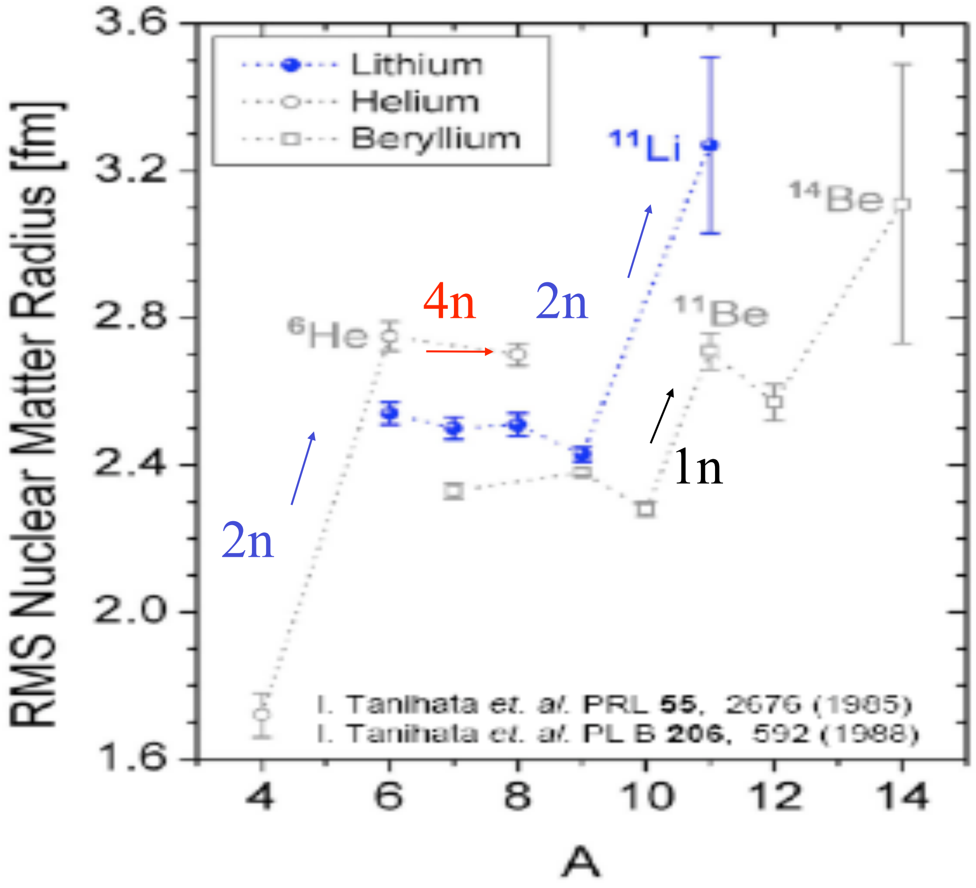
Atomic Physics Techniques Employed at TITAN

Ryan Ringle

workshop on atomic physics with rare atoms

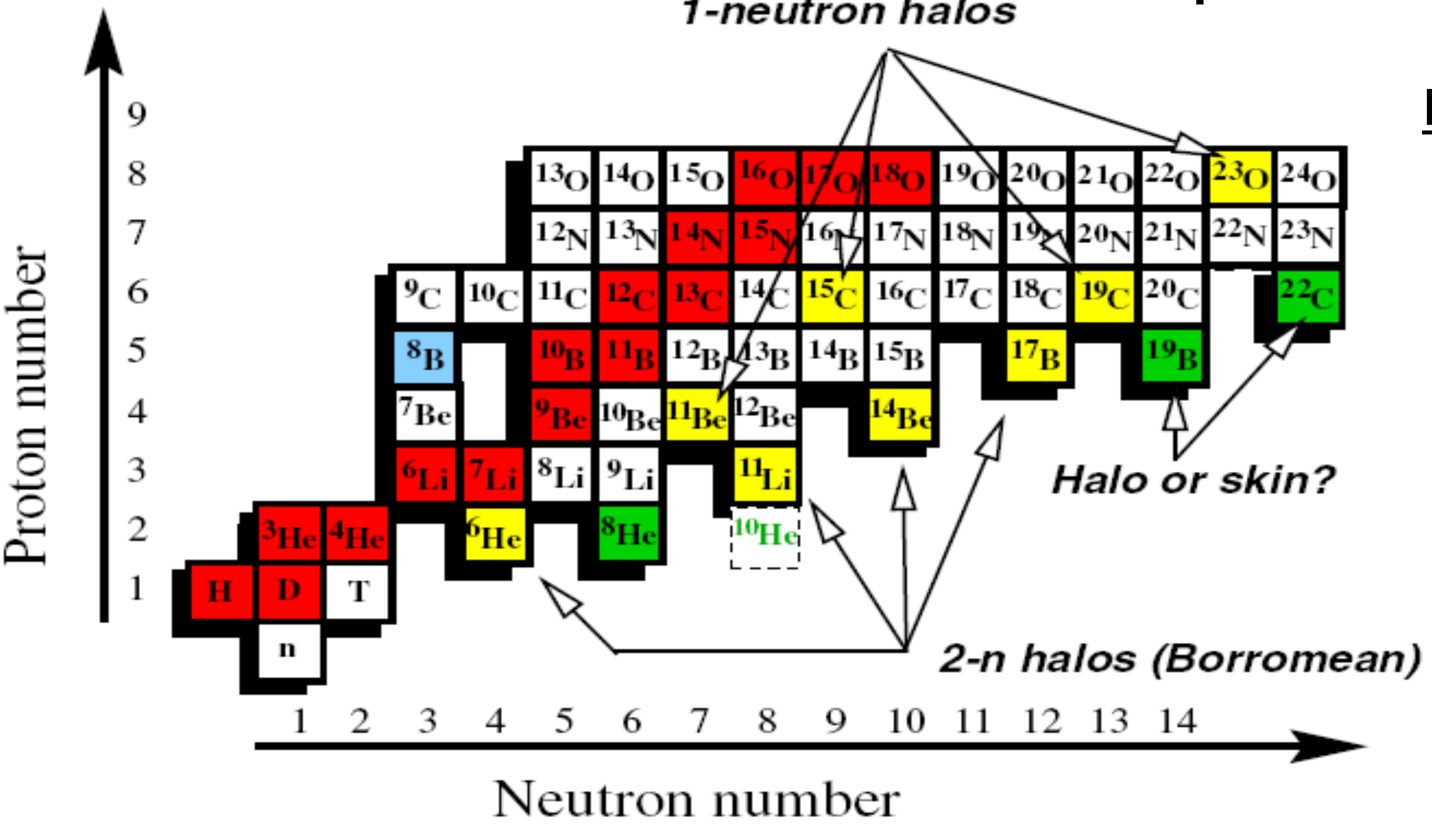
Properties of neutron halo nuclei



- very exotic (large n/p ratios)
- very large RMS matter distribution
- difference in matter and charge radii
- very small S_n or S_{2n}

Why bother?

  - sensitive probe of nuclear structure
  - excellent proving ground for ab-initio nuclear theories
  - opportunity to use atomic techniques to probe nuclear systems



neutron halos occur along the drip line

→ half lives tend to be short
production tends to be low

^{8}He - 119 ms
^{11}Li - 8.8 ms
^{14}Be - 4.4 ms

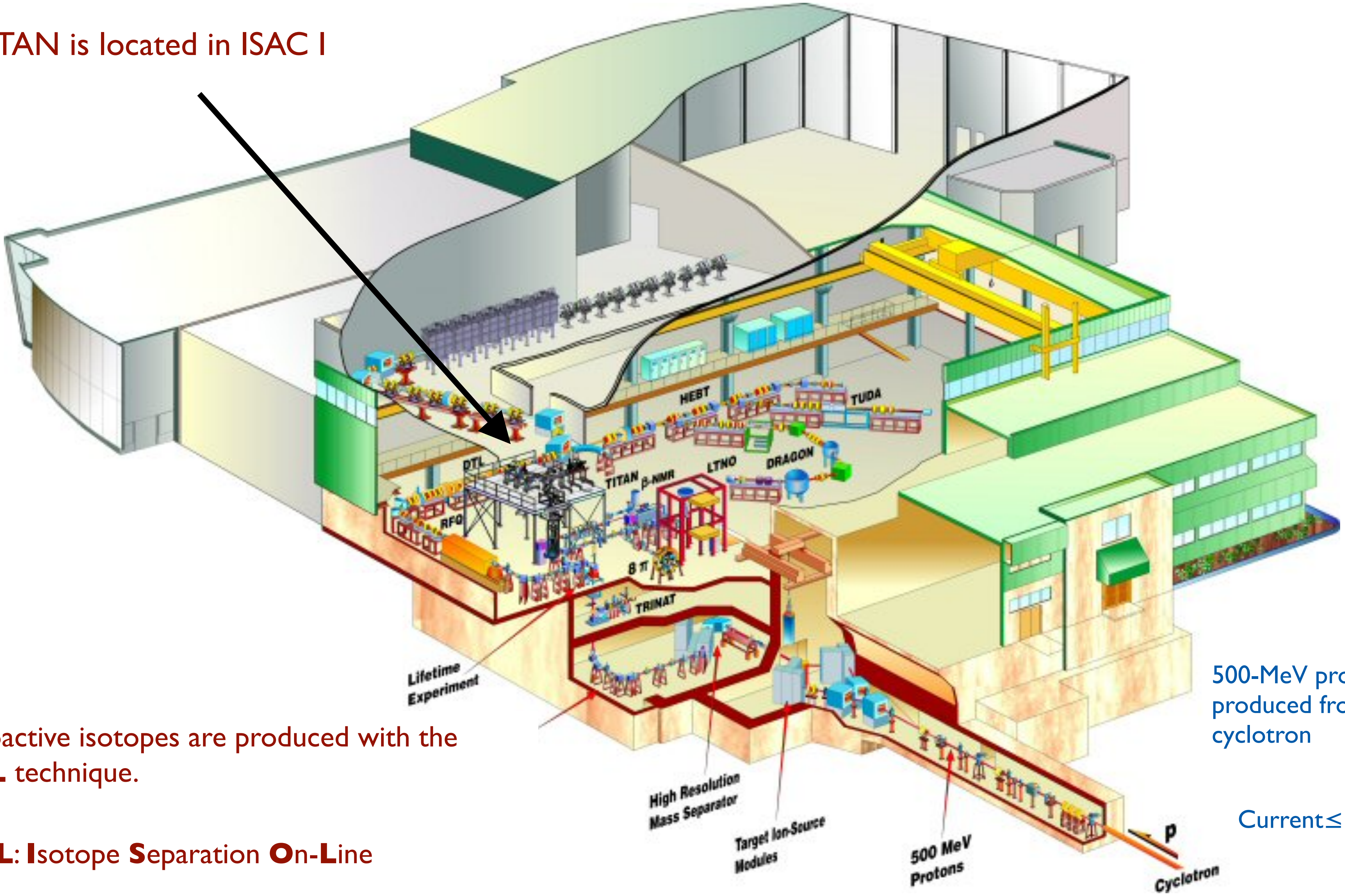
Use the best tool for the job:
Penning traps

TITAN
ISAC•TRIUMF

TRIUMF: ISAC I & II

Use the recently commissioned TITAN facility to measure the masses of halo nuclei

TITAN is located in ISAC I



500-MeV protons produced from a cyclotron

Current≤100 μA

Radioactive isotopes are produced with the **ISOL** technique.

ISOL: **I**sotope **S**eparation **O**n-**L**ine

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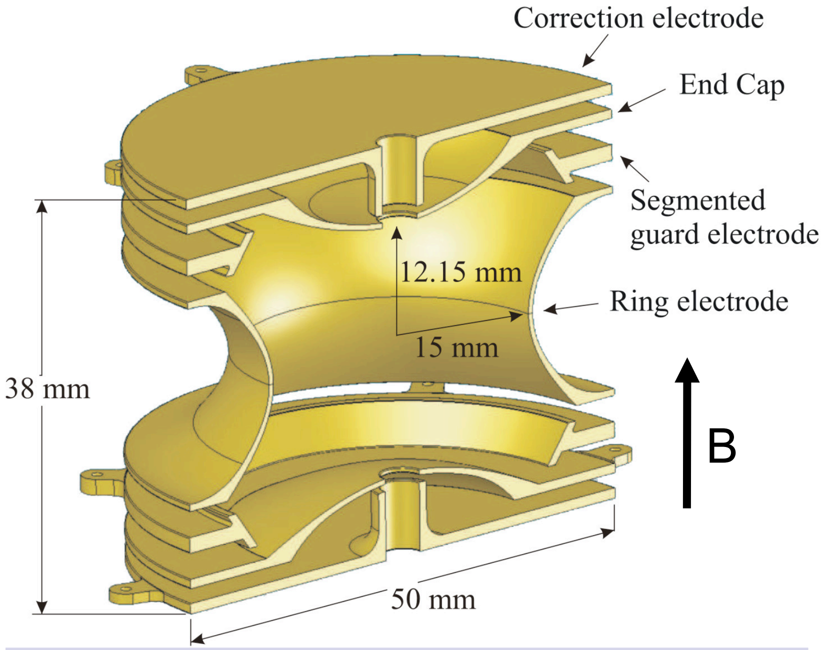
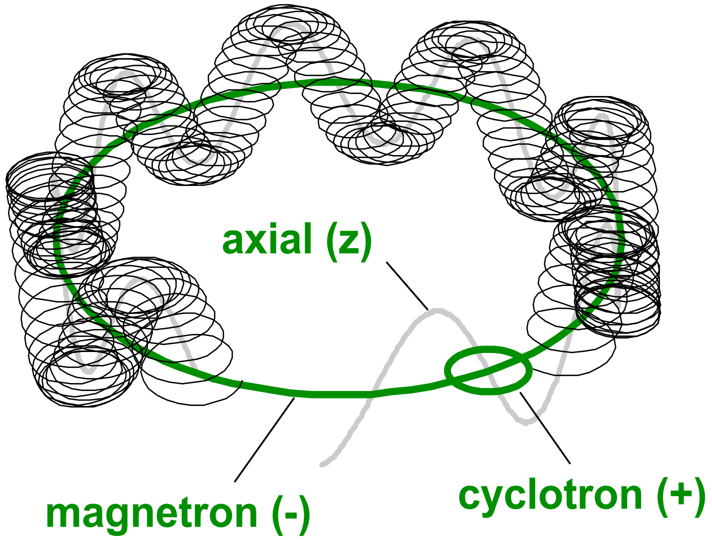
Penning trap mass spectrometry of short-lived radioactive nuclides

Brown and Gabrielse, Rev. Mod. Phys. **58** (1986) 233

Bollen *et. al.*, J. Appl. Phys. **68** (1990) 4355



Linear Magnetic Field + Harmonic Electrostatic Potential



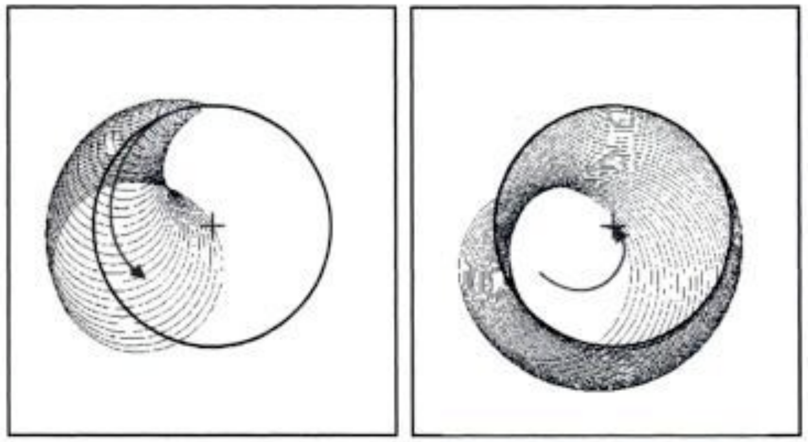
Three Harmonic Eigen-motions

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

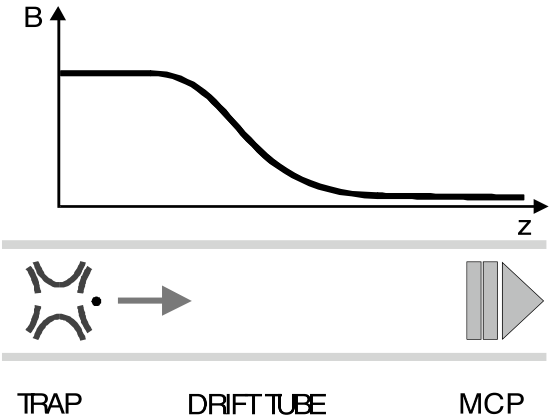
$$\omega_c = \frac{q}{m} B$$

$$\omega_+ >> \omega_-$$

The mass measurement is made by finding the true cyclotron frequency of the ion in the trap



Application of quadrupolar field converts magnetron motion into cyclotron motion

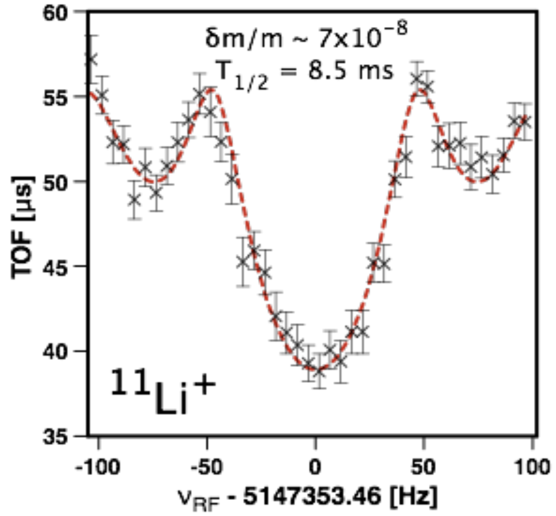


Extraction through magnetic field converts radial energy to longitudinal energy

Gräff *et. al.*, Z. Phys. A **297** (1980) 35

Bollen *et. al.*, J. Mod. Opt. **39** (1992) 257

König *et. al.*, IJMS **142** (1995) 95



Measurement of TOF gives cyclotron frequency and hence the mass

$$\frac{\delta m}{m} \propto \frac{m}{q T_{ex} B \sqrt{N}}$$

The TITAN facility at ISAC

Dilling *et. al.*, IJMS **251** (2006) 198

Cooler Trap

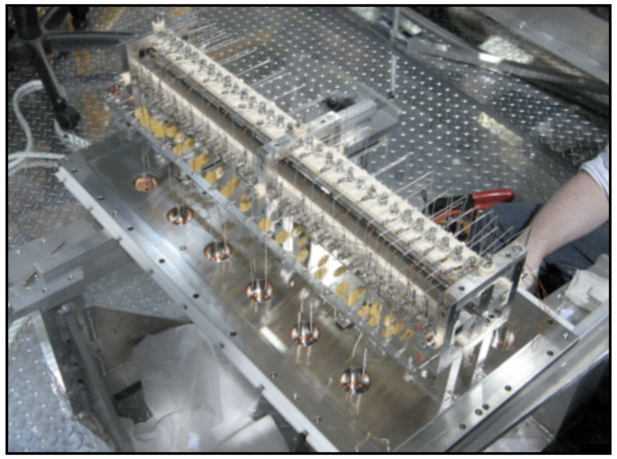
Cooling HCI

(work in progress)
G. Gwinner

(magnet now at TRIUMF)

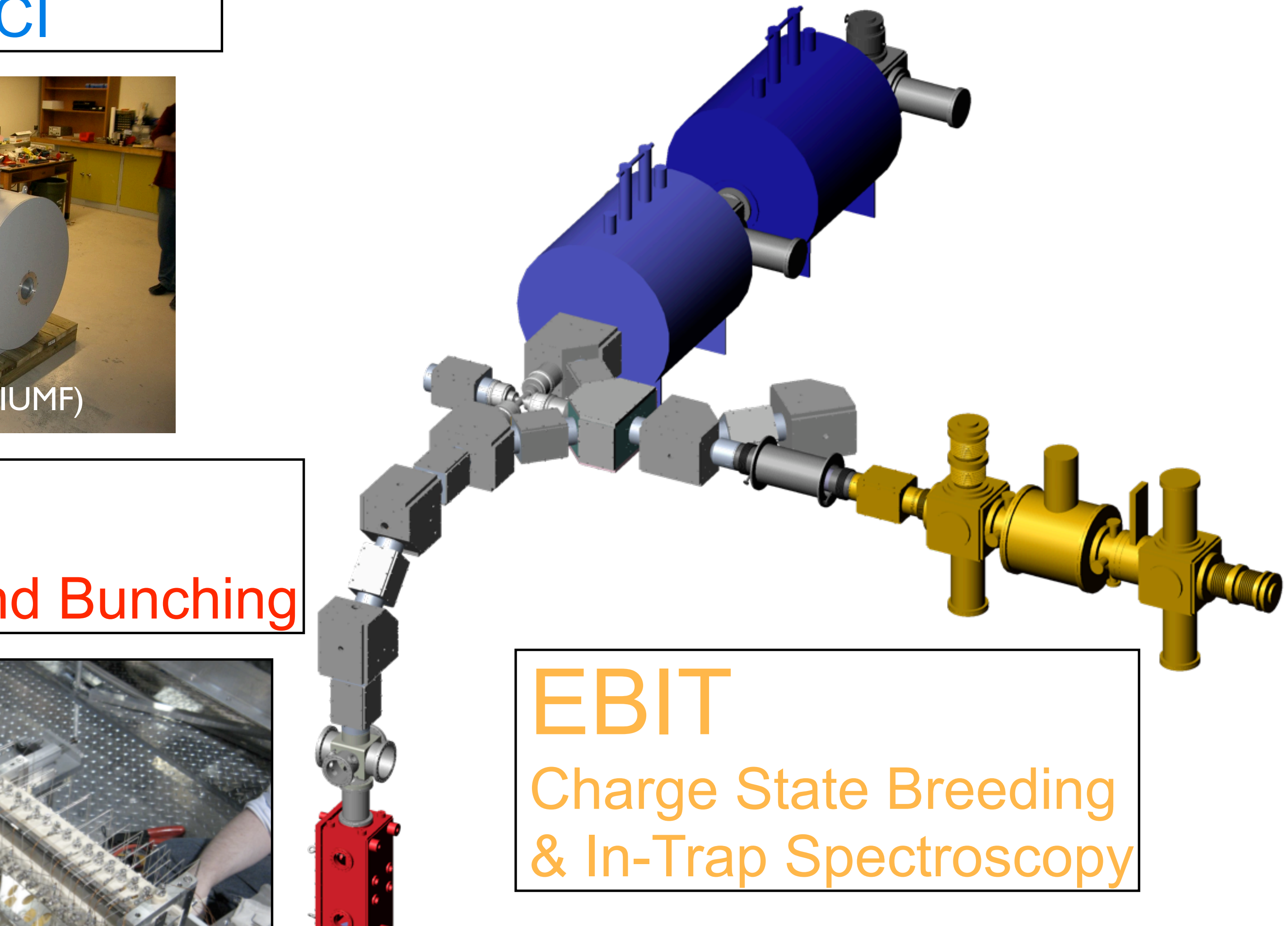
RFQ

Cooling and Bunching



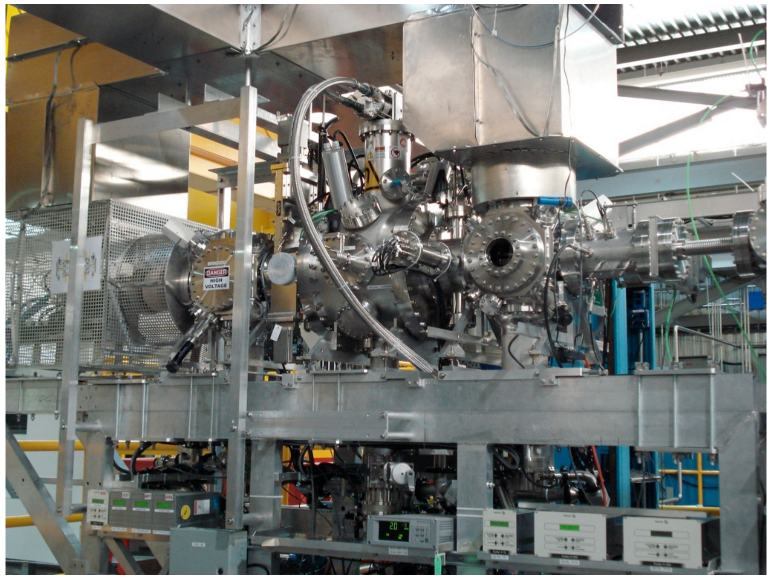
ISAC Beam

(E ~ 20-60 keV)



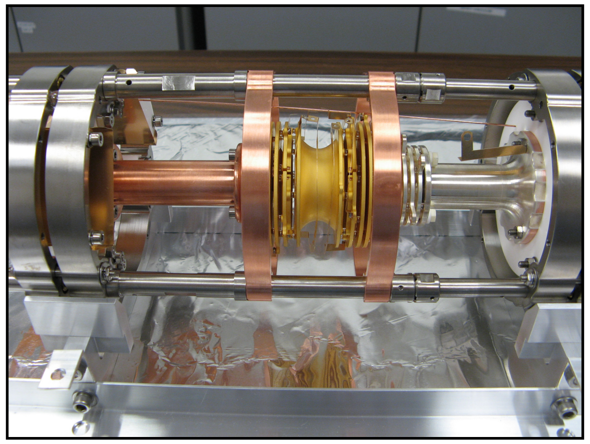
EBIT

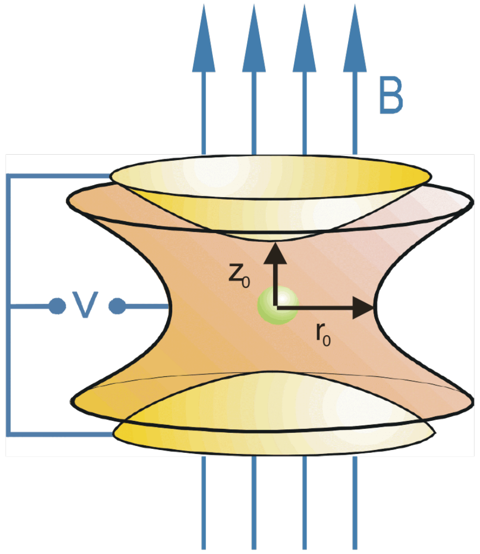
Charge State Breeding
& In-Trap Spectroscopy



Penning Trap

Mass Measurement





$$\frac{\delta m}{m} \propto \frac{m}{\boxed{q} T_{ex} B \sqrt{N}}$$

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TITAN - built for speed

Fast DAQ/Controls

- MIDAS based data acquisition
- minimal software/hardware interaction during measurement
- free-running frequency modulated RF system
- DAQ/controls not limiting measurement repetition rate

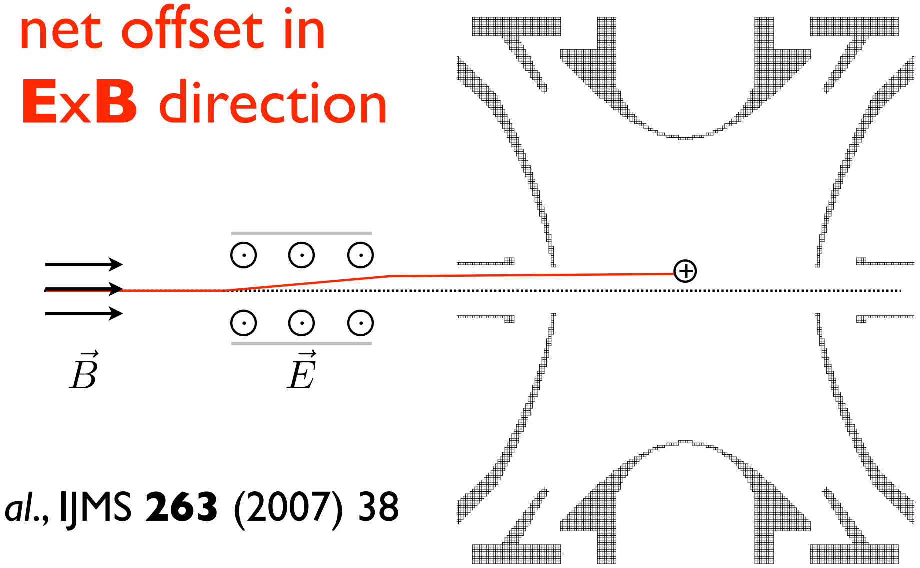
Parallel Operation

- parallel loading of RFQ
- parallel sideband cooling in EBIT (no charge breeding)
- purified samples delivered to MPET on demand

Fast Magnetron Preparation[1]

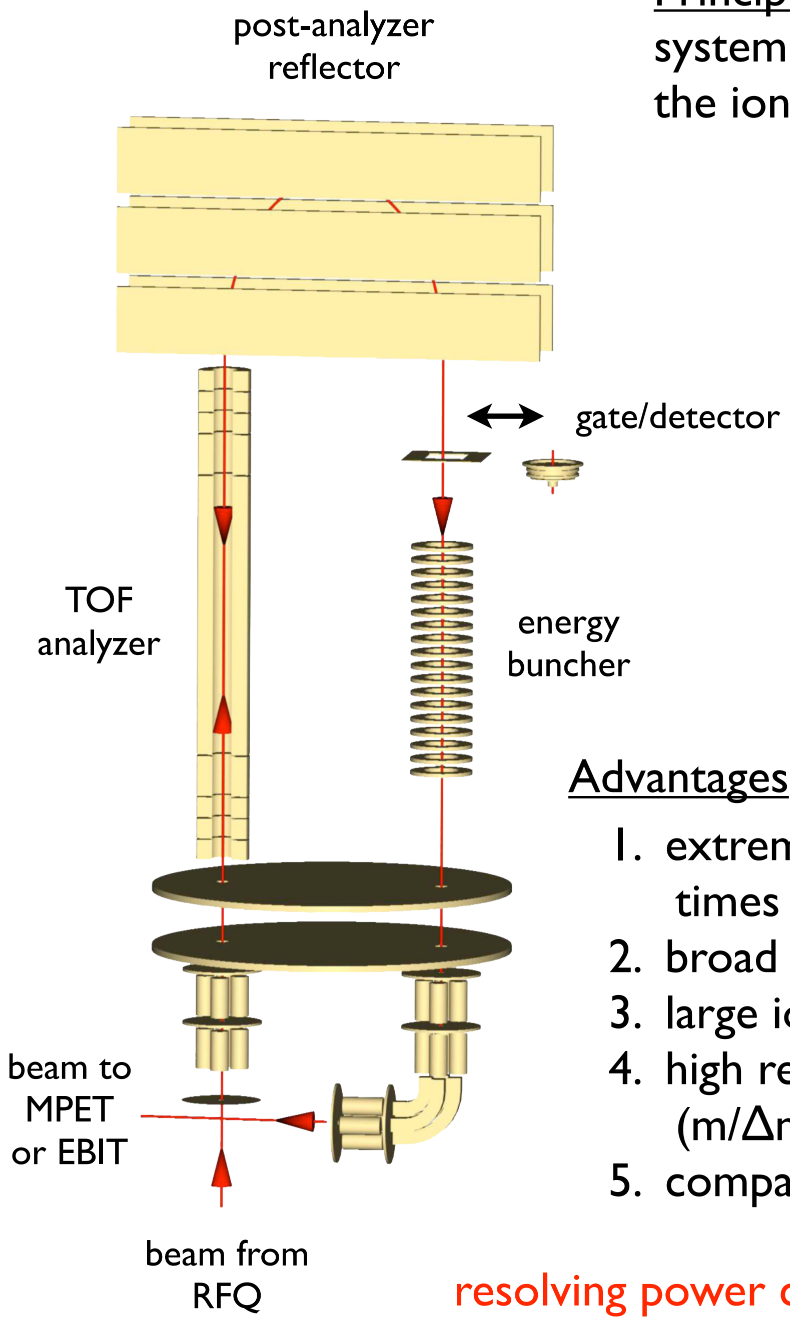
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

→ net offset in **ExB** direction



R. Ringle *et al.*, IJMS **263** (2007) 38

MR-TOF Isobar Separator (coming soon)



Principle: electrostatic mirror system drastically increases the ion flight path

Advantages:

1. extremely short measurement times (100 ns to 10 ms)
2. broad mass range
3. large ion capacity
4. high resolving power ($m/\Delta m \sim 100{,}000$)
5. compact setup, inexpensive

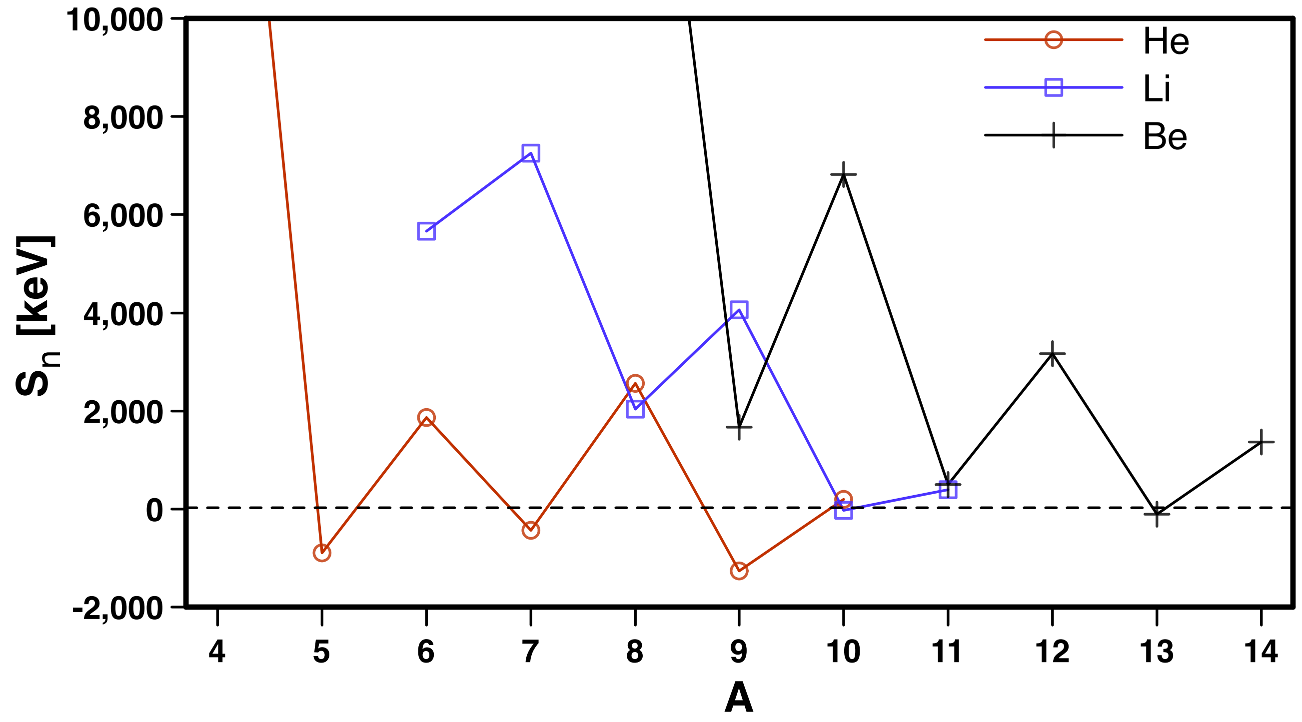
resolving power comparable to sideband cooling in a significantly shorter time

W.R. Plaß *et al.*, Nucl. Instr. Meth. B **266** (2008) 4560

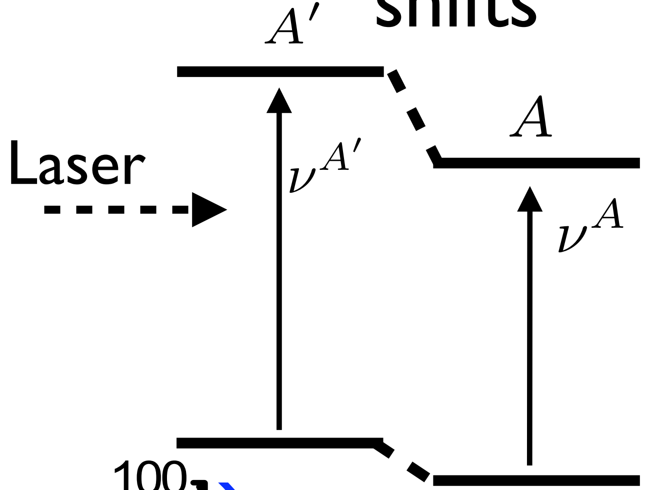
What role do masses play?

Directly: determination of neutron separation energies

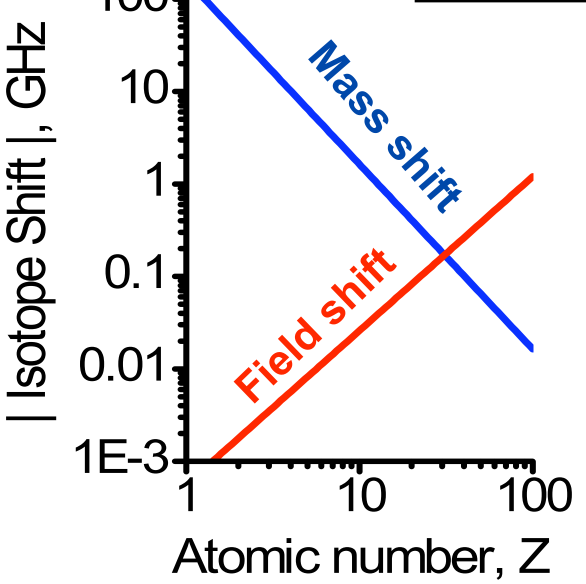
$$S_n(N,Z) = \boxed{M(Z,N-1)} + M_n - \boxed{M(Z,N)}$$



Indirectly: relative charge radius determination via isotope shifts



$$\overbrace{\delta\nu^{A,A'} = \nu^{A'} - \nu^{A}}^{\text{Experiment}} = \overbrace{\underset{\text{mass shift}}{\delta\nu^{A,A'}_{MS}} + K_{FS}}^{\text{Theory}} \cdot \underset{\text{field shift}}{\boxed{\delta < r_c^2 >^{A,A'}}}$$



Mass precision < 1 keV required

Yan and Drake, PRL **91** (2003) 113004
Drake, Nucl. Phys. A **737** (2004) 25
Puchalski and Pachucki, PRA **78** (2008) 052511

Halo nucleus	Reference	Lab	New TITAN mass?
^{6}He	Wang et. al., PRL **93** (2004) 142501	ANL	✓
^{8}He	Mueller et. al., PRL **99** (2007) 252501	GANIL	✓
^{11}Li	Sánchez et. al., PRL **96** (2006) 033002	TRIUMF	✓
^{11}Be	Nörtershäuser et. al., PRL **102** (2009) 062503	ISOLDE	✓

^{6,8}He

2 and 4 neutron halo

TRIUMF FEBIAD ion source made beams of noble gases available

^{8}He: Bricault *et al.*, Rev. Sci. Instrum. **79** (2008) 02A908

H_2 used as buffer gas in RFQ to avoid resonant charge exchange

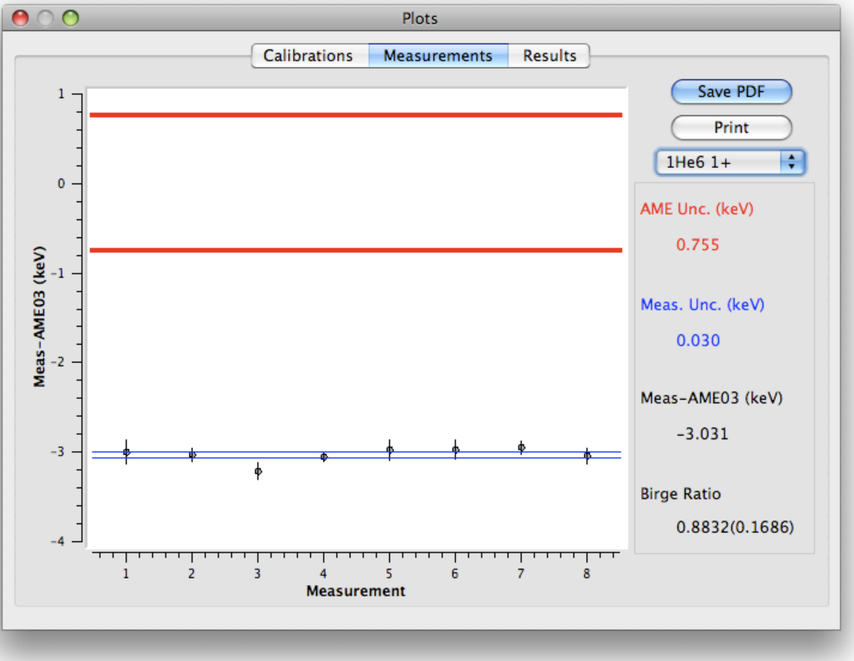
discretionary beam time

- 3 x ^{8}He measurements
- 2 x ^{6}He measurements

^{8}He: Ryjkov *et al.*, PRL **101** (2008) 012501

^{6,8}He: Brodeur *et al.*, in prep.

Currently working with A. Schwenk, S. Bacca and G. Hagen *et. al.* on CC and EFT description of ^{6,8}He

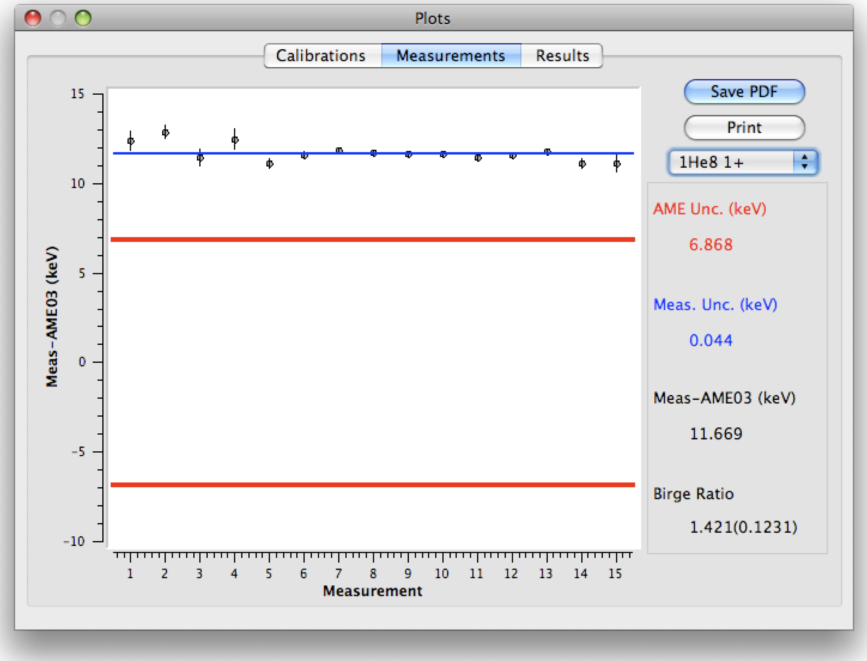


AME Unc. (keV)
0.755

Meas. Unc. (keV)
0.030

Meas-AME03 (keV)
-3.031

Birge Ratio
0.8832(0.1686)



AME Unc. (keV)
6.868

Meas. Unc. (keV)
0.044

Meas-AME03 (keV)
11.669

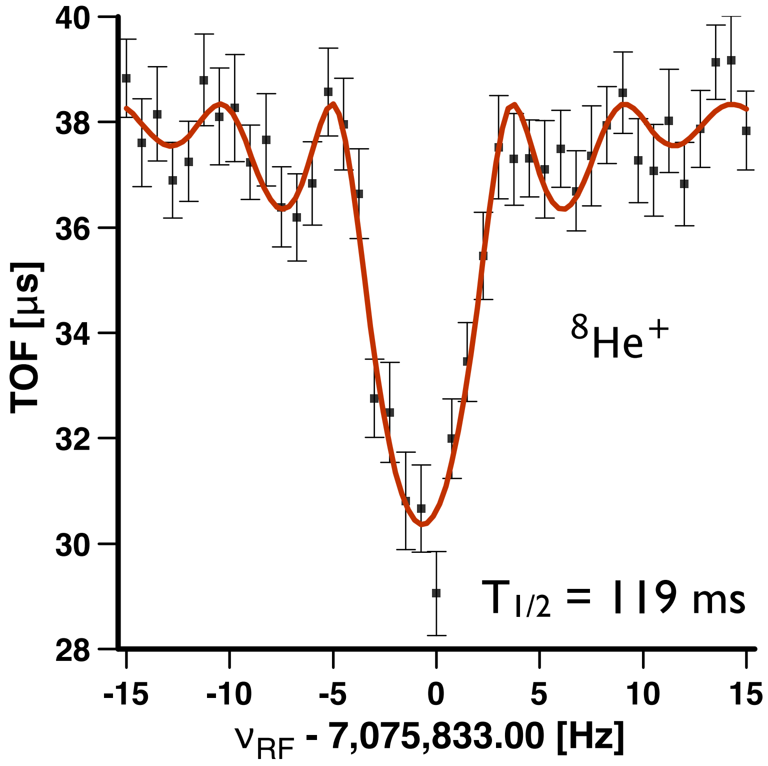
Birge Ratio
1.421(0.1231)

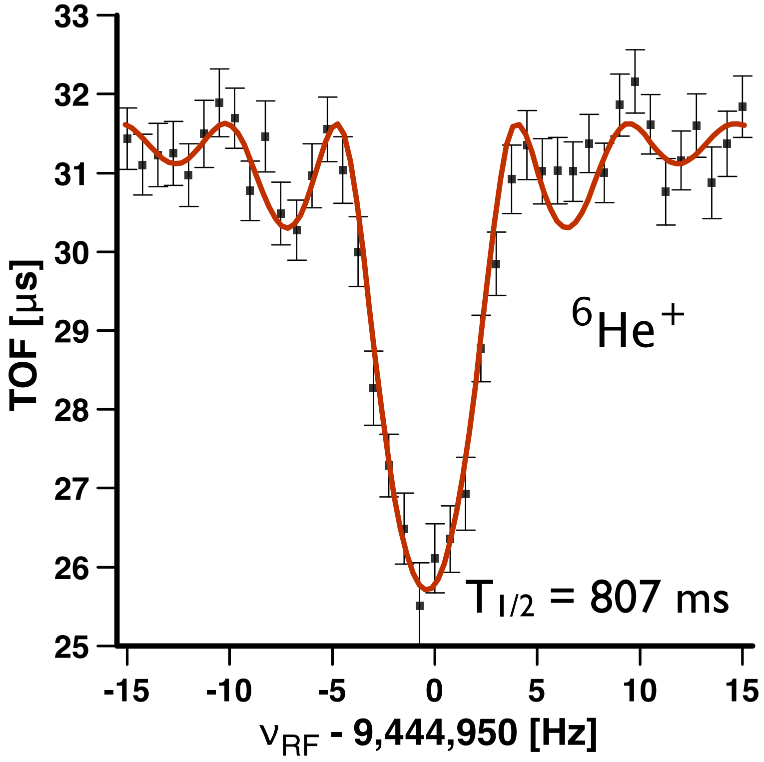
AME03: Audi *et al.*, Nucl. Phys. A **729** (2003) 337

<ins>Preliminary (statistical uncertainty)</ins>

ME(^{6}He) = 17592.081(23) keV

ME(^{8}He) = 31609.687(40) keV





^{11}Li

2 neutron halo

Bachelet *et al.* measured a significant deviation in the ^{11}Li mass

δm < 3 keV required for solid test of nuclear theory

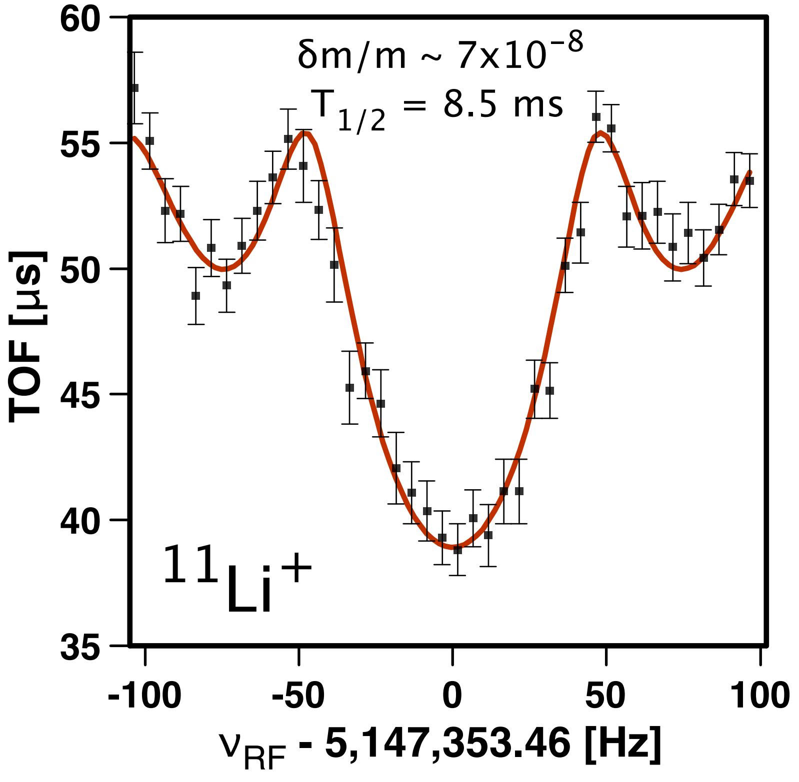
δm < 1 keV required to no longer contribute to CR uncertainty

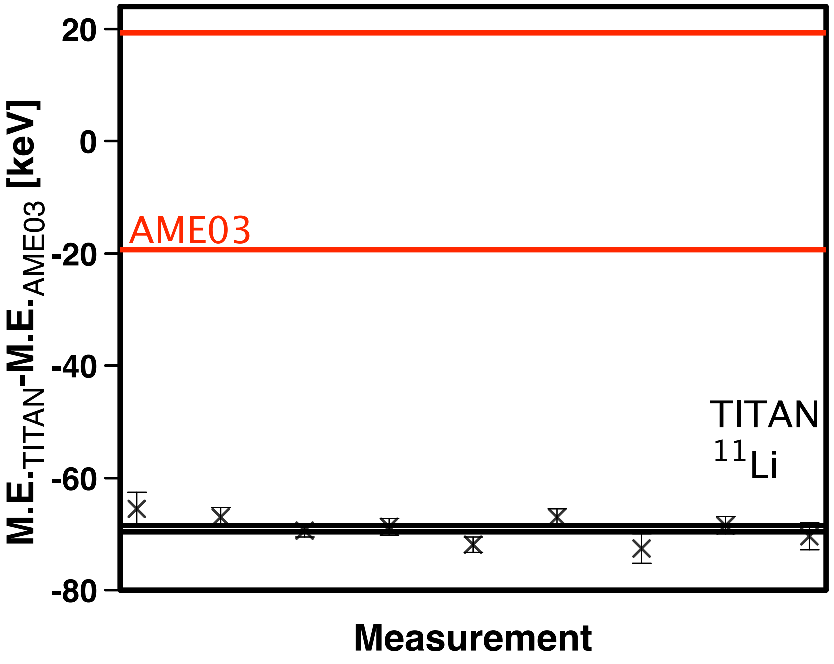
AME ’03: $S_{2n}(^{11}\text{Li}) = 300 \pm 20$ keV

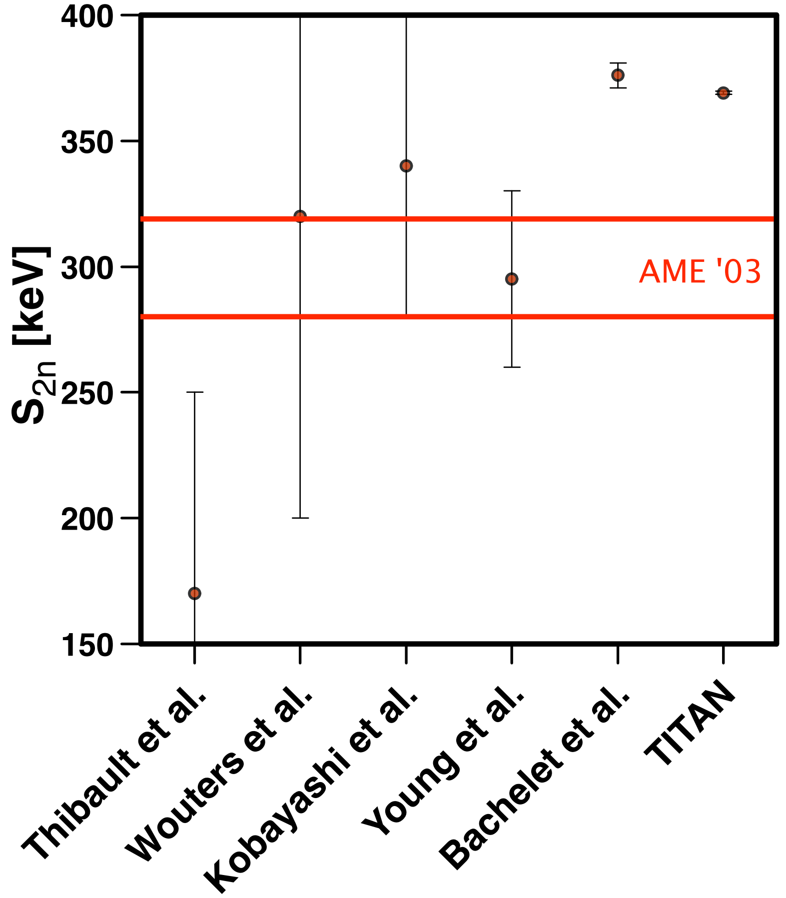
Reference	Method	S_{2n} [keV]
Thibault *et al.* PRC **12**, 644 (1975)	Mass Spec.	170 ± 80
J.M. Wouters *et al.* Z. Phys. A **331**, 229 (1988)	TOF	320 ± 120
T. Kobayashi *et al.* KEK Rep. 91-22 (1991)	$^{11}B(\pi^-,\pi^+)^{11}Li$	340 ± 50
B.M. Young *et al.* PRL **71**, 4124 (1993)	$^{14}C(^{11}B,^{11}Li)^{14}O$	295 ± 35
Bachelet *et al.* PRL **100**, 182501 (2008)	Mass Spec.	376 ± 5

Shortest lived nuclide measured in a Penning trap

Smith *et al.*, PRL **101** (2008) 202501







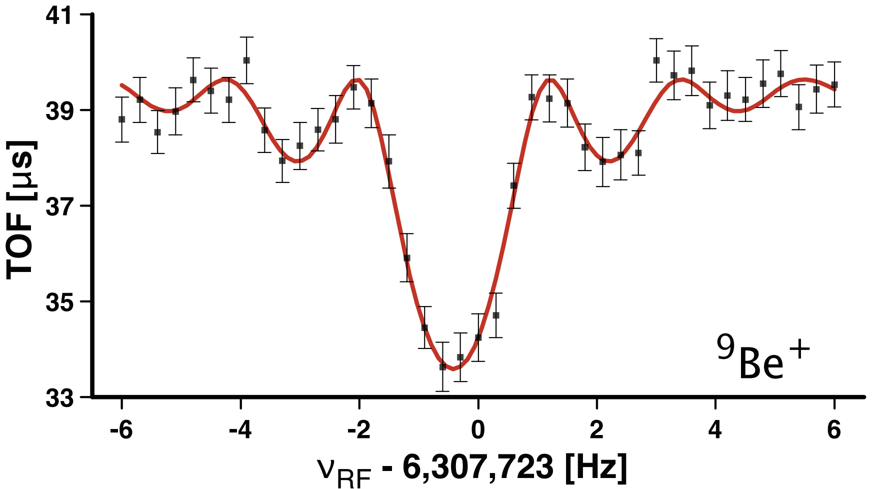
^{11}Be

1 neutron halo

Improved Be metrology at no additional cost

Improved ^{11}Be precision by over an order of magnitude

Ringle *et al.*, PLB **675** (2009) 170



Mobley *et al.*, PR **80** (1950) 309

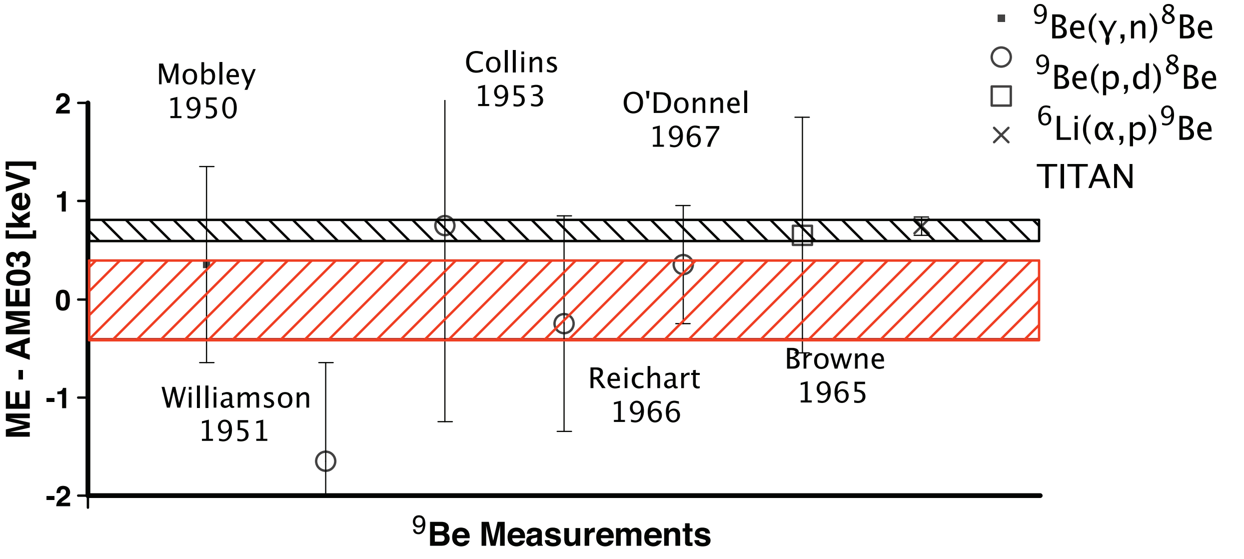
Williamson *et al.*, PR **84** (1951) 731

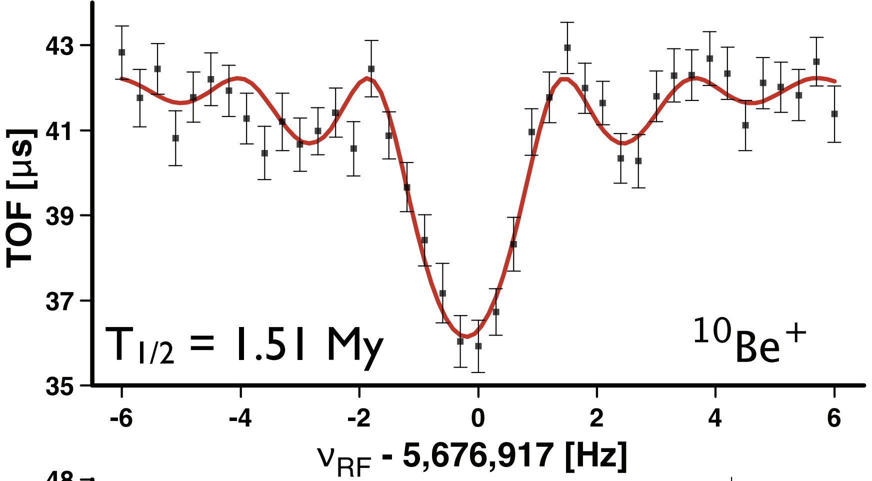
Collins *et al.*, PRSL **216** (1953) 242

Reichart *et al.*, PL **20** (1966) 40

O'Donnel *et al.*, PR **158** (1967) 957

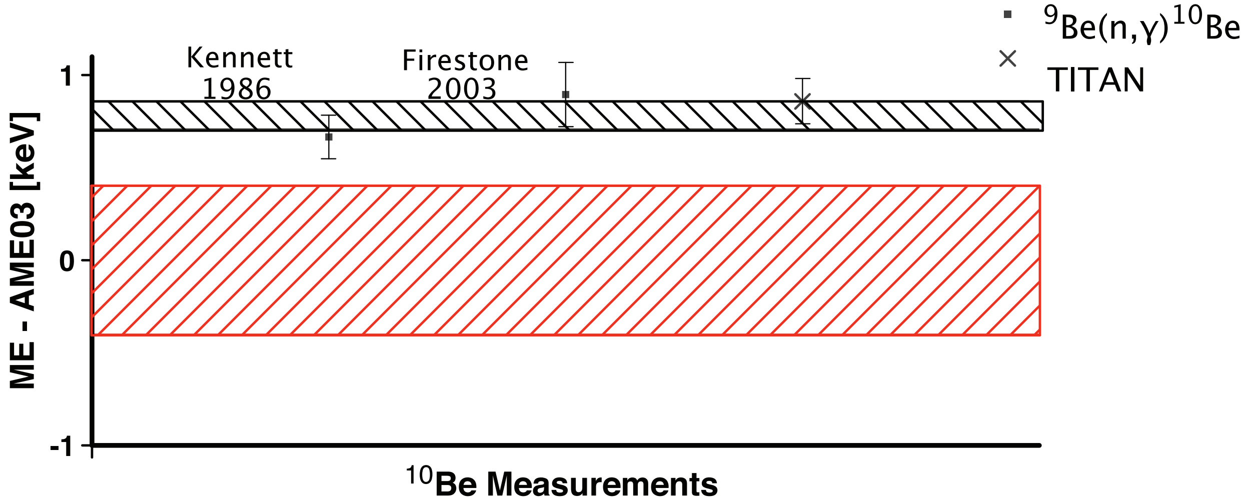
Browne *et al.*, NPA **72** (1965) 194

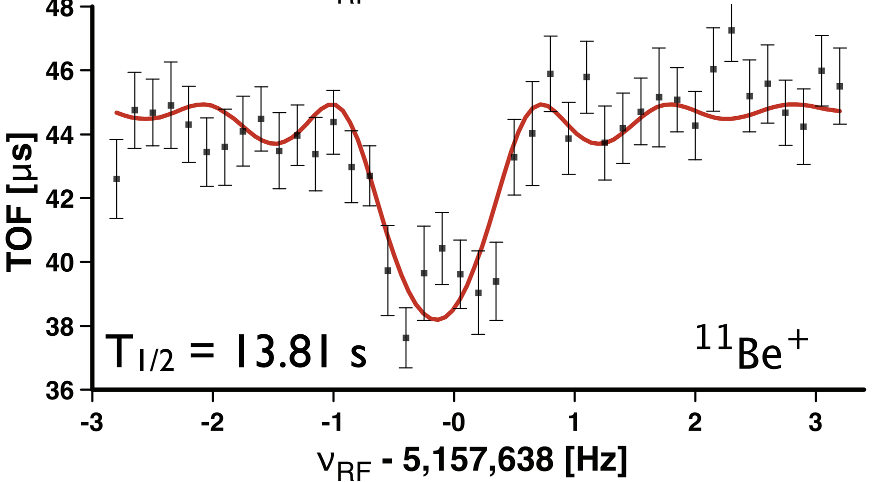




Kennett *et al.*, NIMA **249** (1986) 366

Firestone *et al.*, IAEA-Tecdoc (2003)

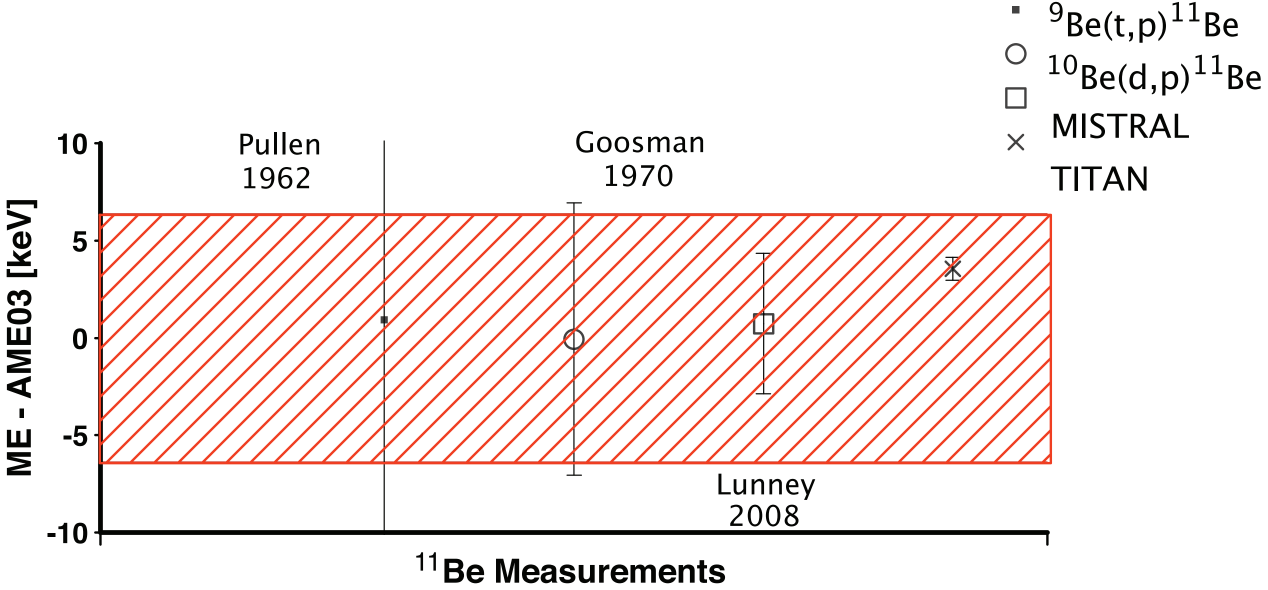




Pullen *et al.*, NP **36** (1962) 1

Goosman *et al.*, PRC **1** (1970) 1939

Lunney *et al.*, NIMA **598** (2008) 379



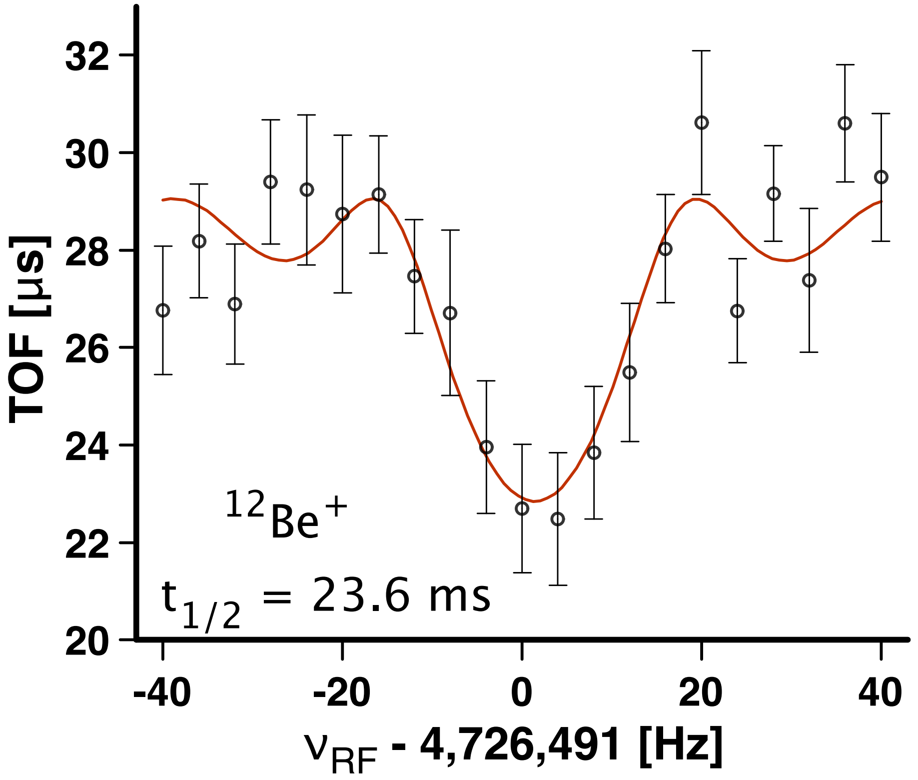
^{12}Be

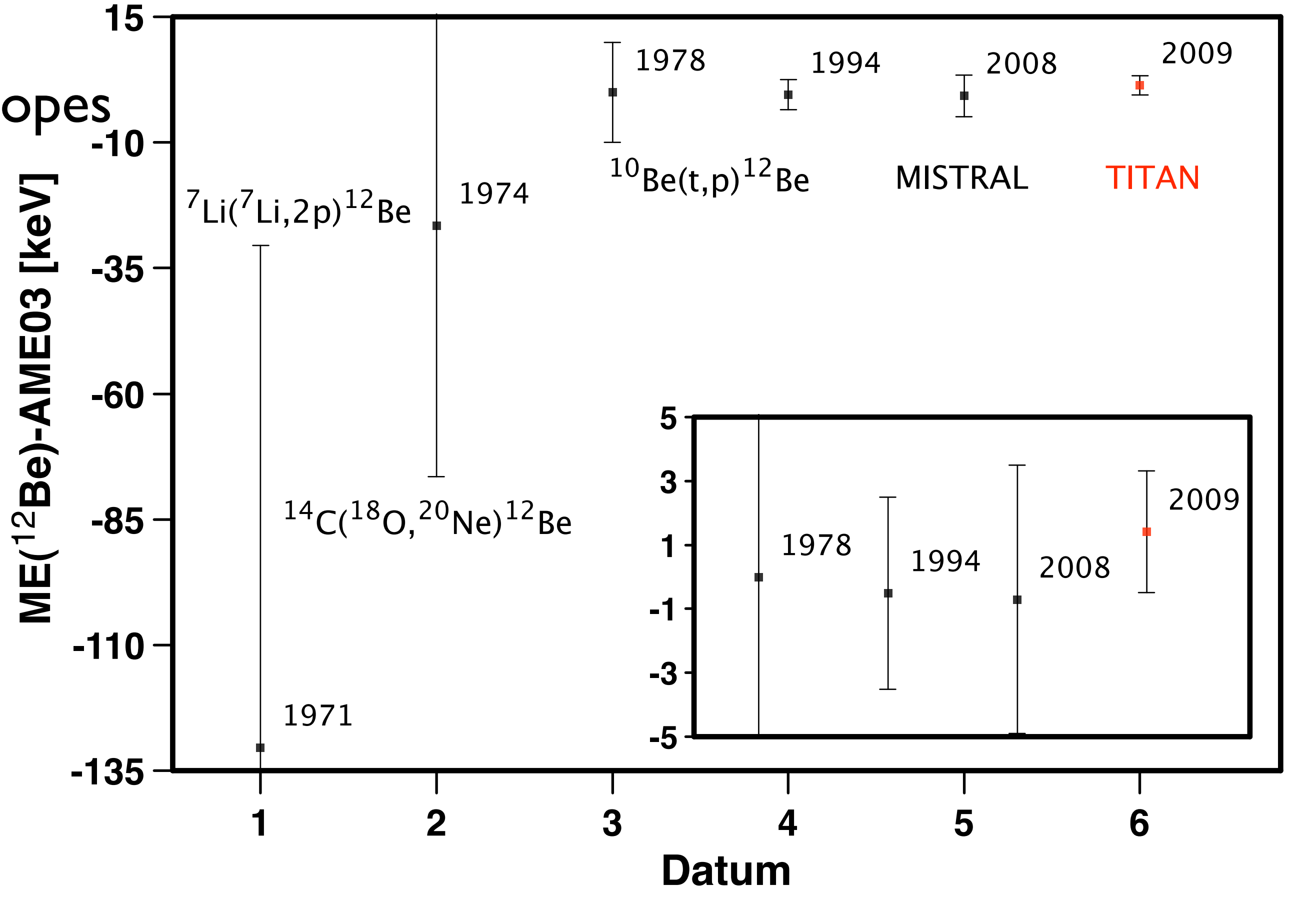
(pushing towards ^{14}Be)

^{14}Be: 2n halo nucleus with short half life ($T_{1/2}$ = 4.35 ms)

Thick Ta target hinders release times for short-lived Be isotopes

Short TaC stack to be used in 2010





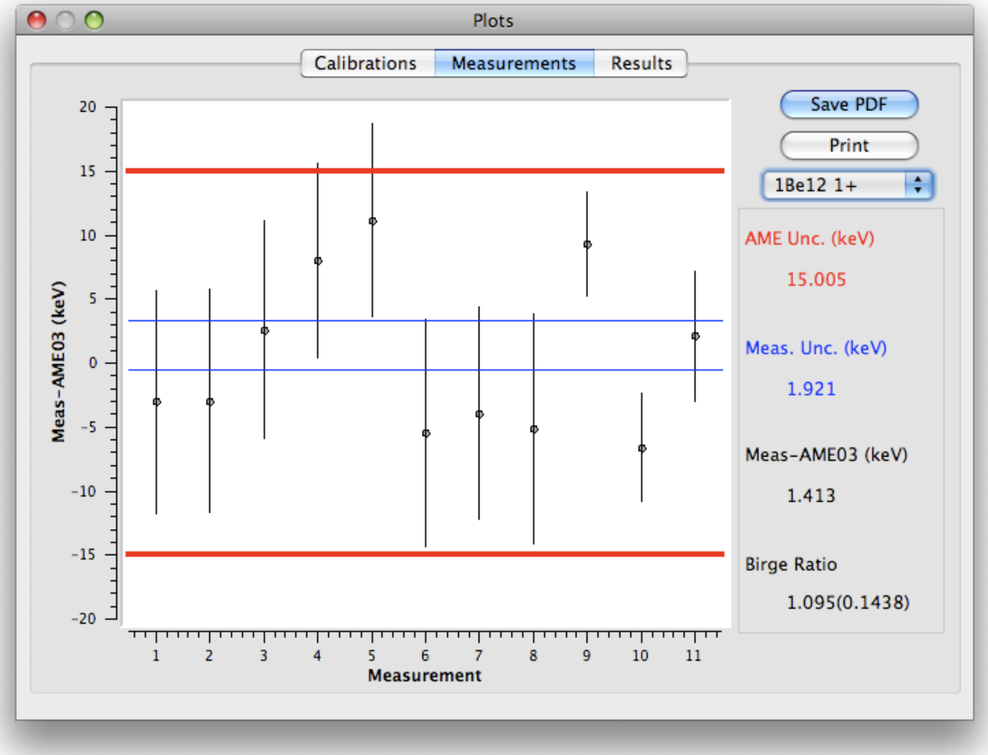
Improved ^{12}Be mass value will contribute to more precise S_{2n}(^{14}Be)

Low yields are expected (10 pps)

Measured ^{12}Be with as few as 30 pps

Preliminary (statistical uncertainty)

ME(^{12}Be) = 25078(2) keV



AME Unc. (keV)
15.005

Meas. Unc. (keV)
1.921

Meas-AME03 (keV)
1.413

Birge Ratio
1.095(0.1438)

Ettenauer *et al.*, in prep.

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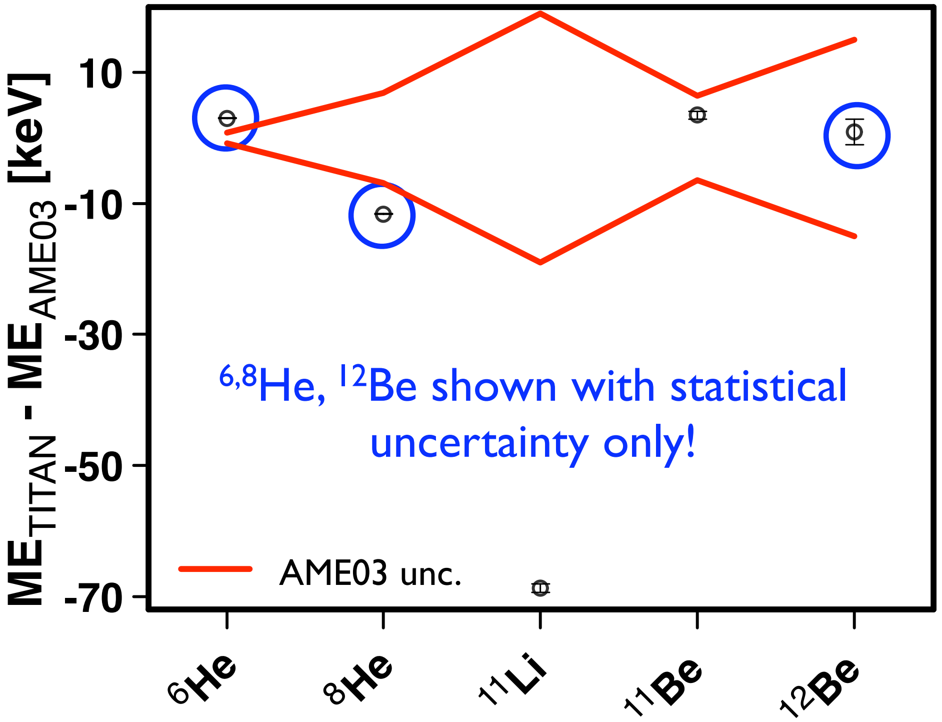
Halo masses and charge radii

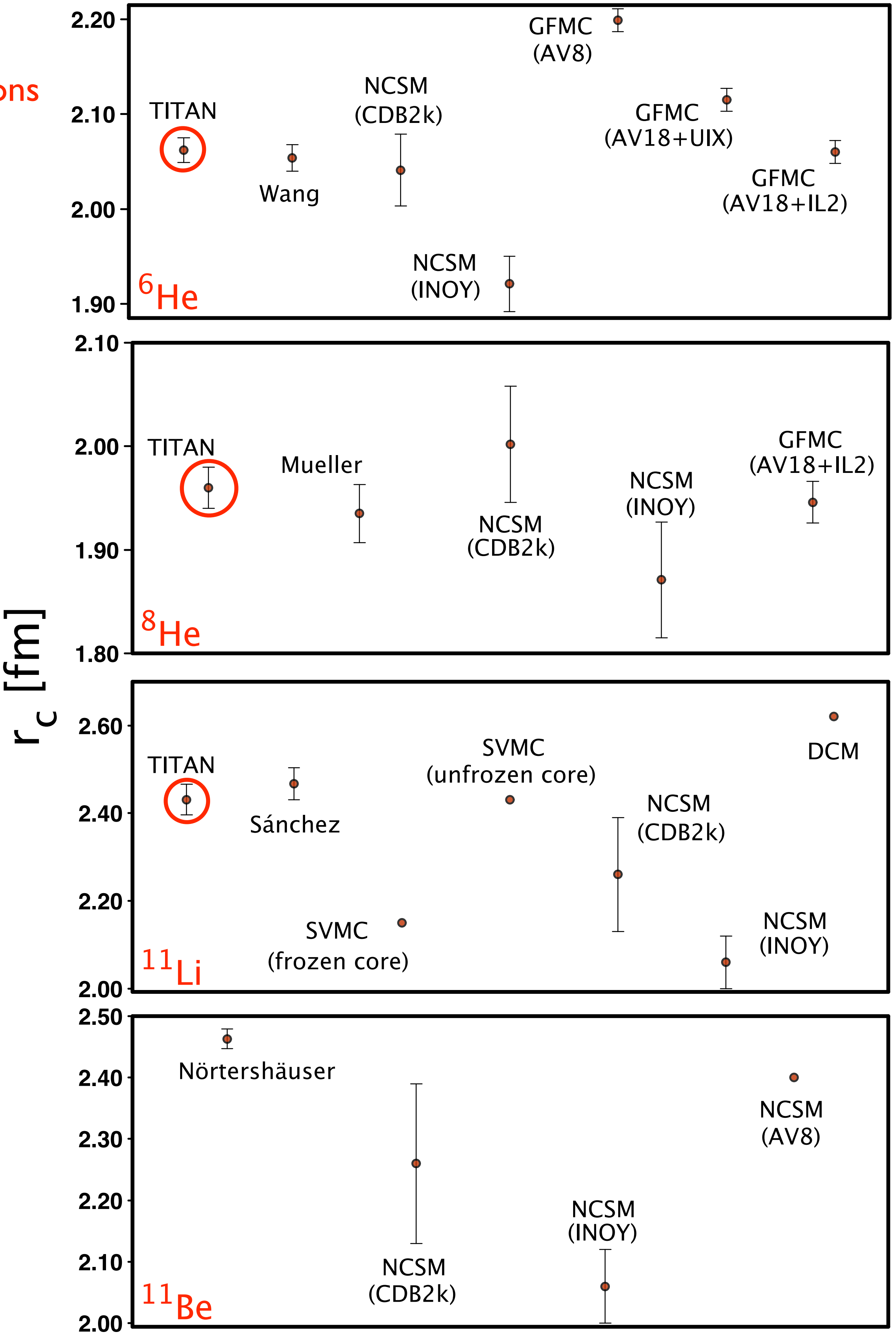


Preliminary

New mass shift term calculations by G. Drake using new TITAN masses

atomic mass no longer a contributing source of uncertainty

$$\overbrace{\delta\nu^{A,A'} = \nu^{A'} - \nu^{A}}^{\text{Experiment}} = \overbrace{\boxed{\delta\nu_{MS}^{A,A'}} + K_{FS}}^{\text{Theory}} \cdot \delta < r_c^2 >^{A,A'}$$



ab-initio nuclear theory references

DCM ^{11}Li: Tomaselli *et al.*, Nucl. Phys. A **690** (2001) 298

GFMC (AV18+UIX, AV8) ^{6}He: Pieper, *et. al.*, PRC **64** (2001) 014001

SVMC ^{11}Li: Varga *et al.*, PRC **66** (2002) 3013

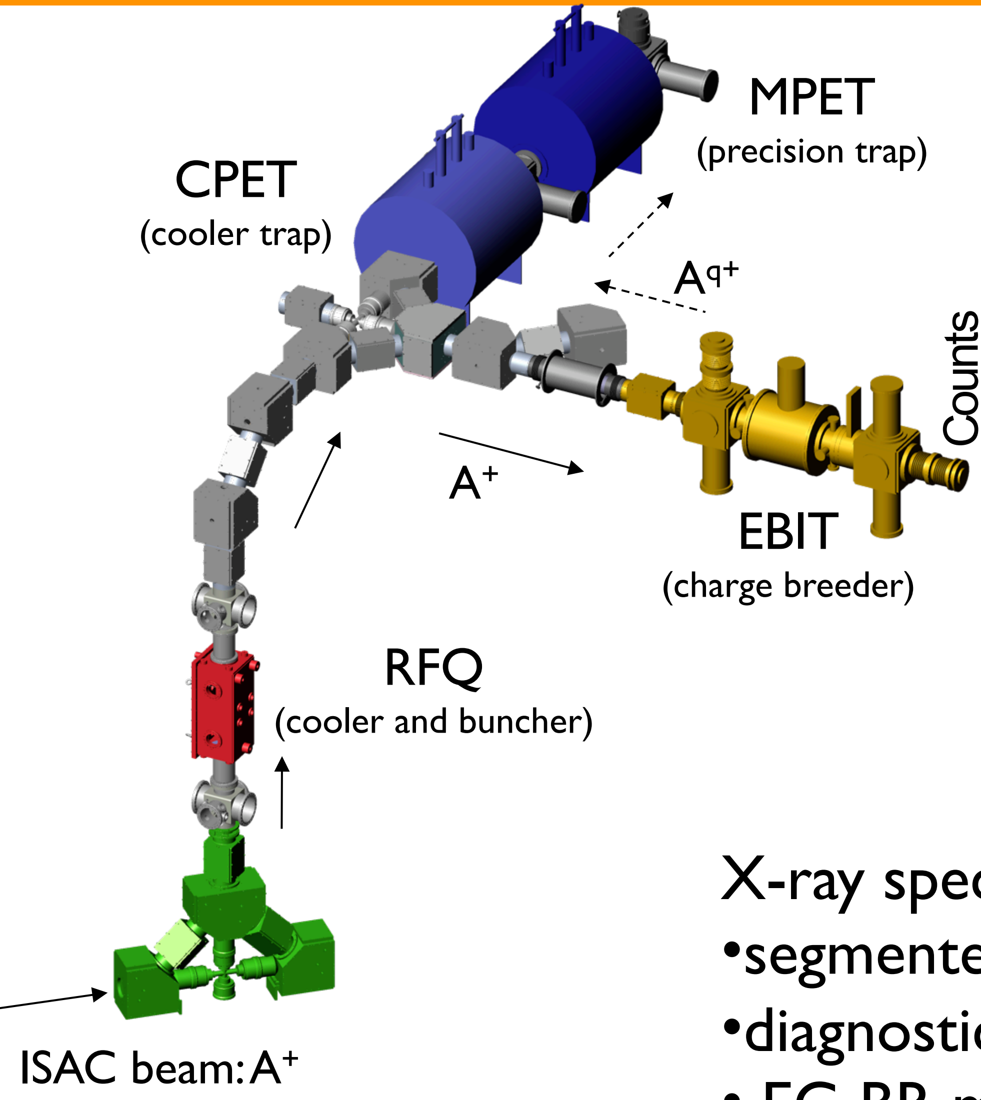
NCSM (AV8) ^{6}He, ^{11}Be: Forssén *et. al.*, PRC **71** (2005) 044312

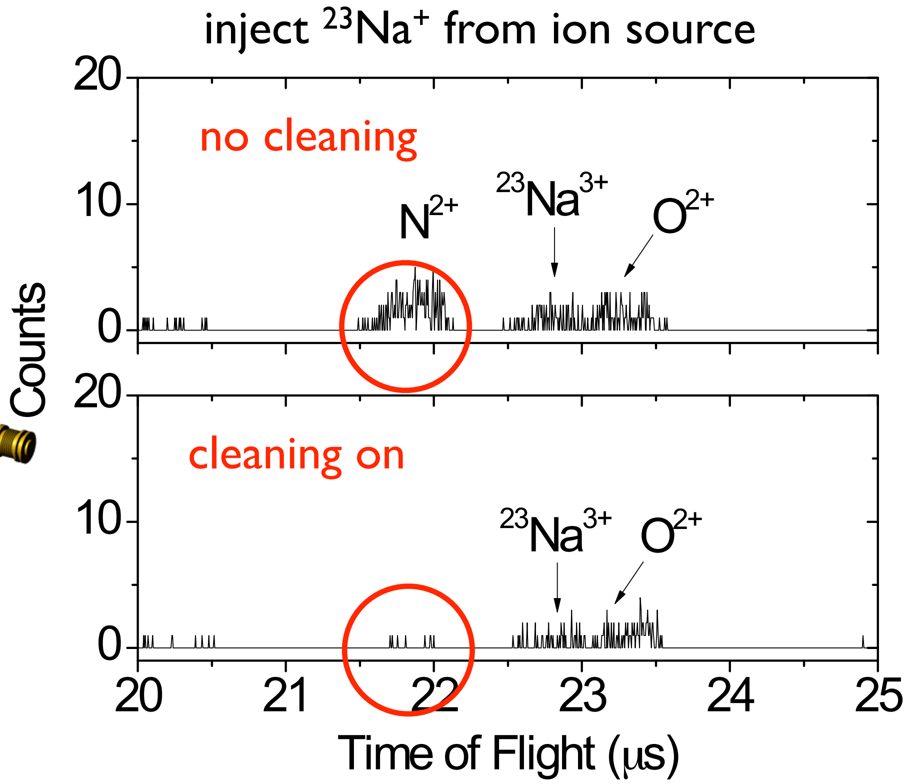
GFMC (AV18+IL2) ^{6,8}He: Pieper, Nucl. Phys. A **751** (2005) 516c

NCSM (CDB2k, INOY) ^{6,8}He: Caurier and Navrátil, PRC **73** (2006) 021302(R)

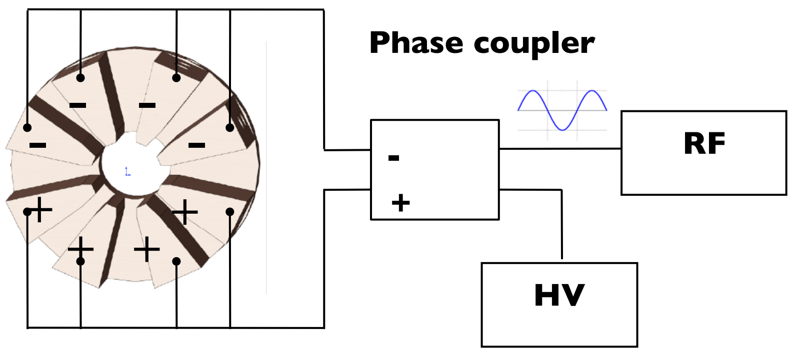
NCSM (CDB2k, INOY) ^{11}Li, ^{11}Be: Forssén *et al.*, PRC **79** (2009) 021303(R)

HCI's with the TITAN EBIT



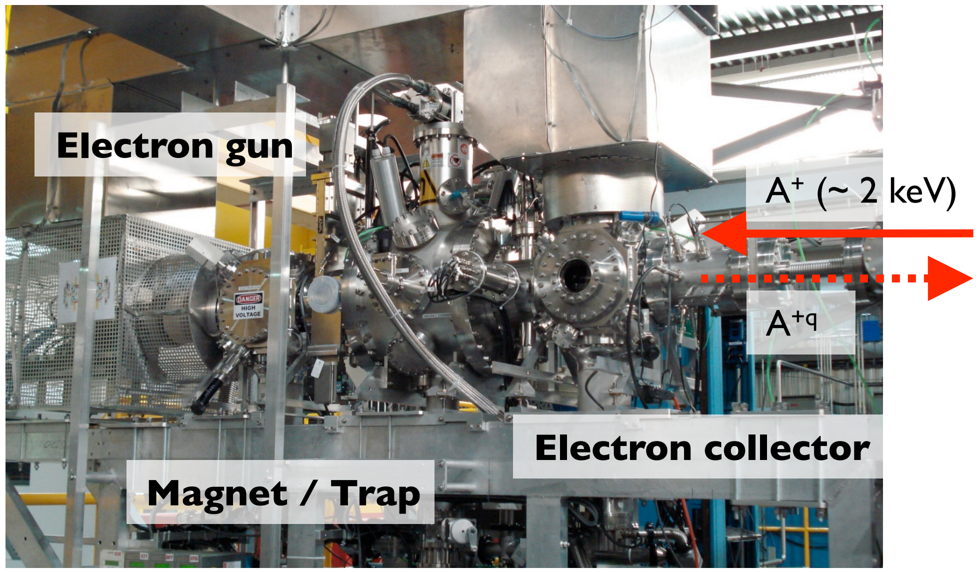


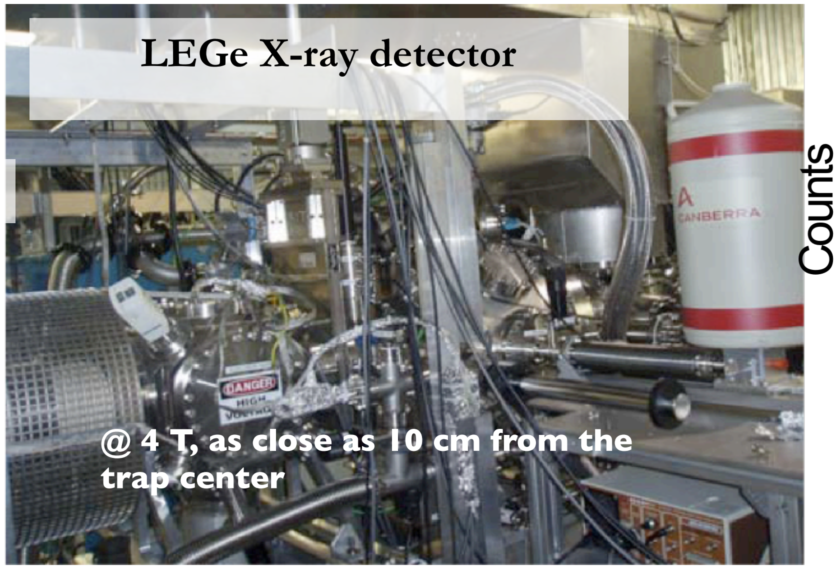
standard dipole excitation used to clean contaminants

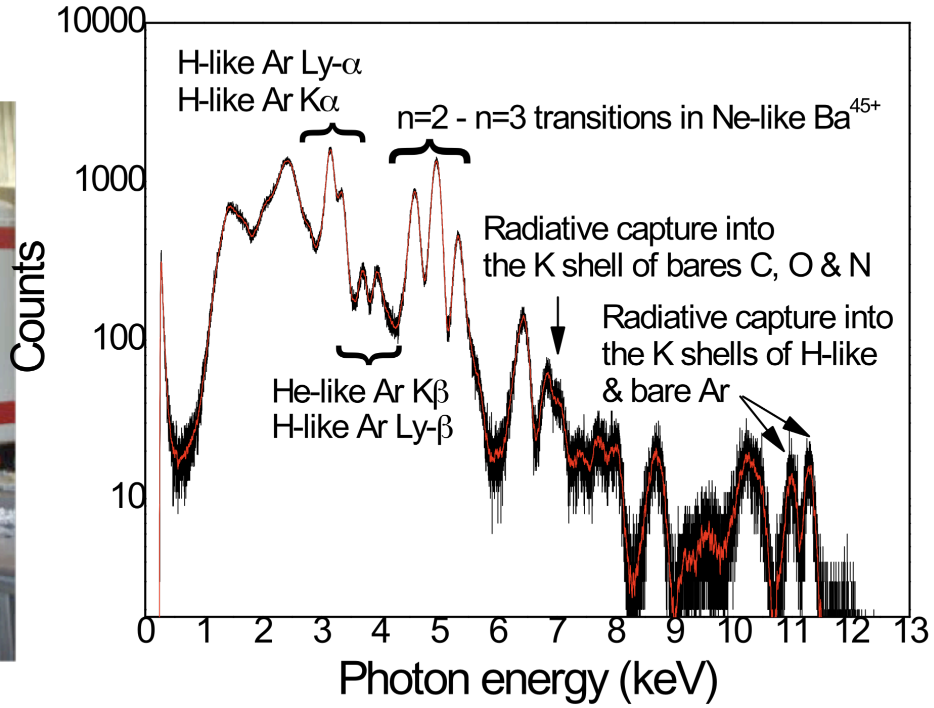


X-ray spectroscopy:

- segmented trap electrode for direct access to trap center
- diagnostics tool for charge breeding
- EC-BR measurement







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Charge breeding times

For mass measurements on **short-lived isotopes** with HCI's, a rapid production of HCI's is necessary:

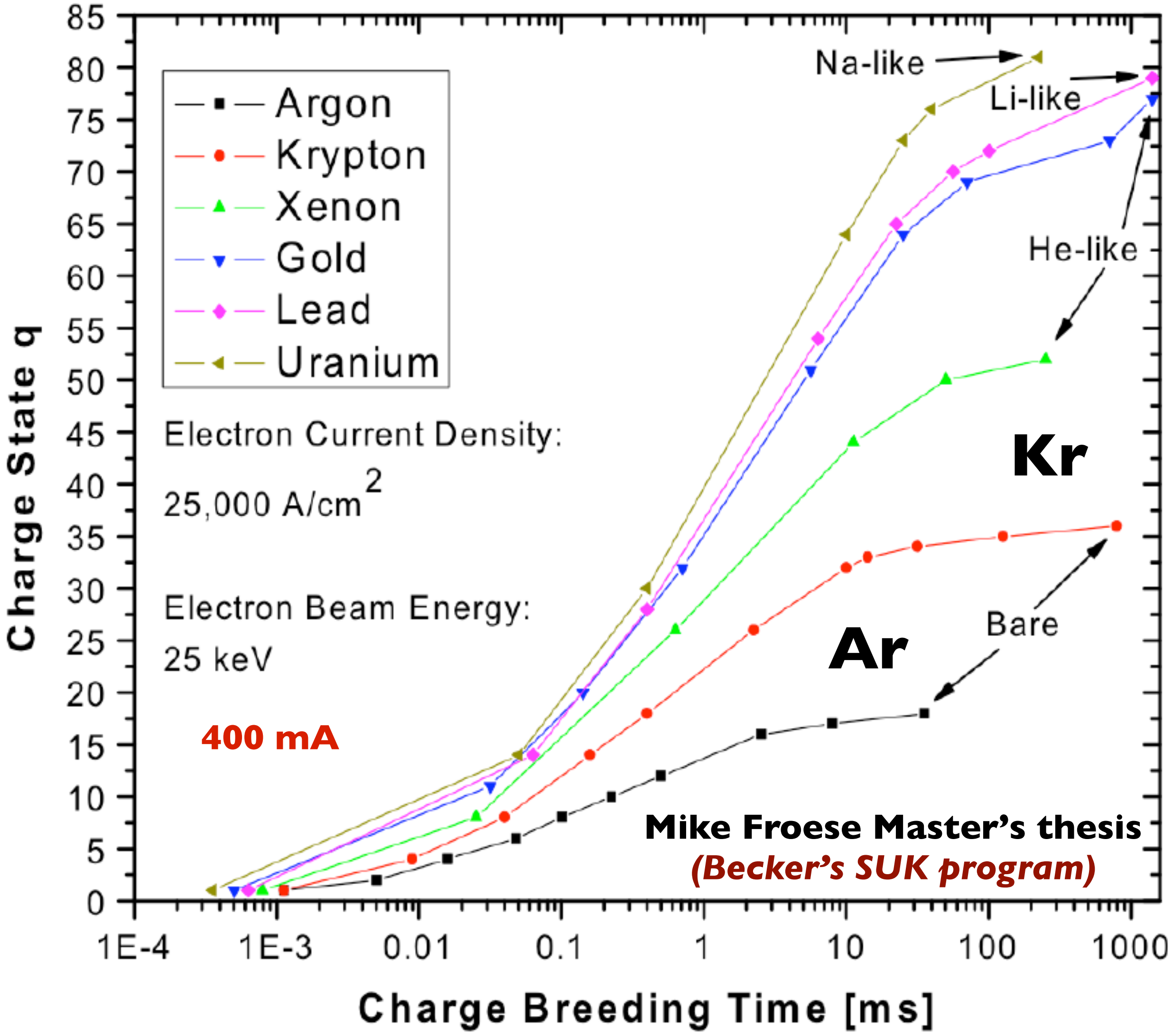
Charge breeding time < half-life

Breeding time: Time to reach given charge states by electron-impact ionization, including electron-recombination and ion heating losses.

Calculated by resolving the coupled rates equations describing the time-evolution of various charge states in the trap.

With the TITAN EBIT working parameters…

E-beam energy: 25 keV
E-beam current: 400 mA (4 A)
Magnetic field: 6 T
Current density: ~25000 A/cm^2

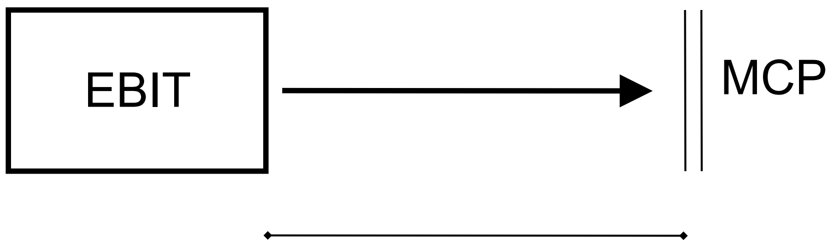


Mike Froese Master's thesis
(Becker's SUK program)

He-like Ar^{16+} (A=40)	~2 ms (0.2)
Bare Ar^{18+} (A=40)	~30 ms (3)
He-like Kr^{34+} (A~84)	~30 ms (3)
Bare Kr^{36+} (A~84)	~1 s (0.1)
He-like Xe^{52+} (A~130)	~300 ms (30)
He-like Au^{77+} (A=197)	~ 1 s (0.1)
Ne-like U^{82+} (A=238)	~ 1 s (0.1)

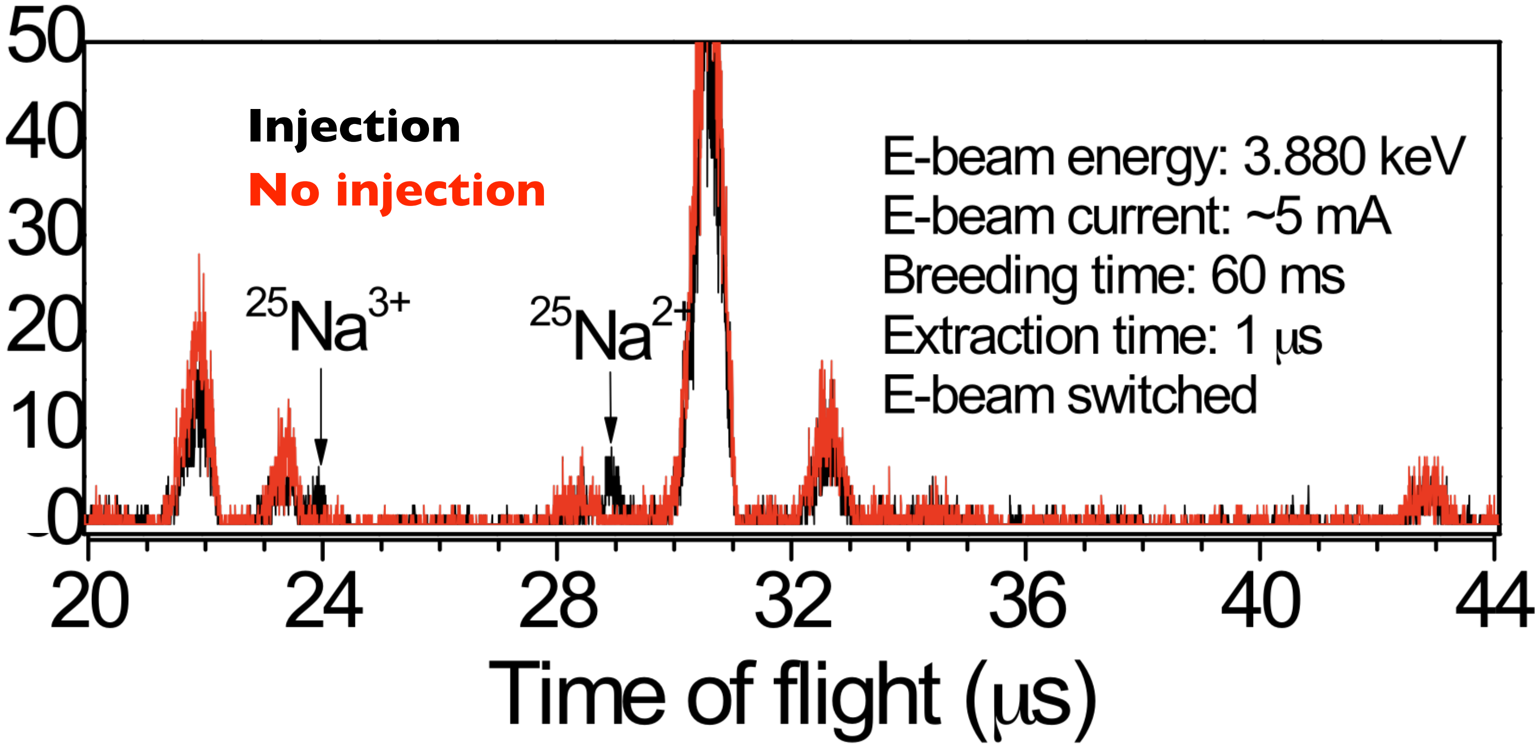
Bare ^{74}Rb CB time: ~300 ms
He-like ^{74}Rb CB time: ~30 ms } 400 mA
^{74}Rb half-life: 65 ms

HCI's with the TITAN EBIT



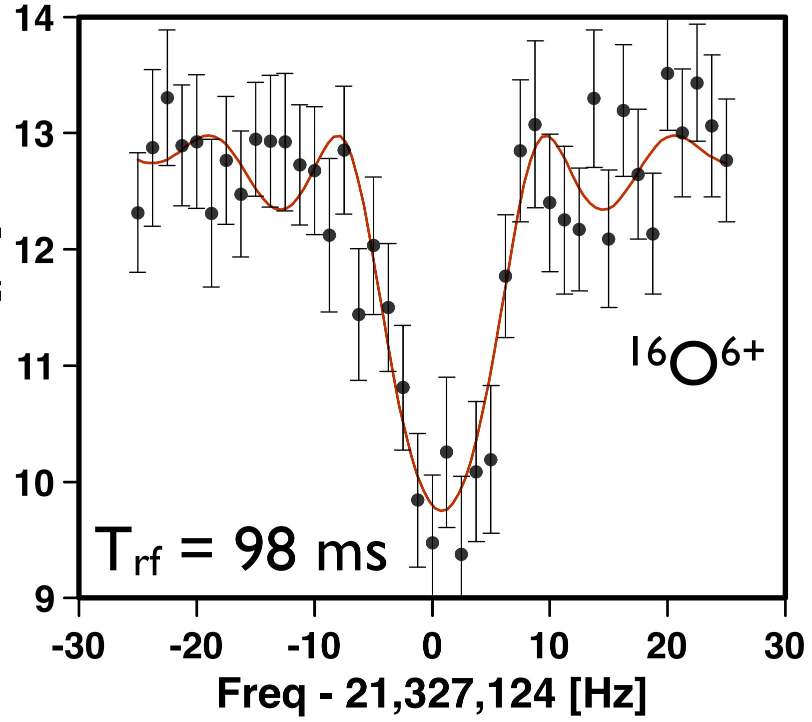
TOF: starts with extraction from EBIT

First radioactive HCI's from TITAN EBIT!

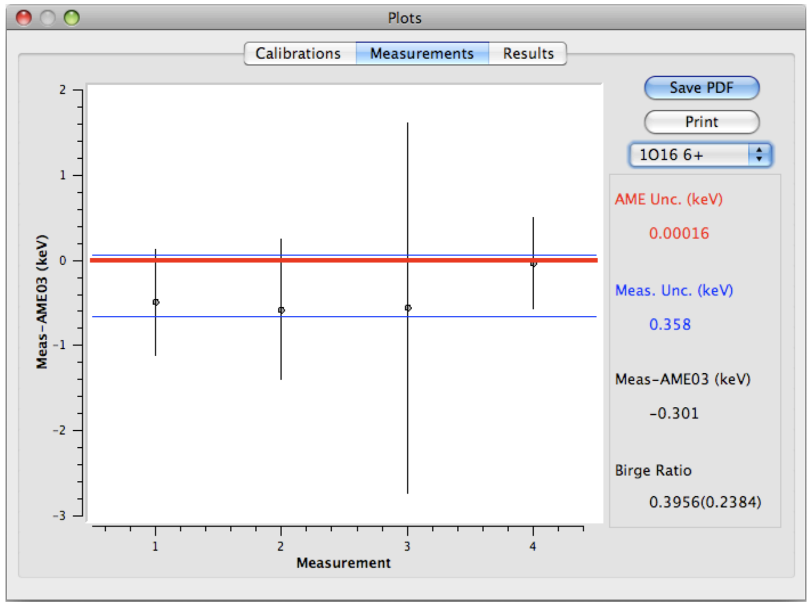


E-beam energy: 3.880 keV
E-beam current: ~5 mA
Breeding time: 60 ms
Extraction time: 1 μs
E-beam switched

Preliminary



$^{16}O^{6+}$ vs. $^{6}Li^{+}$
($^{6}Li^{+}$ from surface ion source)



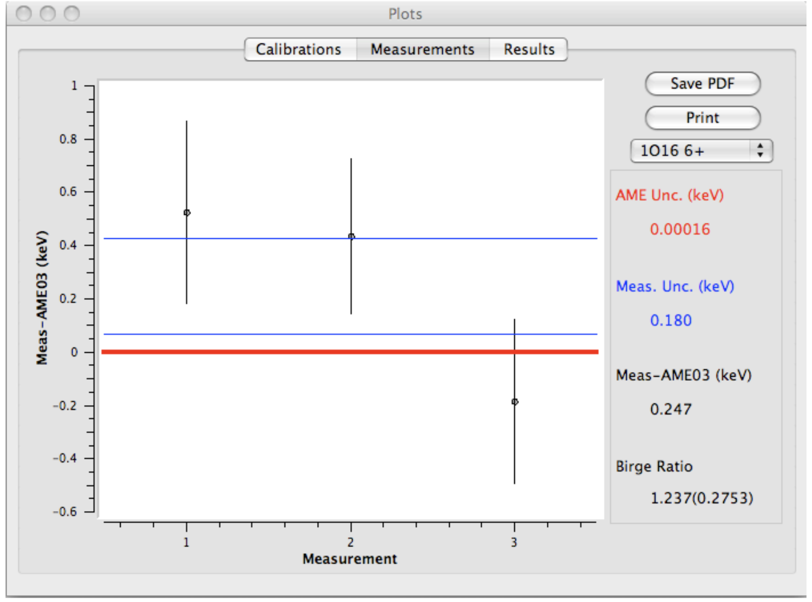
AME Unc. (keV)
0.00016

Meas. Unc. (keV)
0.358

Meas-AME03 (keV)
-0.301

Birge Ratio
0.3956(0.2384)

$^{16}O^{6+}$ vs. $^{1}H^{+}$



AME Unc. (keV)
0.00016

Meas. Unc. (keV)
0.180

Meas-AME03 (keV)
0.247

Birge Ratio
1.237(0.2753)

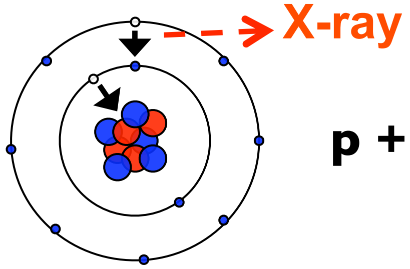
must account for electron
binding energies (~ 433 eV)

In-trap spectroscopy

The EBIT isn't restricted to aiding mass measurements…

Electron Capture Branching Ratio Measurements

Electron capture is the process by which a proton of the nucleus decays to a neutron by capture of a bound electron.



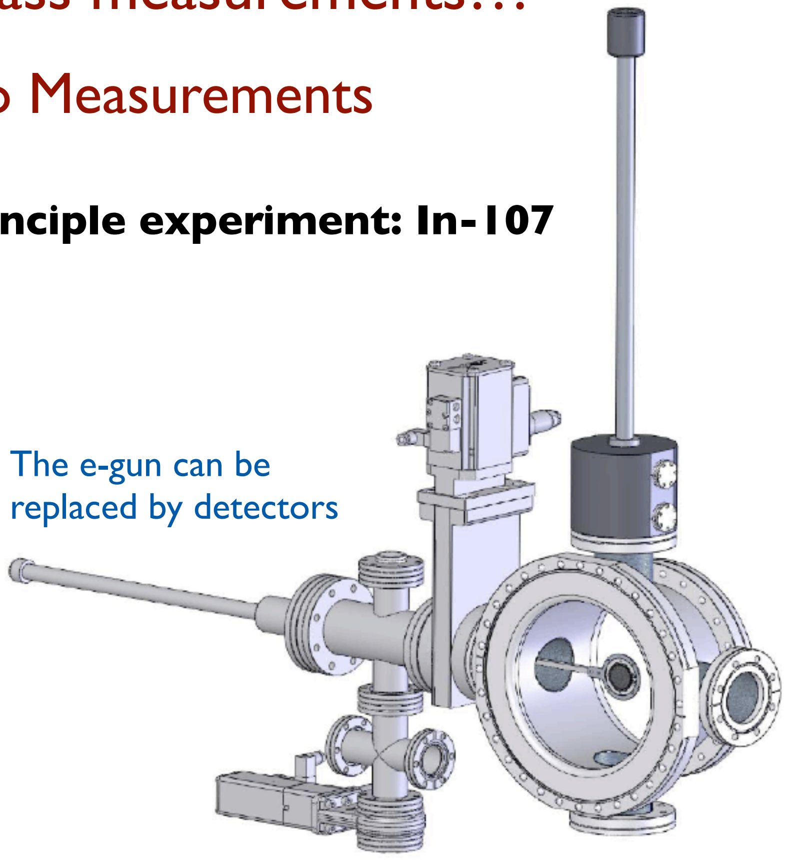
$$p + e^- \rightarrow n + \nu_e$$

Following EC, the daughter emits X-rays as a result of electron decays filling shell vacancies: **X-ray after Electron Capture.**

ECBR in singly charged ions are measured from **X-ray yields**.

- —ECBR used to evaluate double β- and 0νββ-decay nuclear matrix elements.
- —If 0νββ decay is observed, such matrix elements can be used to infer the **neutrino mass**.

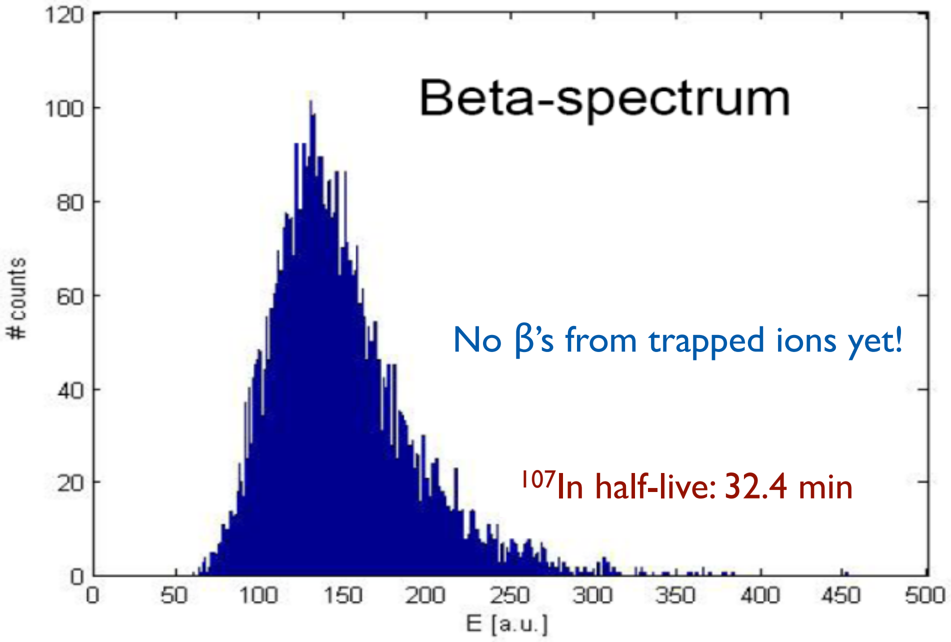
As proof-of-principle experiment: In-107



The e-gun can be replaced by detectors

Silicon detector for β-decay measurements

β decay electrons from ^{107}In ions implanted on a Al foil in front of the Si detector.



Beta-spectrum

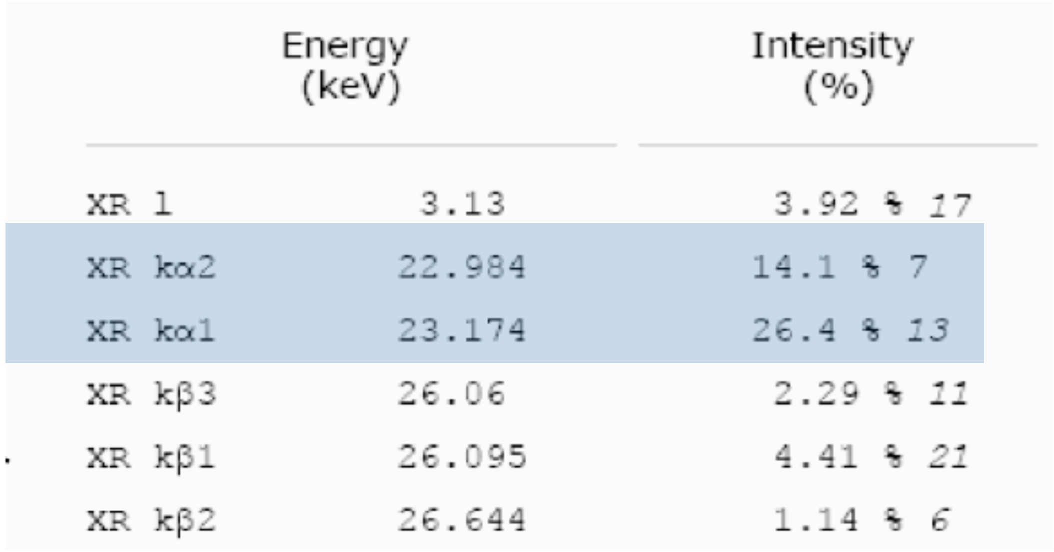
No β's from trapped ions yet!

^{107}In half-live: 32.4 min

In-trap spectroscopy

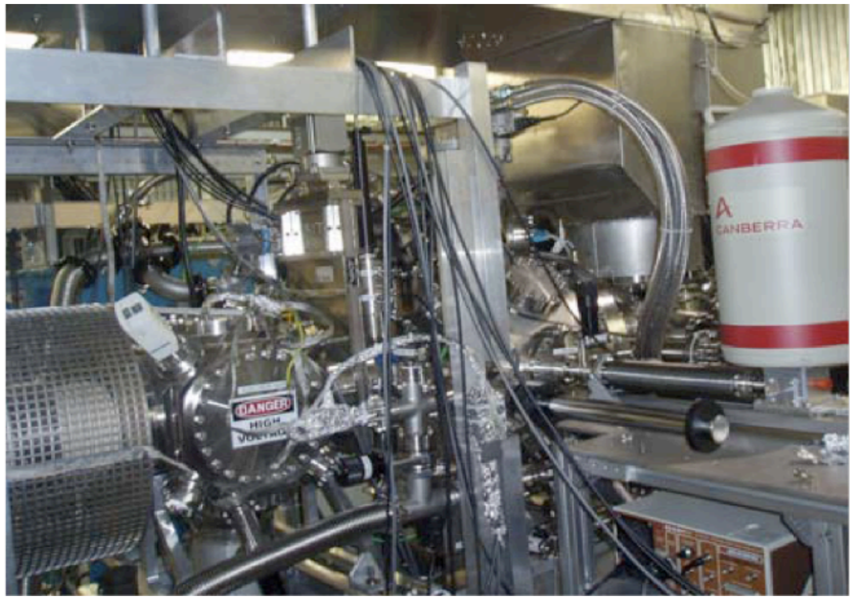
What we expect…Kα lines from ^{107}Cd

→ Ground state decay X-rays from EC (64%):



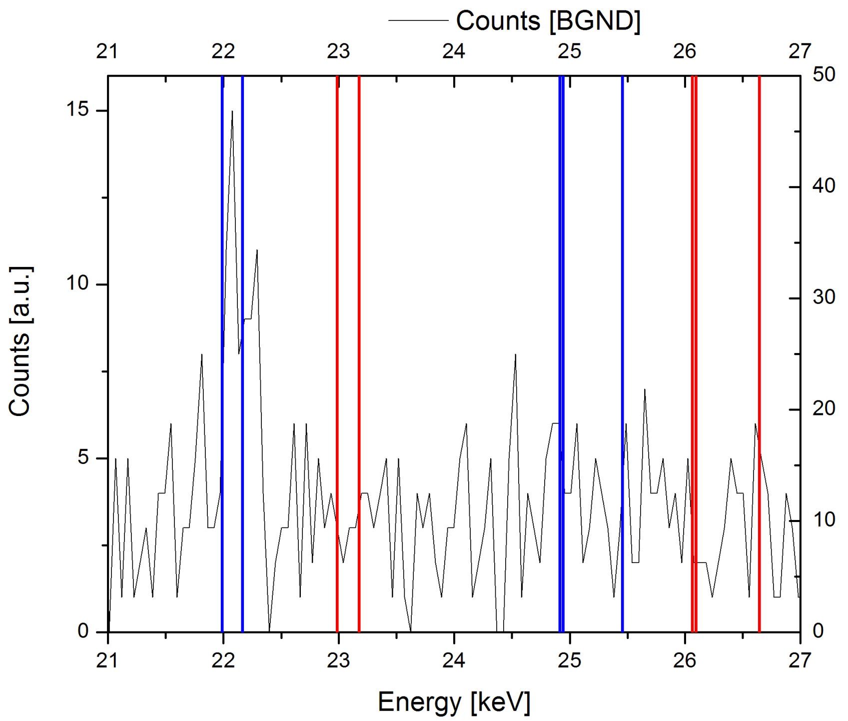
	Energy (keV)	Intensity (%)
XR l	3.13	3.92 % *17*
XR kα2	22.984	14.1 % 7
XR kα1	23.174	26.4 % *13*
XR kβ3	26.06	2.29 % *11*
XR kβ1	26.095	4.41 % *21*
XR kβ2	26.644	1.14 % *6*

LEGe X-ray detector

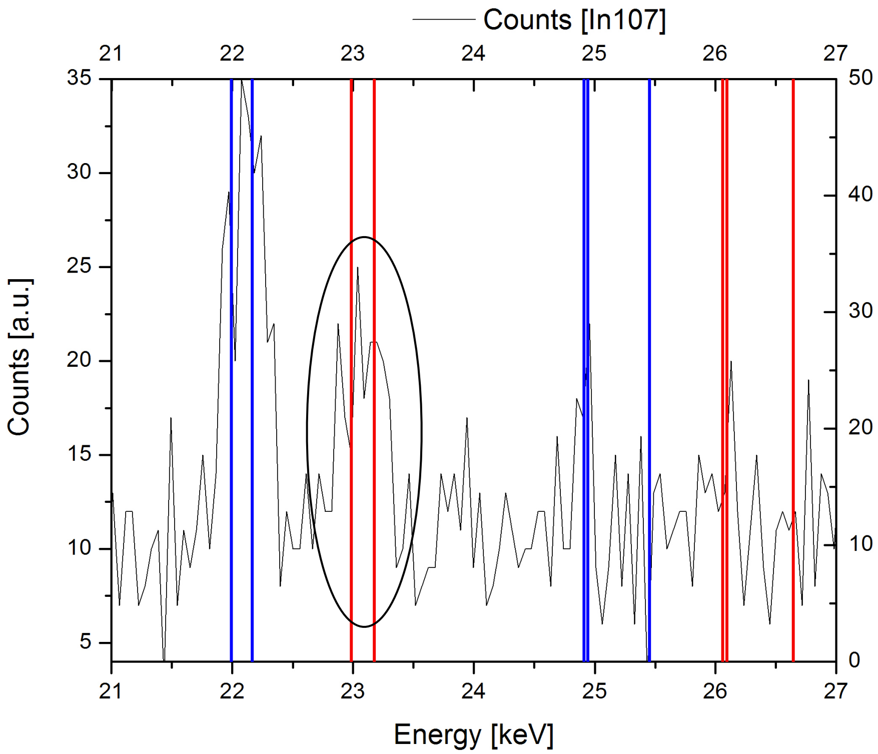


EBIT can be used to observe EC events!

No ^{107}In Injection



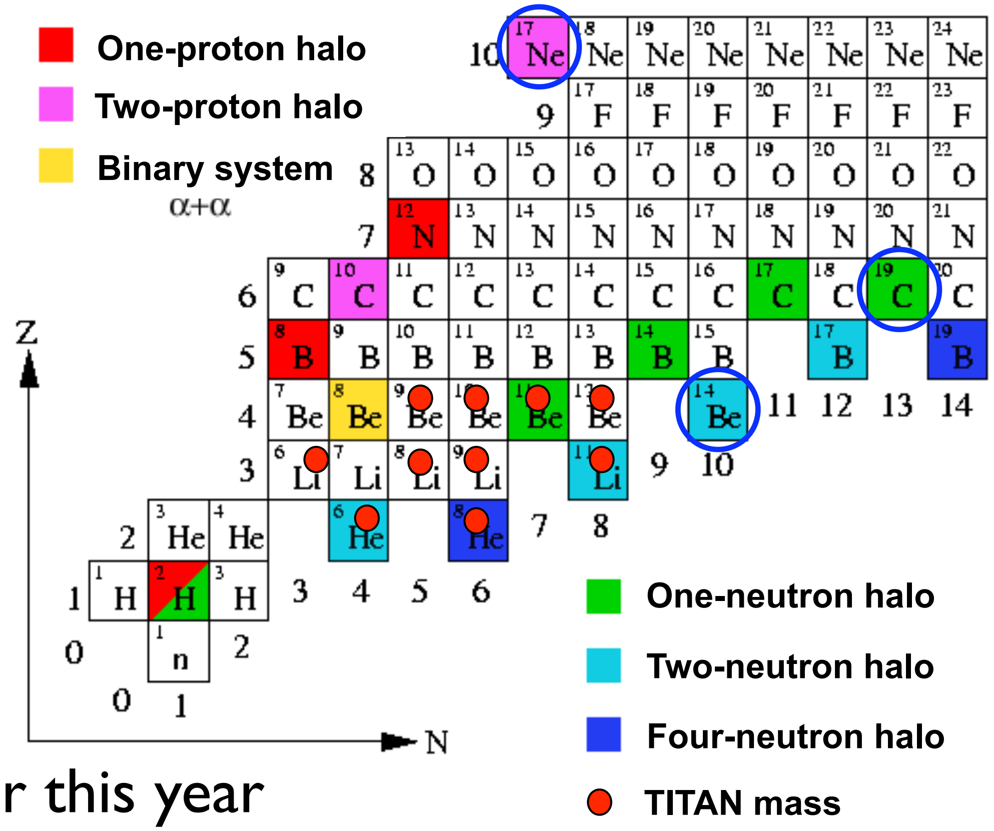
Injection of ^{107}In



Summary and Outlook

Halo nuclei

- High precision penning trap mass measurements of ^{6,8}He, ^{11}Li and ^{11}Be have been performed with $\delta m < 1$ keV
- Mass values obtained with TITAN do not contribute a significant source of uncertainty to relative charge radius determinations
- Future halo mass measurement proposals include ^{19}C (1n), ^{14}Be (2n) and ^{17}Ne (2p).



EBIT

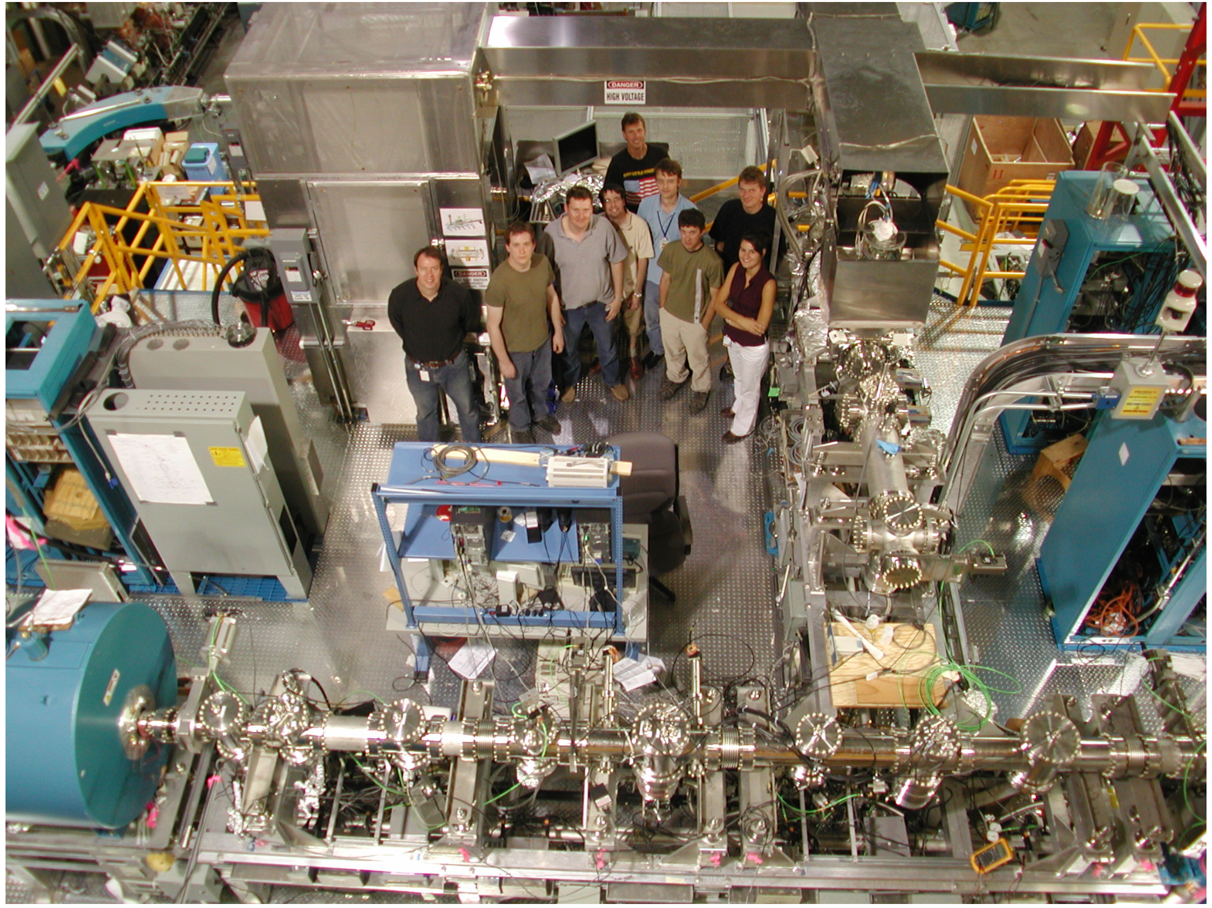
- Electron capture events have been detected
- Stable HCI's have been measured in the MPET
- Radioactive HCI's have been produced
- Purification and identification techniques are being developed
- High-precision mass measurements of radioactive species later this year

($^{49-53}$K, $^{51-53}$Ca and ^{52,53}Sc to constrain models which predict evolution of magic numbers at N=32-34)

RFQ

- M. Pearson will discuss using ion bunches from the TITAN RFQ for laser spectroscopy

Collaborators



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