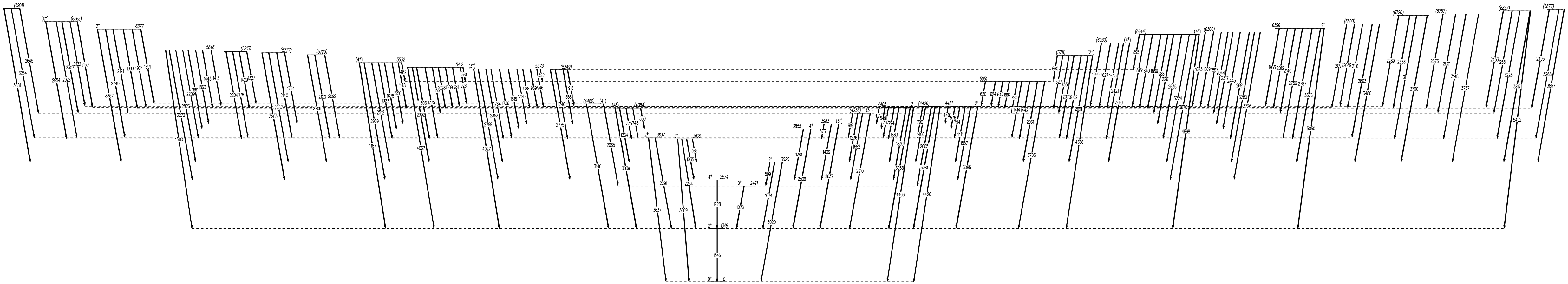
- Energy
- Spin & Parity
- Wavefunction “Matrix element”

$$\langle \Psi_f | \hat{O} | \Psi_i \rangle$$



Discovery, accelerated

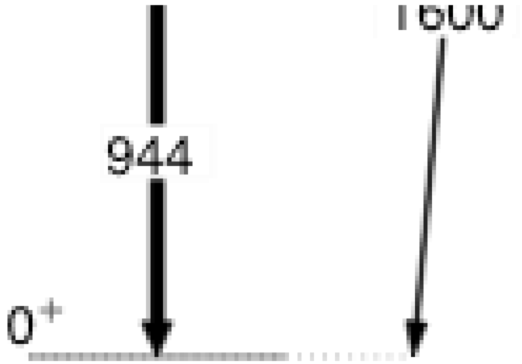
Constructing Nuclei (Nuclear Level Schemes)



^{46}Ca PhD thesis of J. Pore, Simon Fraser University.

Wavefunction Matrix element

$$\langle \Psi_f | \hat{O} | \Psi_i \rangle$$

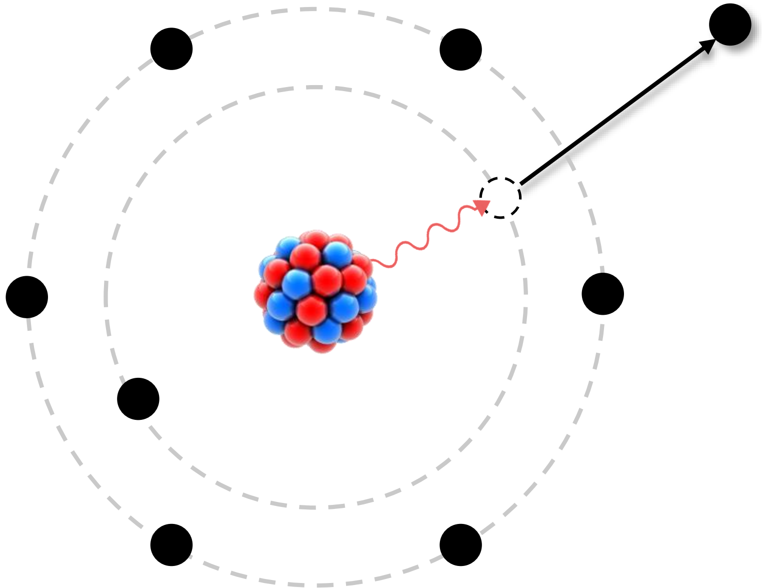


Discovery, accelerated

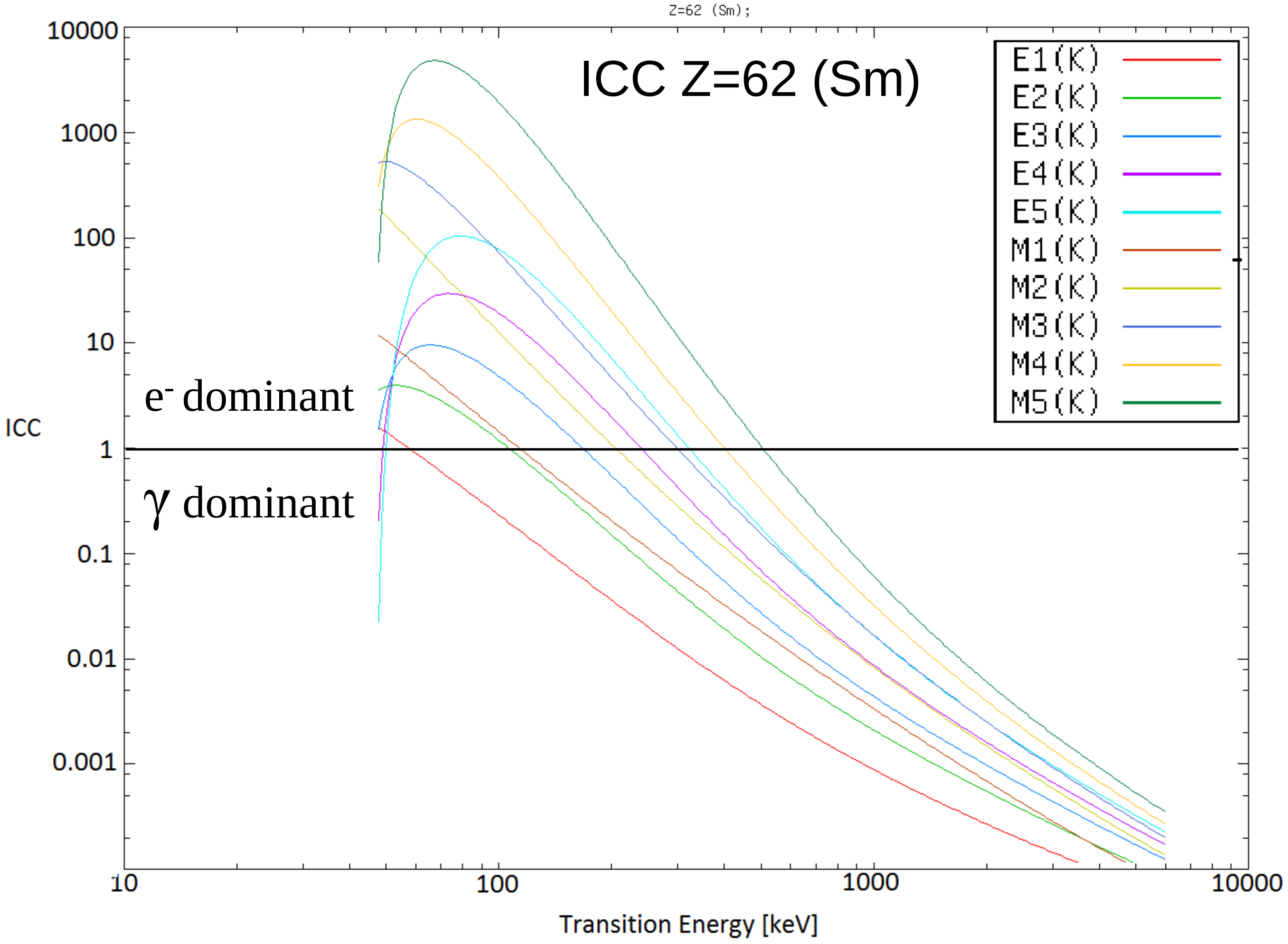
Internal Conversion Process

- Atomic electron absorbs energy of transition
- Free “Internal Conversion Electron” (ICE)
- $E_e=E_\gamma-E_B$
- Competing decay modes

$$I_{TOT} = I_{g} + I_{IC} + I_{p} + I_{gg} + I_{Others}$$



Internal Conversion Coefficients (ICC)



$$a = \frac{I_{IC}}{I_{g}}$$

Measurable + calculable
(no matrix element dependence)
Depends on:

Z E_{γ} ΔL $\Delta\pi$

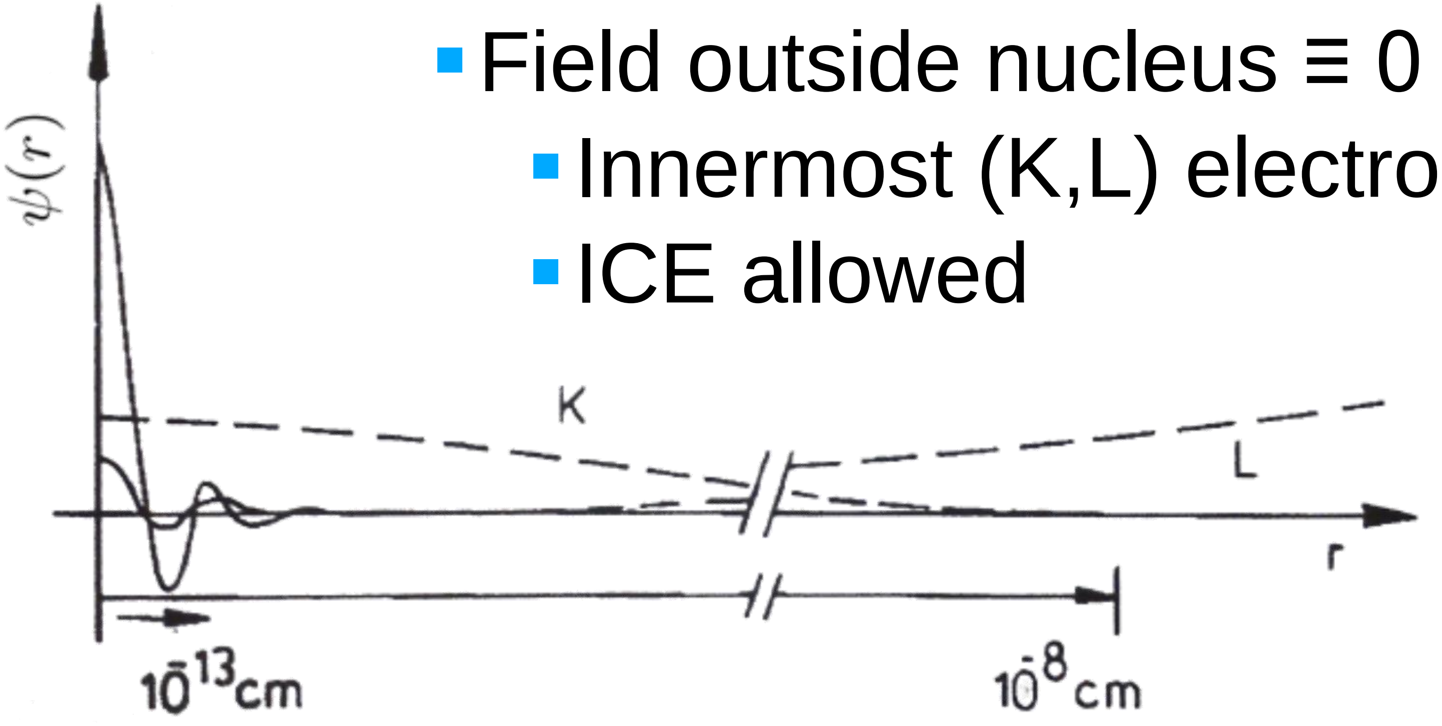
ICE dominant when:

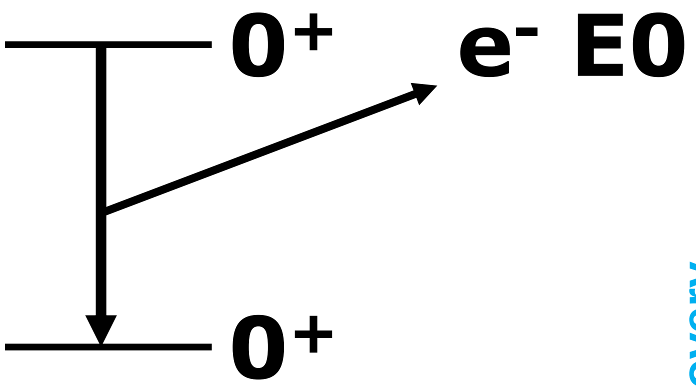
E small
Z large
ΔL large

L=0 (E0) Transitions

$$\vec{J_i} = \vec{J_f} + \vec{L_\gamma}$$

- L = 0 transition, γ rays forbidden
  - Photon must have L≥1
- Field outside nucleus ≡ 0
  - Innermost (K,L) electrons pass inside nucleus
  - ICE allowed





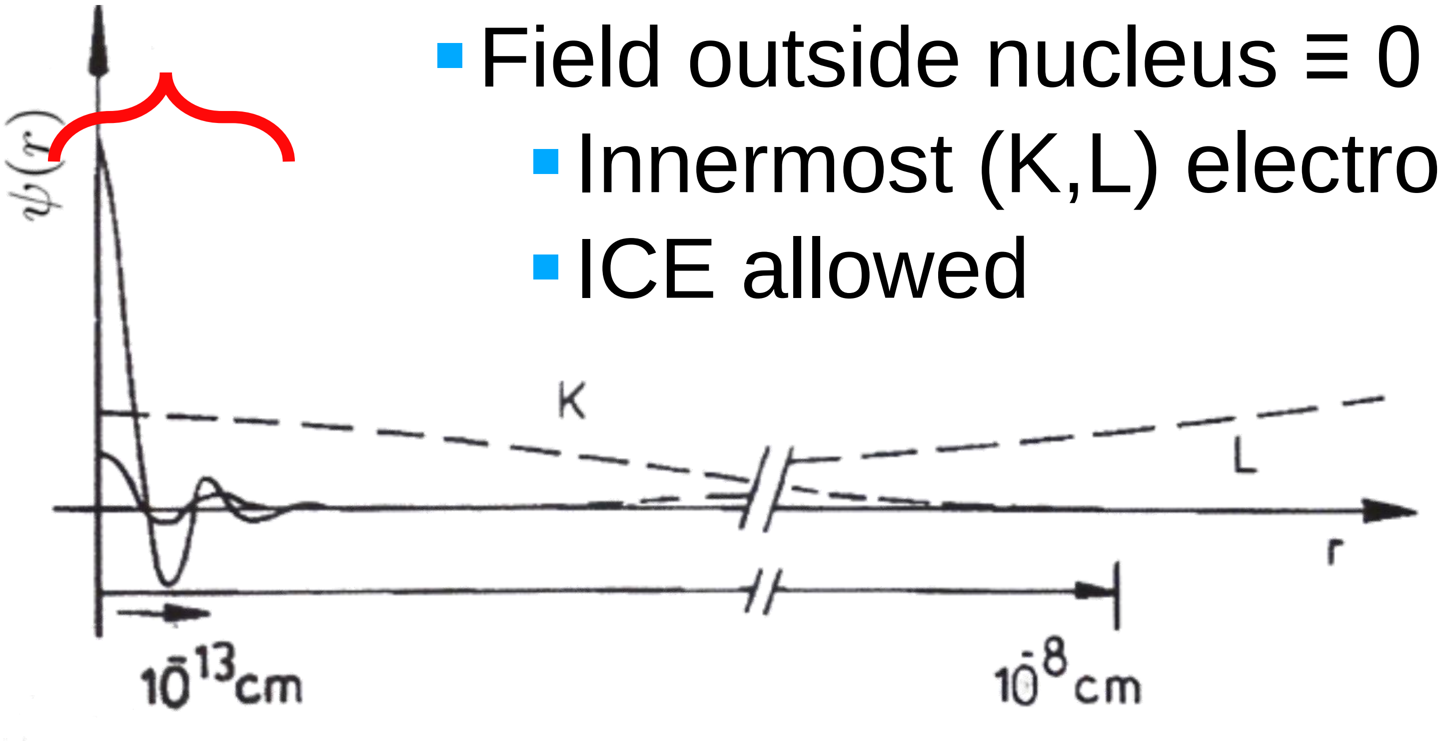
L=0 (E0) Transitions

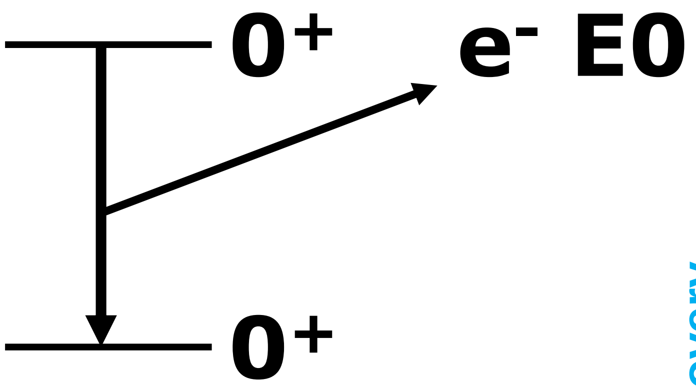
$$\overrightarrow{J_i} = \overrightarrow{J_f} + \overrightarrow{L_\gamma}$$

- L = 0 transition, γ rays forbidden

Atomic K electron wavefunction overlap within nucleus

- Field outside nucleus ≡ 0
  - Innermost (K,L) electrons pass inside nucleus
  - ICE allowed





Why Measure E0 Transitions?

- Transition strength related to wavefunction by well understood operator: $\langle \Psi_f | \hat{O} | \Psi_i \rangle$

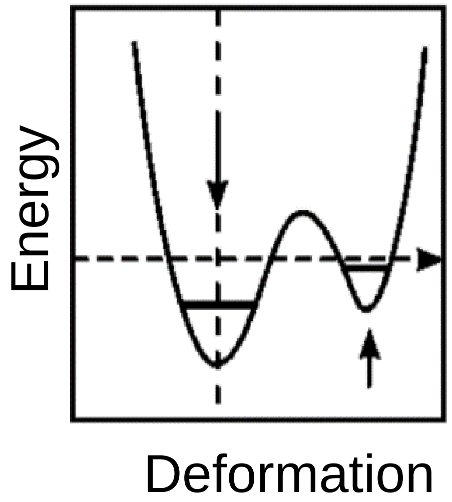
- E0 particularly dependent on shape & shape mixing

$$\hat{O}(E0) = \sum_k e_k r_k^2$$

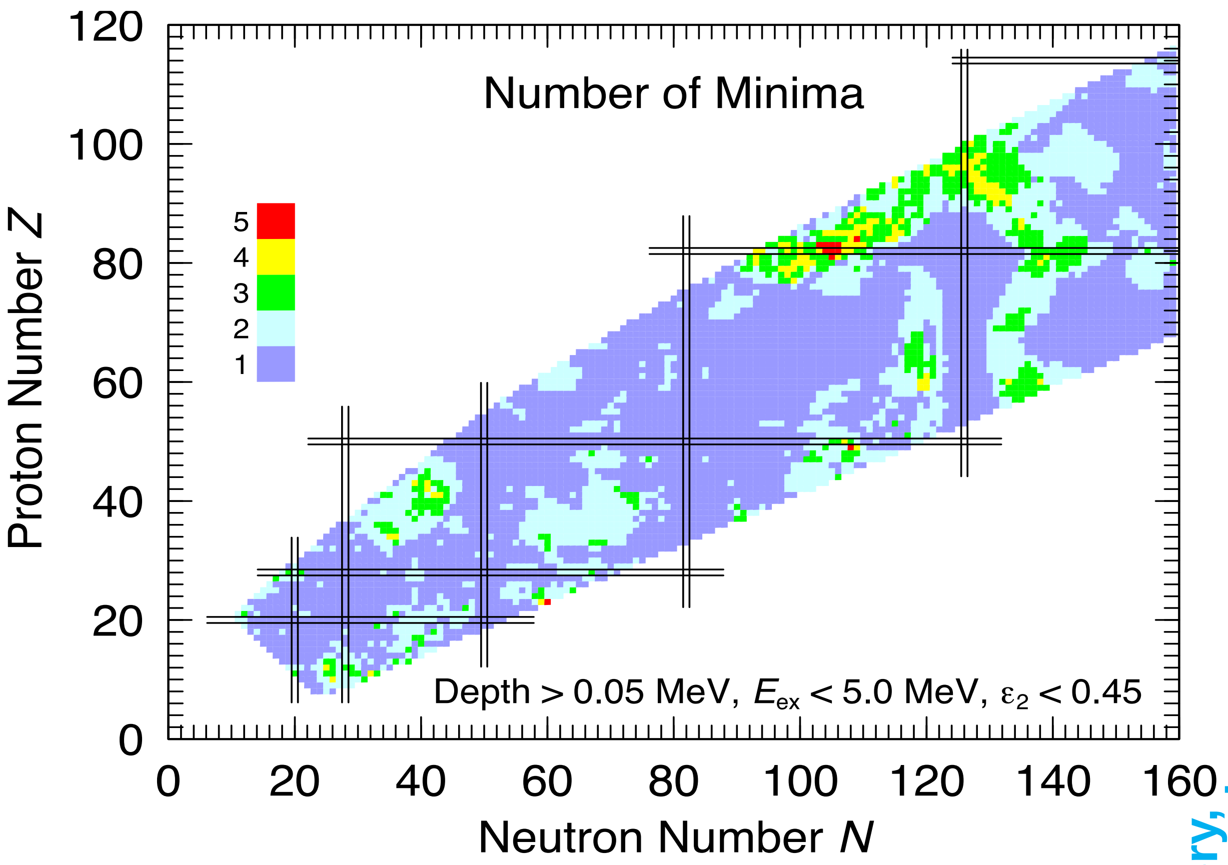
e_k = effective charge
r_k = radius of *k*th nucleon

Why Measure E0 Transitions?

- In even-even nuclei, lowest intrinsic structural configurations should be 0^+ states (pairing).
- Multiple intrinsic structures may coexist independently(?) at low energy. Best described by different deformations of the nucleus.

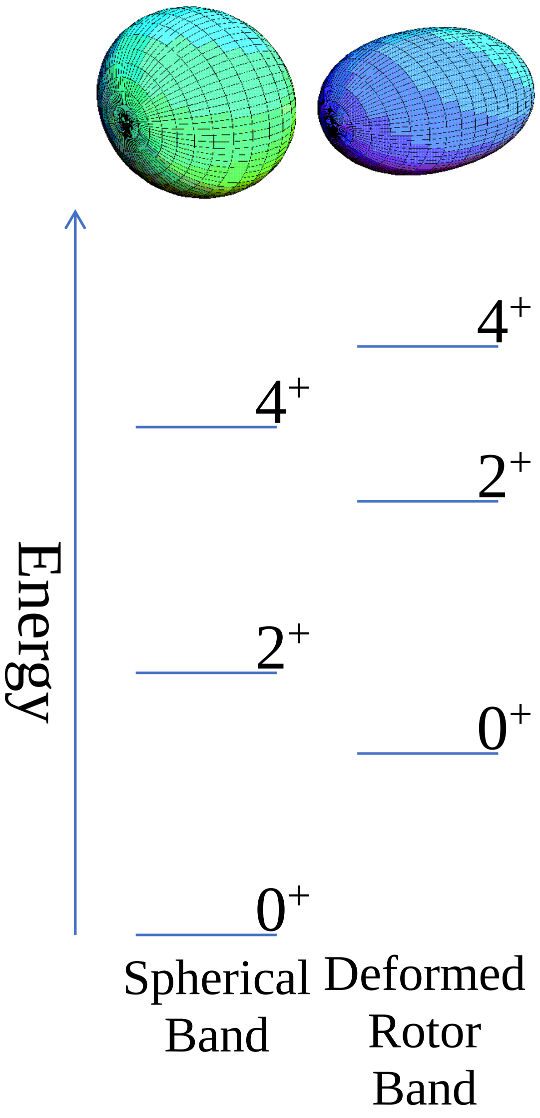


P. Moeller et al, Phys. Rev. Lett. 103 (2009) 212501 and Atom.Nucl. Data Tables. 98 (2012) 149

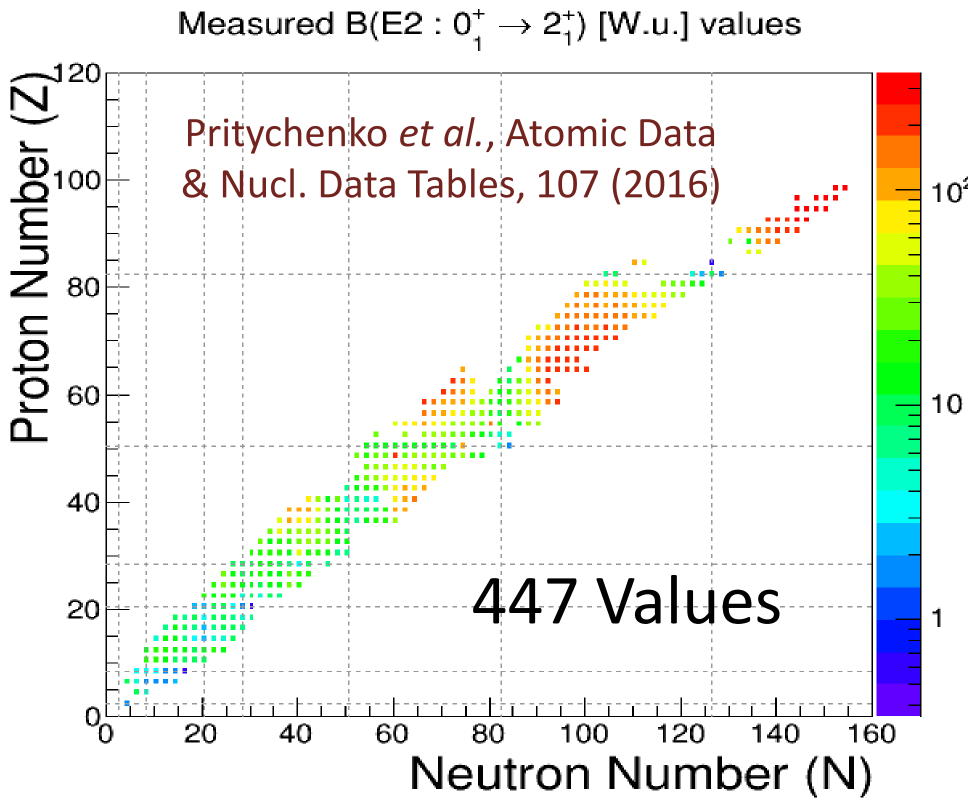


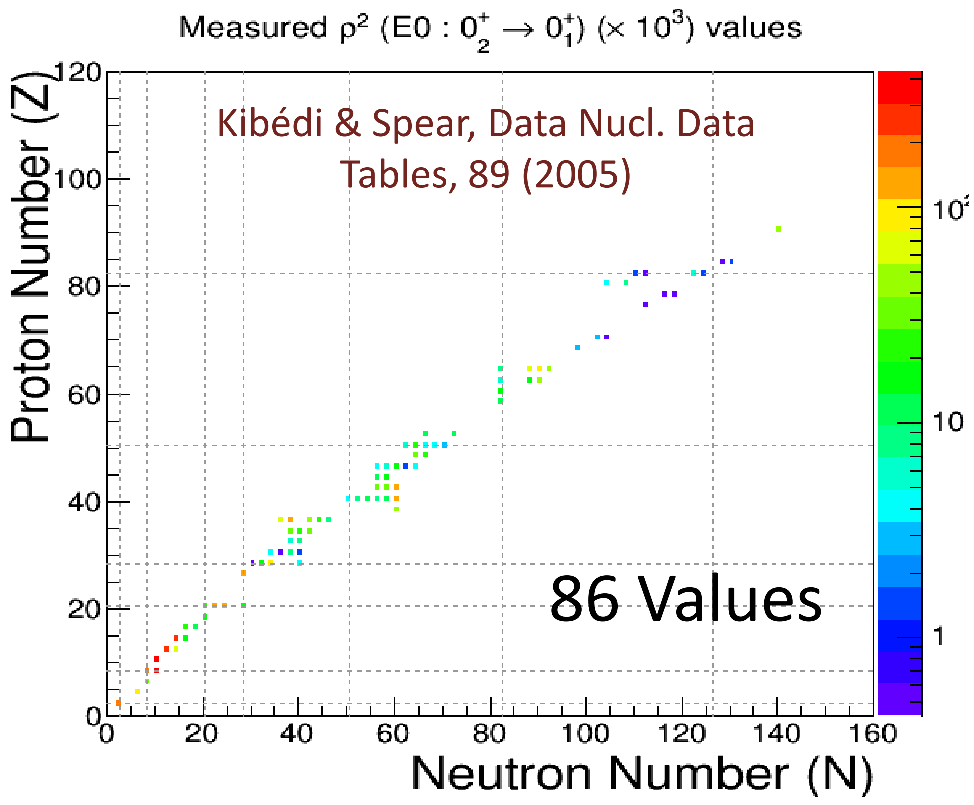
Shape Coexistence

- Multiple coexisting structures coexisting at low energy.
- Widespread. Everywhere?
- Evolution of underlying structures evolves with particle number (isotopes/isotones) we study this to test and improve our understanding of the underlying driving mechanisms.
- E0 strengths are a crucial tool due to shape sensitivity
- ICE are the best way to measure E0 strengths



Why Measure E0 Transitions?

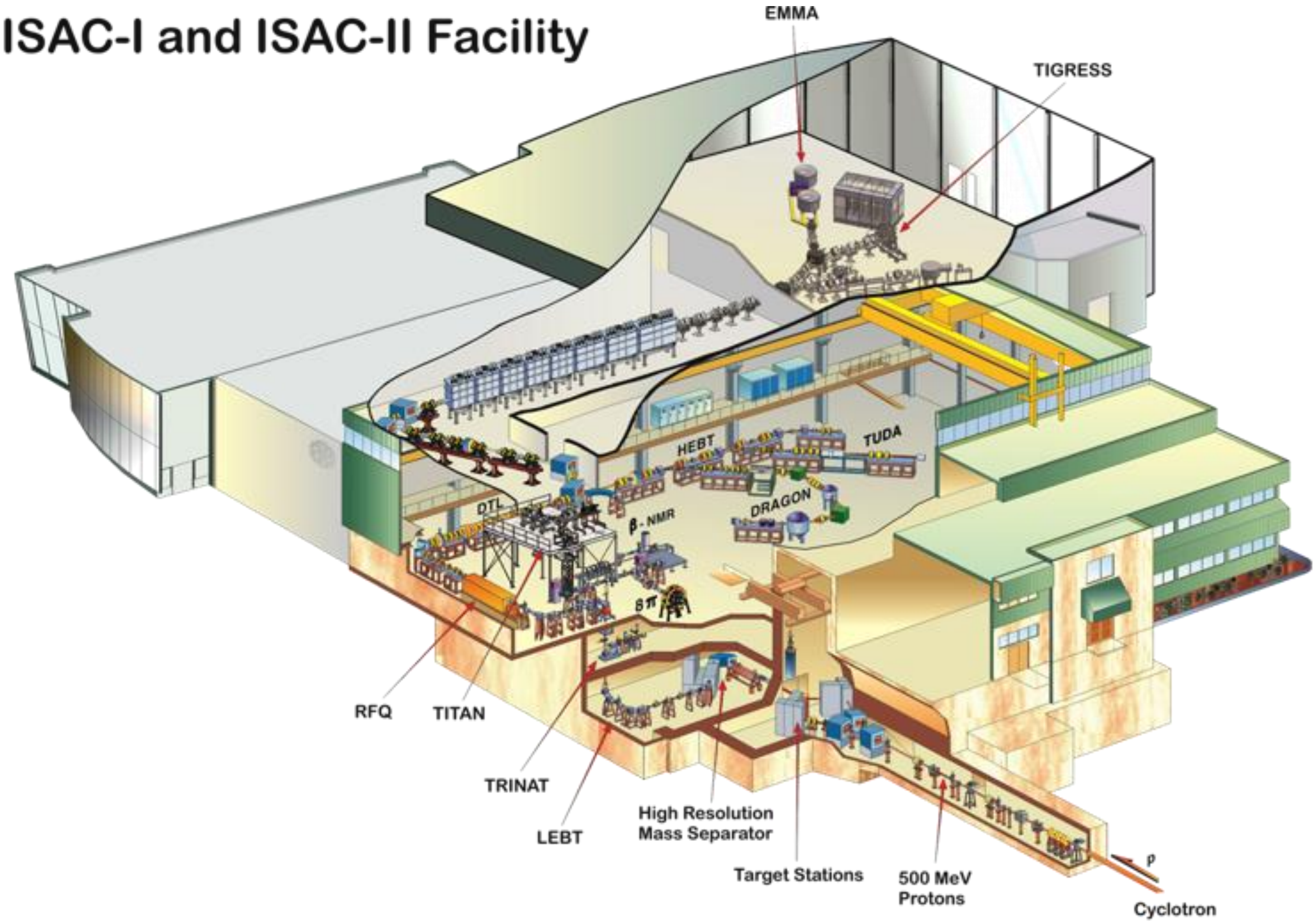


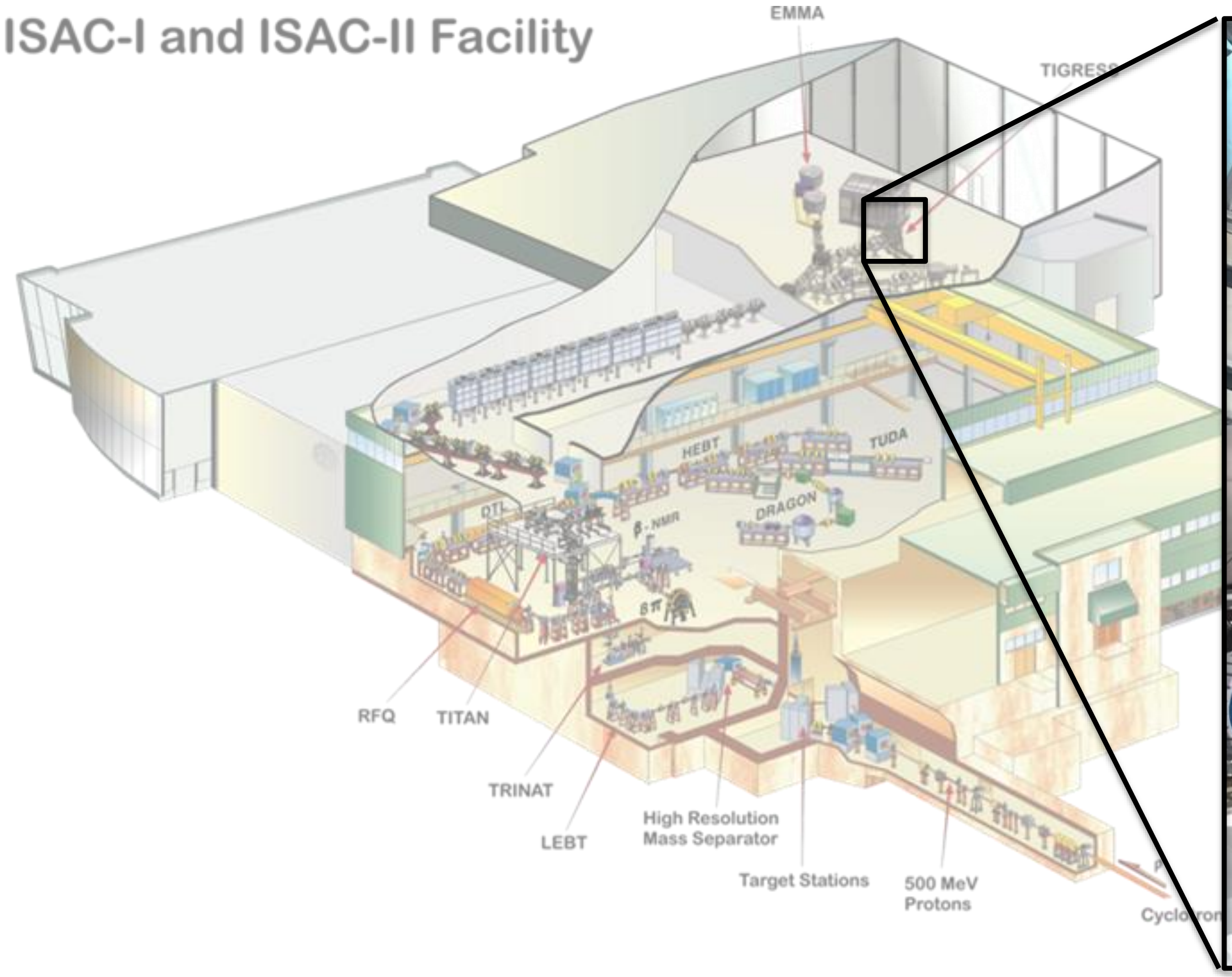


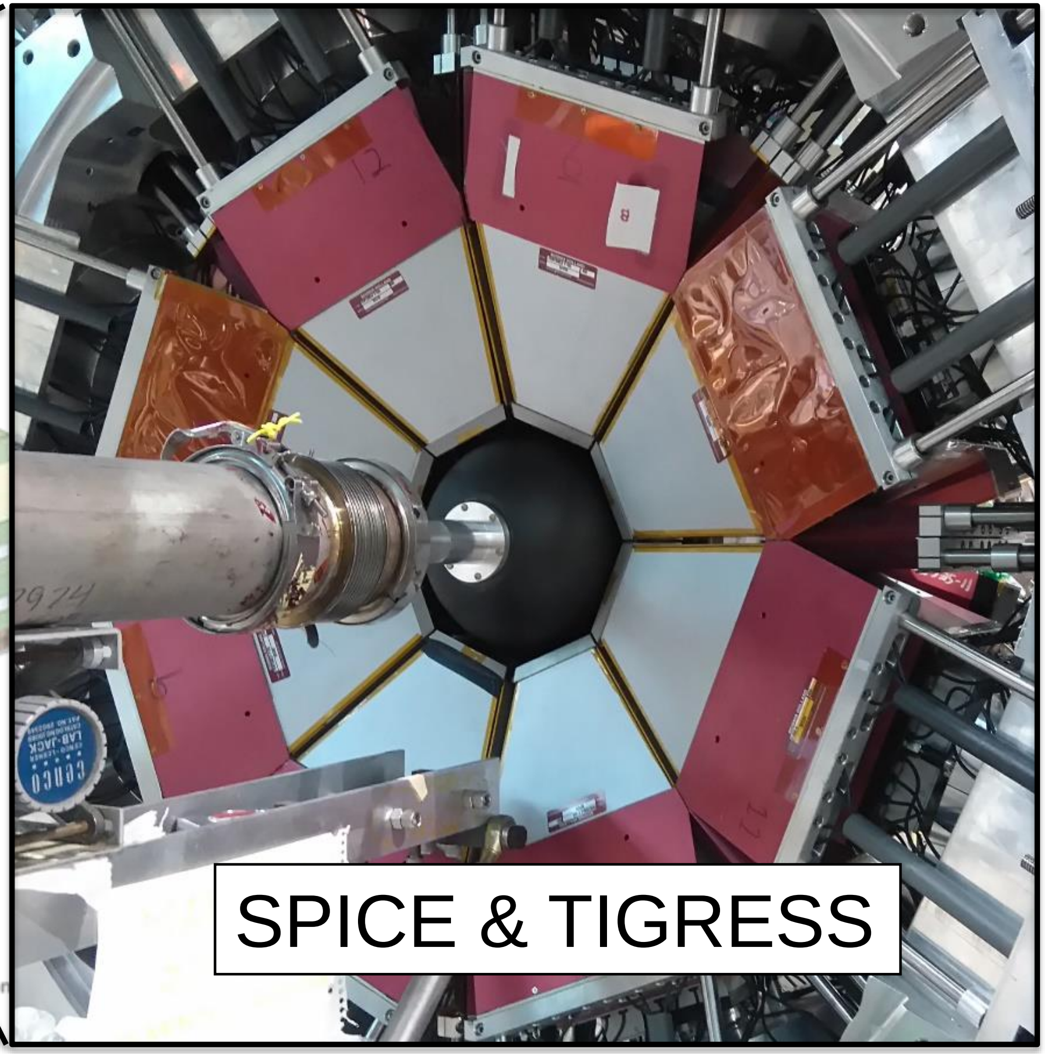
0_2^+ and 2_1^+ dominant features in low-lying structure

Transitions from 0_2^+ -> 0_1^+ scarcely studied (experimentally challenging)

ISAC-I and ISAC-II Facility

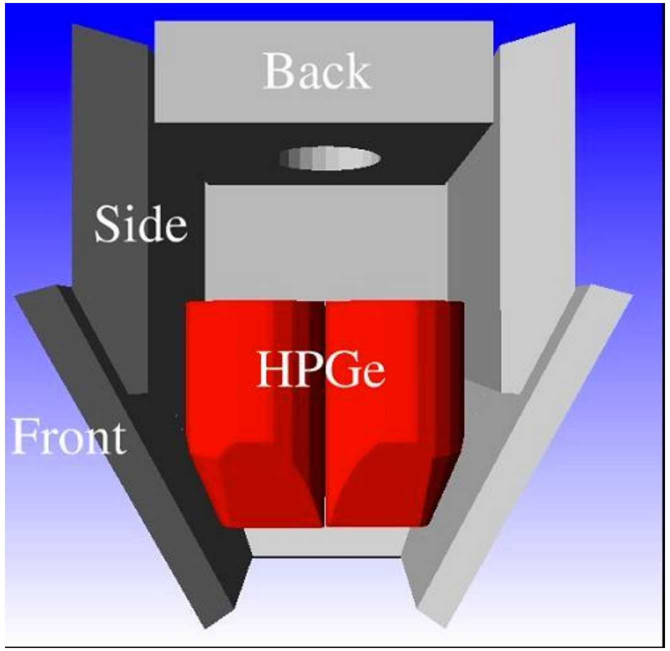


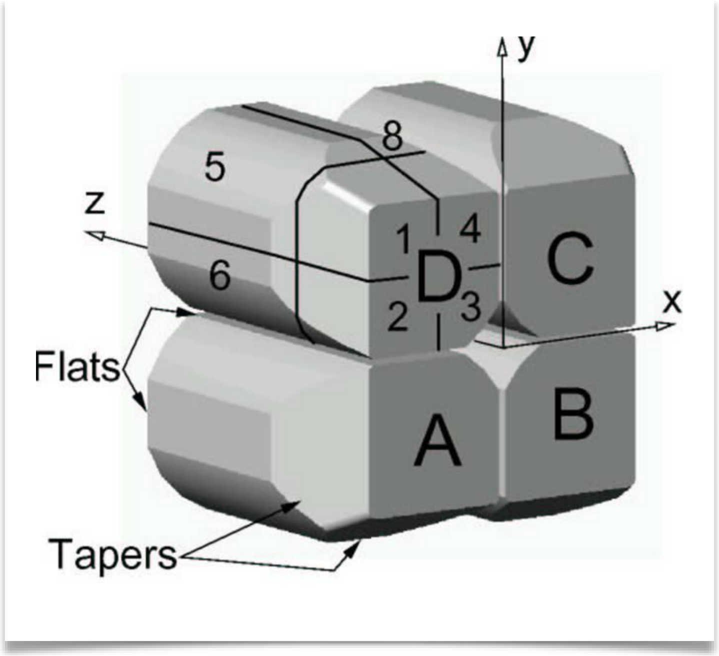

ISAC-I and ISAC-II Facility
EMMA
TIGRESS
HEBT
TUDA
DRAGON
DTL
β-NMR
βπ
RFQ
TITAN
TRINAT
LEBT
High Resolution
Mass Separator
Target Stations
500 MeV
Protons

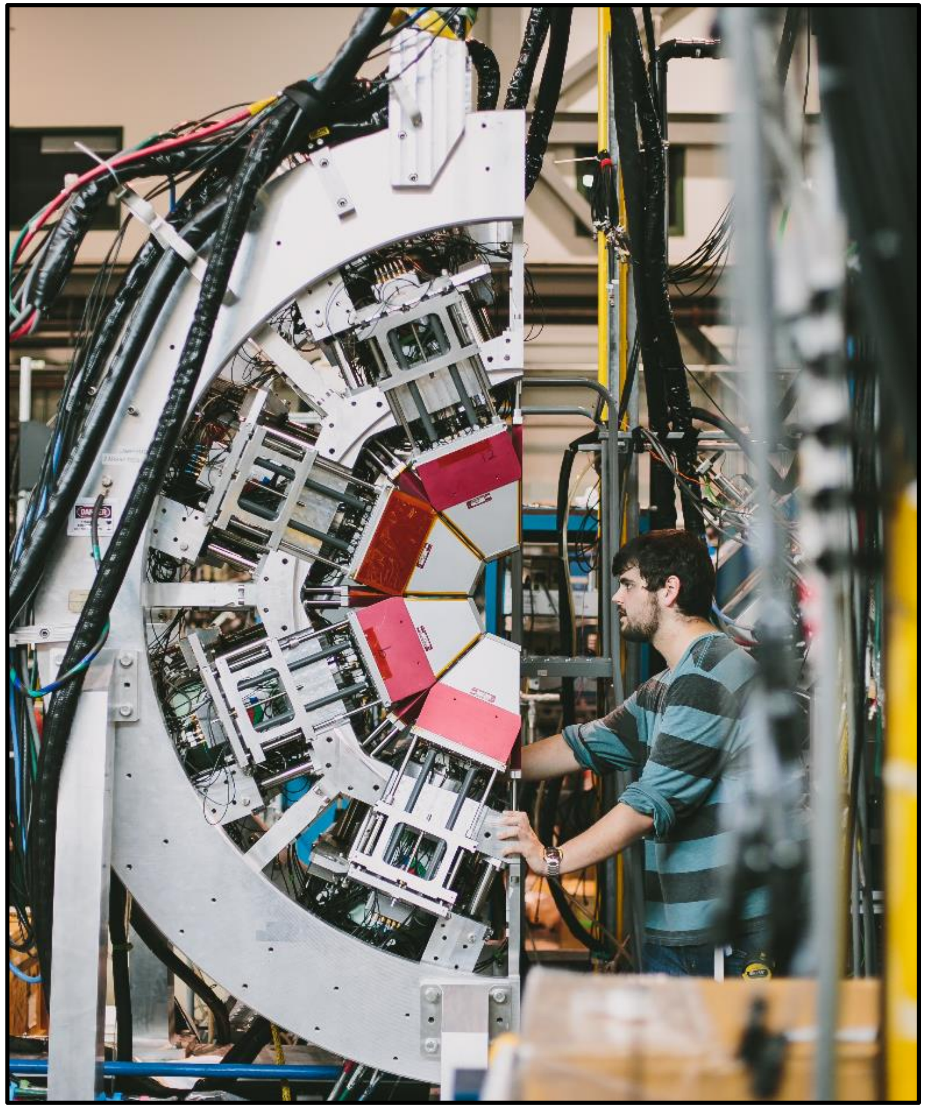

SPICE & TIGRESS

TIGRESS γ-ray spectrometer

- 16 HPGe detectors, 32-fold segmented
- Compton suppressed

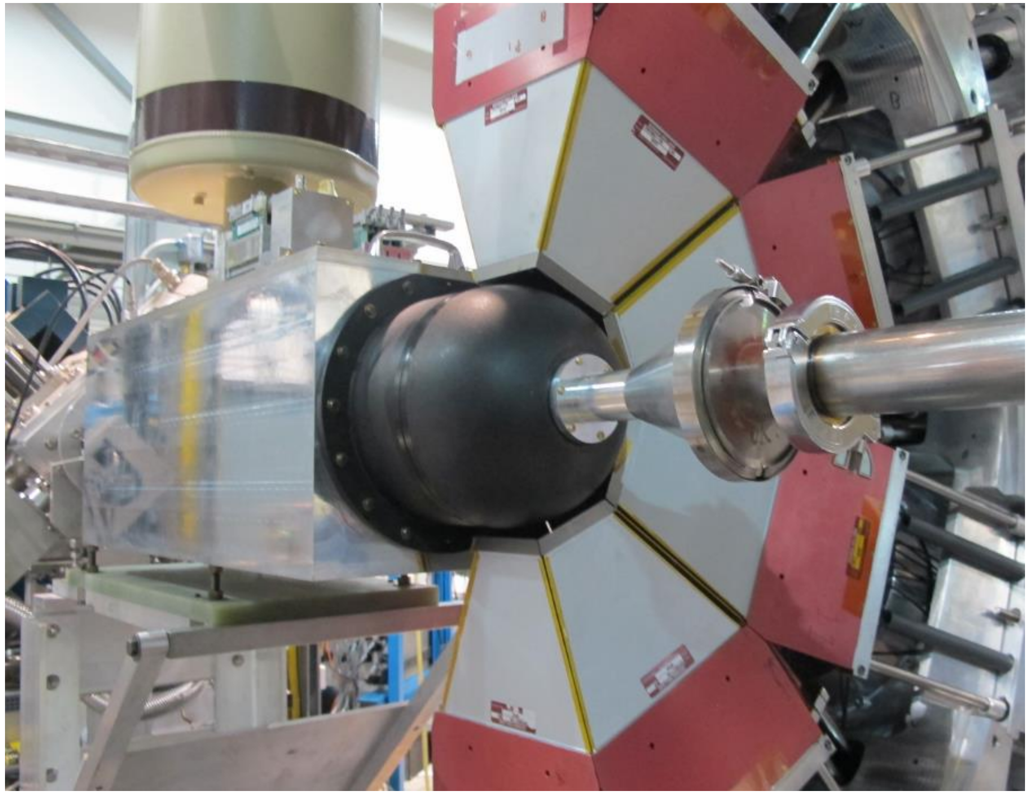




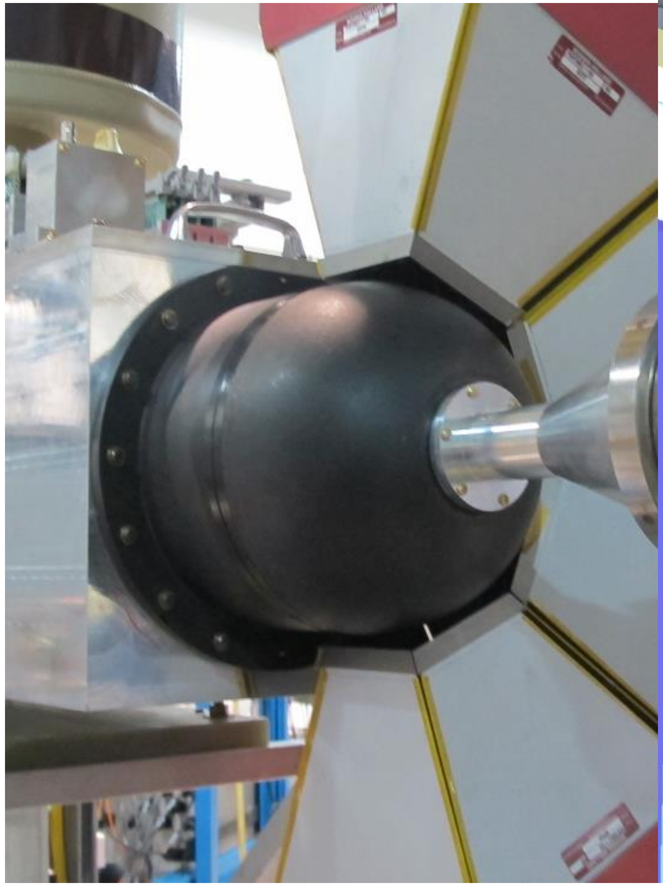


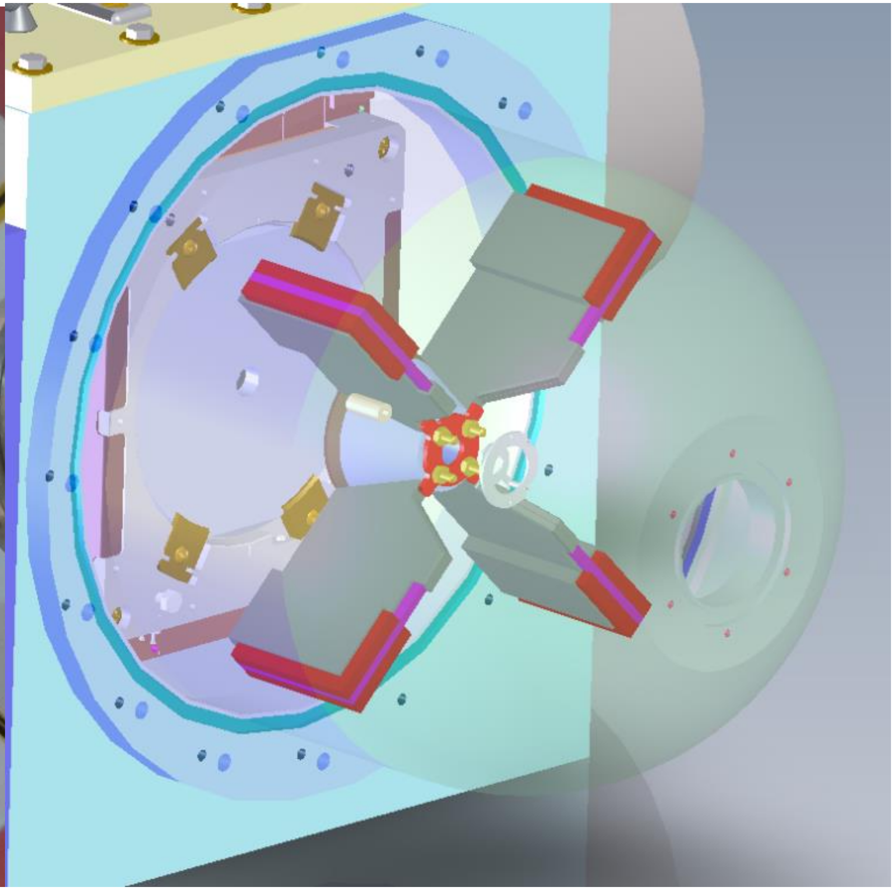
SPICE – SPectrometer for Internal Conversion Electrons

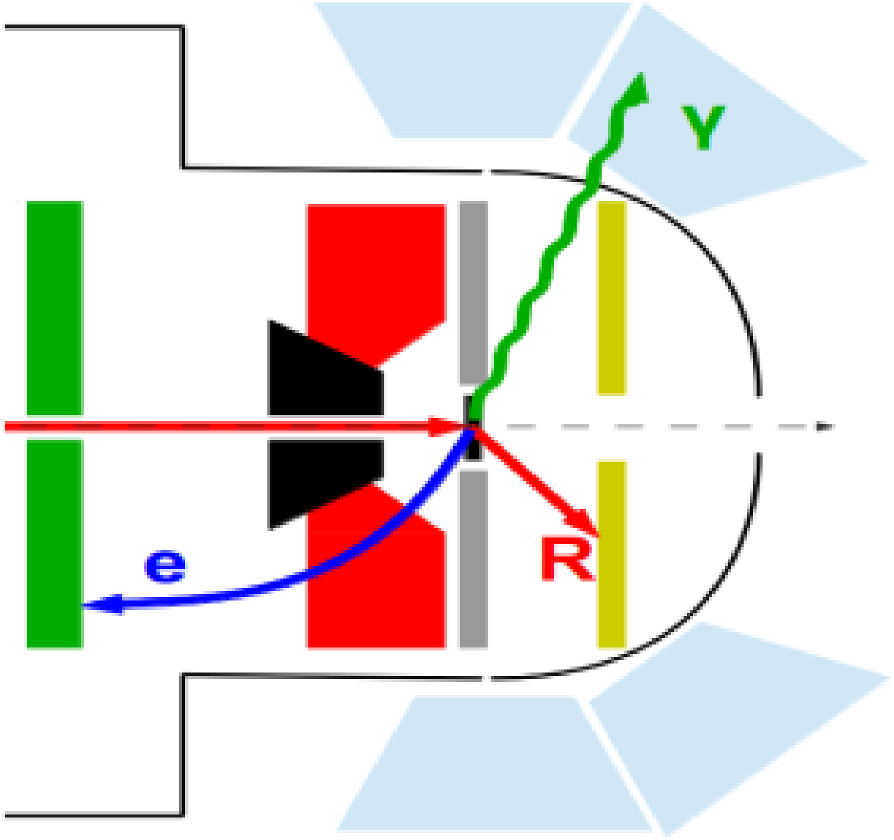
- 6.1 mm thick lithium-drifted silicon detector. Si(Li).
- LN2 cooled for improved resolution
- Photon shield blocks high flux of γ rays, X-rays and secondary electron
- Permanent NdFeB magnets direct electrons.



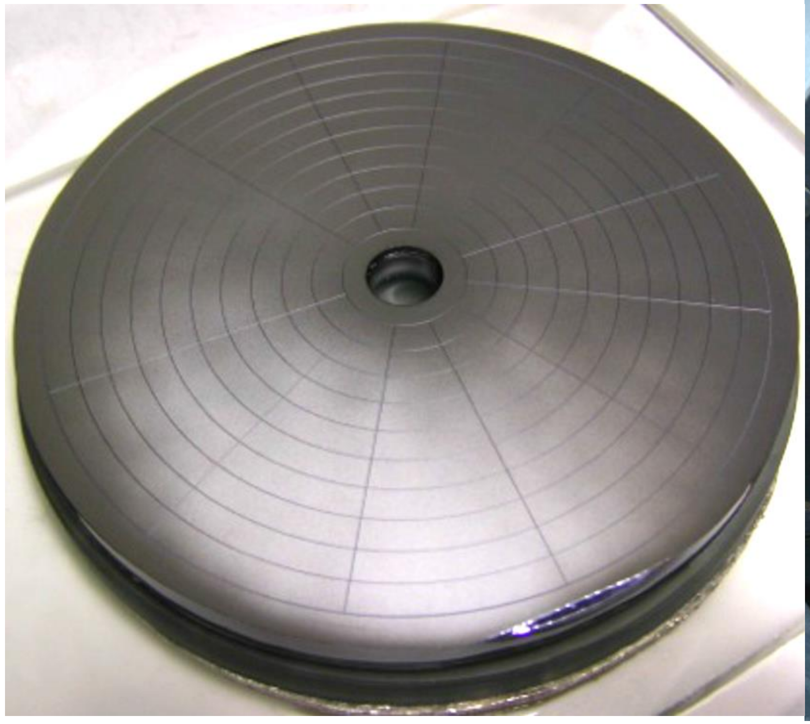
SPICE – SPectrometer for Internal Conversion Electrons



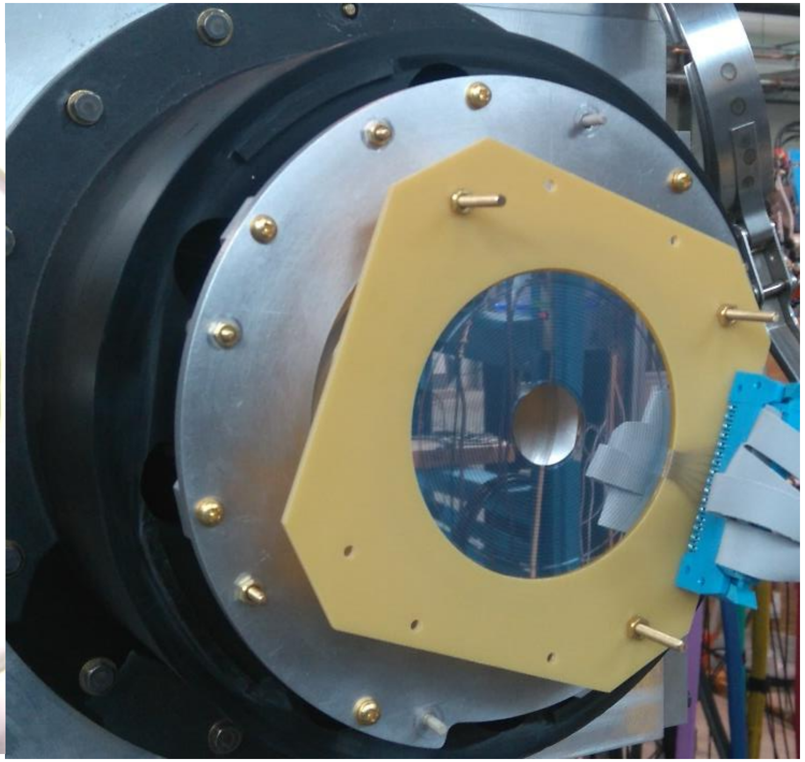




SPICE – SPectrometer for Internal Conversion Electrons



Si(Li). 120 Segments.

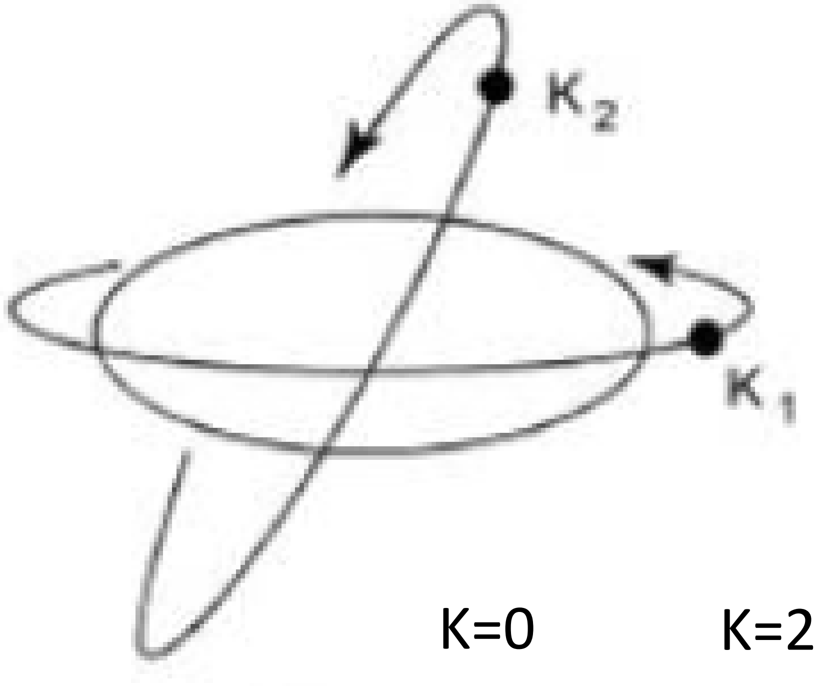


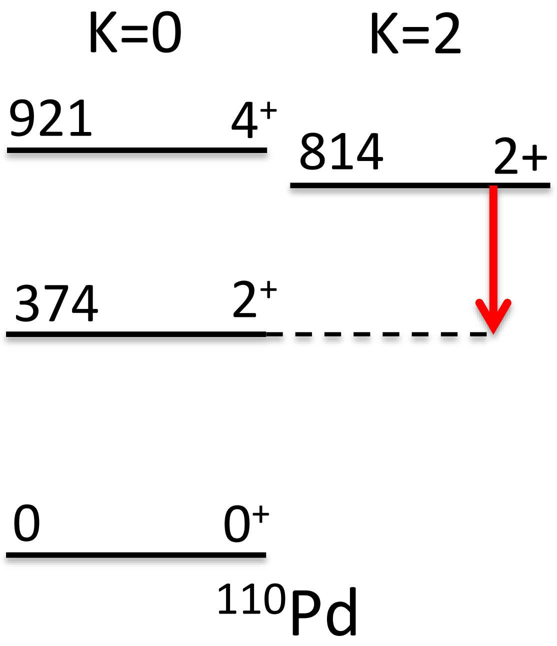
Silicon Recoil Detector

NdFeB magnets

K goodness in ^{110}Pd

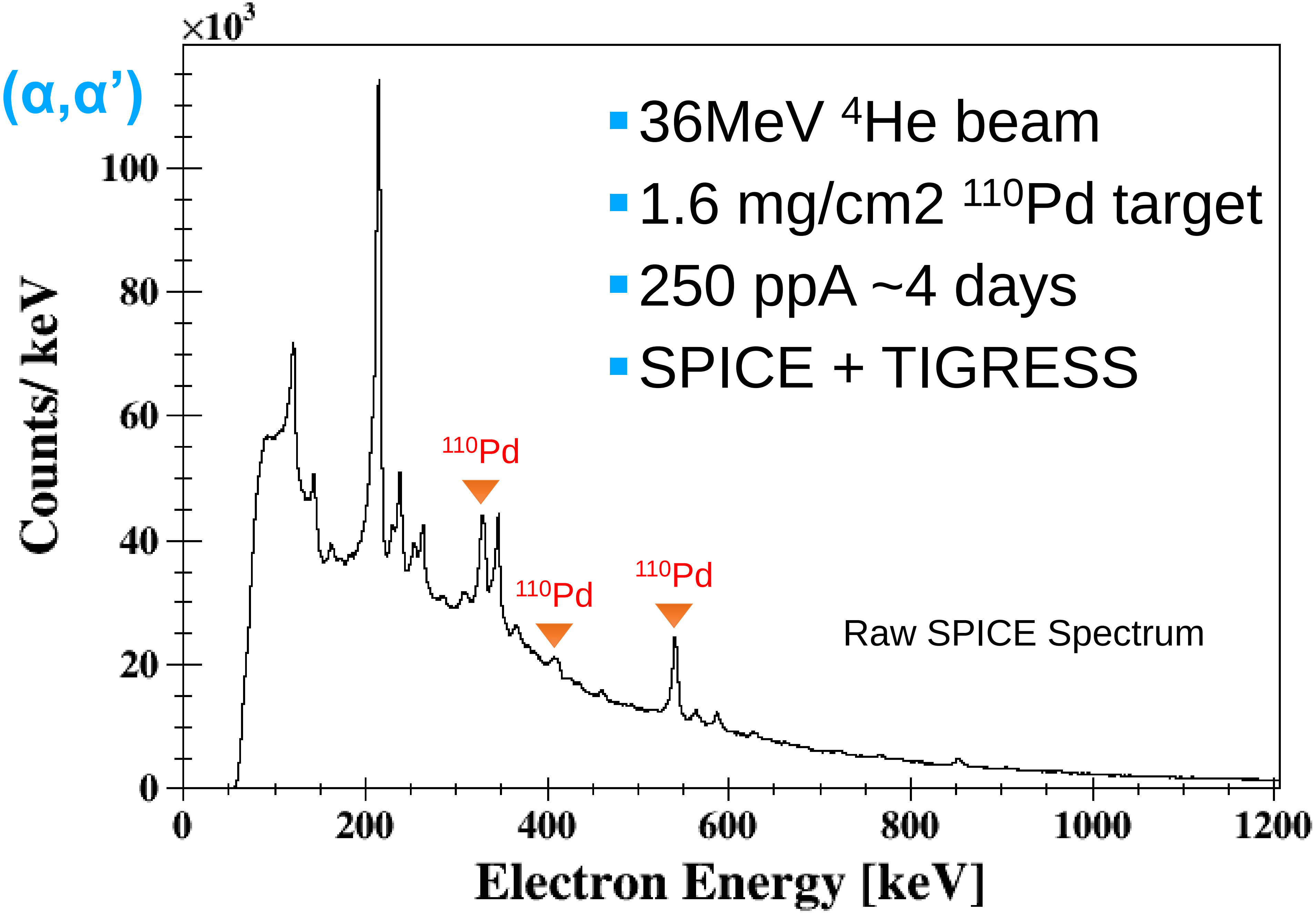
- In axial deformed model of nuclei, rotations have projection on symmetry axis.
- Quantum number K
- $J^{\pi} \rightarrow J^{\pi}$ transition E0 allowed
- $\Delta K \geq 0$ transition E0 forbidden
- Expect small E0 strength



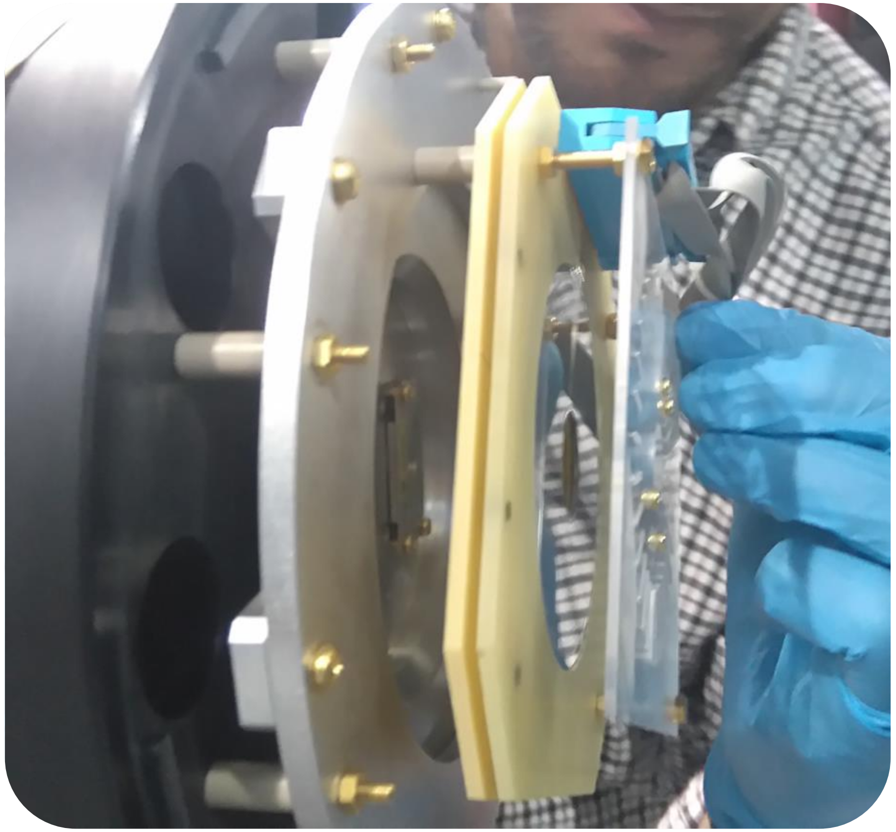


110Pd(α,α')

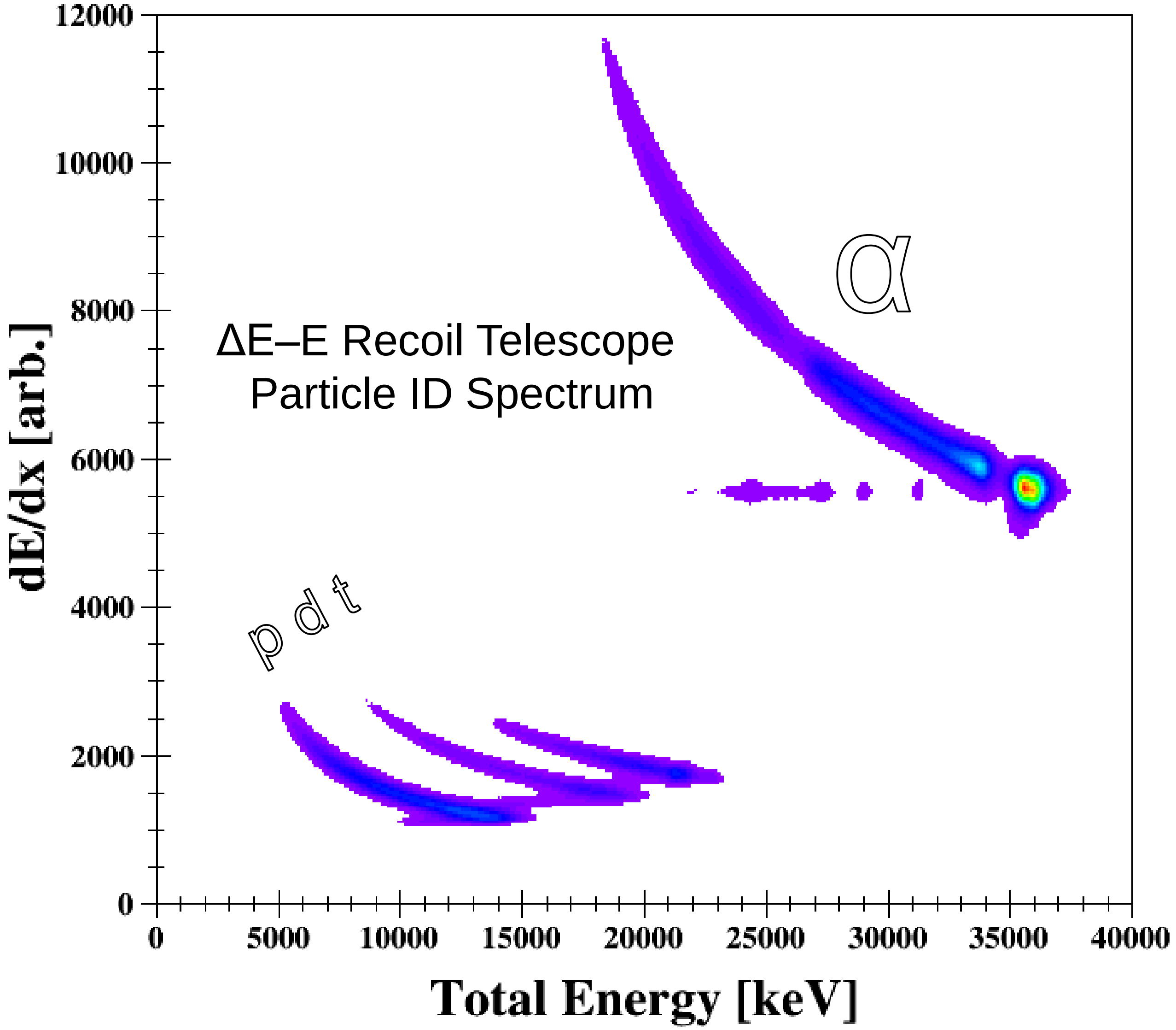
- 36MeV ^{4}He beam
- 1.6 mg/cm2 ^{110}Pd target
- 250 ppA ~4 days
- SPICE + TIGRESS



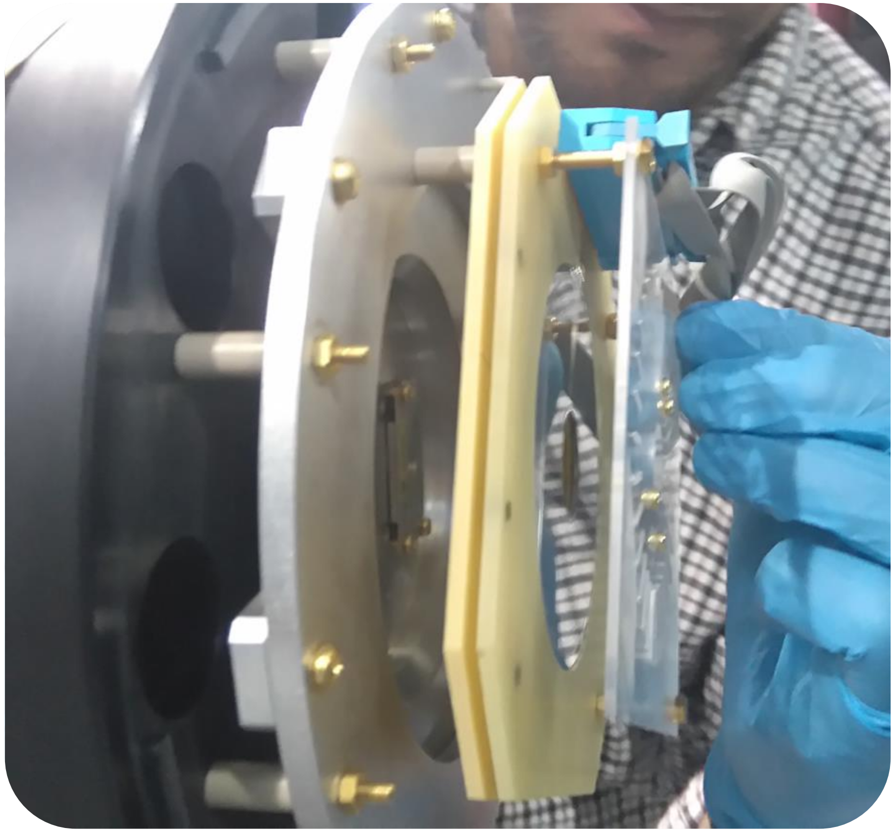
110Pd(α,α') Recoil Particle Coincidence



ΔE – E telescope
(140+1000 um S3)



110Pd(α,α’) Recoil Particle Coincidence



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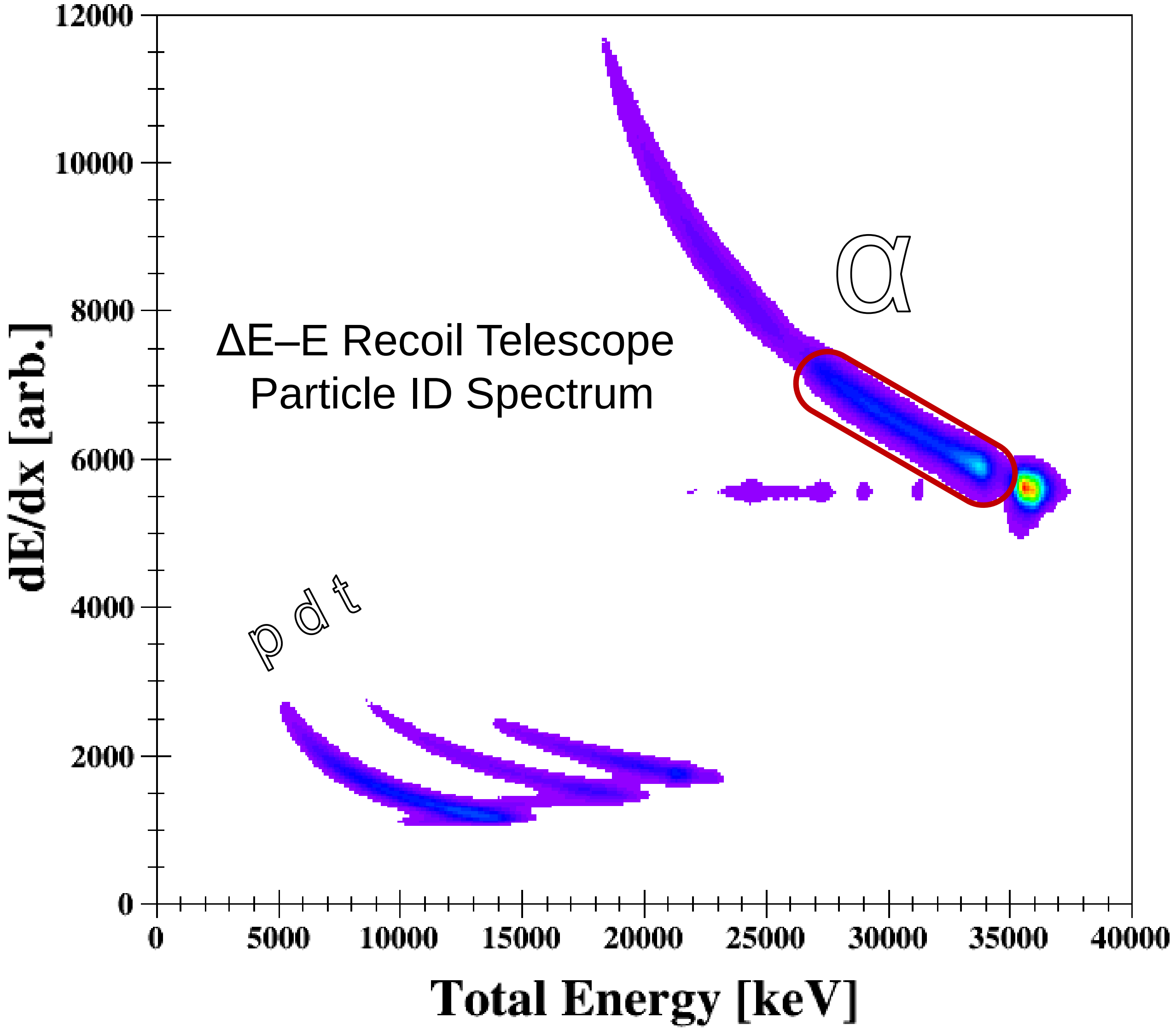
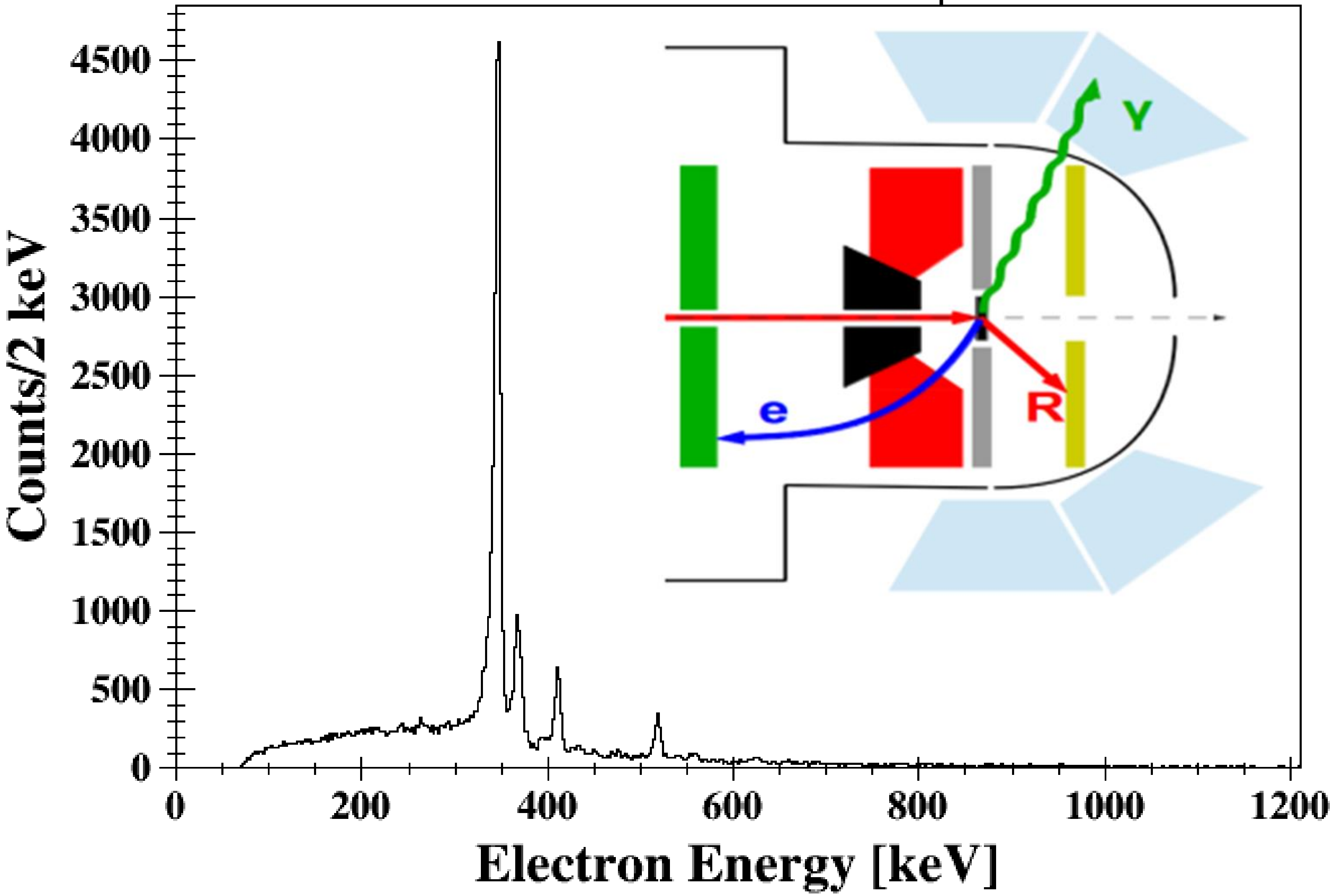
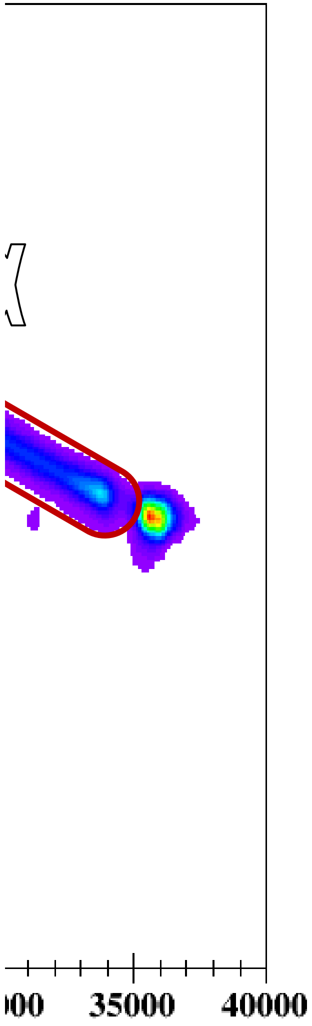


110Pd(α,α’) Recoil Particle Coincidence

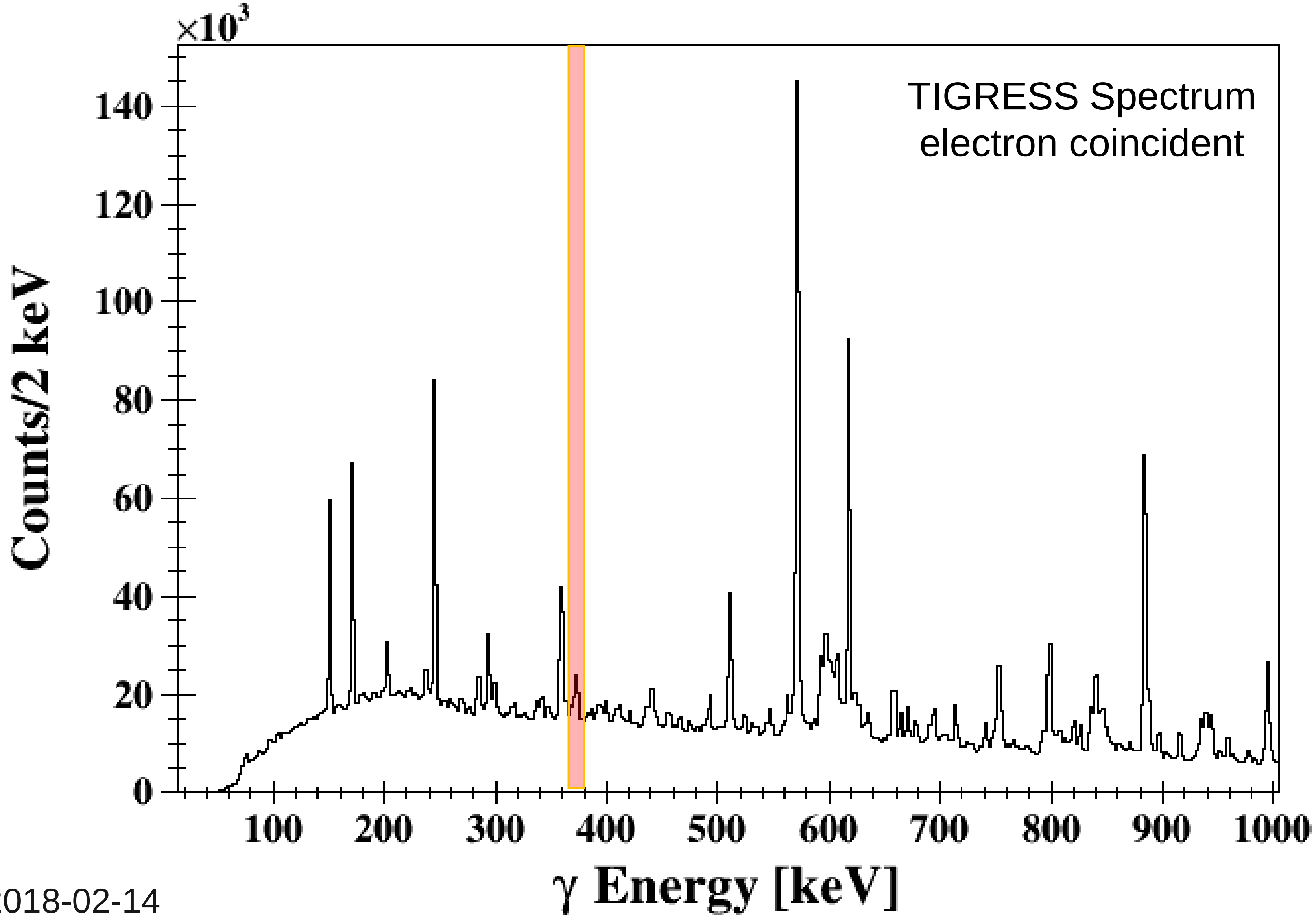
Inelastic α Particle Gated SPICE Spectrum

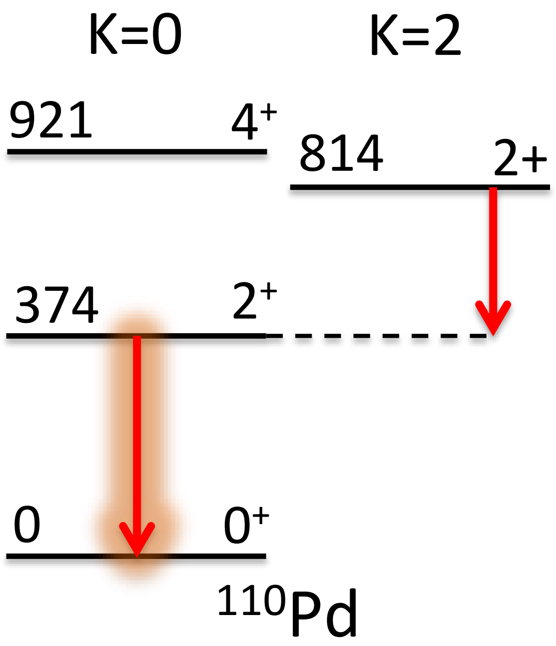




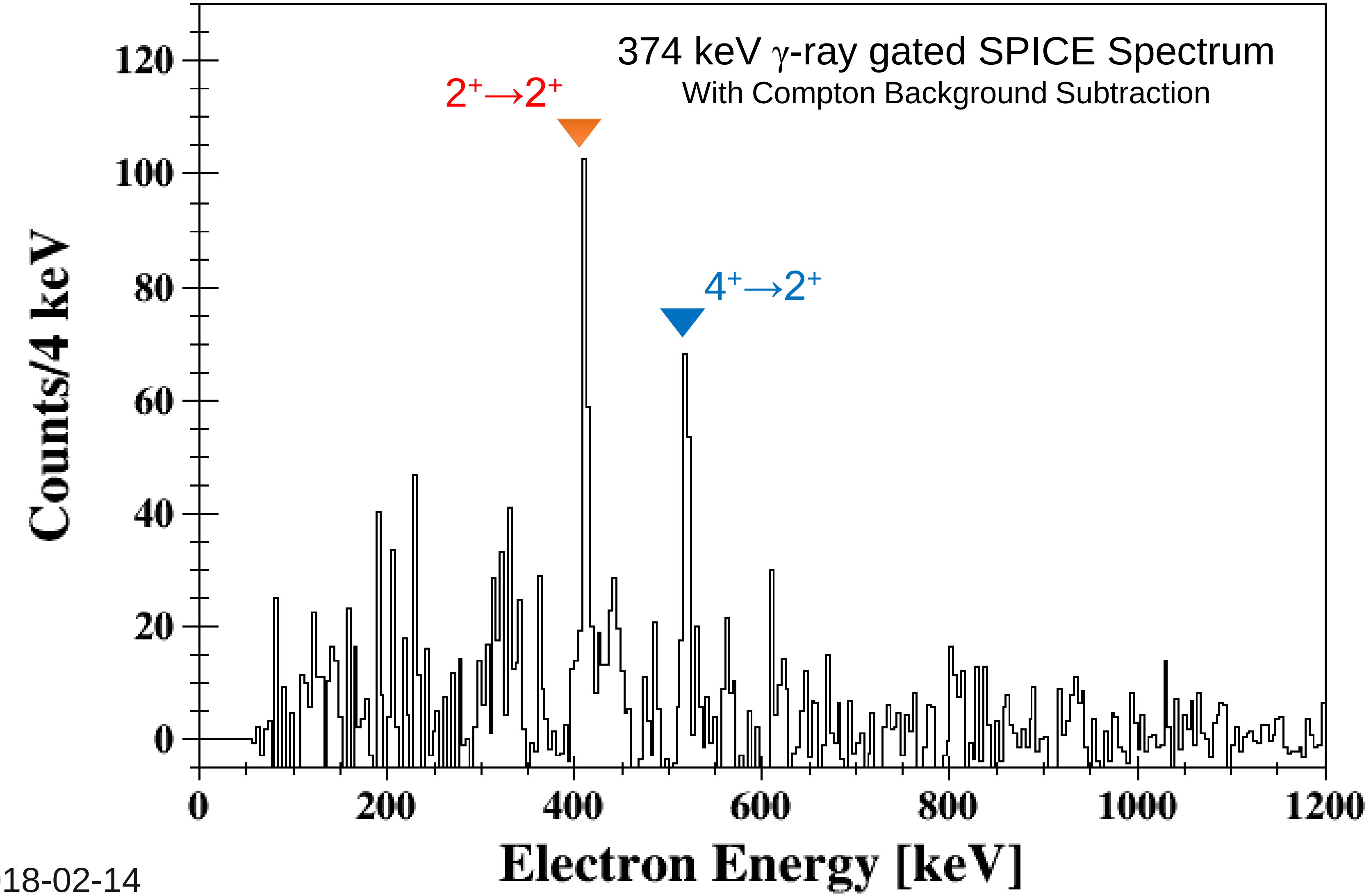
ΔE
(14

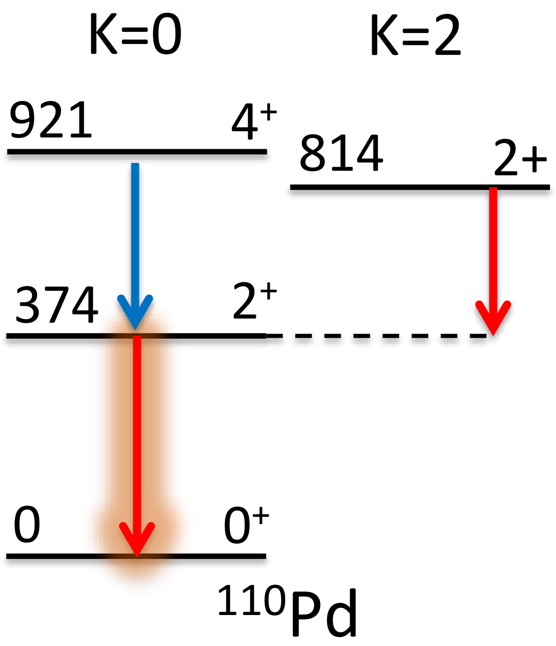
110Pd(α,α’) γ-ray Coincidence





110Pd(α,α') γ-ray Coincidence





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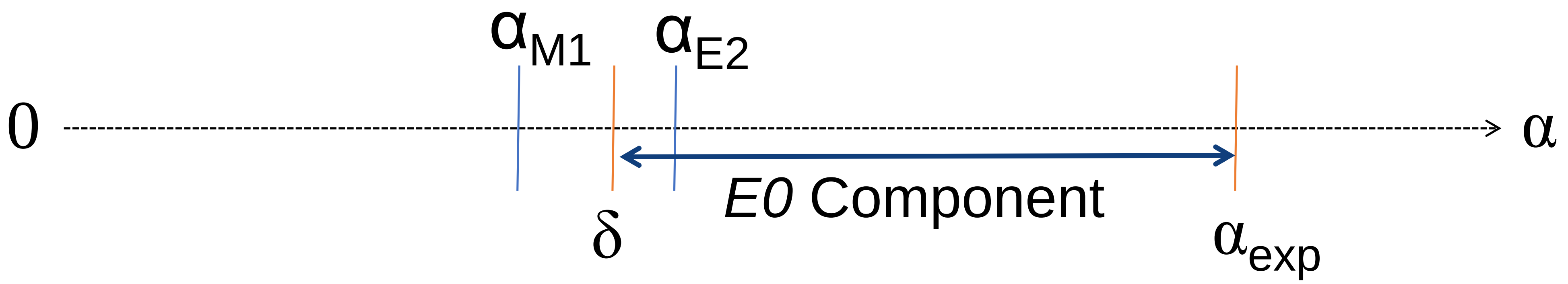
110Pd E0 Measurement

- For a mixed transition (eg. $2^+ \rightarrow 2^+$ contains *E0*+*M1*+*E2*), need to separate *E0* electrons from *M1*+*E2*
- Compare experimental ICC to calculated *M1*+*E2* ICC



$$\delta^2=\lambda(E2)/\lambda(M1)$$

Discovery, accelerated

110Pd E0 Measurement

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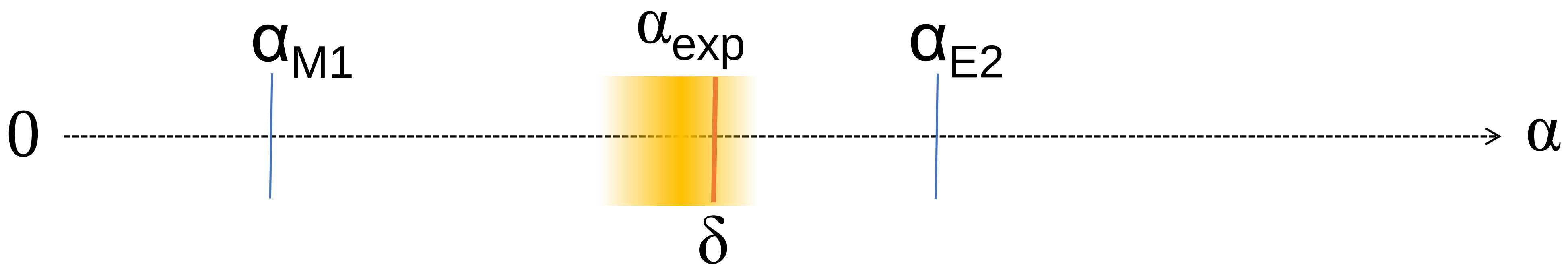


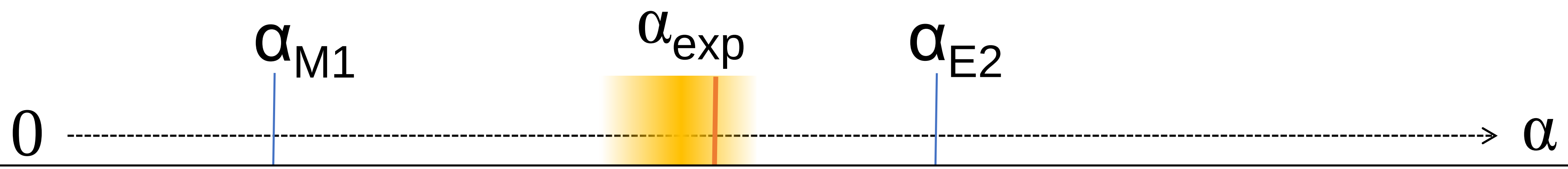
$\alpha_{exp} = 0.0070(14)$

$\alpha_{\delta} = 0.00752(11)$

$\rho^2(E0) < 13 \times 10^{-3}$

110Pd E0 Measurement

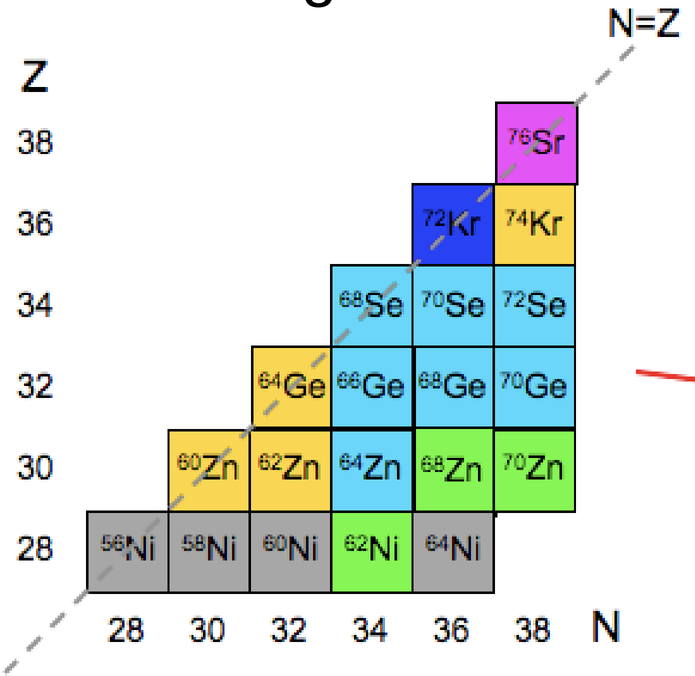
- For a mixed transition (eg. $2^+ \rightarrow 2^+$ contains *E0*+*M1*+*E2*), need to separate *E0* electrons from *M1*+*E2*
- Compare experimental ICC to calculated *M1*+*E2* ICC

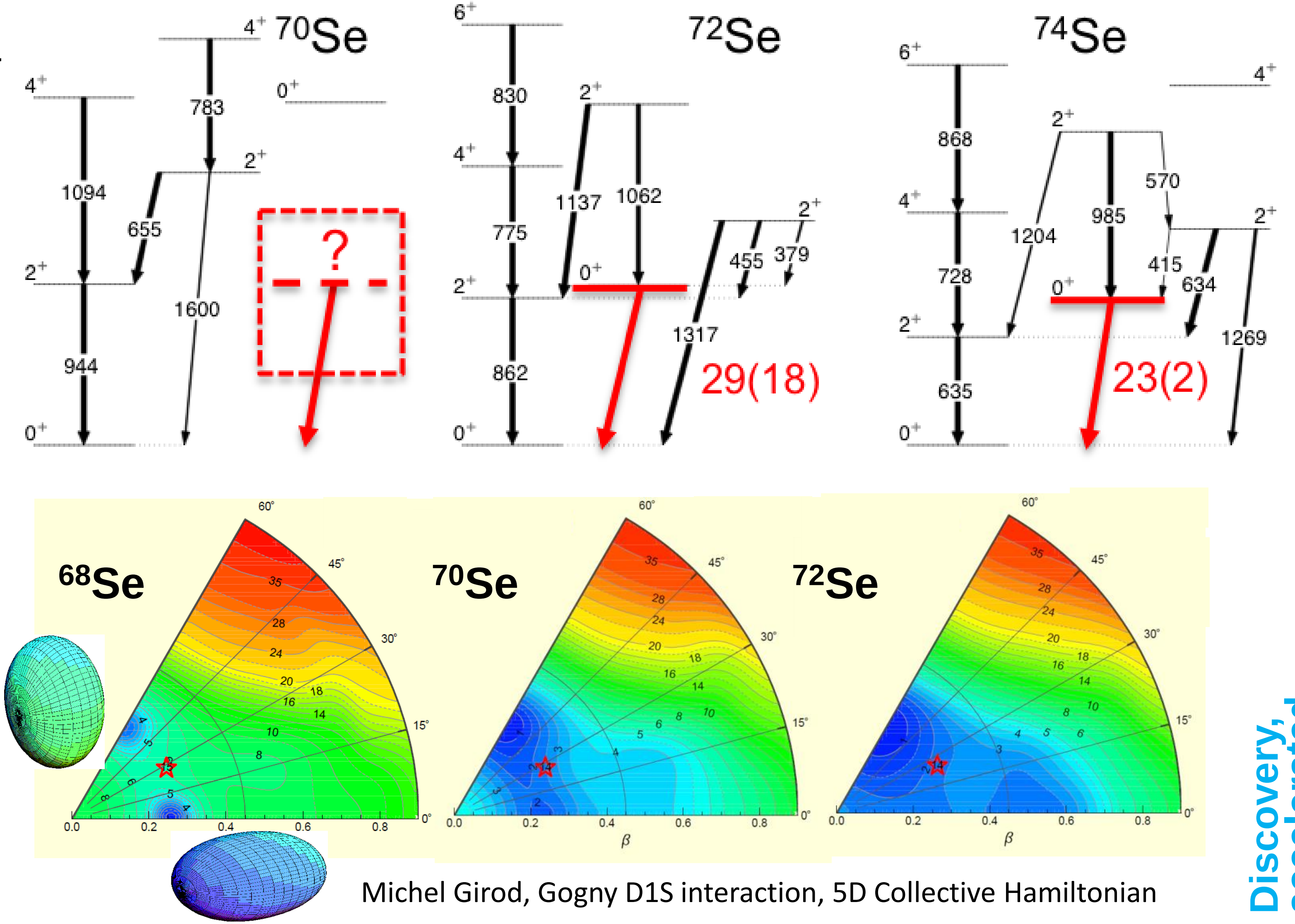


$\rho^2(E0) < 13\ \mathrm{x}10^{-3}$ small E0 measured
Excluded large shape mixing
Measurement of small E0 values important for systematics

Shape Coexistence in Se

Two well established minima in the potential energy surface at **prolate** and **oblate** deformation.
^{70}Se missing?





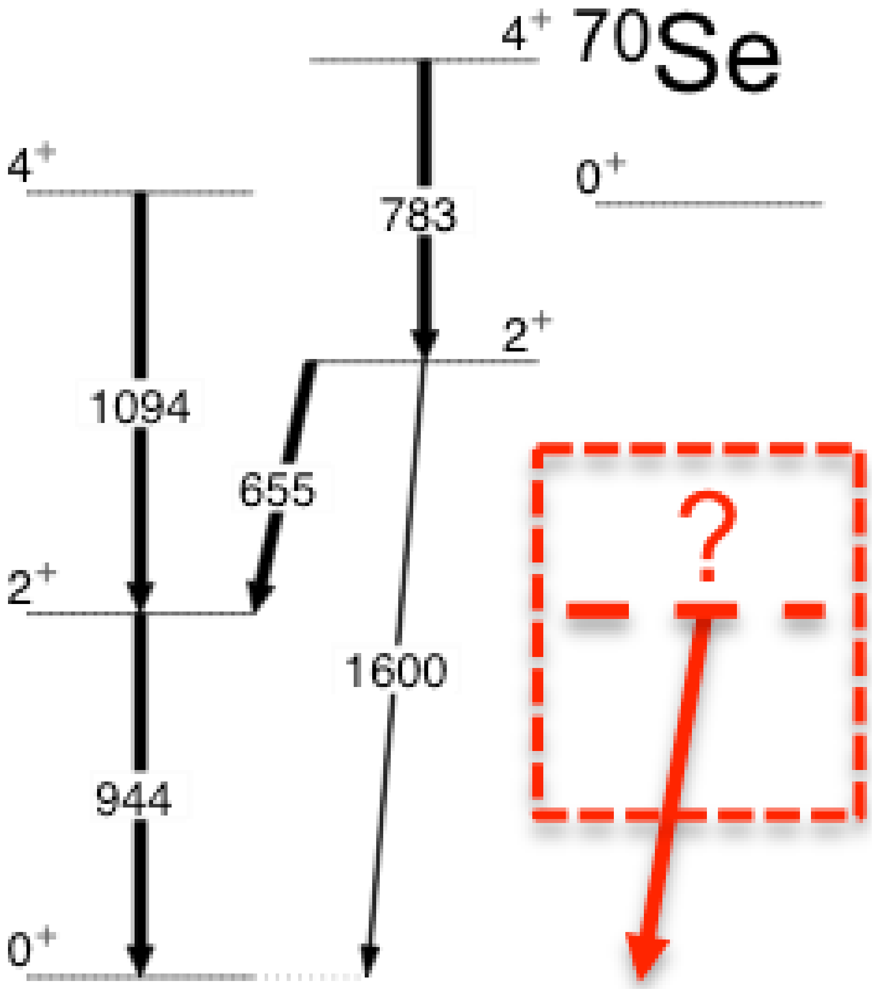
Michel Girod, Gogny D1S interaction, 5D Collective Hamiltonian

Shape Coexistence in ^{70}Se

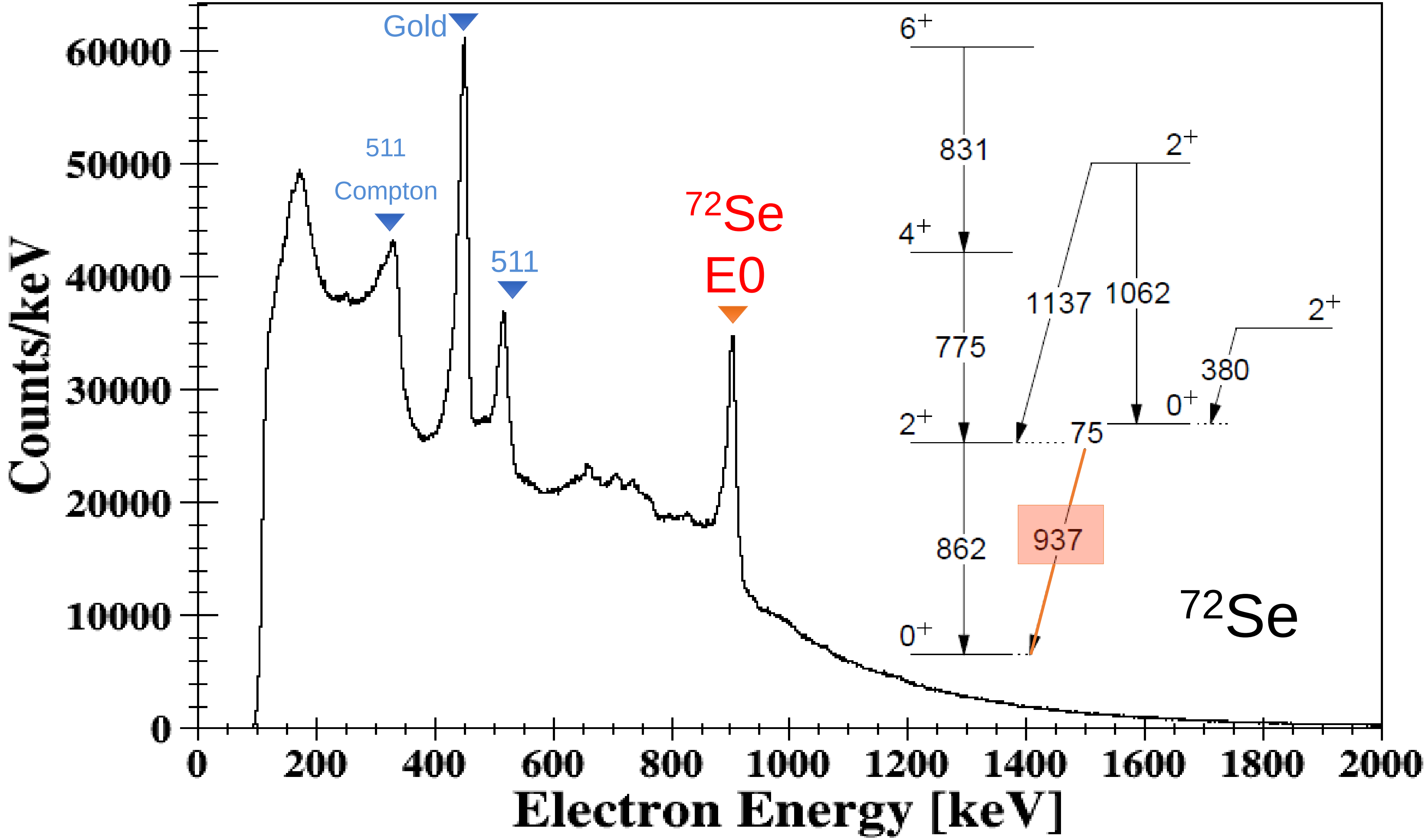
- Aim to observe the expect 0^+ state.
- If near/below 2^+, γ-decay hindered/forbidden.
- ICE dominant.

- Nat. Ca target 0.5 mg/cm^2
- 120 MeV ^{36}Ar beam ~1 pnA x6 days
  - $^{40}Ca(^{36}Ar,\alpha 2p)^{70}Se$
  - $^{40}Ca(^{36}Ar,4p)^{72}Se$

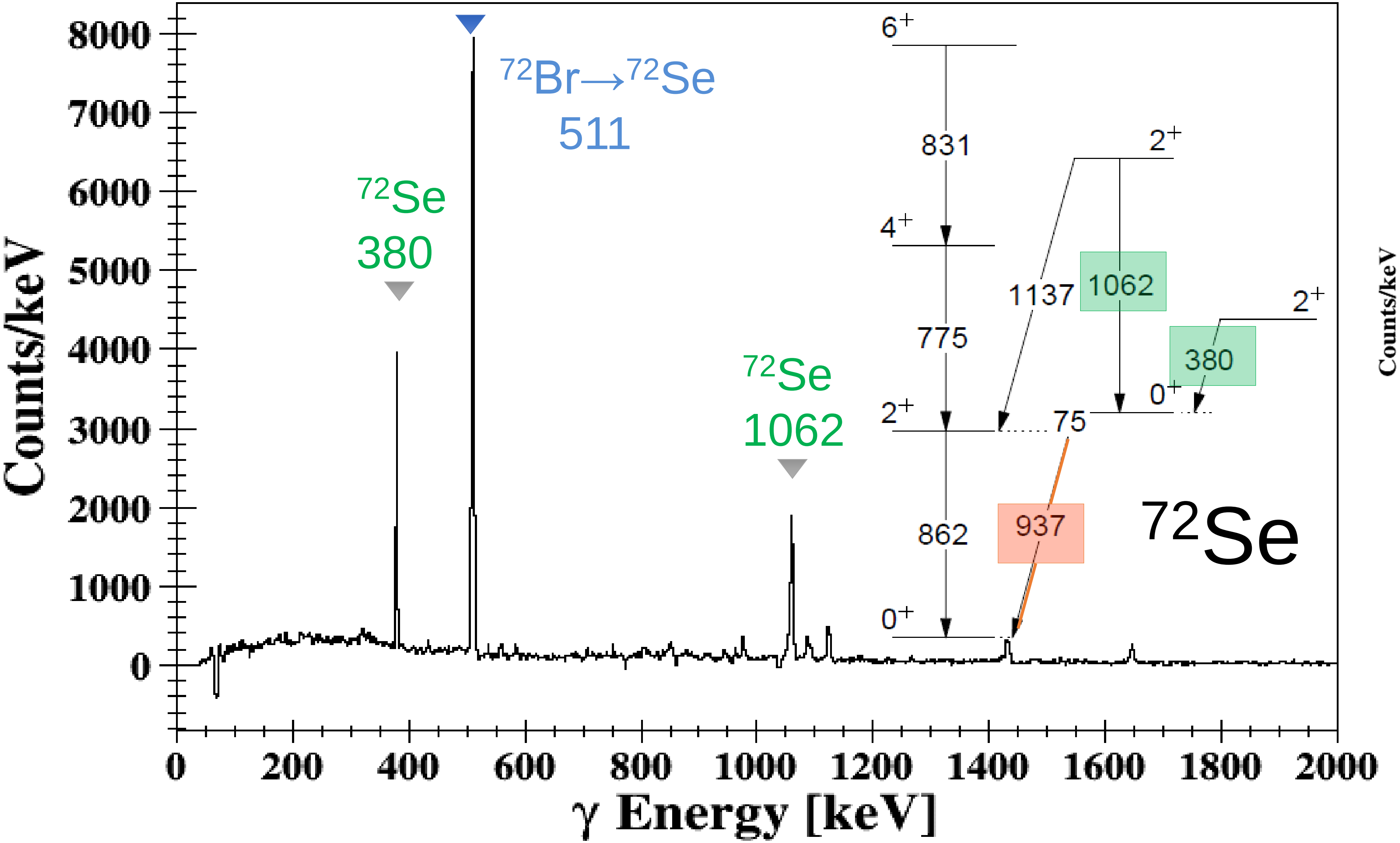
- TIGRESS – Gamma rays
- SPICE – Upstream ICE detector
- S3 – Downstream evaporation residue detector

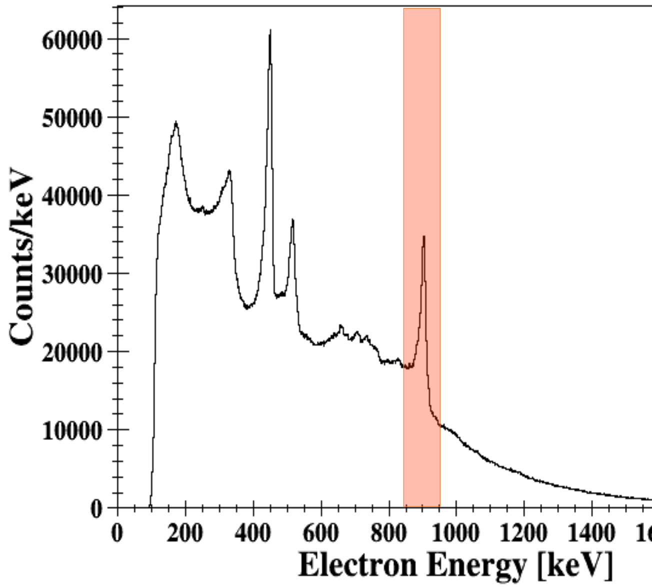


$^{40}Ca+^{36}Ar$ SPICE Singles

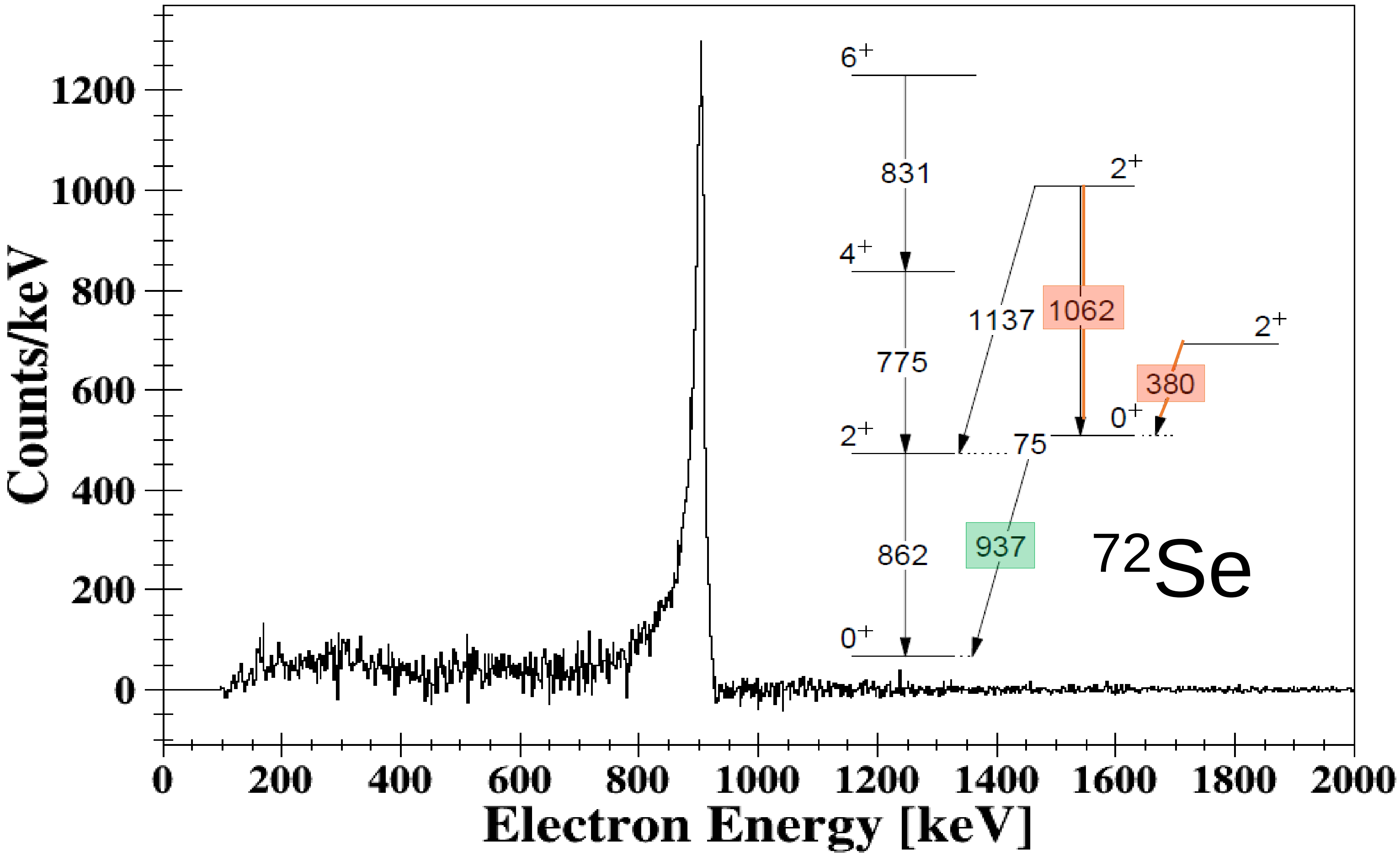


$^{40}Ca+^{36}Ar$ Electron-Gated γ rays



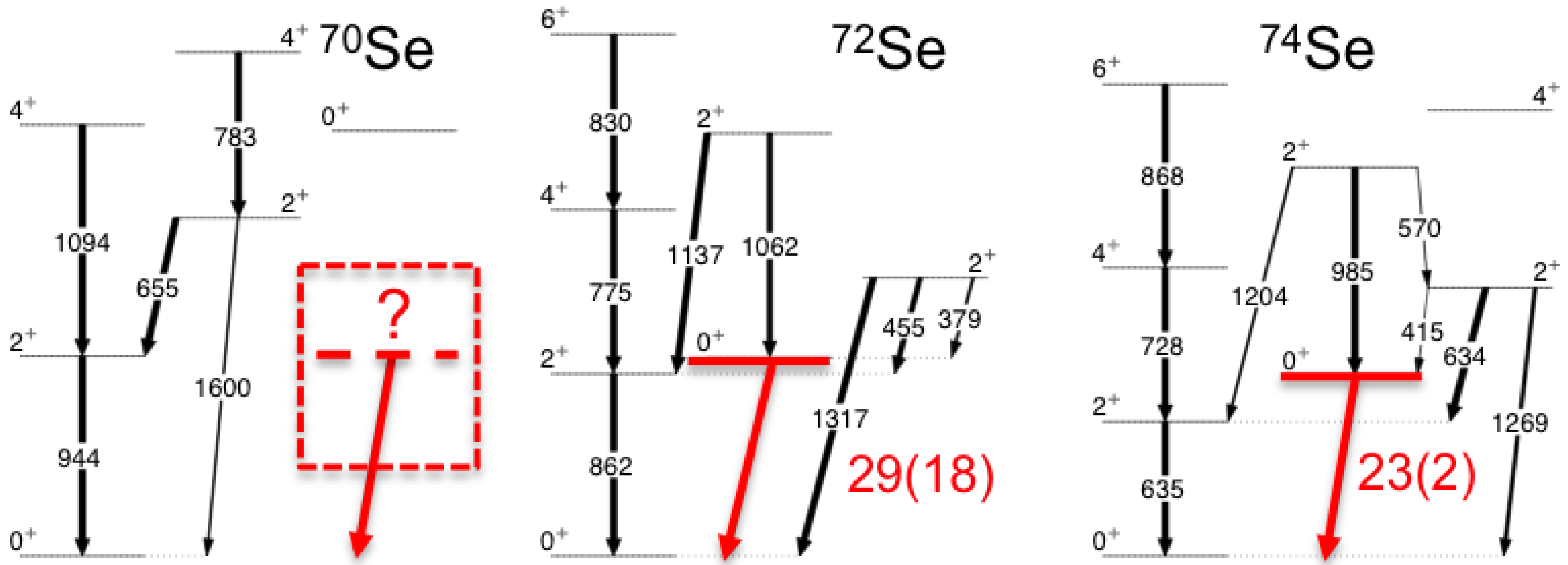


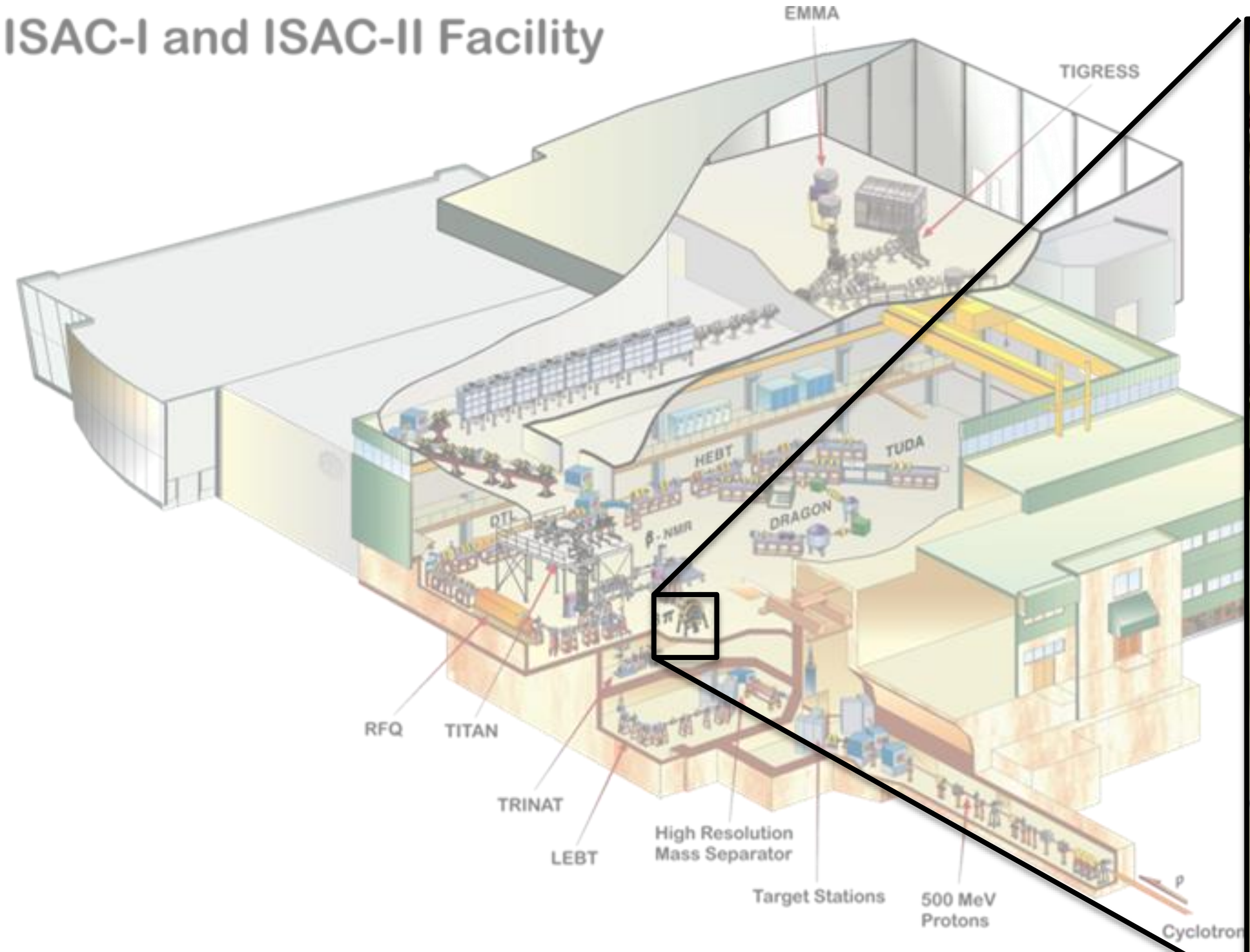
$^{40}Ca+^{36}Ar$ γ-ray-Gated Electrons



^{70}Se Still Elusive

- Techniques working well
- ^{72}Se clearly seen
- Detailed analysis to reveal ^{70}Se ongoing

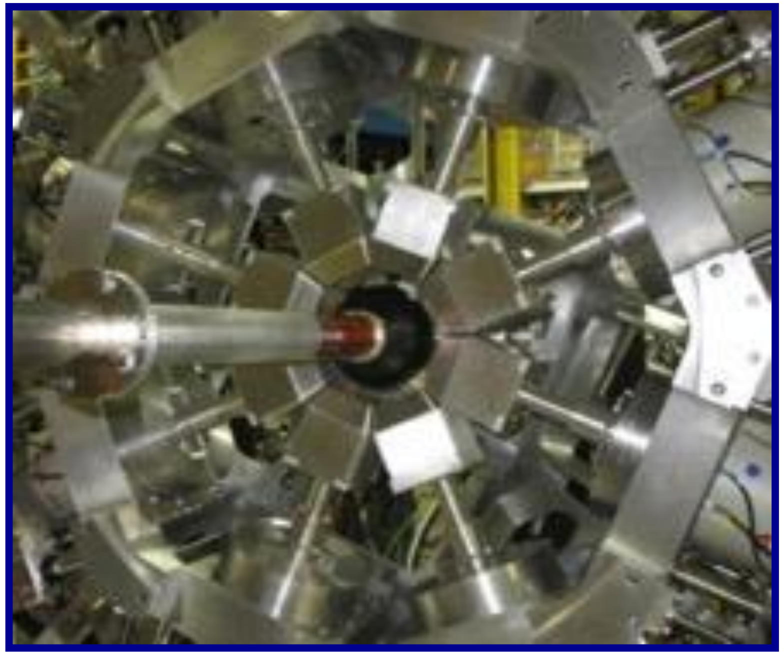



ISAC-I and ISAC-II Facility
EMMA
TIGRESS
HEBT
TUDA
DRAGON
DTL
β-NMR
RFQ
TITAN
TRINAT
LEBT
High Resolution
Mass Separator
Target Stations
500 MeV
Protons
Cyclotron


GRIFFIN & PACES

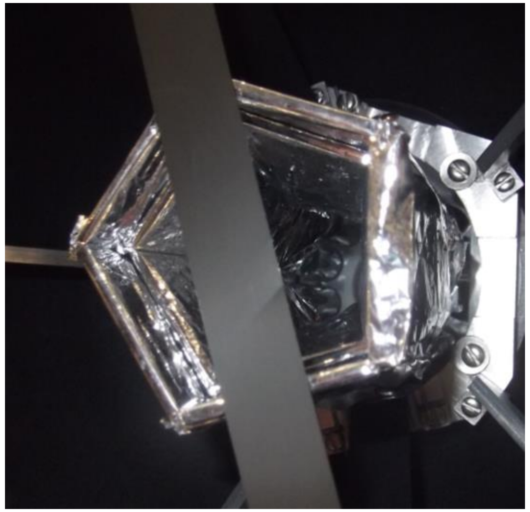
The GRIFFIN Spectrometer for precision decay studies

- RIB beam implanted in tape at centre of array.
- Study beam isomer & beta decay
- 16 HPGe Clovers + Ancillary detectors.
- Detect gamma rays and determines branching ratios, multipolarities and mixing ratios
- Move tape, remove daughters

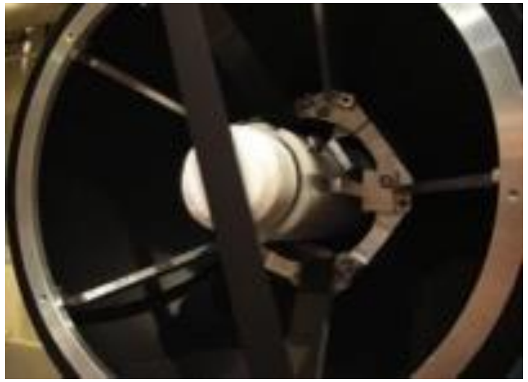


GRIFFIN Ancillary Detectors

SCEPTAR

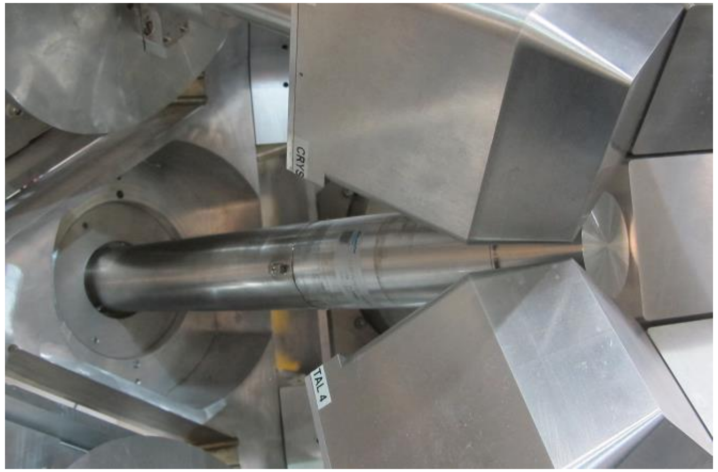


Zero-Degree Scintillator

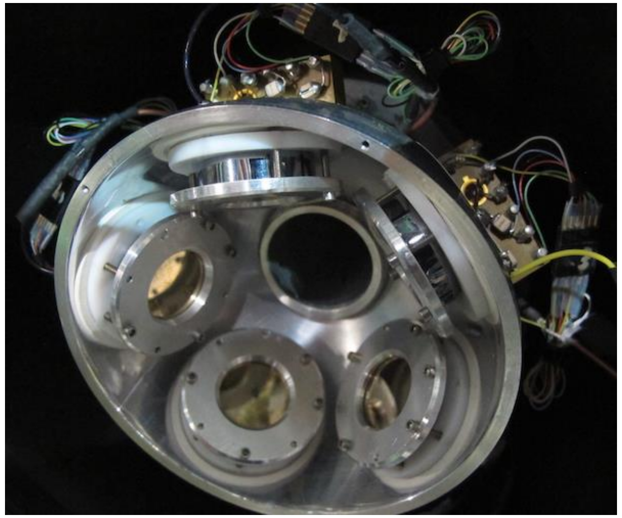


- SCEPTAR - 10+10 plastic scintillators. Detects beta decays and determines branching ratios
- Zero-Degree Fast Scintillator - Fast-timing signal for betas
- $LaBr_3$ - 8 LaBr3 Fast-timing of photons to measure level lifetimes
- PACES - 5 LN2 cooled Si(Li) Detectors. Internal Conversion Electrons (and alphas/protons)

$LaBr_3$



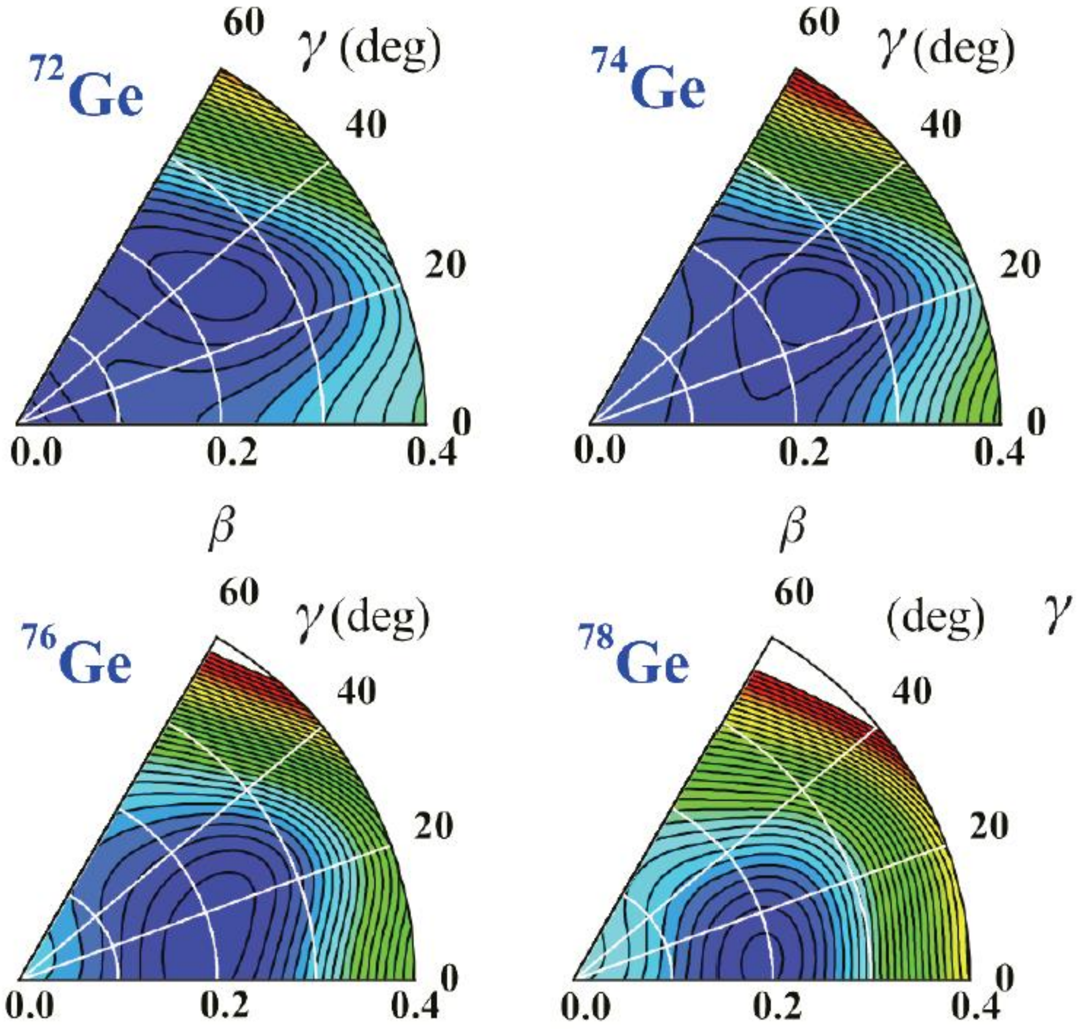
PACES



TRIUMF

^{72,72,76,78}Ge

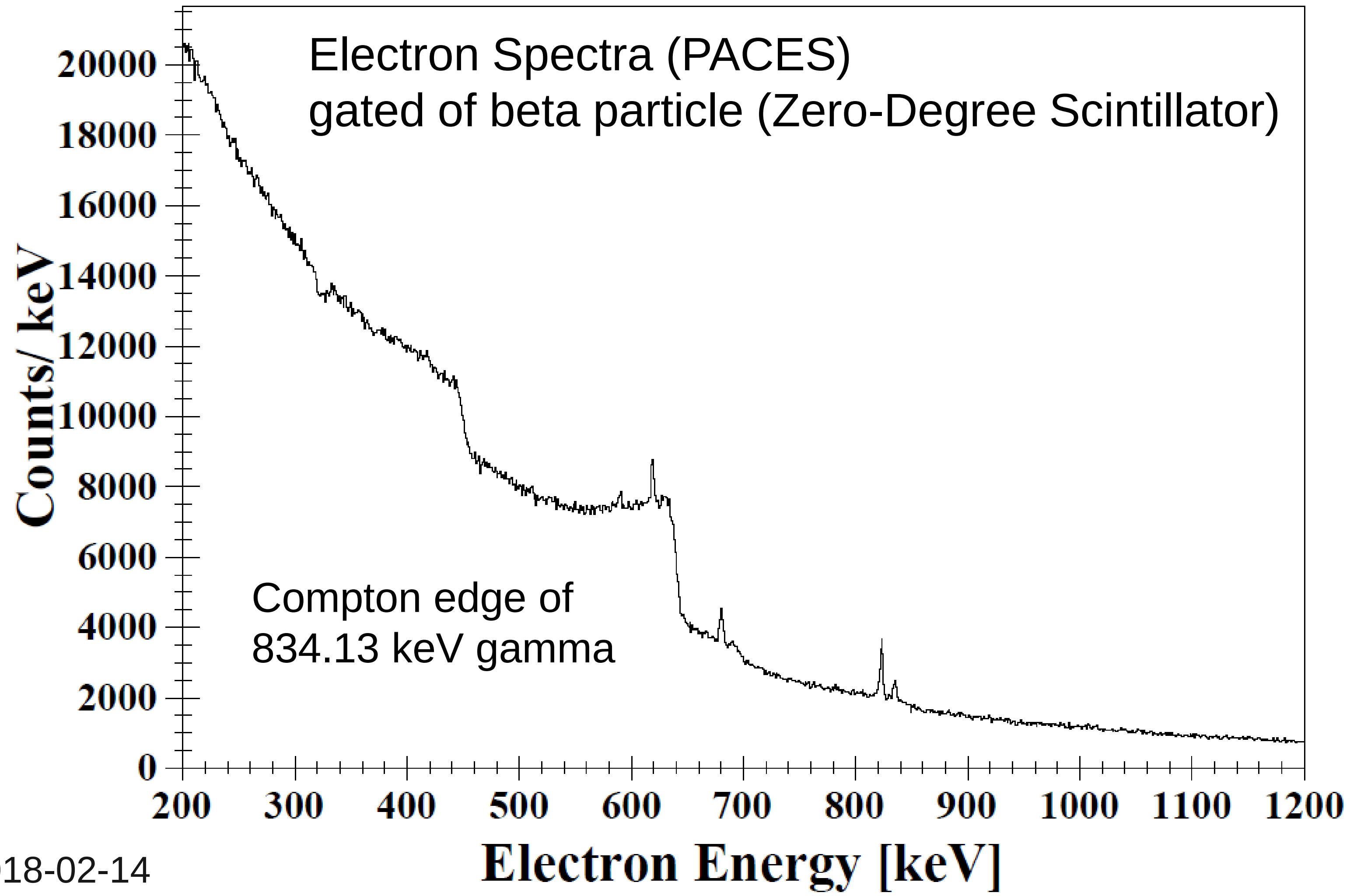
- Recent studies increasingly indicate the significant role of triaxiality in Ge isotopes
- Possible importance of 2 or 3 states mixing to explain low lying structure
- Precise branching ratios and $\rho^2(E0)$ strengths from high statistics Ga beta-decay study



Discovery, accelerated

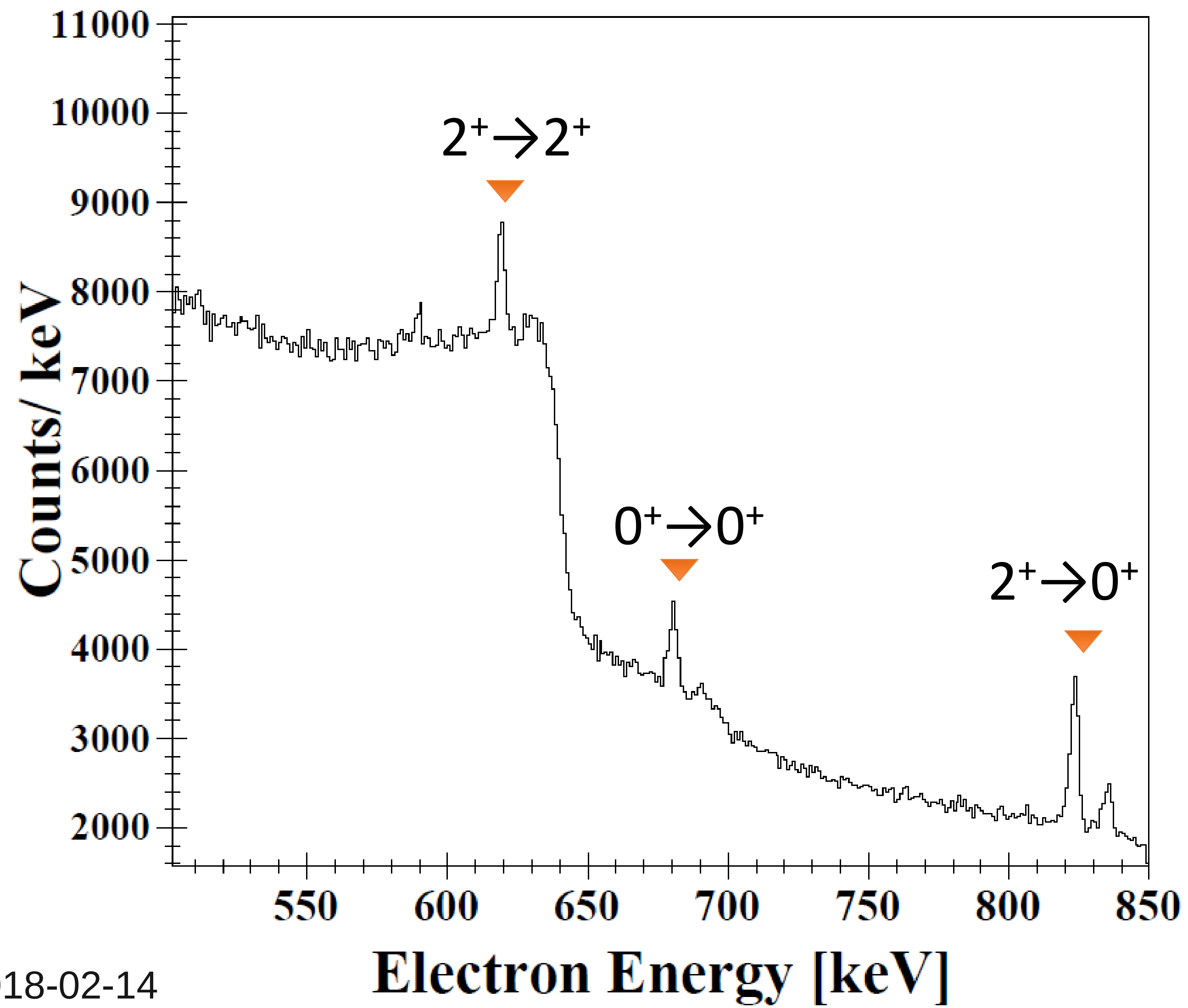
Ultra-high statistics beta-decay spectroscopy of $^{72}Ga \rightarrow ^{72}Ge$

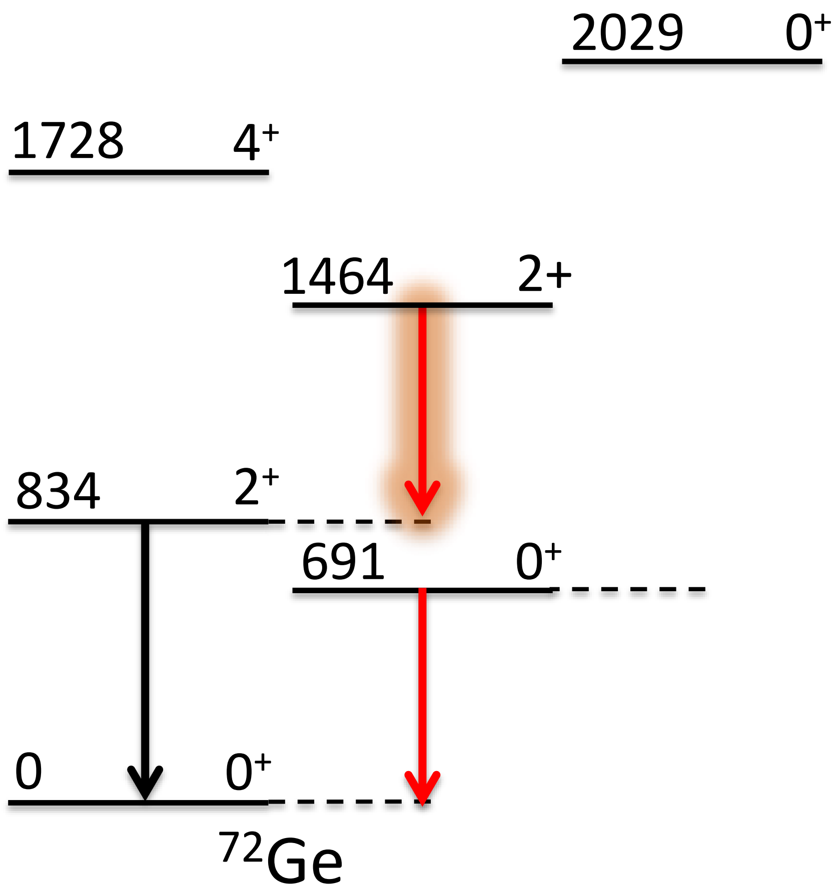
A.B. Garnsworthy, J. Henderson, J. Smallcombe, J.K. Smith, M. Bowry, *et al.*, Beamtime Oct 2017



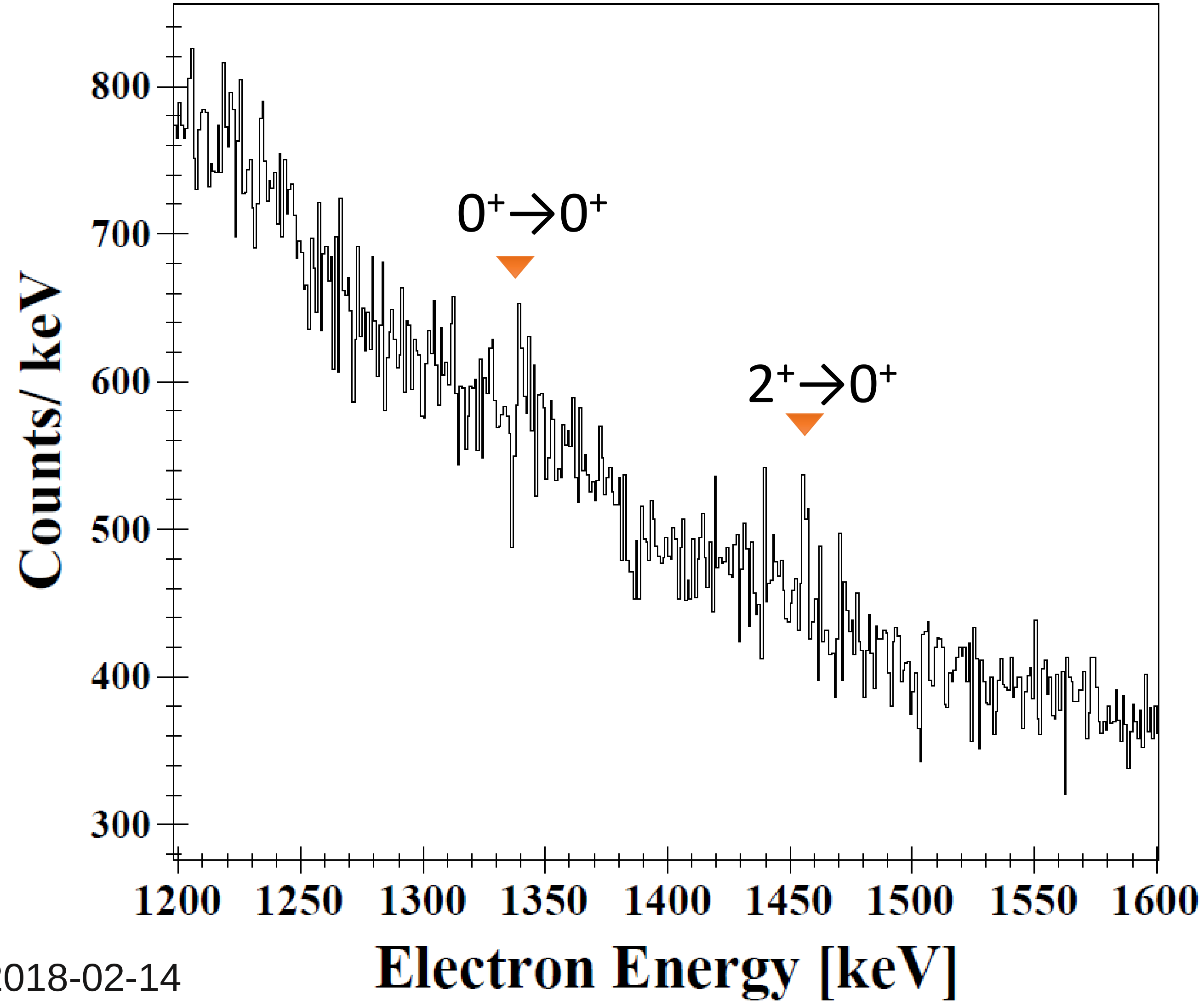
- ^{72}Ga Beam
- $T_{1/2}$=14 hours
- Data collected for 12 half lives.
- 8 TB of data ~2% shown

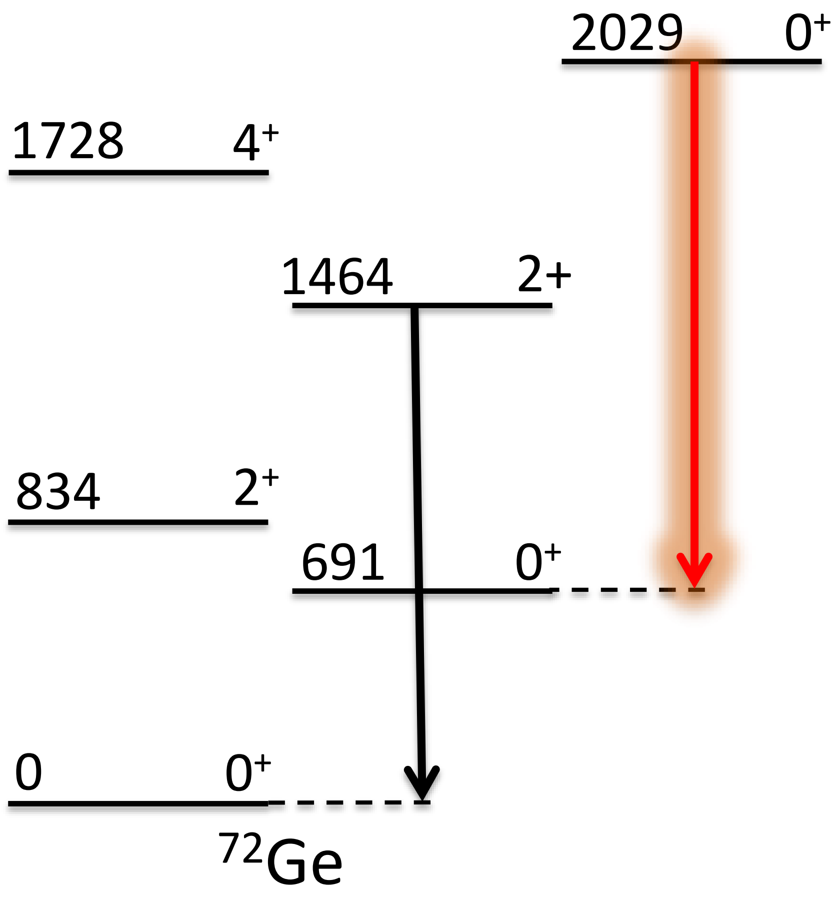
Ultra-high statistics beta-decay spectroscopy of $^{72}Ga \rightarrow ^{72}Ge$



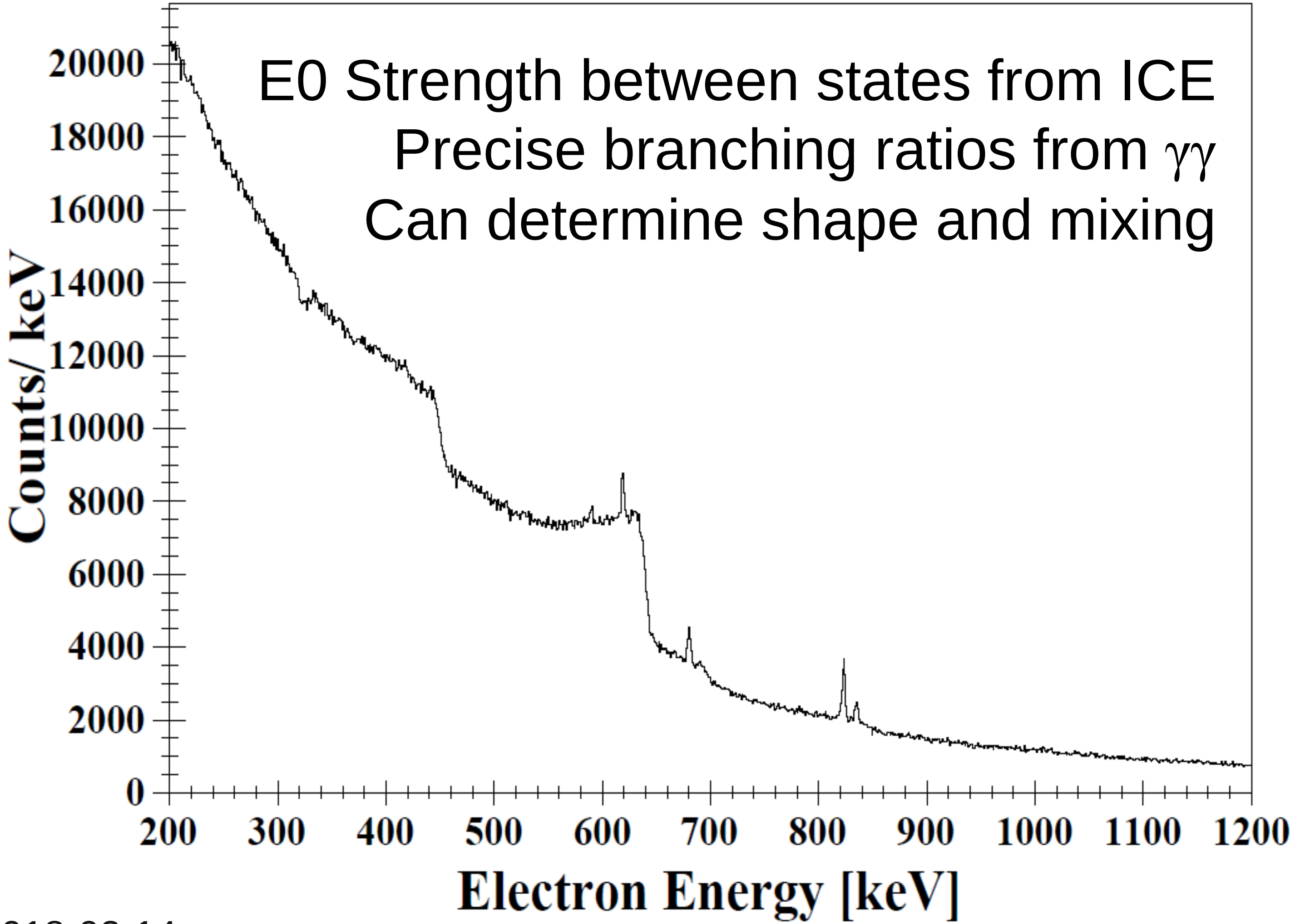


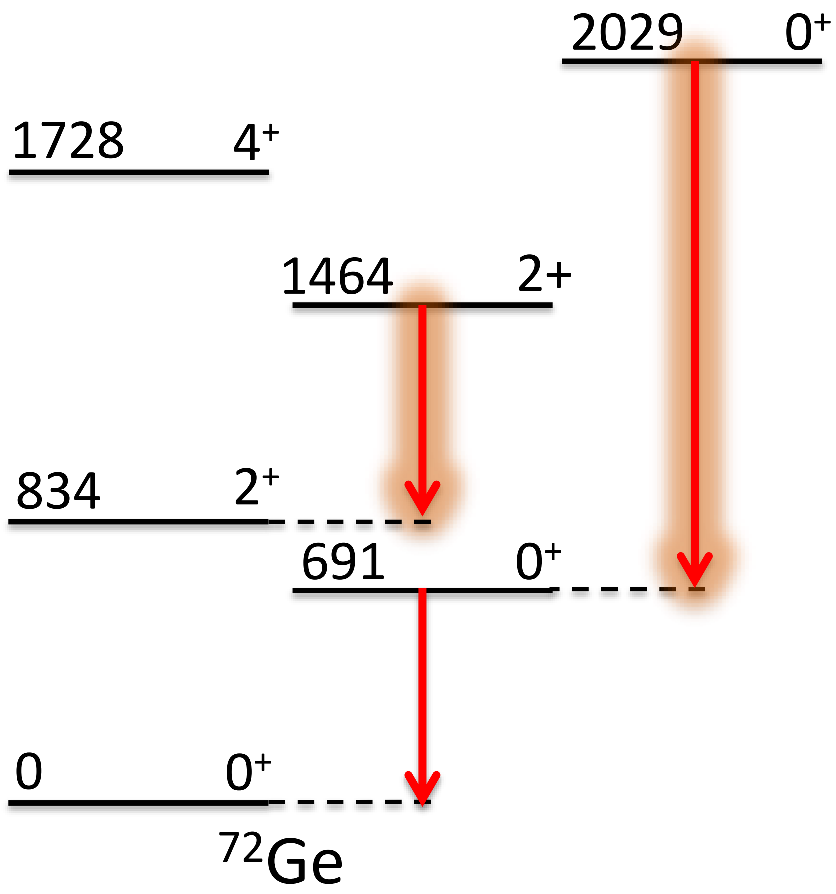
Ultra-high statistics beta-decay spectroscopy of $^{72}Ga \rightarrow ^{72}Ge$





Ultra-high statistics beta-decay spectroscopy of $^{72}Ga \rightarrow ^{72}Ge$

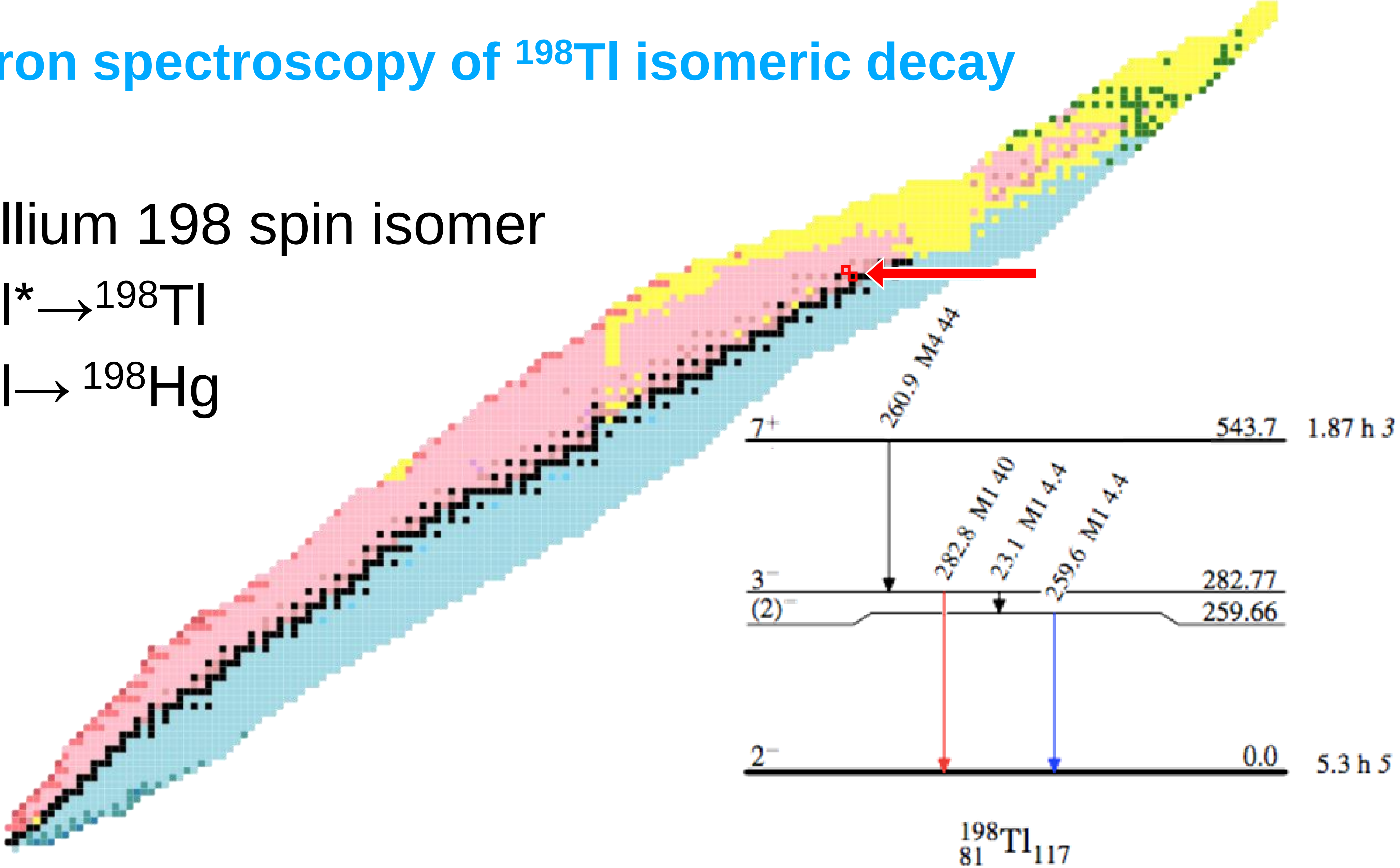




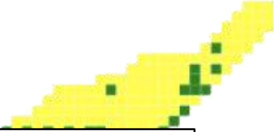
Discovery, accelerated

Electron spectroscopy of ^{198}Tl isomeric decay

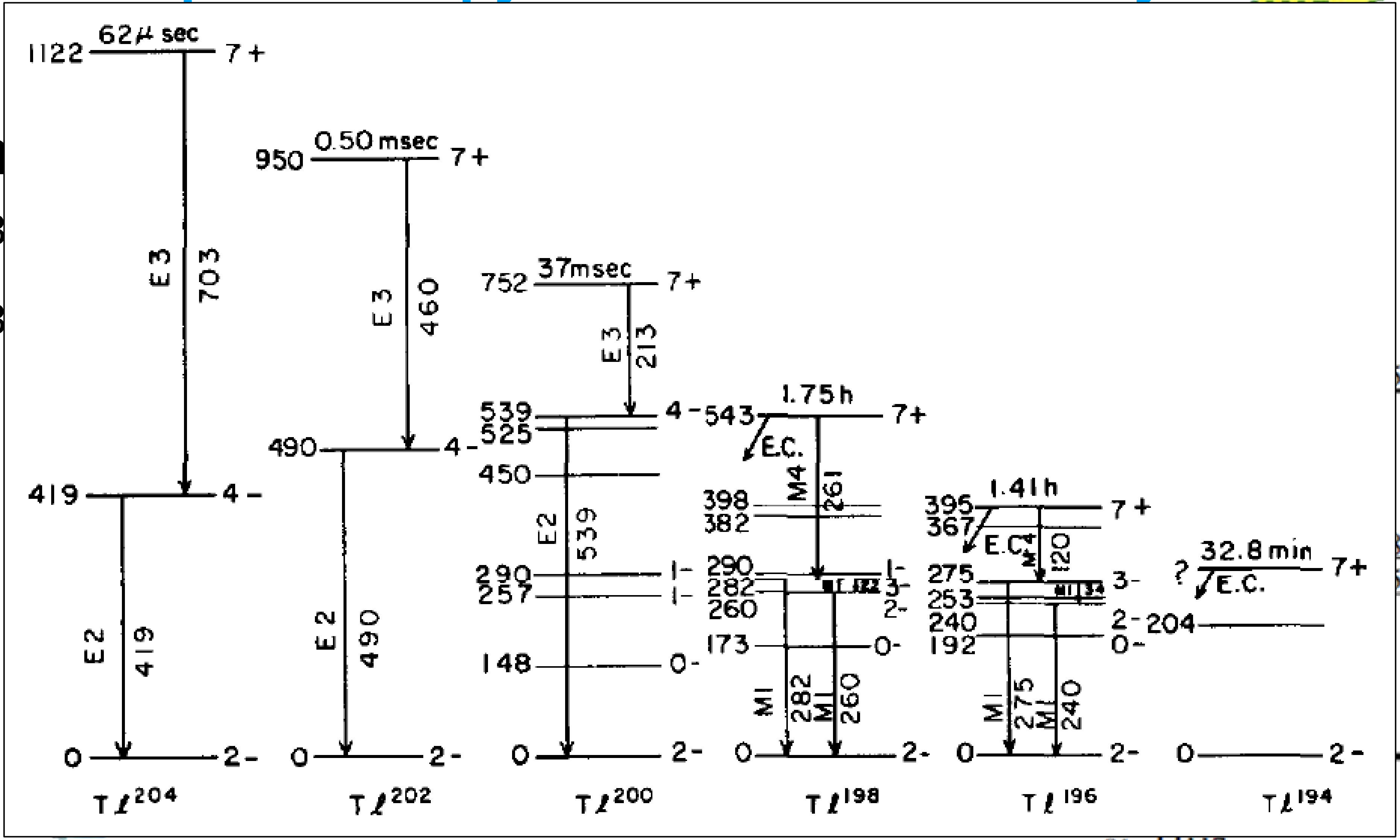
- Thallium 198 spin isomer
- $^{198}Tl^{*} \rightarrow ^{198}Tl$
- $^{198}Tl \rightarrow ^{198}Hg$

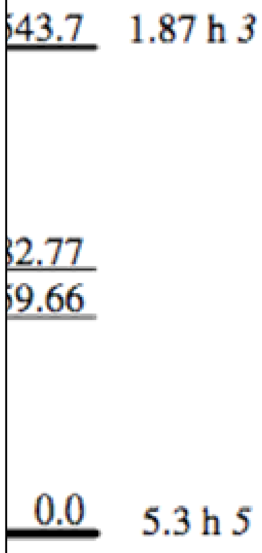


Electron spectroscopy of ^{198}Tl isomeric decay



- Th
- 198
- 198

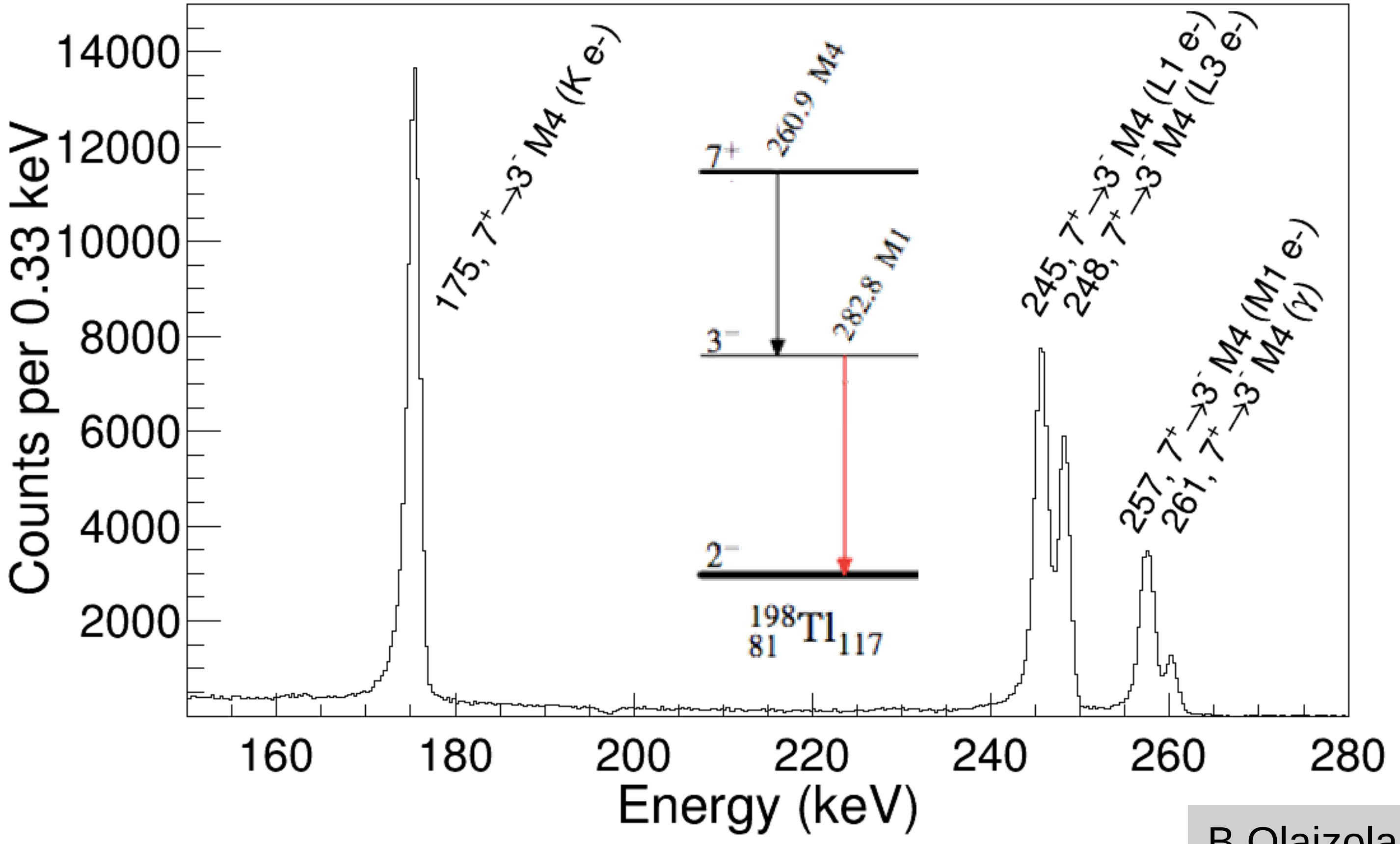




81 117

Electron spectroscopy of ^{198}Tl isomeric decay

ICE Spectrum coincident with 282.8 keV γ ray



Calculated ICC for Atomic Shells

	Energy (keV)	ΔJ=1	ΔJ=4
Tot		0.581(9)	34.6(5)
K	174.47	0.476(7)	14.76(21)
L1	244.65	**0.0725(11)**	**6.55(10)**
L2	245.3	0.00738(11)	1.735(25)
L3	247.34	**0.000575(8)**	**6.1(9)**
M1	256.3	**0.01674(24)**	**1.76(25)**
M2	256.58	0.0019(3)	0.484(7)
M3	257.04	**0.000151(22)**	**1.82(3)**
M4	257.51	3.97(6)E-06	0.0399(6)
M5	257.61	2.83(4)E-06	0.034(5)

L1/L3

M1/M3

B.Olaizola, M. Bowry *et al.* TRIUMF Beamtime April 2017

Summary

- Electron spectroscopy key tool for nuclear spectroscopy
  - E0 measurements
  - Multipolarity measurements
  - Extremes of L,Z or E
- In beam ICE as a test K goodness (^{110}Pd)
- ICE searching for shape coexisting 0^{+} states(^{70}Se)
- E0 strengths to probe configuration mixing (^{72}Ge)
- ICC for extracting multipolarities (^{198}Tl)

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