COLORADOSCHOOLOFMINES
Department of Physics

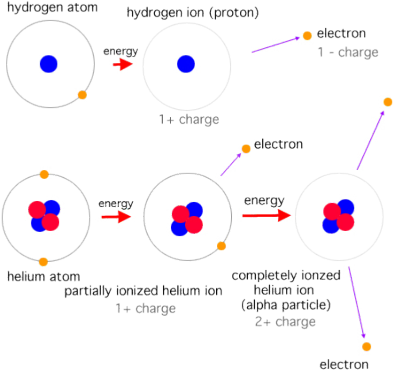
Decay Spectroscopy of Highly Charged Radioactive Ions with TITAN at TRIUMF

INPC 2016

Kyle Leach

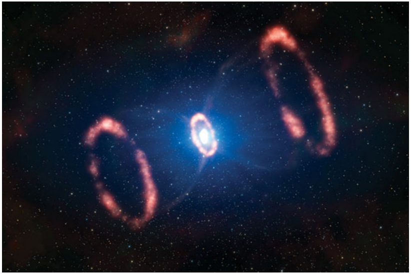
Single and Highly Charged Ions

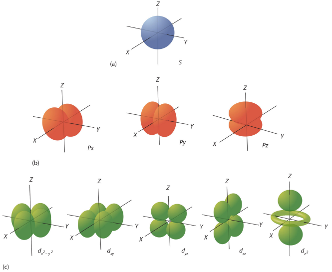
A positive ion is generated from a neutral atom by removing one (or more) electrons, typically from the outermost atomic shells.



- In experimental low-energy nuclear physics, we typically deal with singly charged ions for beam manipulation.
- In most cases, removing a single electron from the atom has a negligible effect on any radioactive decay mode of the nucleus.

Environments for Highly Charged Ions





- If the conditions where the ion exists are such that the energy is increased slightly, multiple ionizations can (and will) occur.
- As the charge state increases closer to the innermost electrons, the effects on various forms of electroweak decay can become dramatic.
  - ^{7}Be electron capture $L/K = 4.0(6)\%^{\dagger}$
  - ^{207}Pb electron capture $L/K = 27(4)\%^{\ddagger}$

† P.A. Voytas *et al.*, Phys. Rev. Lett. **88**, 012501 (2002)
‡ N. Coron *et al.*, Eur. Phys. Journ. A **48**, 89 (2012)

Effects of HCI on Electroweak Decay Modes

Electron Capture

- $T_{1/2}$ a function of q
- Some cases: H-like ions have smaller $T_{1/2}$ than neutral[†]
- For EC-only decay, bare ion becomes stable (or free EC)

Internal Conversion

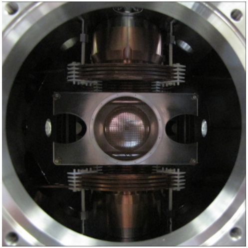
- γ/IC emission a function of q
- For E0 only decay, bare ions generate nearly stable isomer
- Decay can thus only occur via second order 2γ emission

Other Effects of HCIs

- Change in screening effects for both charged lepton and hadron emission ($\beta^{\pm}$ decay, p and α decay). This is particularly important at very low energies.
- Can change atomic masses enough to change accessible nuclear states in decay, resulting in orders of magnitude decrease in lifetime[‡]

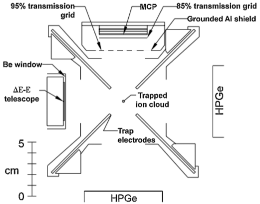
[†] Y.A. Litvinov *et al.*, Phys. Rev. Lett. **99**, 262501 (2007)
[‡] F. Bosch *et al.*, Phys. Rev. Lett. **77**, 5190 (1996)

Decay Spectroscopy with Trapped Nuclei

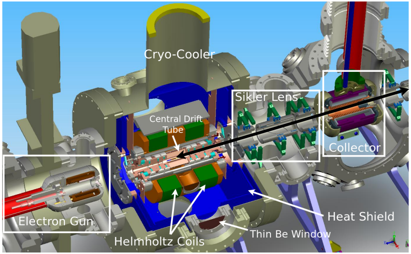


Courtesy: TRINAT

- Neutral atom traps (MOT) and ion traps are currently used for decay studies
- Greater control over the decay environment
- Requirement: A place to generate and store highly charged ions at low energies



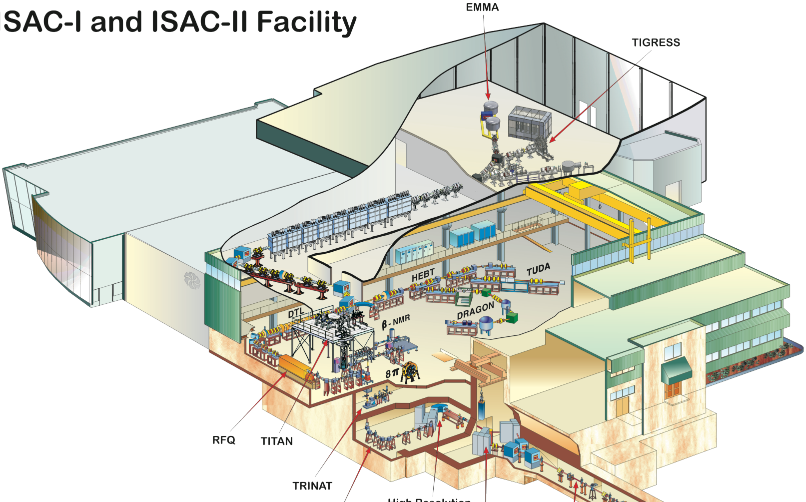
M.G. Sternberg *et al.*, Phys. Rev. Lett. **115**, 182501 (2015)

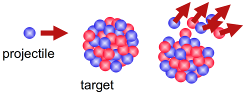


K.G. Leach *et al.*, Nucl. Instr. Meth. A **780**, 91 (2015)

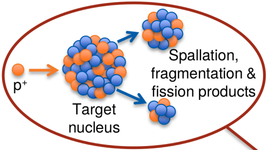
The TRIUMF-ISAC Facility

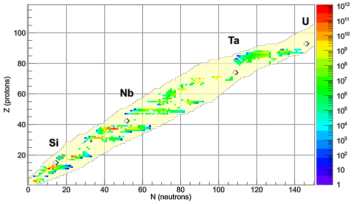
ISAC-I and ISAC-II Facility





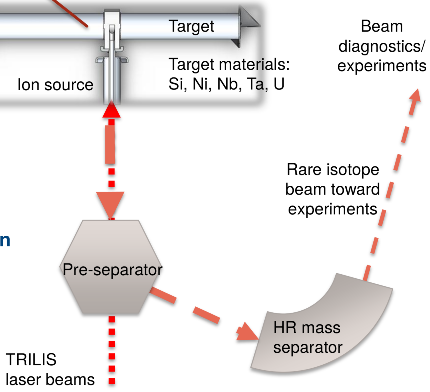
Rare Isotope Production at ISAC





1. Isotope production

10-100 µA, ≤ 500 MeV
p^+ beam



Delivered RIB

All nuclides that are

- Produced
- Released from target
- Ionized
- Not filtered by magnets

2. Ionization

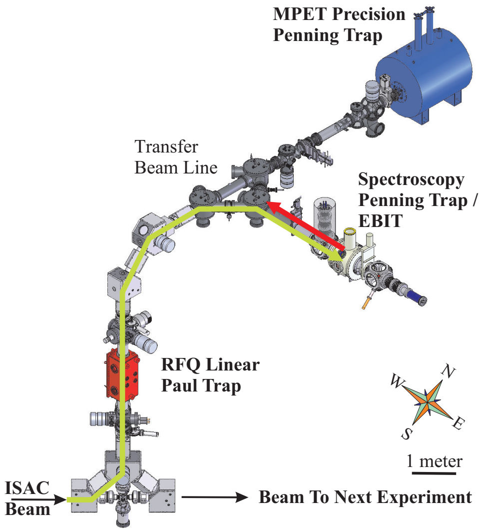
- Surface ionization
- Laser ionization
- Electron impact ionization

How to increase RIB purity?

- Production not very selective
- Magnet res. competes against beam intensity
- ➢ Ionization main element for selectivity increase

Courtesy: J. Lassen

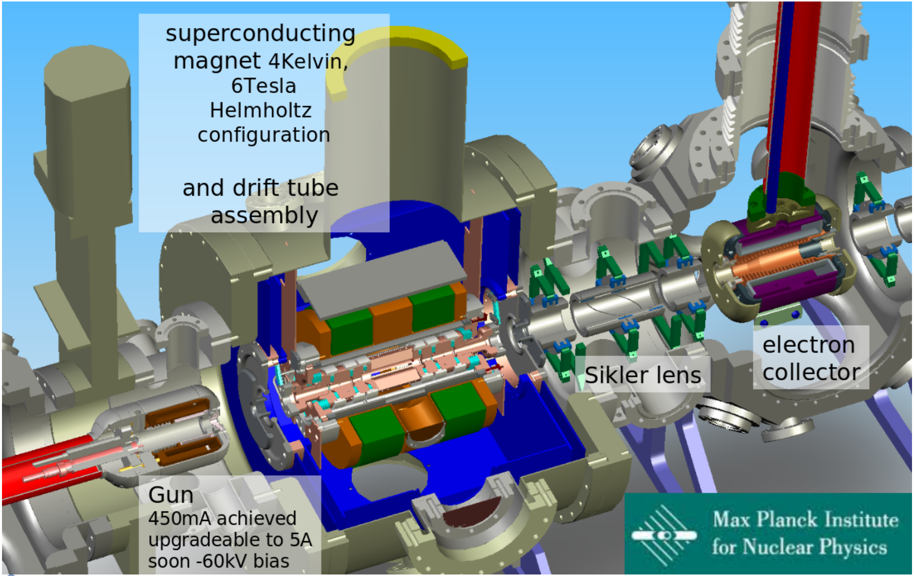
The TITAN Facility at TRIUMF



J. Dilling *et al.*, Int. Journ. Mass Spec. **251**, 198 (2006)

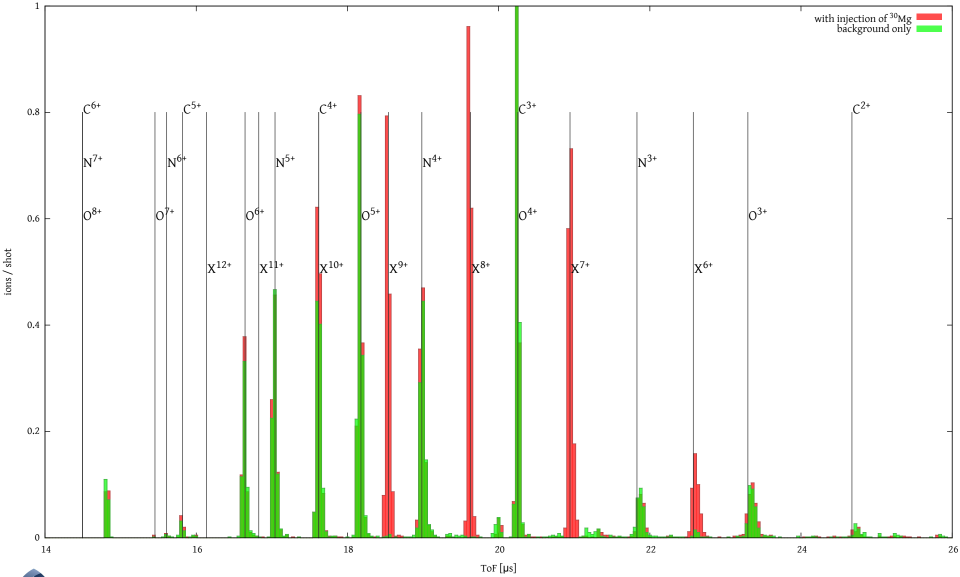
- TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN)
- Consists of three distinct ion traps:
  1. A buffer-gas-filled radio-frequency quadrupole (RFQ) linear Paul trap
  2. An electron-beam ion trap (EBIT) to create highly charged ions (HCIs)
  3. A 3.7 T high-precision mass-measurement Penning trap (MPET)
- Two additional traps will be included in the system next year.

Generating HCIs with the TITAN EBIT



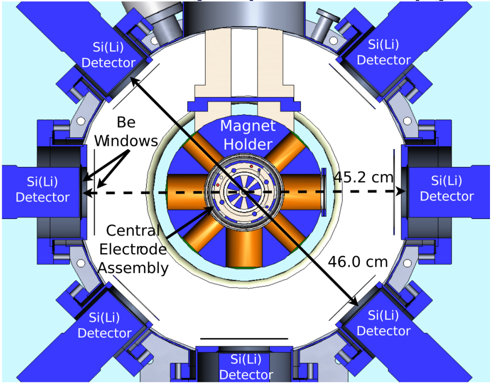
A. Lapierre *et al.*, Nucl. Instr. Meth. A **624**, 54 (2010)
K.G. Leach *et al.*, Nucl. Instr. Meth. A **780**, 91 (2015)

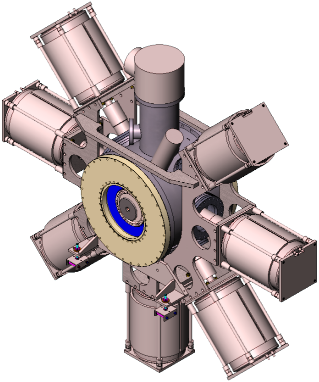
Charge-State Distributions from the TITAN EBIT



Courtesy: R. Klawitter

HCI Decay Spectroscopy at TRIUMF

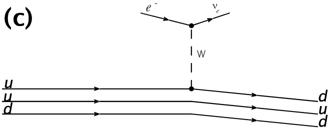




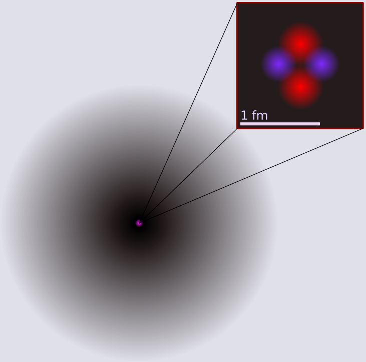
- Need to i) preserve high charge states, ii) provide a high-sensitivity decay environment, and iii) allow for a high space-charge limit
- Up to 6 T magnetic field, and 500 mA e^--beam
- Seven access ports for Si(Li) X-ray detectors or HPGe detectors

K.G. Leach *et al.*, Nucl. Instr. Meth. A **780**, 91 (2015)

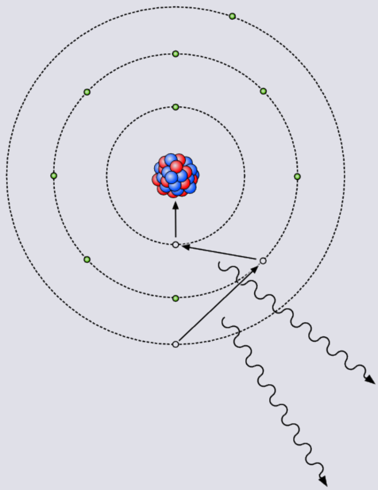
Observing Electron Capture Decays



Orbital Electron Capture



Signature of EC

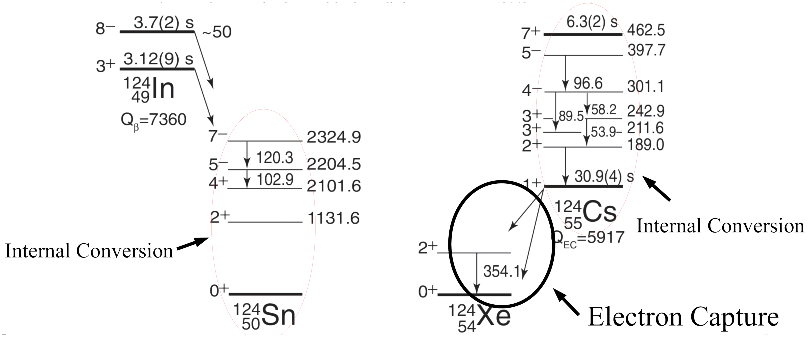


First Decay Spectroscopy Measurement of HCI

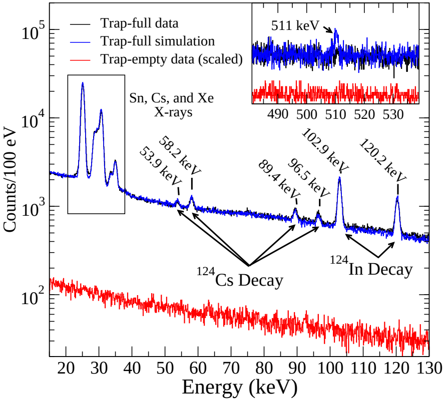
PRL 113, 082502 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

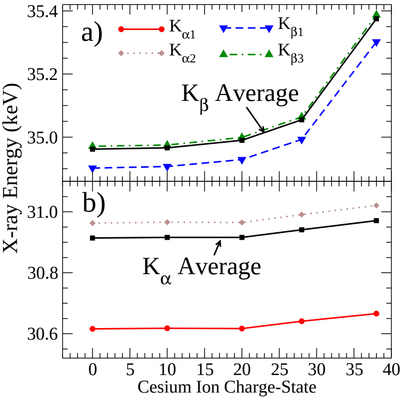
In-Trap Spectroscopy of Charge-Bred Radioactive Ions

A. Lennarz,[1,2] A. Grossheim,[2,3] K. G. Leach,[2,3] M. Alanssari,[1] T. Brunner,[2,†] A. Chaudhuri,[2] U. Chowdhury,[2,4] J. R. Crespo López-Urrutia,[5] A. T. Gallant,[2,6] M. Holl,[1] A. A. Kwiatkowski,[2] J. Lassen,[2] T. D. Macdonald,[2,6] B. E. Schultz,[2] S. Seeraji,[3] M. C. Simon,[2] C. Andreoiu,[3] J. Dilling,[2,6] and D. Frekers[1,*]



^{124}Cs EC Decay

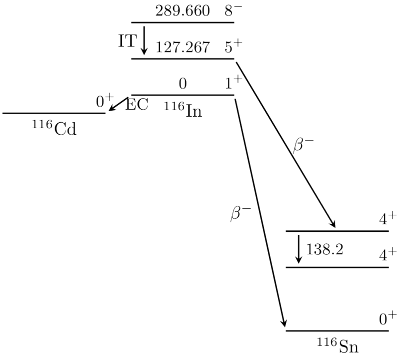


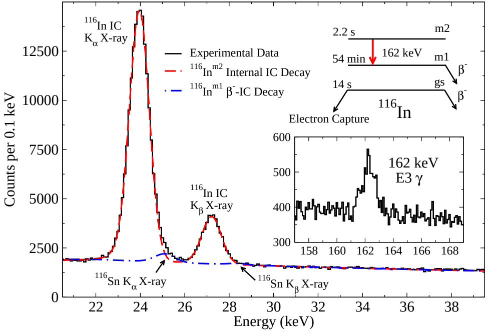


- Commissioning with $q \approx 28^{+}$ $^{124}_{55}$Cs using 7 Si(Li) detectors
- Corresponding to a stripped atomic N-shell (27 e^{-} remaining)
- Observed variations in the ratio of K_{α}/K_{β} X-rays and energy shifts of ~ 100 eV

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

^{116}In IC Decay





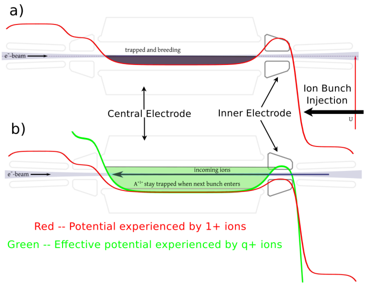
- In ($Z = 49$) stripped to an average of $q = 22^+$ (Ni-like)
- X-ray energy and ratio shifts are similar to Cs
- Measured ICCs for ^{116}In^{m2} decay

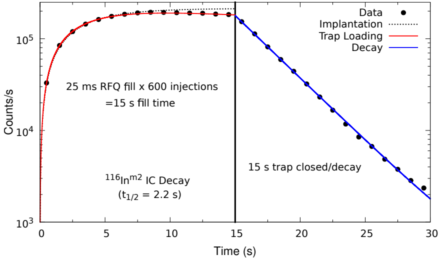
  α_K(exp.)=1.04(5)

  α_K(the.)=1.098(16)

K.G. Leach *et al.*, JPS Conf. Ser. **6**, 020040 (2015)
A. Lennarz and K.G. Leach (2016)

Multiple Ion-Bunch Injection with RIB





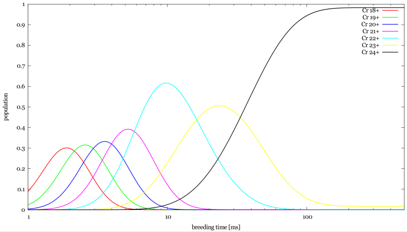
- To increase the number of total decays detected, a new technique was implemented
- By quickly and successively injecting singly charged ion bunches from the RFQ to the EBIT, the duty cycle is dramatically increased
- Current space-charge limit of the EBIT is $\sim 10^9\ e$, and will be upgraded soon.

R. Klawitter *et al.*, AIP Conf. Proc. **1640**, 112 (2015)
K.G. Leach *et al.*, JPS Conf. Ser. **6**, 020040 (2015)

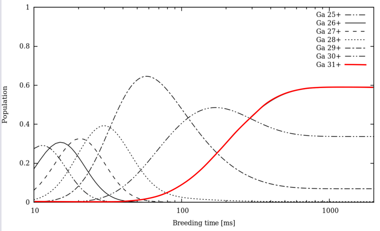
Towards Exotic Decay Modes with Bare Ions

- With the commissioning of our current device completed, we are now upgrading the stripping capability of the EBIT
- Will allow for experimentation on He-like, H-like, and bare ionic systems.

^{48}Cr In-Trap Charge States



^{76}Ga In-Trap Charge States



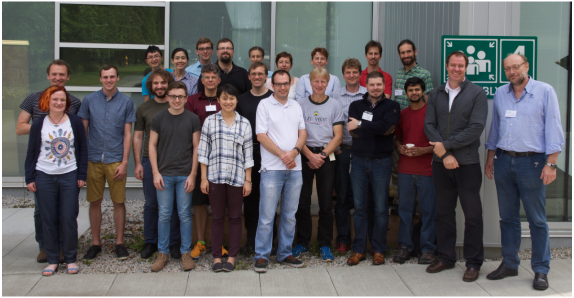
Courtesy: R. Klawitter

Conclusions

- Highly charged ions can have a dramatic effect on various radioactive decay modes, and provide an excellent tool for studying some second order decay modes
- An in-trap decay spectroscopy device has been developed and recently commissioned using the TITAN EBIT at TRIUMF
- An upgrade is nearing completion which will allow for significantly increased e^- gun energy and intensity (5 A at 60 kV)
- This will allow for experiments on He-like, H-like, and bare radioactive ions to probe effects of the complete suppression of decay modes
- Future plans for the construction of a dedicated HCI decay trap are currently underway to improve control over the decay environment

Acknowledgements

The TITAN collaboration



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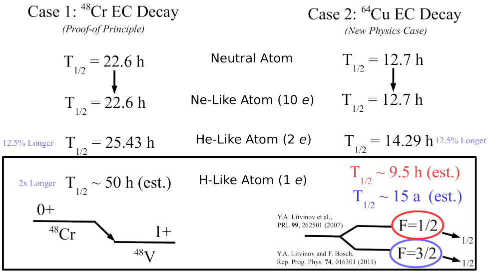
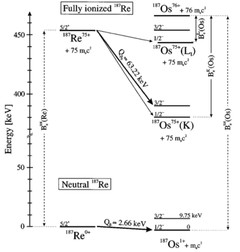
Decay of Highly Charged Radioactive Ions

- Decay rates can be influenced by atomic charge states.
- Orbital EC is strictly forbidden for bare ions (ie. becomes stable)
- For H-like/He-like the $T_{1/2}$ gets longer (and shorter!!)
- Very exotic decay modes become possible (ie. bound-state β decay, free electron capture)



K.G. Leach, I. Dillmann, and R. Klawitter, TRIUMF Experiment S1478



F. Bosch *et al.*, PRL **77**, 5190 (1996)