In-Trap Spectroscopy at TITAN for NME Calculations

Thomas Brunner for the TITAN collaboration

EC-BR Motivation

- Experimental data required to test theoretical models describing ββ
- (Only) 2νββ accessible experimentally

  → testing ground for nuclear models

- ECBRs provide information about **g.s. properties** of the **nucl. wave function** connected to ββ decay (2νββ, 0νββ)

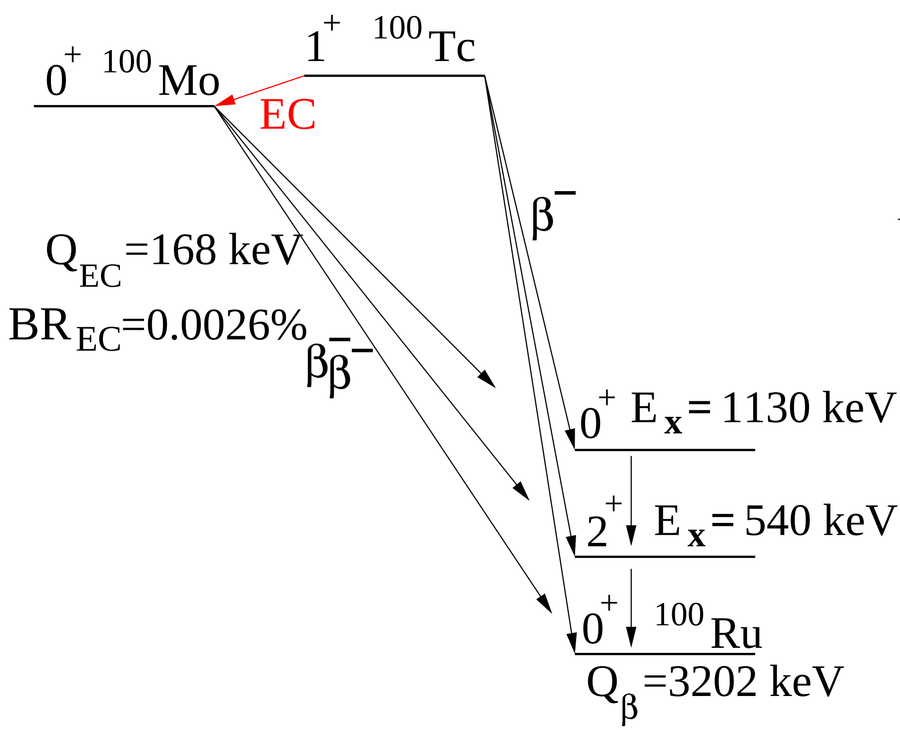


Figure from S.K.L. Sjue et al., Phys. Rev. C 78(2008)064317

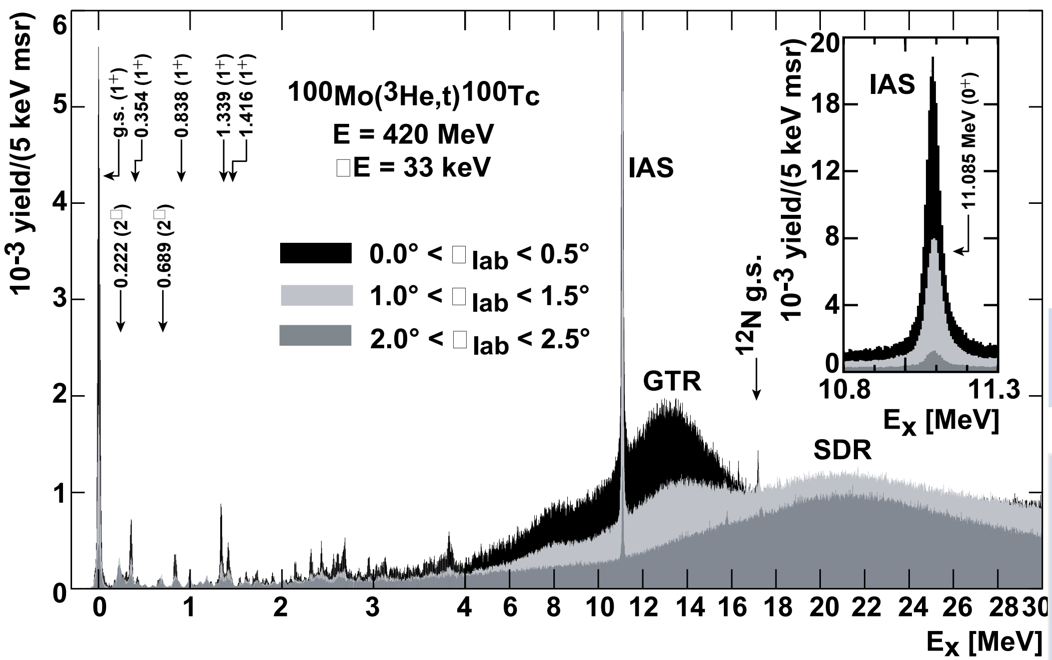
$$M^{2\nu} \propto \sum_m \frac{\left\langle 0^f_{g.s.} \middle| \hat{O} \middle| 1^+_m \right\rangle \left\langle 1^+_m \middle| \hat{O} \middle| 0^i_{g.s.} \right\rangle}{E_m - E_i + Q_{\beta\beta}/2}$$

Single-State Dominance hypothesis

Transition via lowest 1^+ state in intermediate nucleus accounts for entire $M^{2\nu}$

D. Fang et al., Phys. Rev. C 81(2010)037303

Physics case ^{100}Mo



J.H. Thies et. al. Phys. Rev. C 86:044309 2012

Almost the entire low energy GT strength is located in one single state only! (i.e. the g.s.)

For SSD the NME simplifies to:

$$M^{2\nu}_{tot} \approx \frac{M_{EC} M_{\beta^-}}{\frac{1}{2} Q_{\beta\beta}(0^{+(f)}_{g.s.}) + E_{g.s.}(1^+) - E_0}$$

- (^{3}He,t) measurement by Ejiri et al. in 1998 with ΔE = 300 keV

→ **B(GT)(g.s.) = 0.33(4)**

- Recent (^{3}He,t) measurement by Thies et. al. with ΔE = 29 keV

→ **B(GT)(g.s) = 0.35(1)**

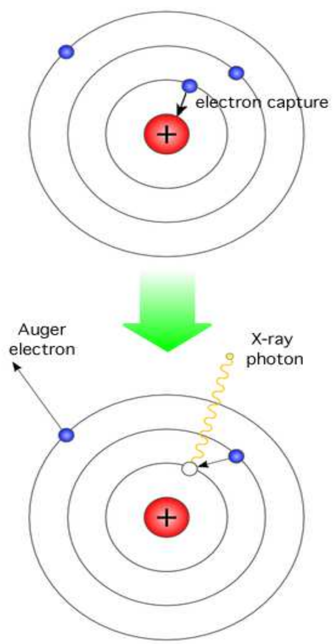
- **<u>In conflict</u>** with BR(EC) measurement from ^{100}Tc by Sjue et.al.

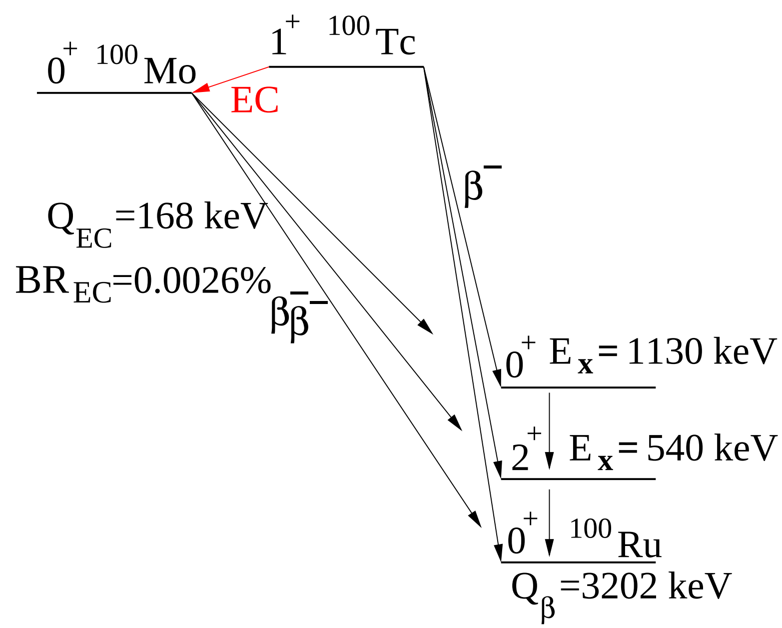
→ **B(GT) = 0.60(9)**

Challenges in EC BR measurements

Challenges

- Difficult measurement due to a weak EC branch and difficult x-ray signatures
- High background due to dominating beta decay and possible bremsstrahlung
- Isobaric contamination

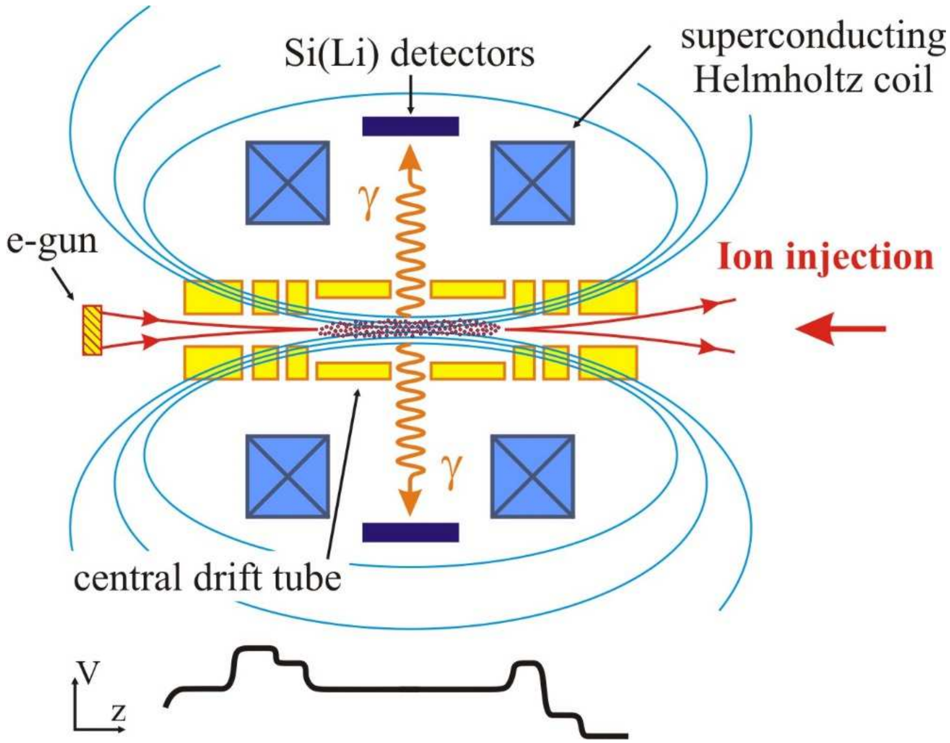




New approach using a Penning trap (Frekers et al., Can. J. Phys 85(2007)57)

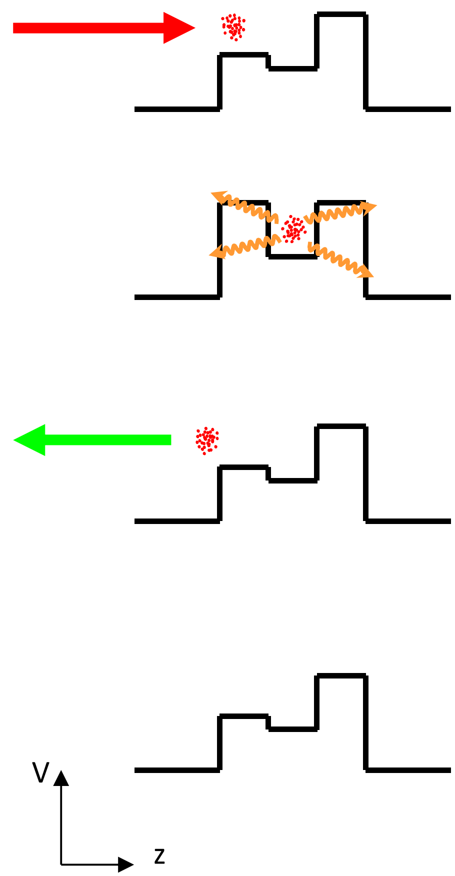
Basic concept of TITAN-EC

B-field up to 5.5T



- Ions stored in EBIT
- Backing free environment
- Spatial separation of β- and photon detection
- Potential to clean ion sample

Measurement cycle



Injection of ions

Storage of ions

Observation of decays

Ejection of ions

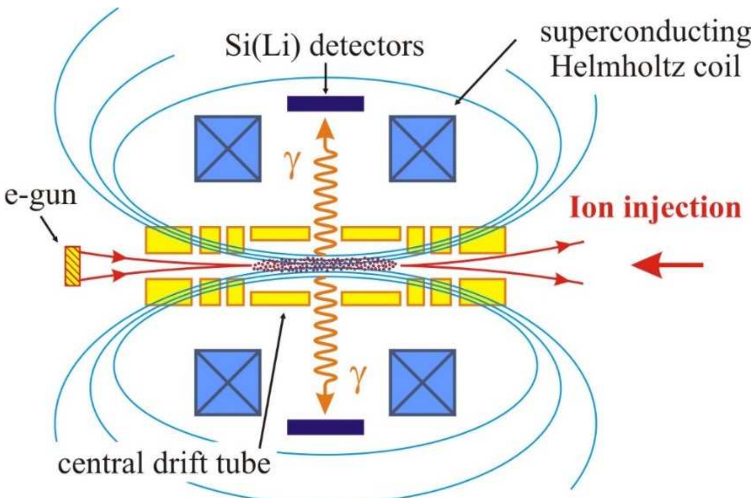
The trap is kept open to empty completely

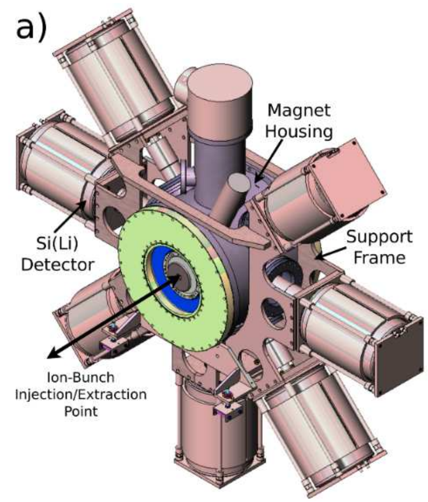
Empty trap

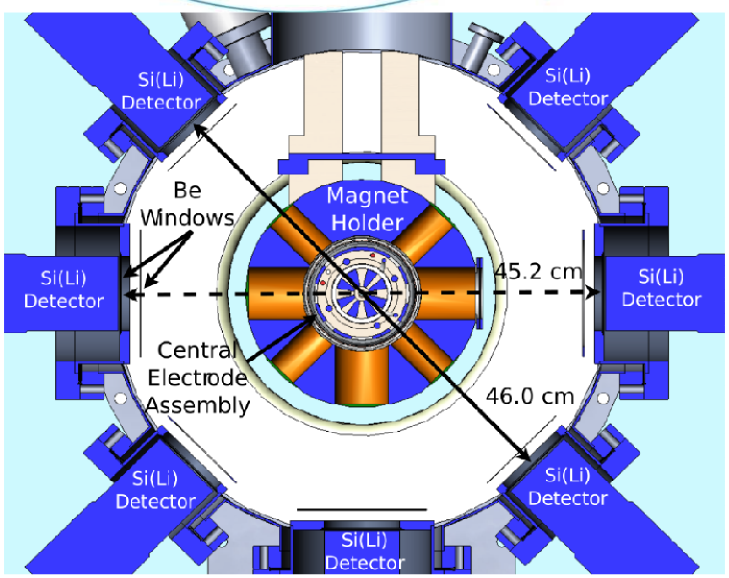
Background measurement

TITAN-EC detector configuration

Acceptance ~2.1%







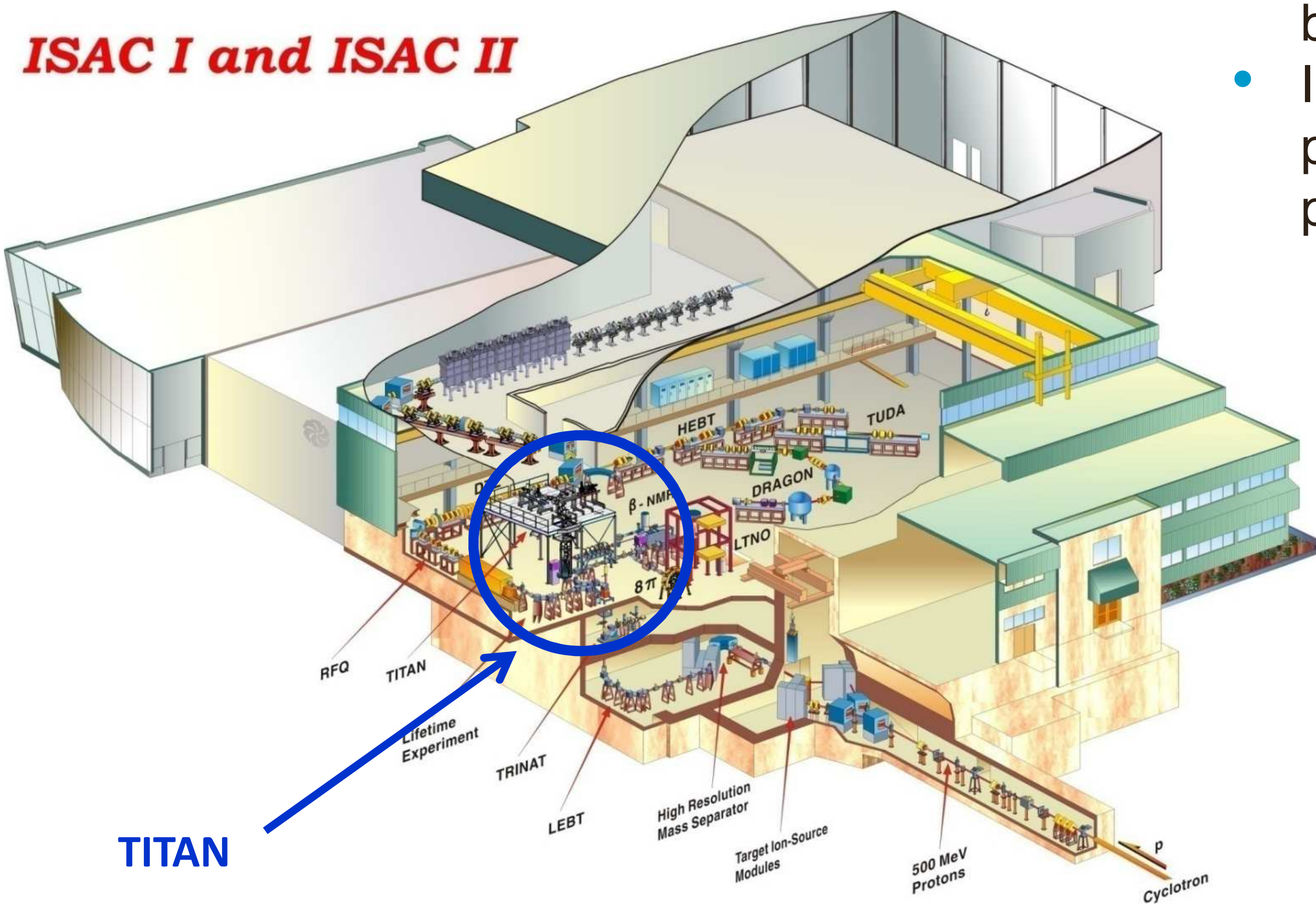
Leach et al., NIMA 780(2015)91

Advantages of the TITAN-EC program:

- Pure and intense ion beams from ISAC
- **No isobaric contamination** of the sample
- **No X-ray absorption**
- **Open trap** access for **7 X-ray detectors**
- **Shielded detectors**
- Spatial **separation of X-rays and β⁻** by B-field

→ **Potential to measure weak ECBRs (10^{-4})**

ISAC



- Production of rare ion beams
- Irradiation of thick production target with proton beam

500 MeV proton beam
Up to ~100 μA

TITAN

TRIUMF's Ion Trap for Atomic and Nuclear science

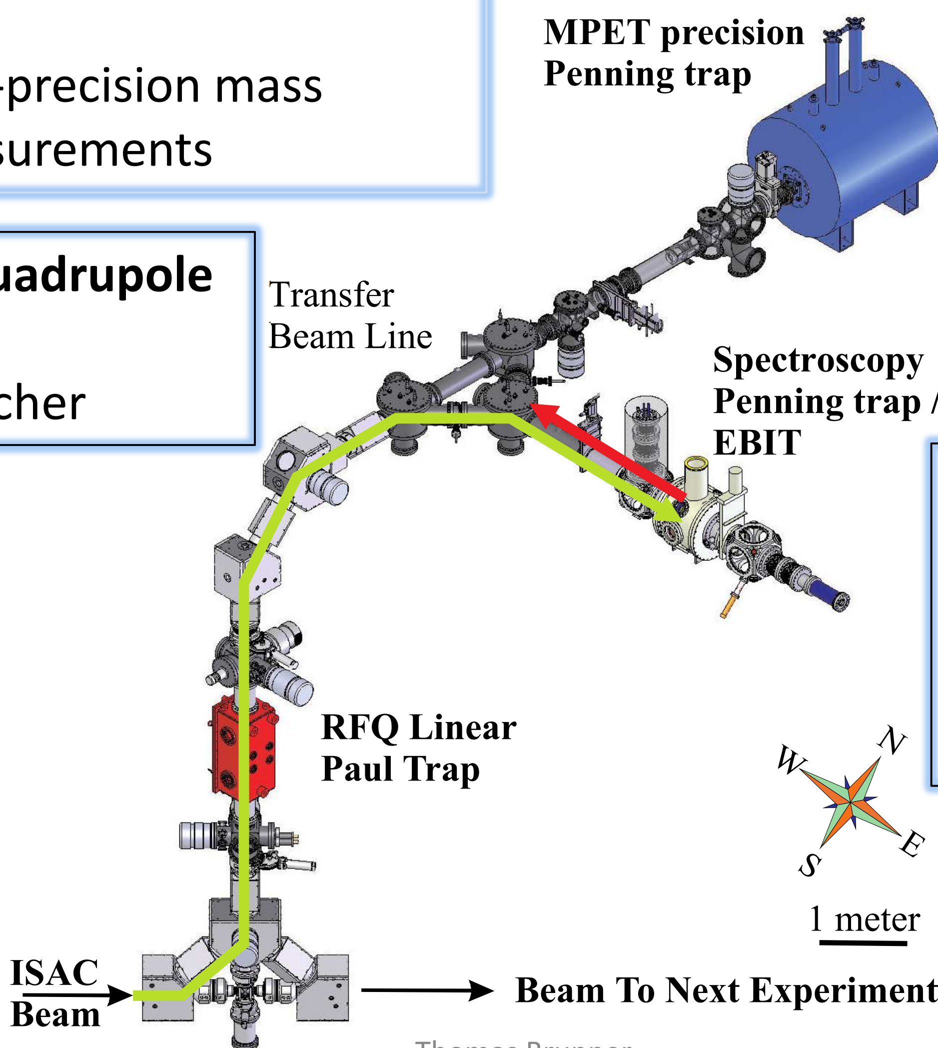
Measurement Penning Trap (MPET)

- High-precision mass measurements

Radiofrequency Quadrupole - RFQ

- Cooler and buncher

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}\cdot B$$



Electron Beam Ion Trap – EBIT

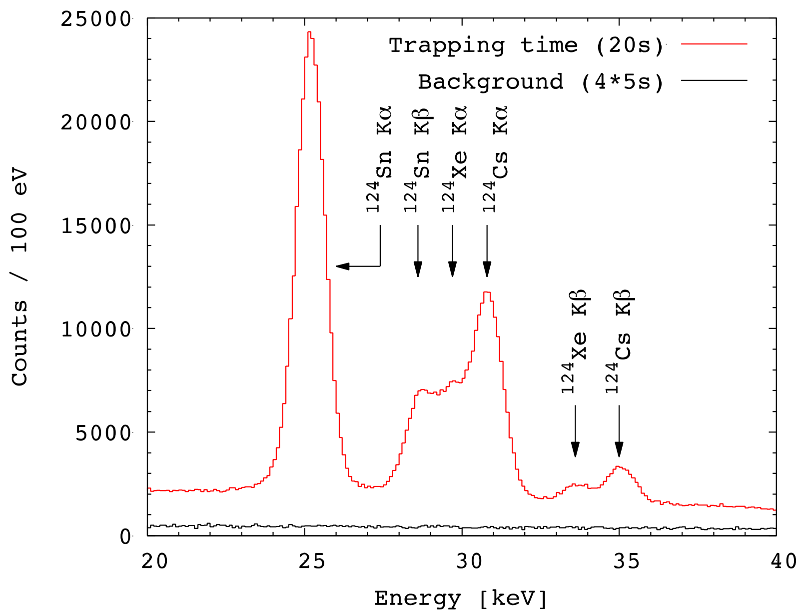
- Charge breeder
- Spectroscopy ion trap

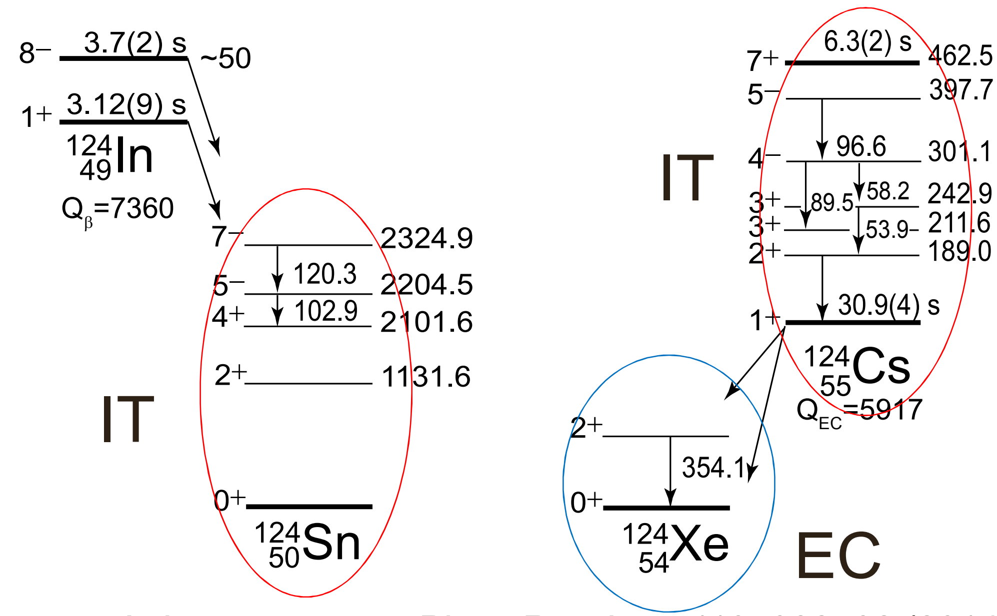
TITAN

ISAC-TRIUMF

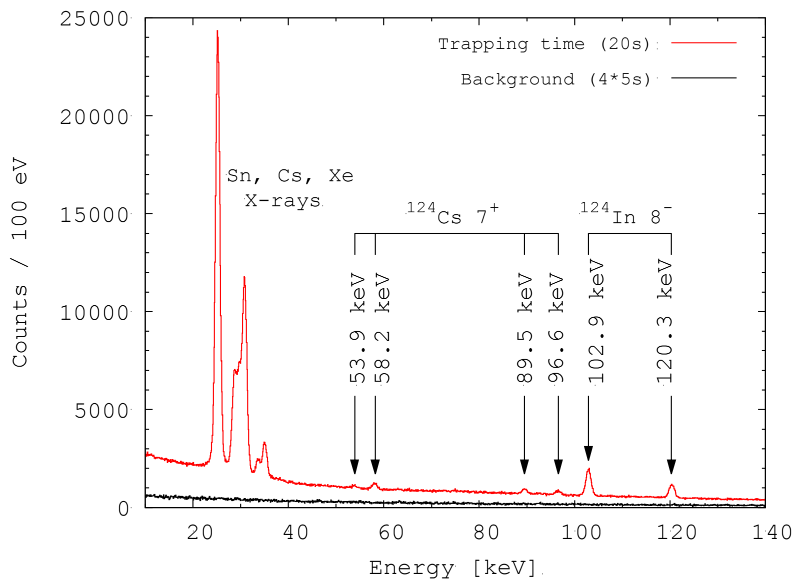
Commissioning experiments – ^{124}Cs

Slide courtesy of A. Lennarz





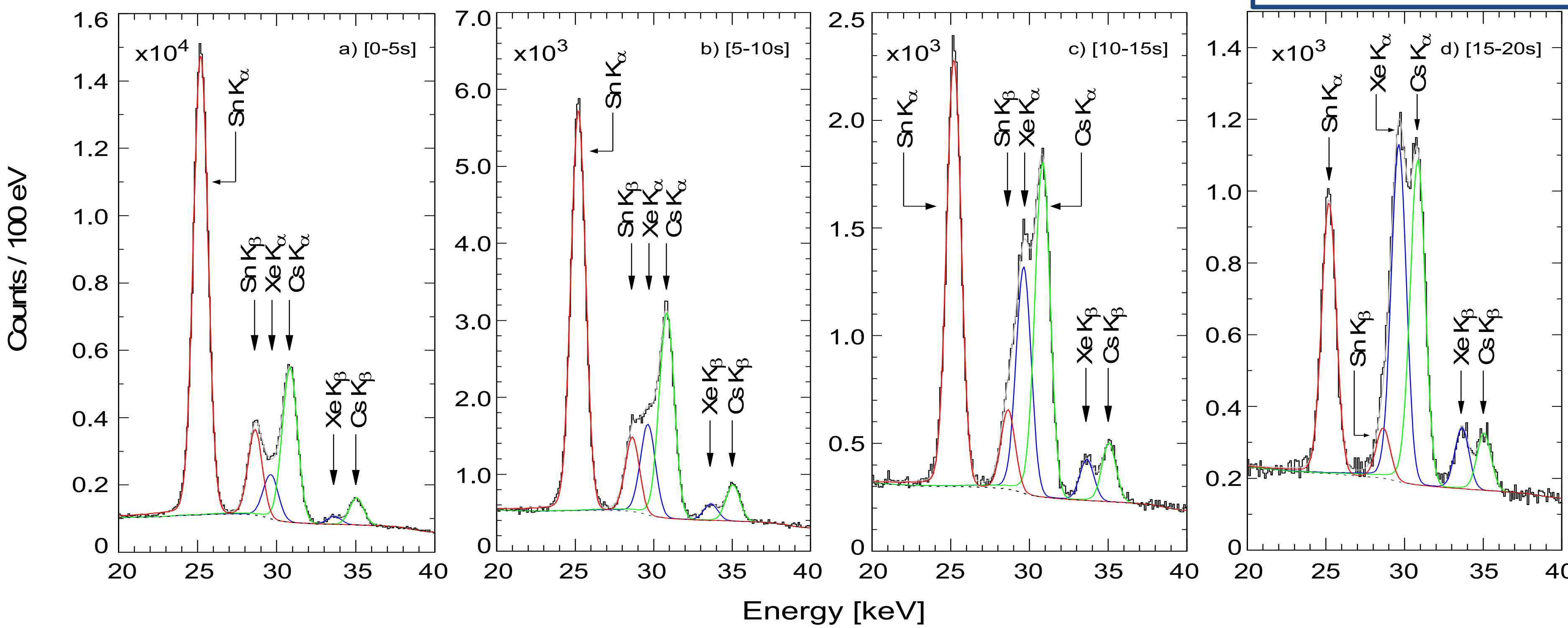
A. Lennarz et. al., Phys. Rev. Lett. 113, 082502 (2014)



- ^{124}Cs High ECBR ~7%, $T_{1/2}$=30.9 s
- Beam composition: ^{124}Cs g.s., ^{124m}Cs, ^{124m}In
- X-rays from 3 isobars: **Sn, Xe, Cs**
- 6 Si(Li)s, 1 HPGe
- Used **electron beam for ion trapping**
- Charge bred Cs to q=27^{+} (average)
- ➢ **better ion confinement**
- ➢ **Factor of 20 511 keV suppression**

Time structure

Slide courtesy of
A. Lennarz



- Time-stamped events

→ Identify contaminants
- Reduction of ^{124m}In (3.7s) and ^{124m}Cs (6.3s)
- Xe X-rays dominant towards longer T_{trap}
- $T_{1/2}$ determination possible

Half-lives

- Measured $T_{1/2}$ confirm lit. values
- Accuracy increased for ^{124m}In & ^{124m}Cs

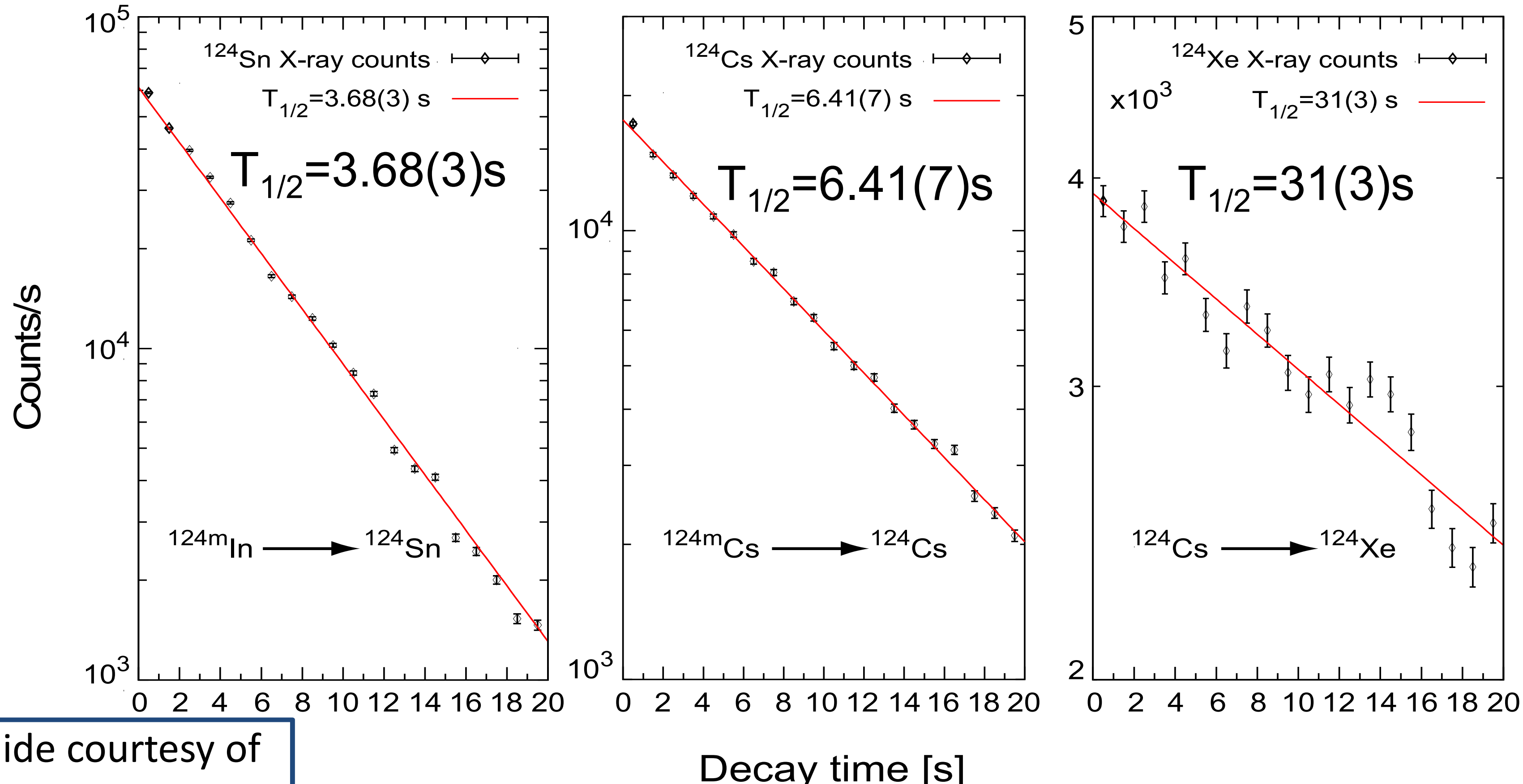
→ Efficient trapping for order of minutes

→ Understand background

- Calculate N_{ions} in the trap via activity at t_{decay}=0s

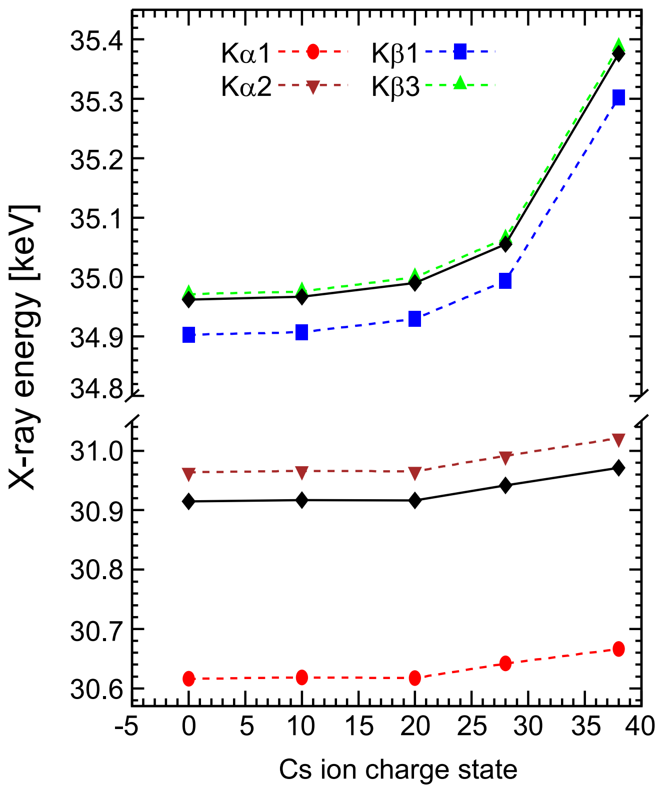
→ Information about transport eff.

→ Calculate beam composition: ^{124m}Cs 3%, ^{124}Cs 65%, and ^{124m}In 32%



Slide courtesy of A. Lennarz

Atomic structure effects in highly-charged ions



- Charge breeding → atomic structure is altered
- Electron correlation, relativistic & quantum electrodynamical effects
- Electronic-binding energies get larger with increased charge state
- → Atomic spectrum varies with the electronic configuration
- → **Ionization-energy shift**
- Multiconfigurational Dirac-Fock code **FAC** (flexible atomic code)

→ Calculate atomic collisional & radiative processes

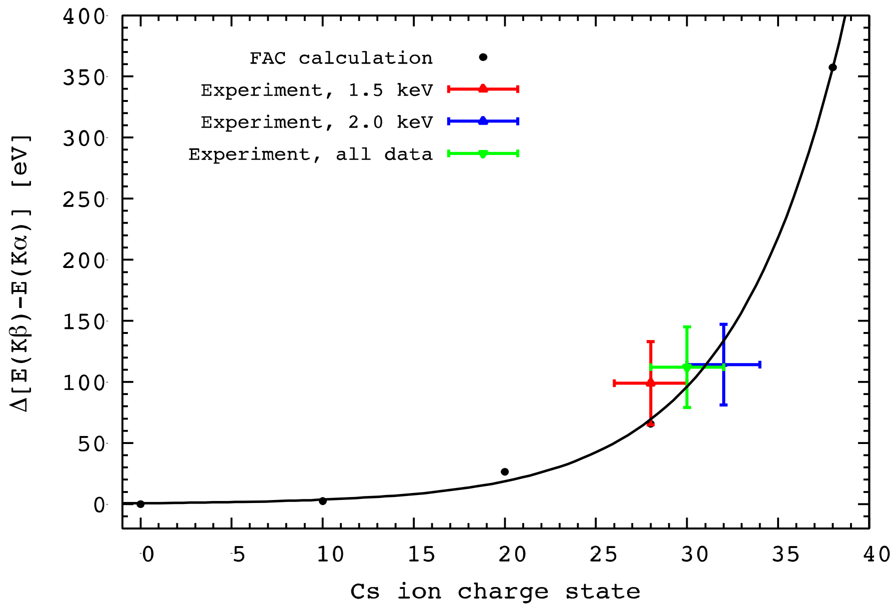
$$\mathrm{H} = \sum_{i=1}^{N} H_D(i) + \sum_{i \leq j}^{N} \frac{1}{r_{ij}}$$

Non-relativistic Coulomb interaction operator

single electron Dirac operator for the i^{th} electron in the potential field of the nucleus

Slide courtesy of A. Lennarz

X-ray energy shifts and intensity ratios



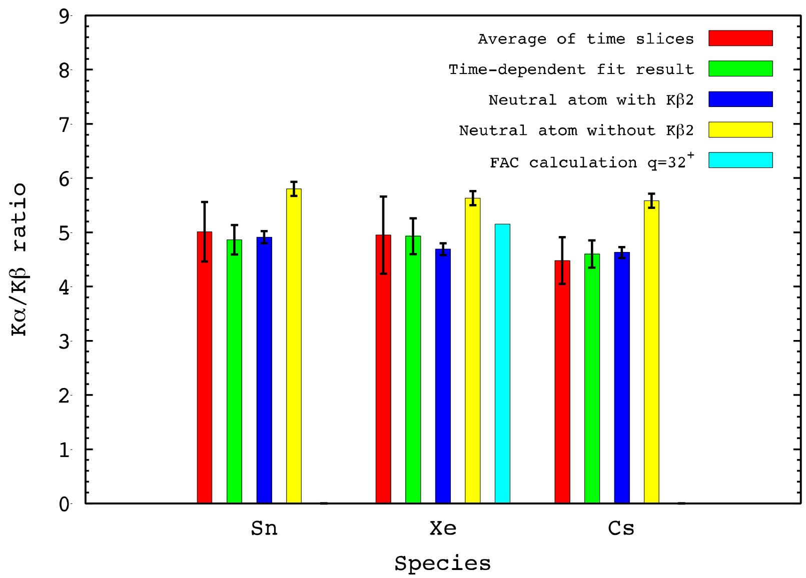
- Observed K-shell X-ray energy shift
- Consistent with FAC calculation

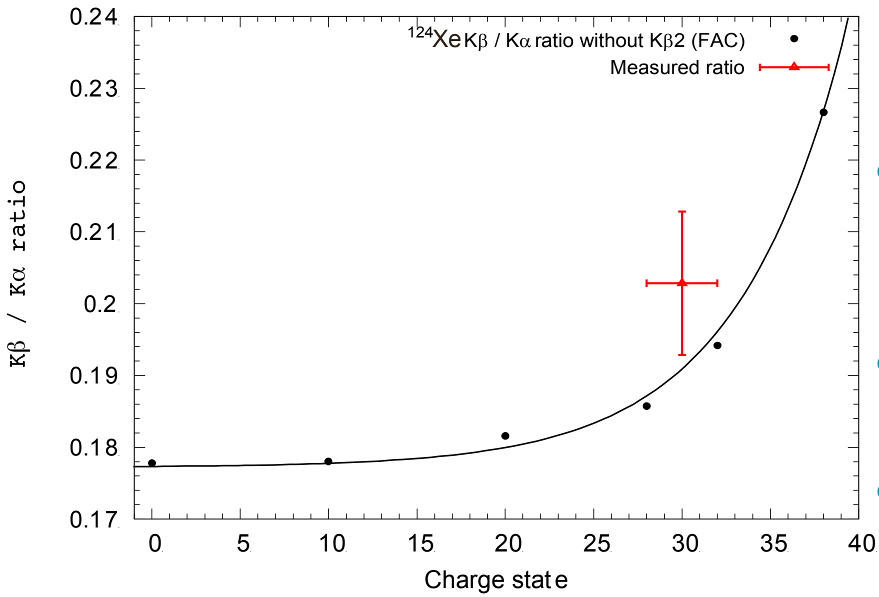
Species	Shift [eV]	FAC
Xe	96(37)	92
Cs	120(34)	111
Sn	139(34)	143

In low-energy X-ray:
Accuracy 50 eV
≈1.1 keV spectral resolution

X-ray intensity ratios

Slide courtesy of
A. Lennarz





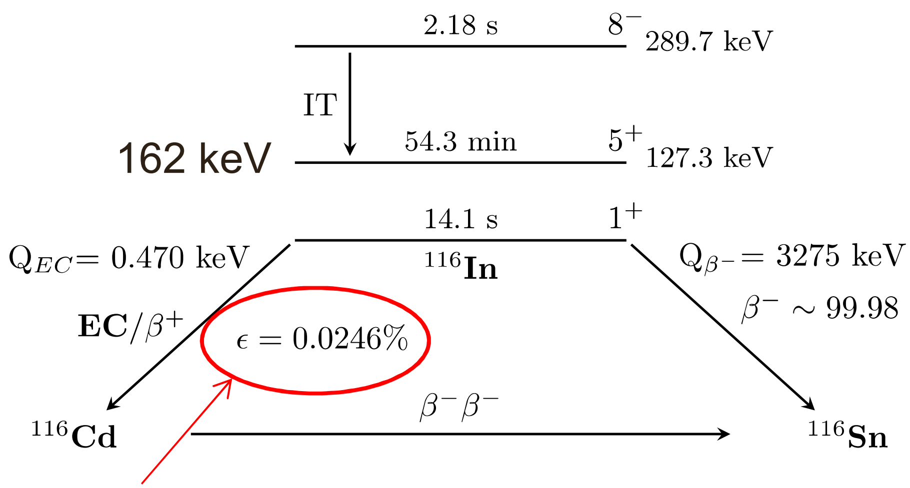
Species	Kα/Kβ exp.	Kα/Kβ neut.	Kα/Kβ no $K\beta_2$
Xe	4.95(66)	4.69(11)	5.63(13)
Cs	4.48(37)	4.63(10)	5.58(13)
Sn	5.01(49)	4.91(11)	5.80(13)

- Stripping N-shell
  → $K_{\beta 2}$ transition is non-existent
- Expected is an increased Kα/Kβ ratio
- **<u>BUT:</u>** Measured Kα/Kβ X-ray intensity ratio is consistent with neutral atom

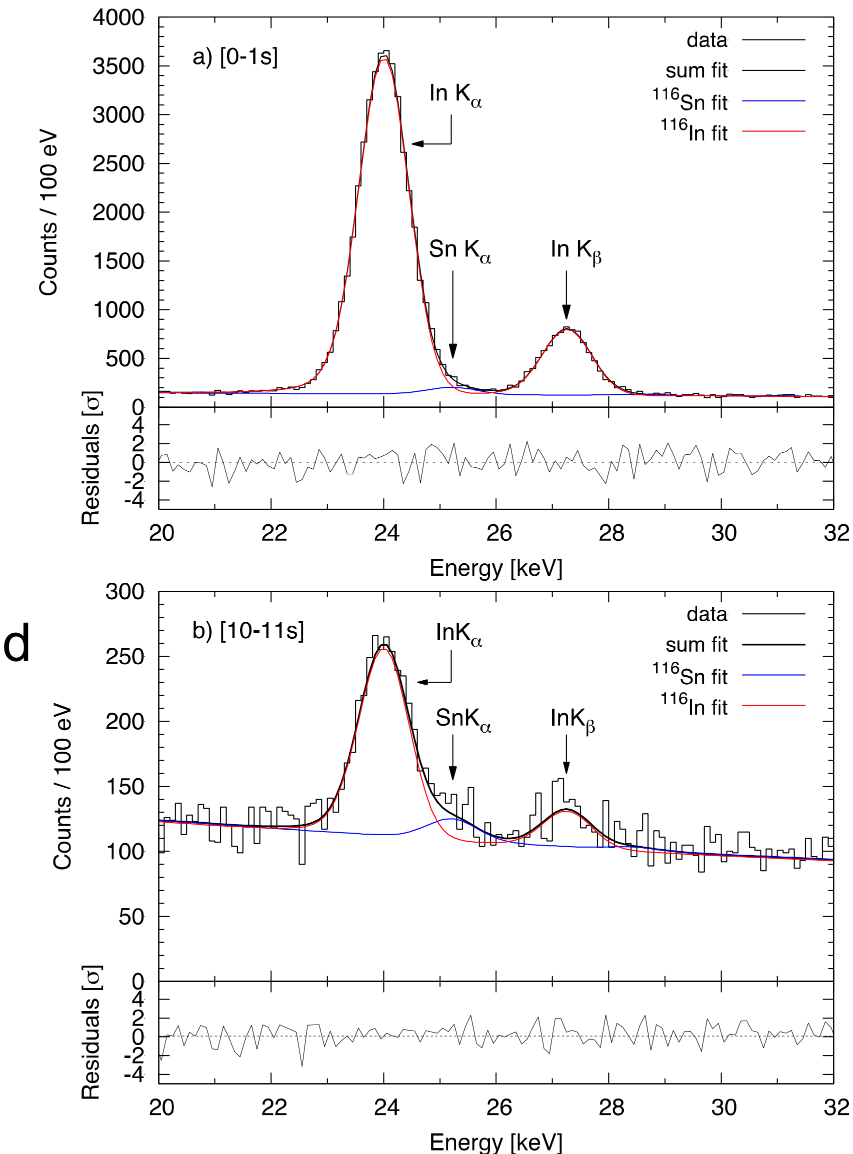
- <u>Neutral atoms</u>: Auger effect competes with X-ray emission & limits emission probability of Kβ X-rays.
- <u>Highly charged ions</u>: Fewer electrons, Auger effect reduced
- Emission probabilities change
  → higher $K_{\beta 13}$ intensity.

^{116}In – first attempt of a physics measurement

Slide courtesy of A. Lennarz

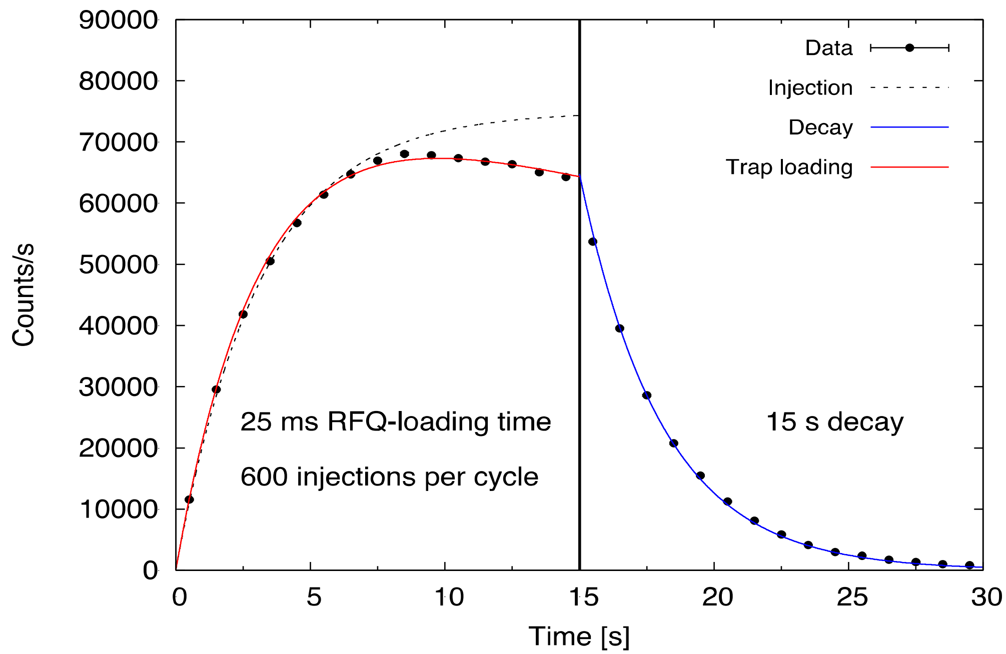


Wrede et al. Phys. Rev. C – Nucl. Phys. 87(3), 2013

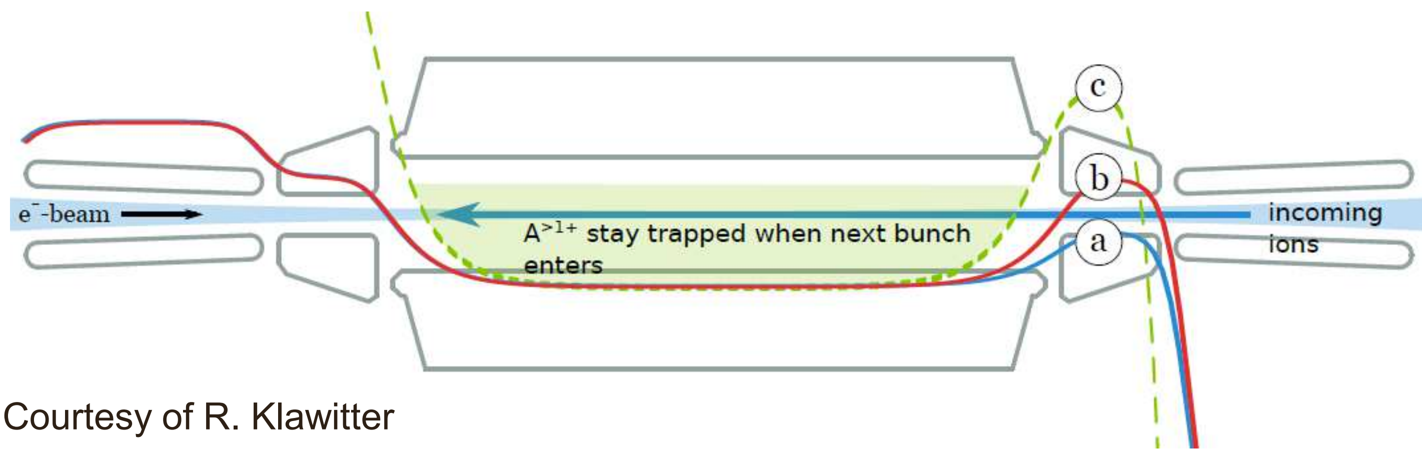


- Intermediate nucleus in ββ decay of ^{116}Cd
- Goal: Observe Cd EC X-rays
- Problems:
  - Low g.s. yield (~10^4 pps), high isomeric yields (5^+:10^6 pps, 8^-:10^5 pps)
  - Weak EC branch
- Observed In and Sn X-rays (time structure)

^{116}In – Multiple ion-bunch injection



- Maximize statistics in limited time
- Overcome RFQ space-charge limit ~10^6 ions
- Multiple ion bunch stacking
- First ever MI with RIBs
- Tested up to 3000 injections in 15s
- Stored ~10^9 ions in the trap



Courtesy of R. Klawitter

a: injection of A^+ ions
b: trapping during charge breading
c: potential a seen by $A^{>1+}$

Perform measurements even at lower ISAC beam rates!

Summary

- TITAN-EC is a powerful technique to measure weak EC branches
- Successful commissioning of technique with ^{124}Cs
- Technique suited for atomic spectroscopy measurements
- Beam purification from isobaric contamination coming soon (MR-TOF)
- ^{116}In planned for fall 2016 (TRIUMF proposal S1622)

Candidates for TITAN-EC

	ββ-nucleus	Interm. nucleus	transition	$T_{1/2}$	K_α-energy (keV)
SSD	^{100}Mo	^{100}Tc (EC)	1+→0+	15.8 s	17.5
	^{110}Pd	^{110}Ag (EC)	1+→0+	24.6 s	21.2
	^{114}Cd	^{114}In (EC)	1+→0+	71.9 s	25.3
SSD	^{116}Cd	^{116}In (EC)	1+→0+	14.1 s	25.3
	^{82}Se	^{82m}Br (EC)	2-→0+	6.1 min	11.2
	^{128}Te	^{128}I (EC)	1+→0+	25.0 min	27.5
	^{76}Ge	^{76}As (EC)	2-→0+	26.2 h	9.9

Input from theorists required:
- Prioritize isotopes in list
- Suggest different isotopes
- Suggest different experiment

Acknowledgements – Thanks to the TITAN group!

TITAN
ISAC-TRIUMF

M. Alanssari, C. Andreoiu, J. Bale, B. Barquest, T. Brunner, U. Chowdhury, J. Dilling, J. Even, A. Finlay, D. Frekers, A. T. Gallant, M. Good, **A. Großheim,** R. Klawitter, B. Kootte, A. A. Kwiatkowski, D. Lascar, **K. G. Leach, A. Lennarz,** E. Leistenschneider, T. D. Macdonald, B. Schultz, R. Schupp S. Seeraji, M. Simon, D. Short, … and the TITAN collaboration

U. of Manitoba

McGill U.

Muenster U.

MPI-K

SFU

UBC

Mines

TRIUMF