Nuclear Structure Studies
and
Tests of Fundamental Symmetries
at TITAN / TRIUMF

stephan ettenauer
for the TITAN collaboration

RIKEN, May 10th, 2010

Outline

TITAN's program on

- Nuclear Structure
  - Halo Nuclei
- Fundamental Symmetries
  - Q-values for V_{ud} (CKM) with HCI

"Bonus"

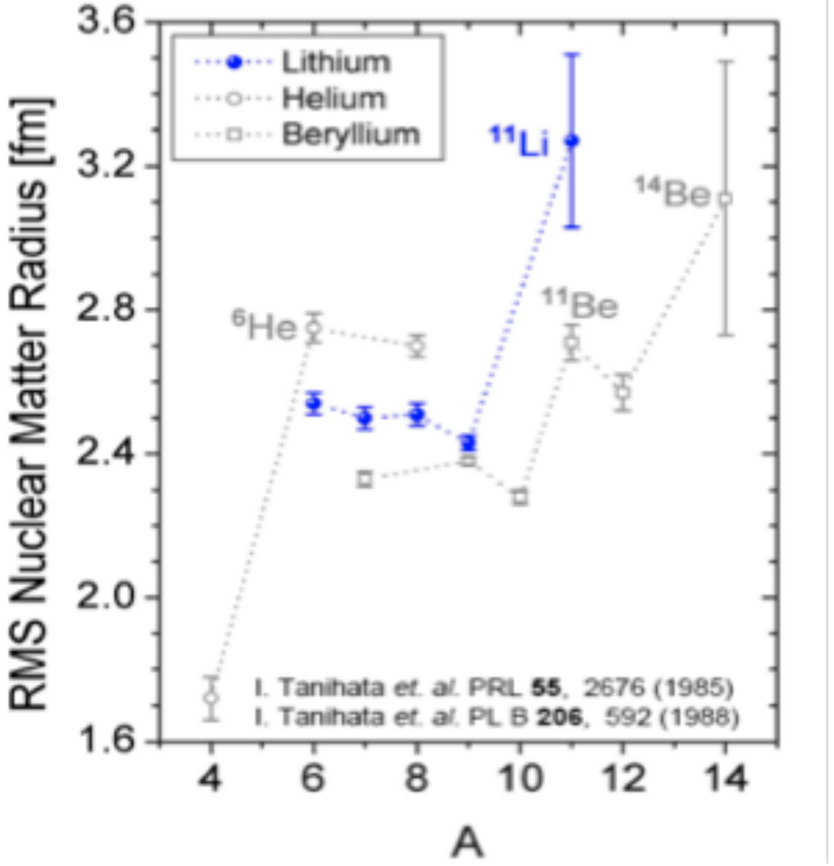
- In-trap Decay Spectroscopy for 2νββ Matrix Elements
- Laser Spectroscopy on Bunched Beams

Halo Nuclei

extreme n/p ratios

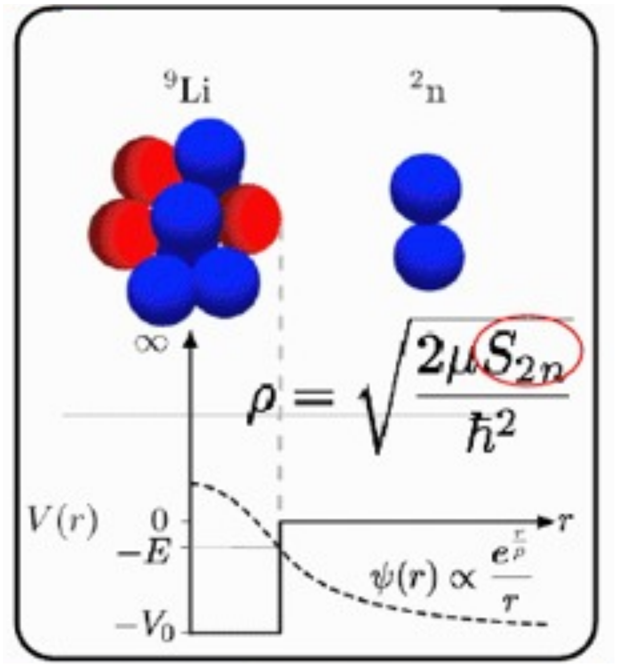
Halo	n/p
^{6}He	2
^{8}He	3
^{11}Li	2.66
^{14}Be	2.5
^{19}C	2.17
^{12}C	1

large radii

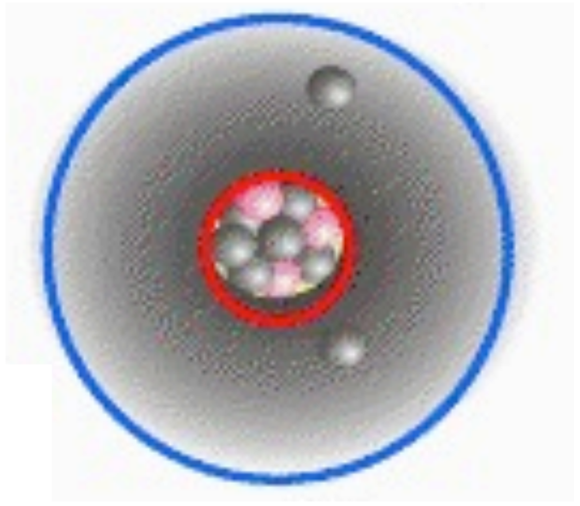


I. Tanihata *et. al.* PRL **55**, 2676 (1985)
I. Tanihata *et. al.* PL B **206**, 592 (1988)

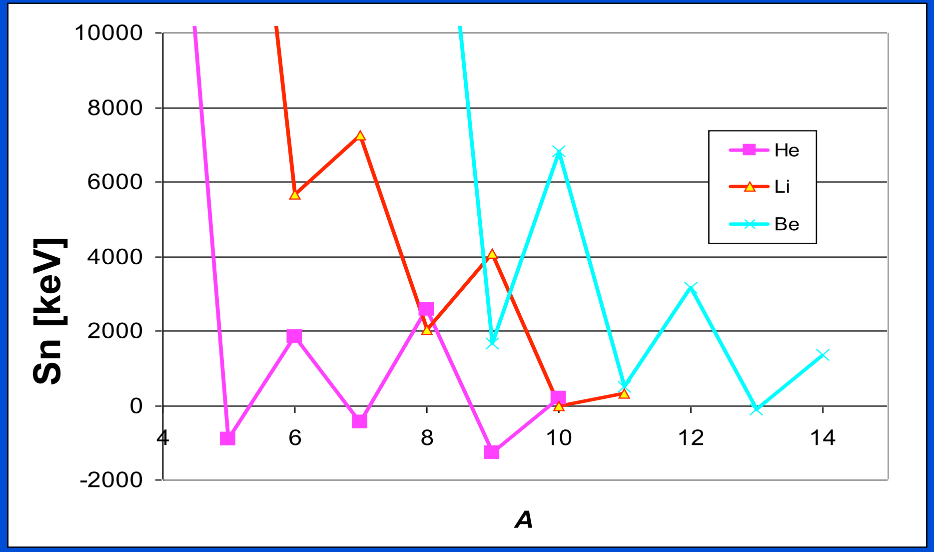
nucleons in classically forbidden region



but R_{matter} ≠ R_{charge}



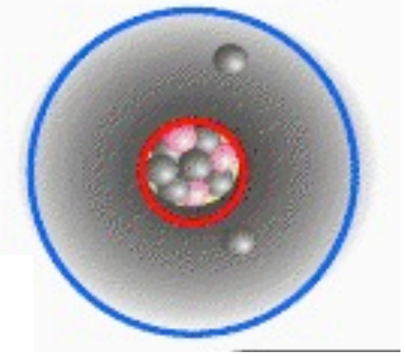
tiny separation energies



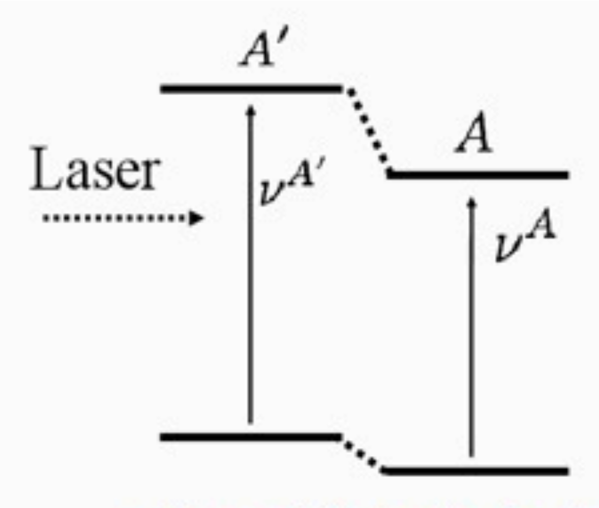
often very short-lived

Halo	$T_{1/2}$
^{8}He	119 ms
^{11}Li	8.8 ms
^{14}Be	4.4 ms

Charge Radius



$r_c \neq r_m$



Isotope Shift

$$\delta\nu_{A,A'} = \boxed{\delta^{\mathtt{MS}}_{A,A'}} + \boxed{K_{\mathtt{FS}}}\,\delta < r_c^2 >_{A,A'}$$

Mass shift

Field Shift / Finite Size Shift

atomic laser spectroscopy

relative measurement

⇒need reference:

electron scattering

(only possible with stables)

Techniques:

- (anti)collinear LS
- two photon resonant LS } in-beam
- LS of individual atoms in MOT
- LS of trapped ions

high precision atomic physics calculation

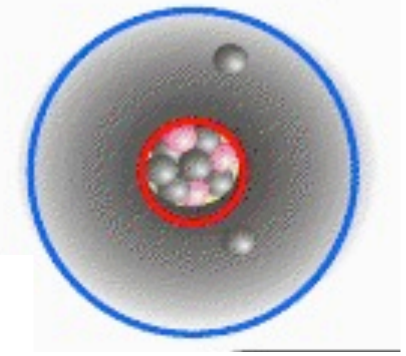
Z.-C. Yan et al., PRL 100, 243002 (2008)

$$E = \boxed{\mathcal{E}^{(0)}_{\rm NR} + \lambda\mathcal{E}^{(1)}_{\rm NR} + \lambda^2\mathcal{E}^{(2)}_{\rm NR} + \alpha^2(\mathcal{E}^{(0)}_{\rm rel} + \lambda\mathcal{E}^{(1)}_{\rm rel}) + \alpha^3(\mathcal{E}^{(0)}_{\rm QED} + \lambda\mathcal{E}^{(1)}_{\rm QED}) + \alpha^4(\mathcal{E}^{(0)}_{\rm ho} + \lambda\mathcal{E}^{(1)}_{\rm ho})}$$
$$\boxed{+\ \bar{r}_c^2(\mathcal{E}^{(0)}_{\rm nuc} + \lambda\mathcal{E}^{(1)}_{\rm nuc})} + \cdots$$

$$\text{with } \lambda = \frac{\mu}{M} = \frac{m_e}{m_e + M}$$

for He, Li, Be: MS ~10 GHz ⇔ FS ~1 MHz

Charge Radius



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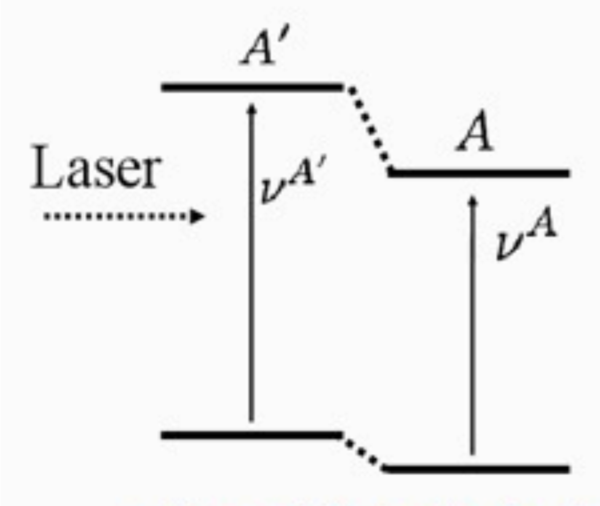

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$$\boxed{+\ \bar{r}_c^2(\mathcal{E}^{(0)}_{\rm nuc} + \lambda\mathcal{E}^{(1)}_{\rm nuc})} + \cdots$$

with $\lambda = \dfrac{\mu}{M} = \dfrac{m_e}{m_e + \boxed{M}}$

nuclear mass:

- need δm < 1keV
- short lived (<10 ms)

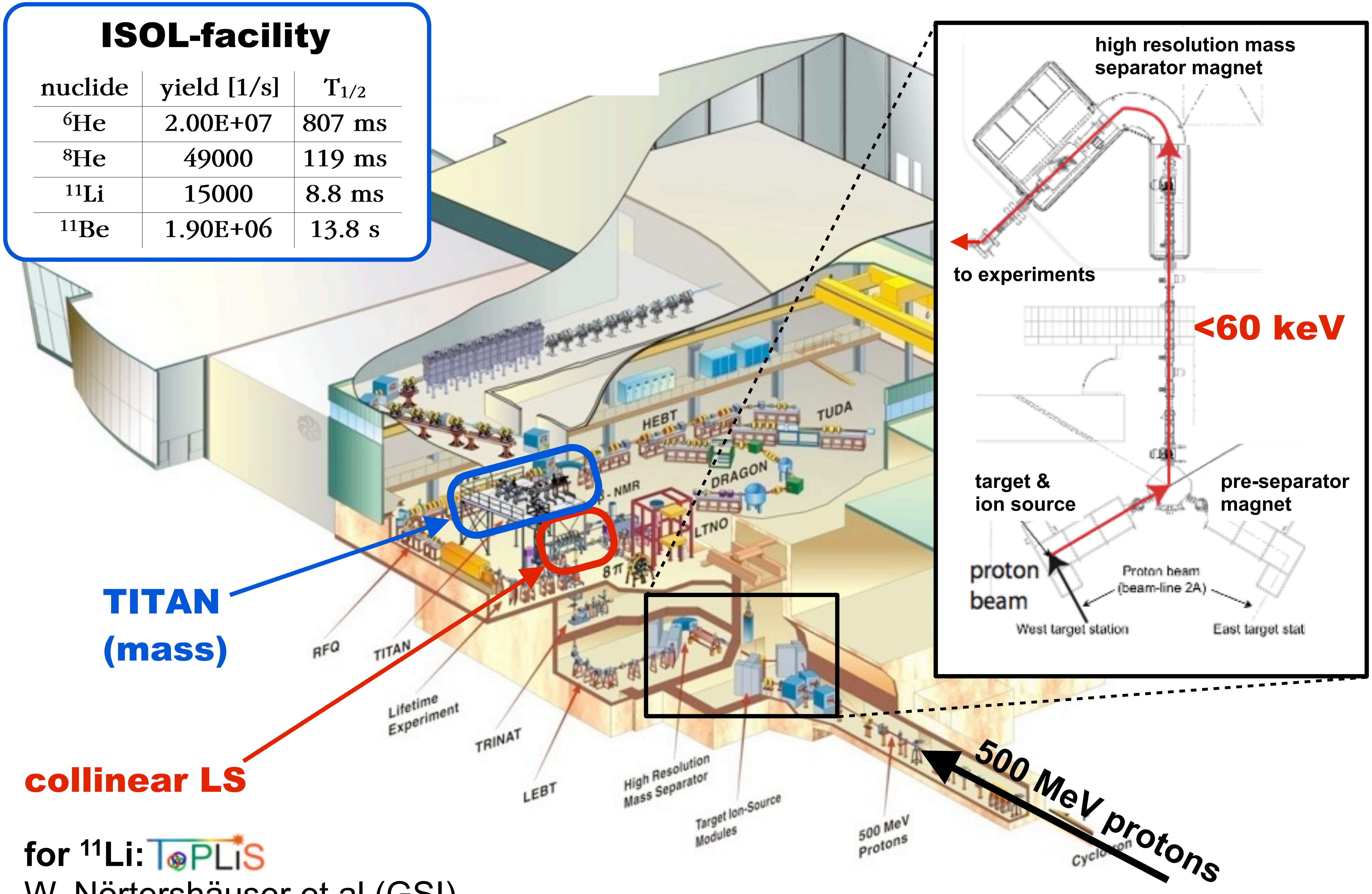
⇒ Penning Traps

for He, Li, Be: MS ~10 GHz ⇔ FS ~1 MHz

ISAC @ TRIUMF

ISOL-facility

nuclide	yield [1/s]	$T_{1/2}$
^{6}He	2.00E+07	807 ms
^{8}He	49000	119 ms
^{11}Li	15000	8.8 ms
^{11}Be	1.90E+06	13.8 s



TITAN (mass)

collinear LS

for ^{11}Li: TOPLiS
W. Nörtershäuser et al.(GSI)

Isotope Shift ^{11}Li

isotope shifts ^{7}Li-^{A}Li:

- 2s→3s
- reference $r_c(^{7}\mathrm{Li})$ = 2.39(3) fm

At. Data Nucl. Data Tables 14, 479 (1974)

Isotope		Isotope Shift, kHz
^{6}Li	TRIUMF	−11 453 984(20)
	GSI	−11 453 950(130)
	avg	−11 453 983(20)
^{8}Li	TRIUMF	8 635 781(46)
	GSI	8 635 790(150)
	avg	8 635 782(44)
^{9}Li	TRIUMF	15 333 279(40)
	GSI	15 333 140(180)
	avg	15 333 272(39)
^{11}Li	TRIUMF	25 101 226(125)[a]

R. Sanchez et al., PRL 96, 033002 (2006)

$$\delta\nu_{A,A'} = \delta^{\mathtt{MS}}_{A,A'} + K_{\mathtt{FS}}\,\delta < r_c^2 >_{A,A'}$$

mass shifts

Isotopes	$2\,^2P_{1/2} - 2\,^2S$	$2\,^2P_{3/2} - 2\,^2S$	$3\,^2S - 2\,^2S$
^{7}Li − ^{6}Li	−10 532.111(6)	−10 532.506(6)	−11 452.821(2)
^{7}Li − ^{8}Li	7940.627(5)	7940.925(5)	8634.989(2)
^{7}Li − ^{9}Li	14 098.840(14)	14 099.369(14)	15 331.799(13)
^{7}Li − ^{11}Li[a]	23 082.642(24)	23 083.493(24)	25 101.470(22)
^{9}Be − ^{7}Be	−49 225.765(19)	−49 231.814(19)	−48 514.03(2)
^{9}Be − ^{10}Be	17 310.44(6)	17 312.57(6)	17 060.56(6)
^{9}Be − ^{11}Be	31 560.01(6)	31 563.89(6)	31 104.60(6)

Z.-C. Yan et al., PRL 100, 243002 (2008)

M. Puchalski et al., PRL 97,133001 (2006)

$r_c(^{11}\mathrm{Li})$ = 2.423(17)(30) fm

reference r_c

Isotope Shift ^{11}Li

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- 2s→3s
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^{9}Be − ^{7}Be			−48 514.03(2)
^{9}Be − ^{10}Be			17 060.56(6)
^{9}Be − ^{11}Be	31 560.01(6)	31 563.89(6)	31 104.60(6)

mass: MISTRAL (2005)

! need mass !

243002 (2008)

M. Pucha ki et al., PRL 97,133001 (2006)

mass: AME'03

$r_c(^{11}\text{Li})$ = 2.423(17)(30) fm

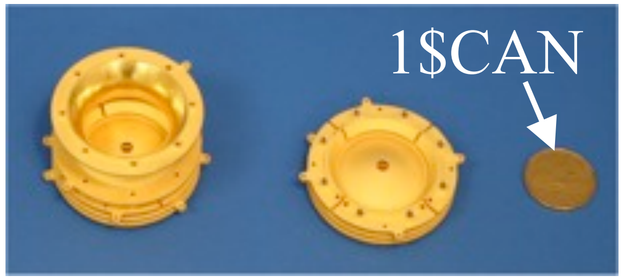
reference r_c

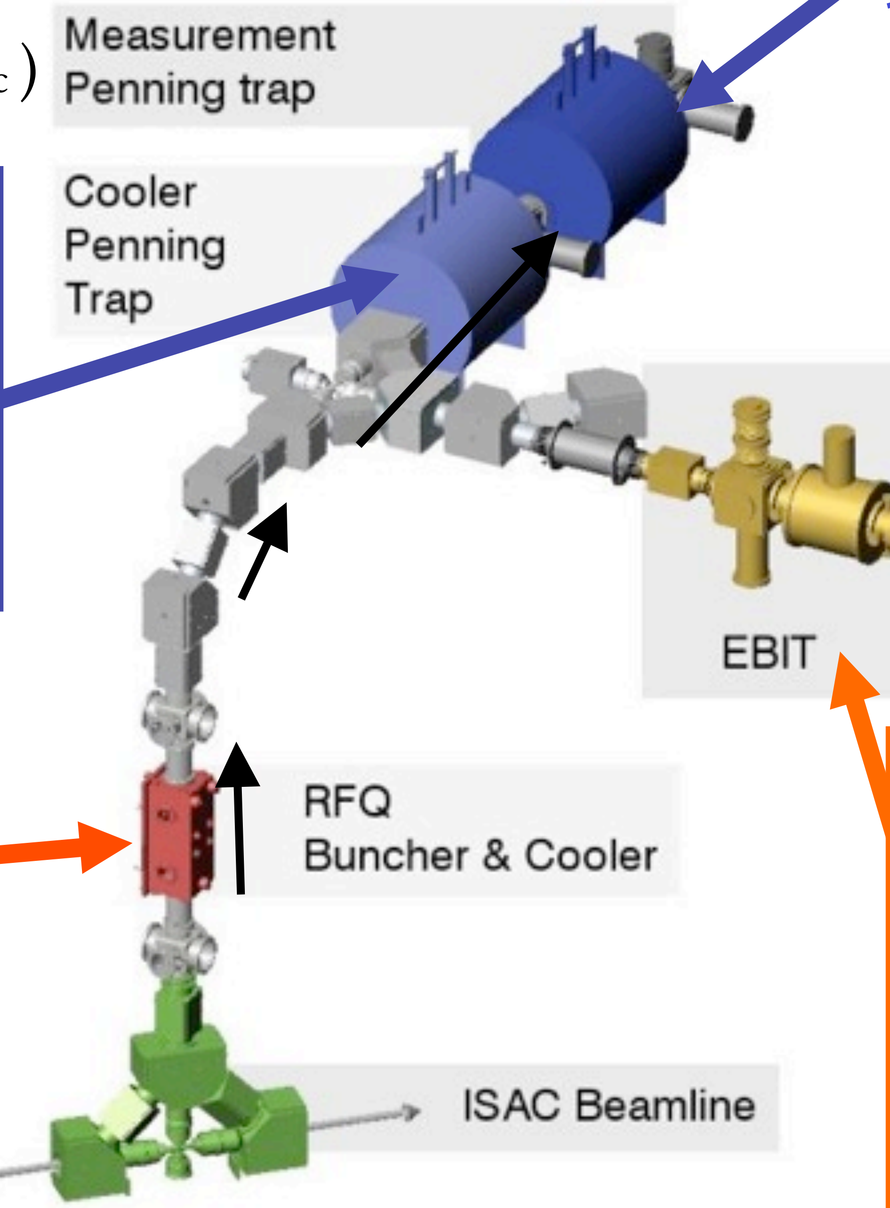
$r_c(^{11}\text{Li})$ = 2.465(19)(30) fm

TITAN

masses of halos:

- reflect binding energy
- separation energy: S_n, S_p
- input to extract physical quantities from exp. (e.g. r_c)





ISAC beam: A$^+$

Penning traps:

- highest precision
- previously shortest ^{74}Rb with $T_{1/2}$=65 ms ISOLTRAP @ CERN

A. Kellerbauer et al., PRL 93, 072502 (2004)

- but ^{11}Li $T_{1/2}$ = 8.8 ms

Measurement Principle

- confinement:
  - – strong axial, hom. B-field (3.7 T)
  - – electrostatic quadrupolar field
- 3 eigenmotions

$$\nu_+ >> \nu_z >> \nu_-$$

- cyclotron frequency

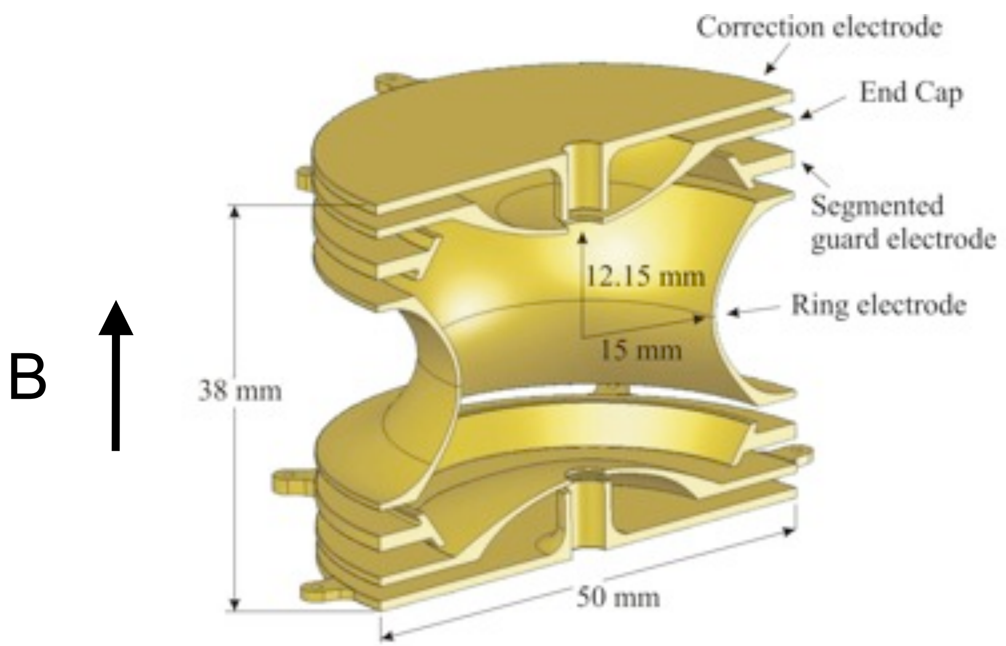
$$\nu_c = \nu_+ + \nu_- = \frac{1}{2\pi}\frac{q}{m}B$$

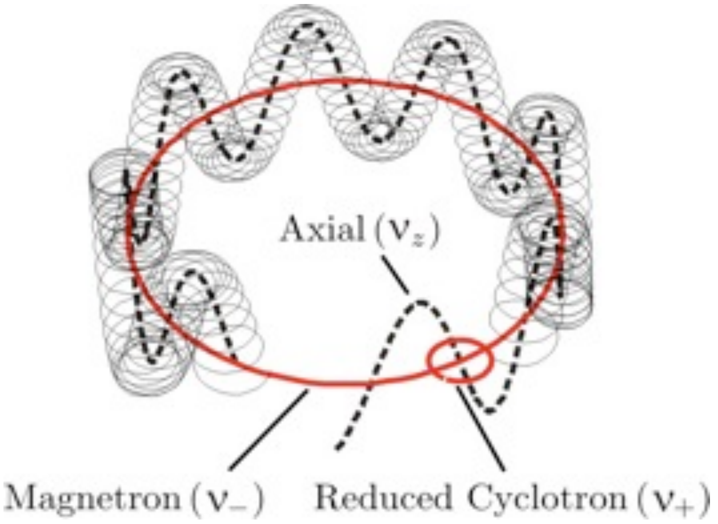
- quadrupolor rf- field (ring electrode) leads to conversion:

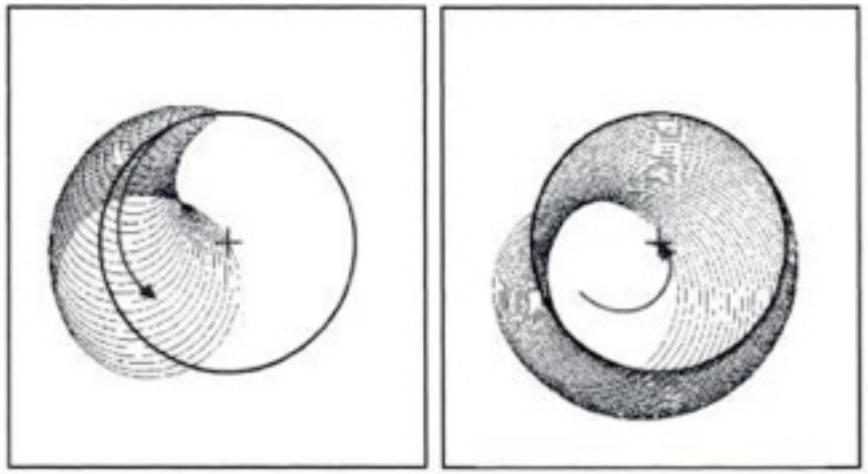
magnetron ↔ reduced cyclotron

- radial energy:

$$E_r(t) \propto \omega_+^2 \rho_+(t)^2 + \omega_-^2 \rho_-(t)^2 \approx \omega_+^2 \rho_+(t)^2$$

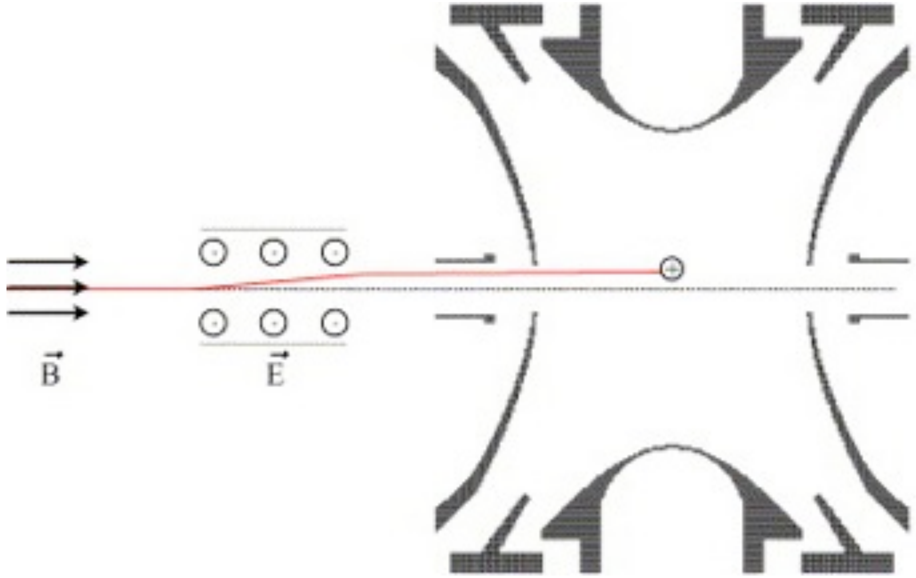


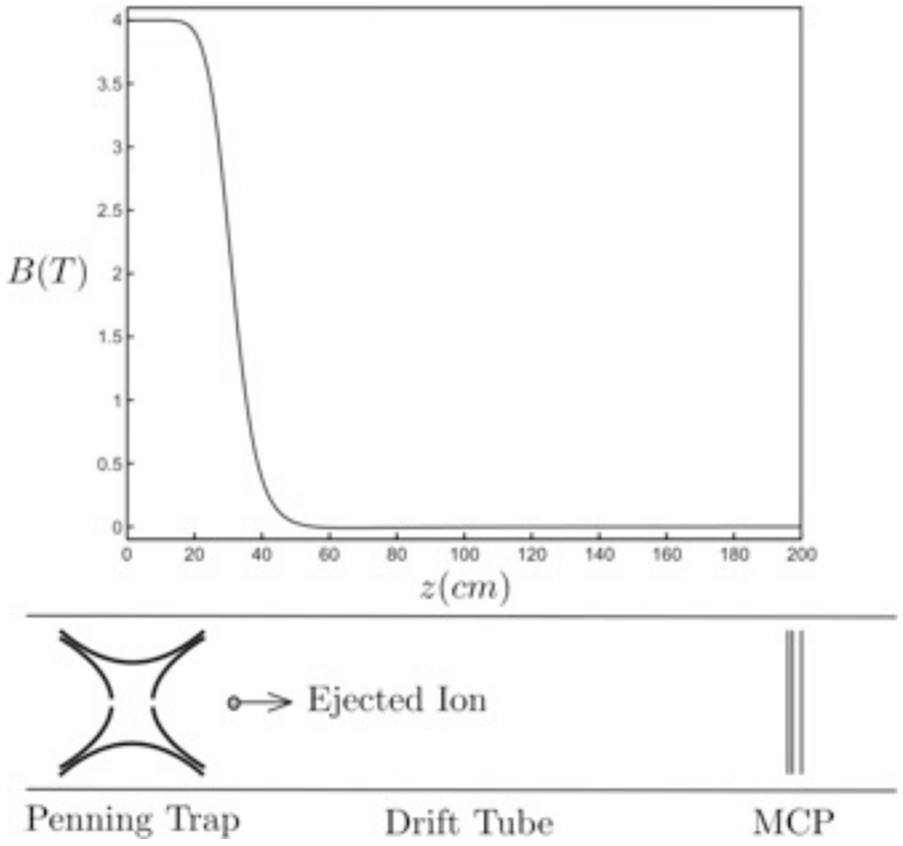


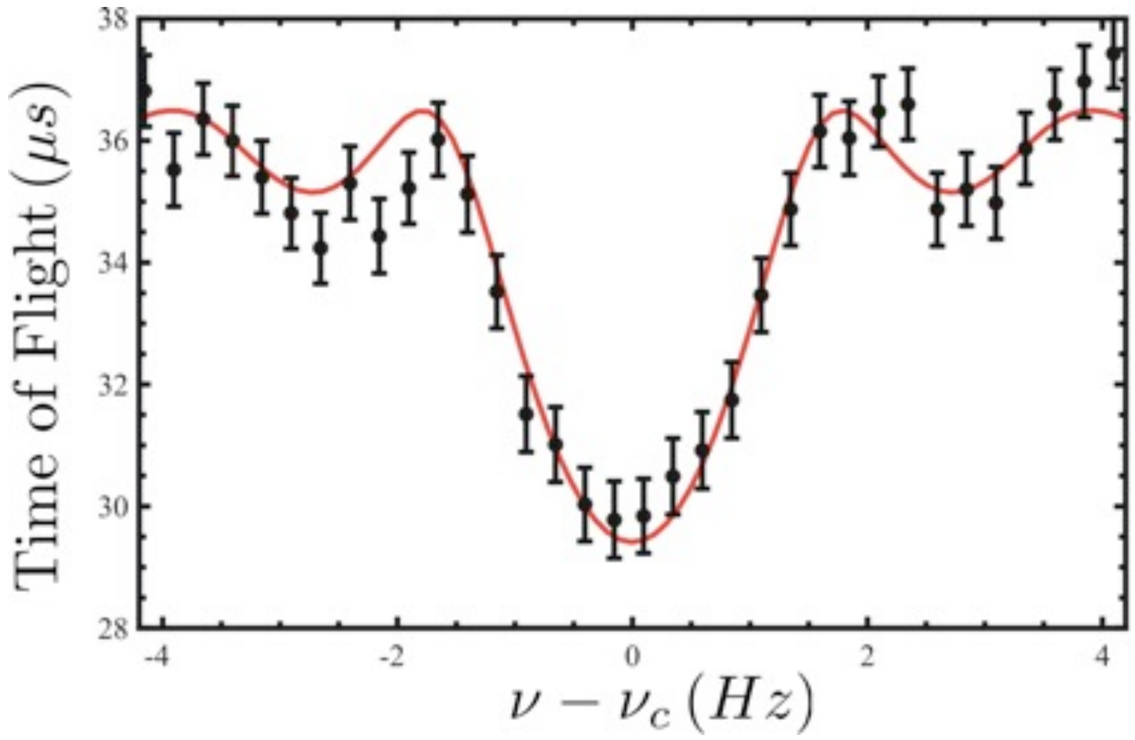


Mass measurements in the MPET

- initial magnetron preparation
  - dipolar RF excitation ~ 10 ms
  - Lorentz steerer
- quadrupolor rf- field
- extraction: through B-field E_r to E_l
- E_l measured by TOF
- minimum at ν_c
- comparison to well known isotope







Precise & Accurate

line width (FWHM):

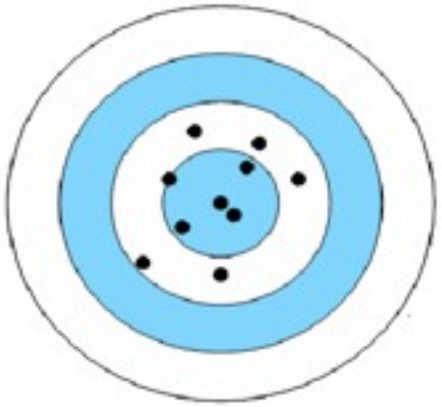
$$\Delta\nu \approx 1/T_{rf}$$

⇒ resolution:

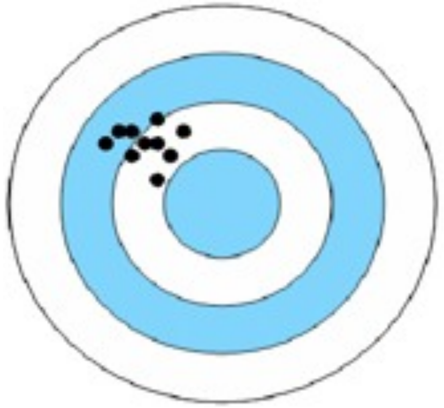
$$R = \frac{m}{\Delta m} = \frac{\nu_c}{\Delta\nu_c} \approx \nu_c T_{rf} \approx \frac{qBT_{rf}}{2\pi m}$$

⇒ even for $T_{rf} \sim 10$ms

$$(\delta m/m)_{\texttt{stat}} < 10^{-7}$$



accurate,
but not precise



precise,
but not accurate

- exact theoretical description

L.S. Brown and G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986)
G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)
M. König et al., Int. J. Mass Spect. 142, 95 (1995)
M. Kretzschmarr, Int. J. Mass Spect. 246, 122 (2007)

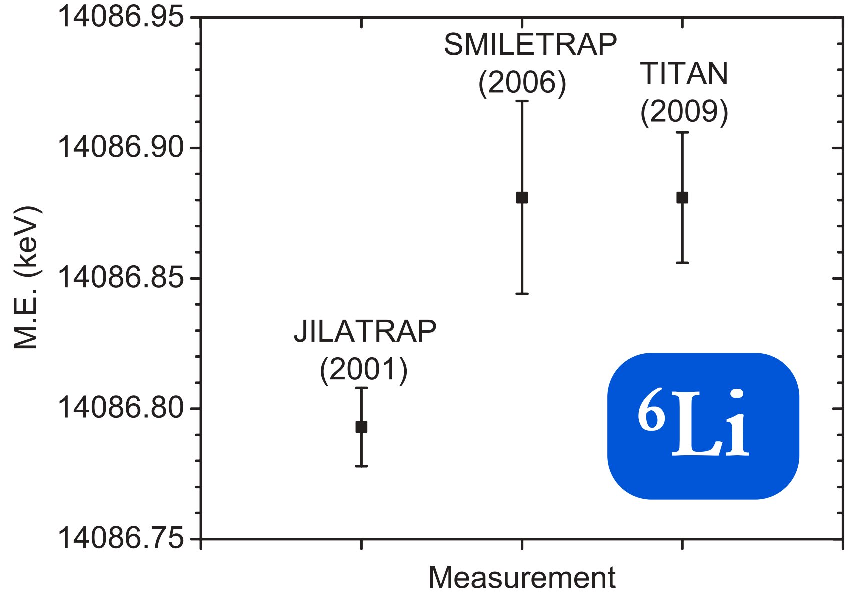
- even for non-ideal traps

G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)
G. Gabrielse, PRL 102, 172501 (2009)

- off-line tests with stables

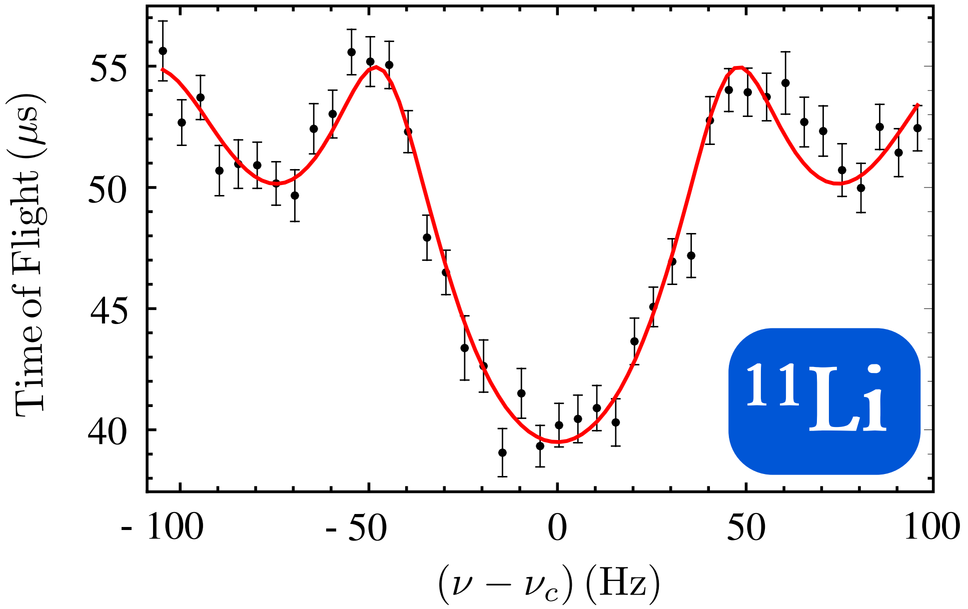
⇒ control over systematics

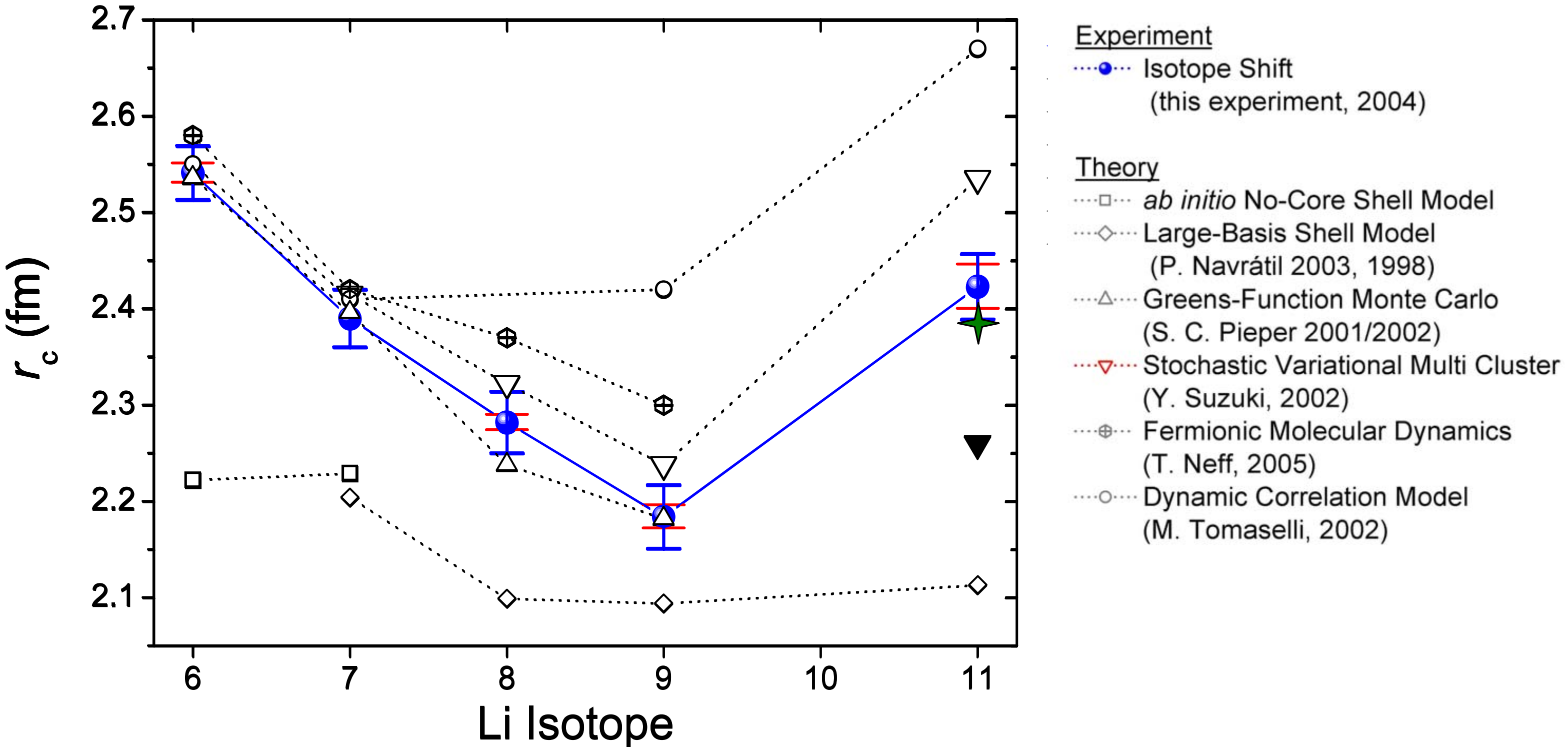
<u>for TITAN:</u> < 5 ppb possible



M. Brodeur et al, PRC 80, 044318 (2009)

Mass of ^{11}Li





Reference	Mass [u]
AME'03	11.043 798(21)
MISTRAL 2005	11.043 715 7(54)
TITAN 2007	11.043 723 61 (69)

$$r_c\,(^{11}\mathrm{Li}) = 2.427(16)(30)\ \mathrm{fm}$$

eliminates mass as source of uncertainty!

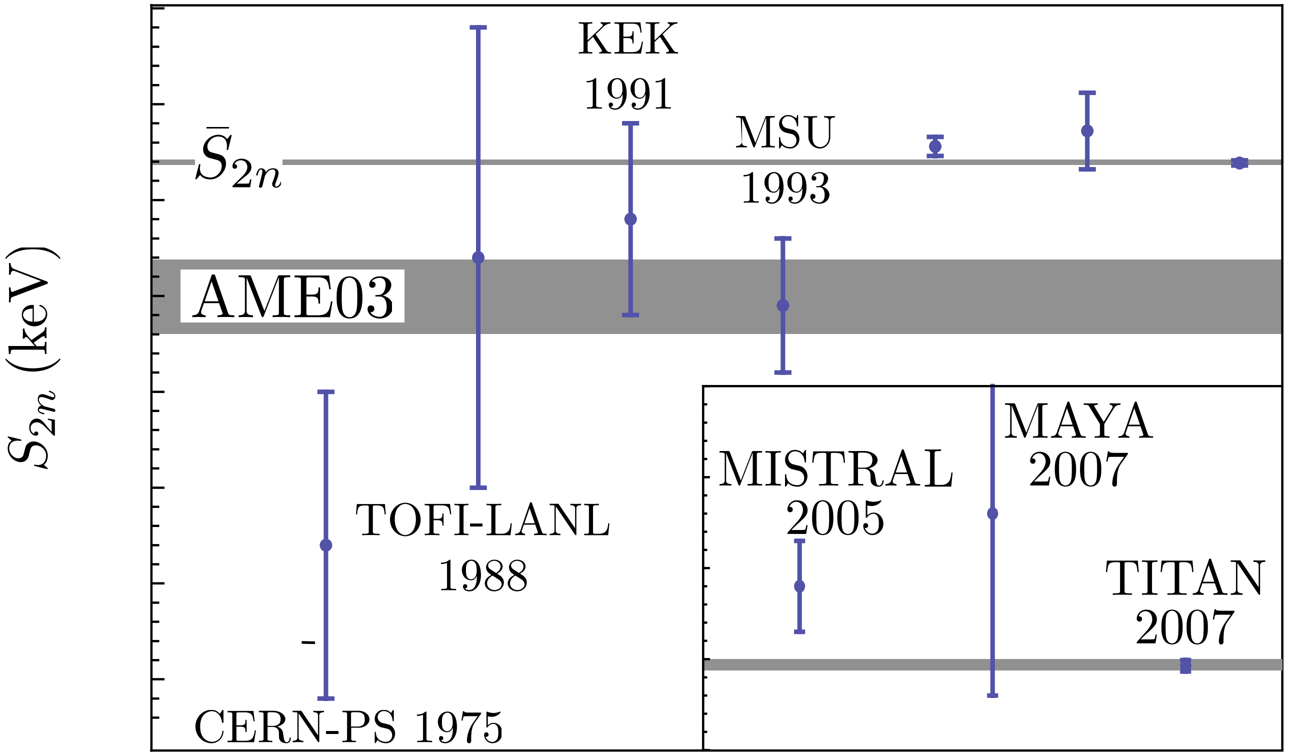
two neutron separation energy:

$$S_{2n} = -M(A,Z) + M(A-2,Z) + 2n$$

- asymptotic waveform for Borromean system
- soft electric-dipole excitation

T. Nakamura et al., PRL 96, 252502 (2006)

- models of ^{11}Li: adjust ^{9}Li-n interaction



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

Other Halos: Laser Spectroscopy

^{6}He and ^{8}He

- Argonne Lab / GANIL
- LS in MOT

all in MHz

	^{6}He		^{8}He	
	Value	Error	Value	Error
Statistical				
Photon counting		0.008		0.032
Probing laser alignment		0.002		0.012
Reference laser drift		0.002		0.024
Systematic				
Probing power shift				0.015
Zeeman shift		0.030		0.045
Nuclear mass		0.015		0.074
Corrections				
Recoil effect	0.110	0.000	0.165	0.000
Nuclear polarization	−0.014	0.003	−0.002	0.001
$\delta\nu^{FS}_{A,4}$ combined	−1.478	0.035	−0.918	0.097

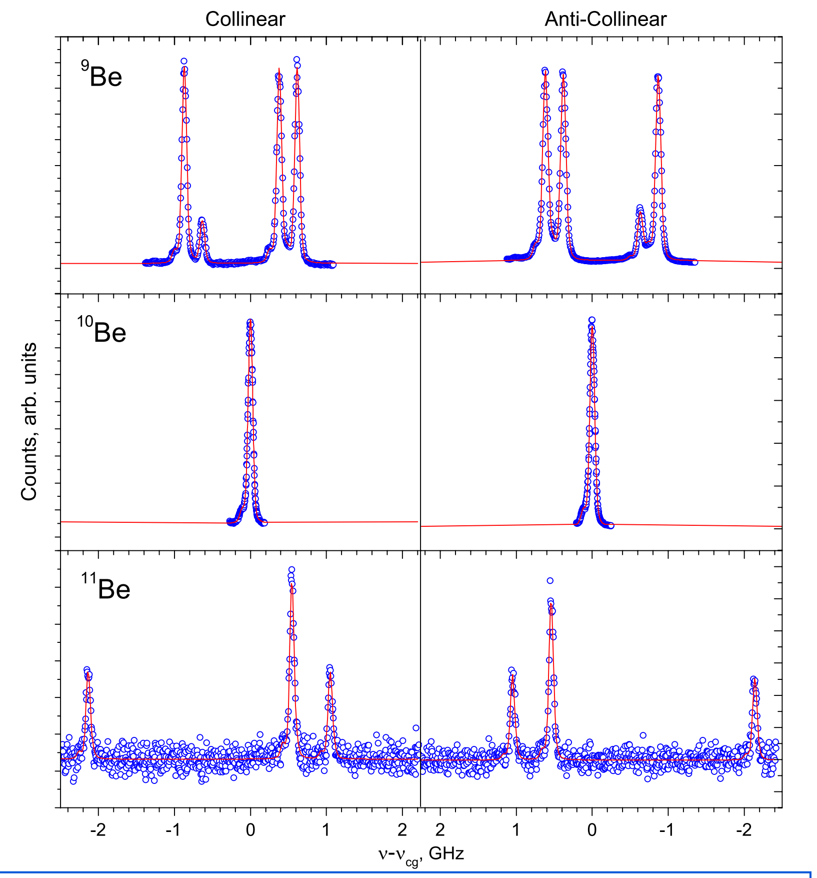
mass: dominating uncertainty

P. Mueller et al., PRL 99, 252501 (2007)

^{11}Be:

- *GSI*

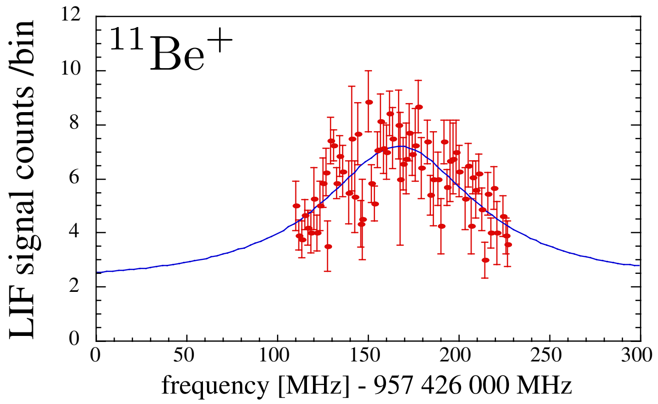
collinear LS



W. Nörtershäuseret al., PRL 102, 062503 (2009)

- *SLOWRI @ RIKEN*

laser cooled ions
in trap

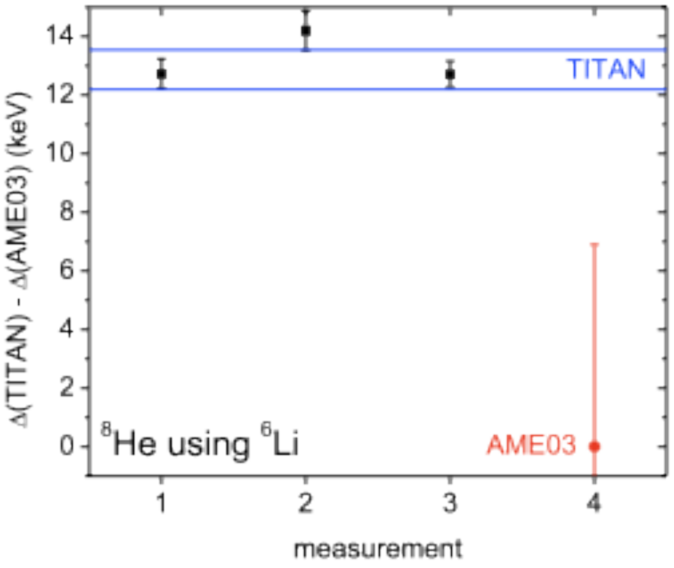


A. Takamine et al., Eur. Phys. J. A 42, 369 (2009)

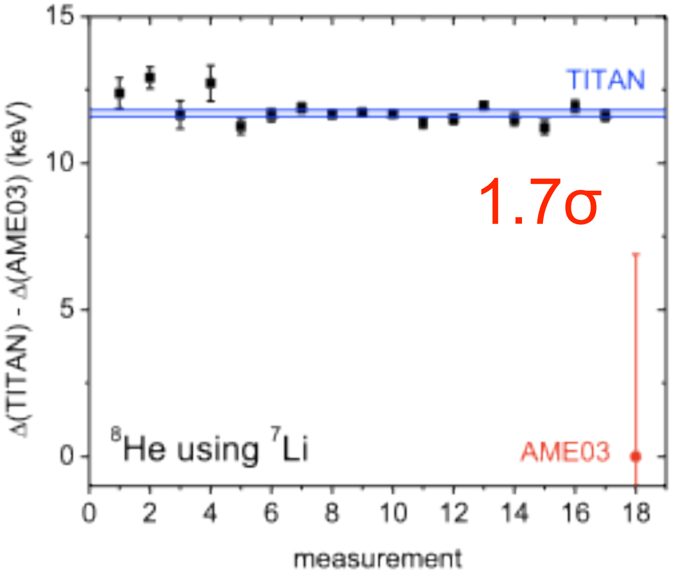
δm=6.4 keV (AME’03)

TITAN: ^{6}He & ^{8}He

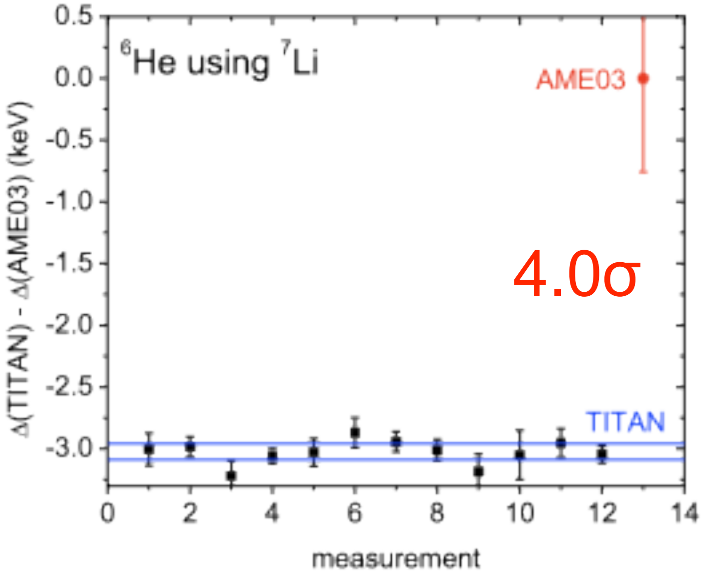
1st ^{8}He mass meas.



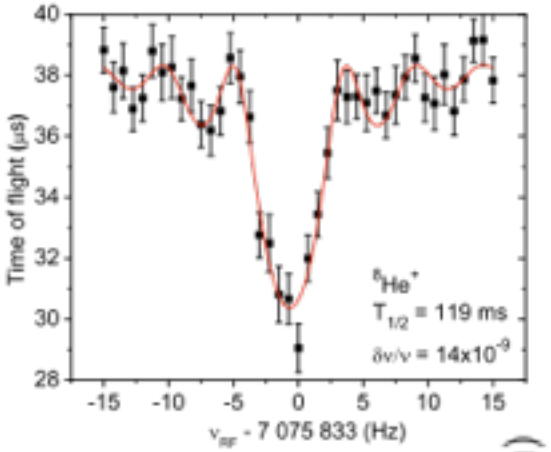
2nd ^{8}He mass meas.



^{6}He mass meas.



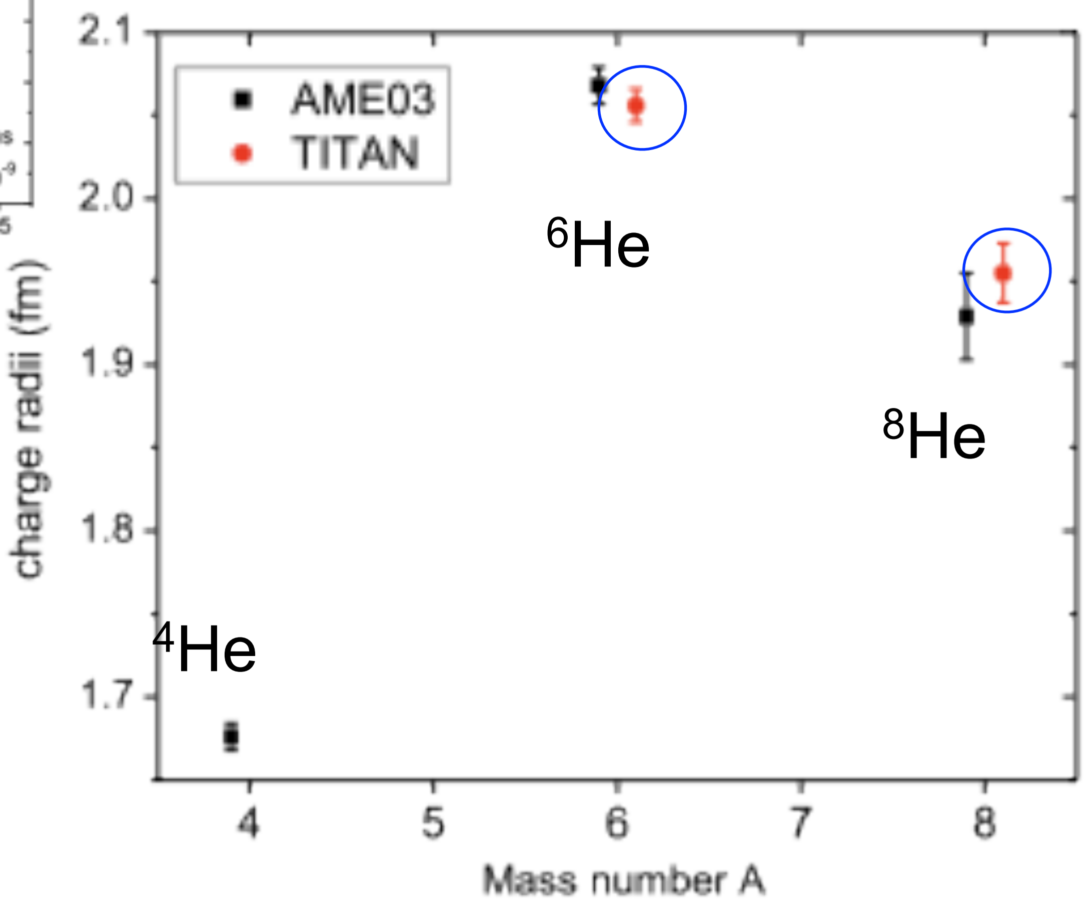
V. L. Ryjkov et al., PRL 101, 012501 (2008)



M. Brodeur et al., in prep.

New masses (M.E.=m-A)

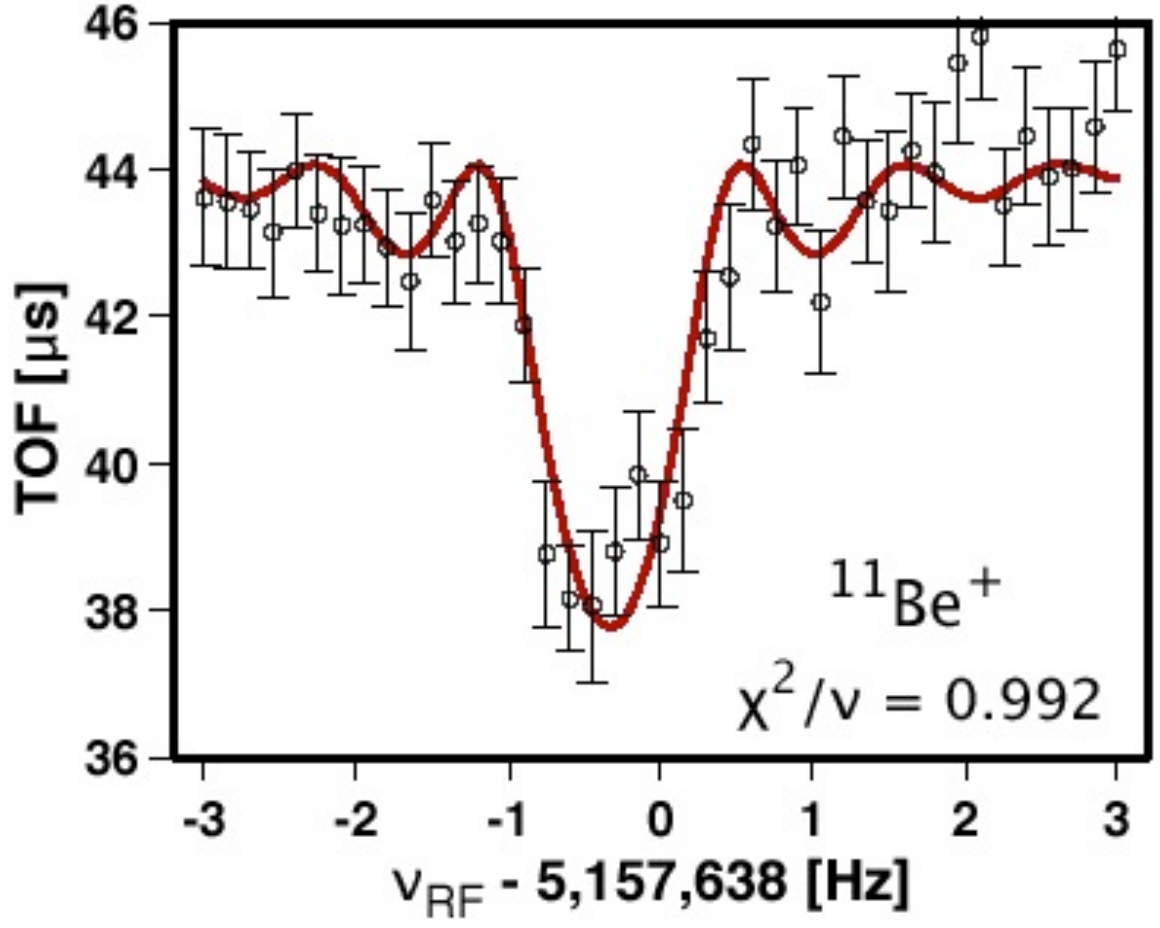
Isotope	mass (× 10^6 u)	M.E. (keV)
^{6}He	6 018 885.883(70)	17 592.087(65)
^{8}He (1st)	8.033 935 669(722)	31 610.872(673)
^{8}He (2nd)	8.033 934 410(128)	31 609.700(120)
^{8}He (average)	8.033 934 449(126)	31 609.736(118)

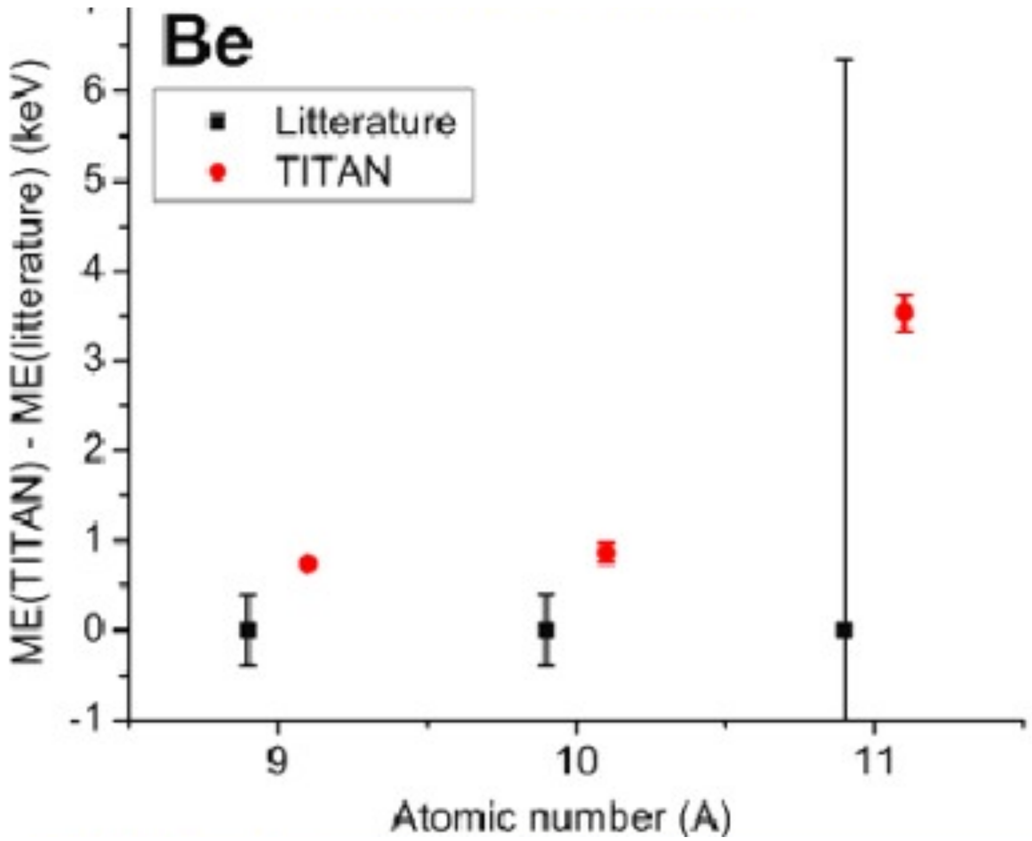


comparison to theory: need 3N interactions

S. Bacca et al., Eur. Phys. J. A 42, 553 (2009)

TITAN: ^{11}Be



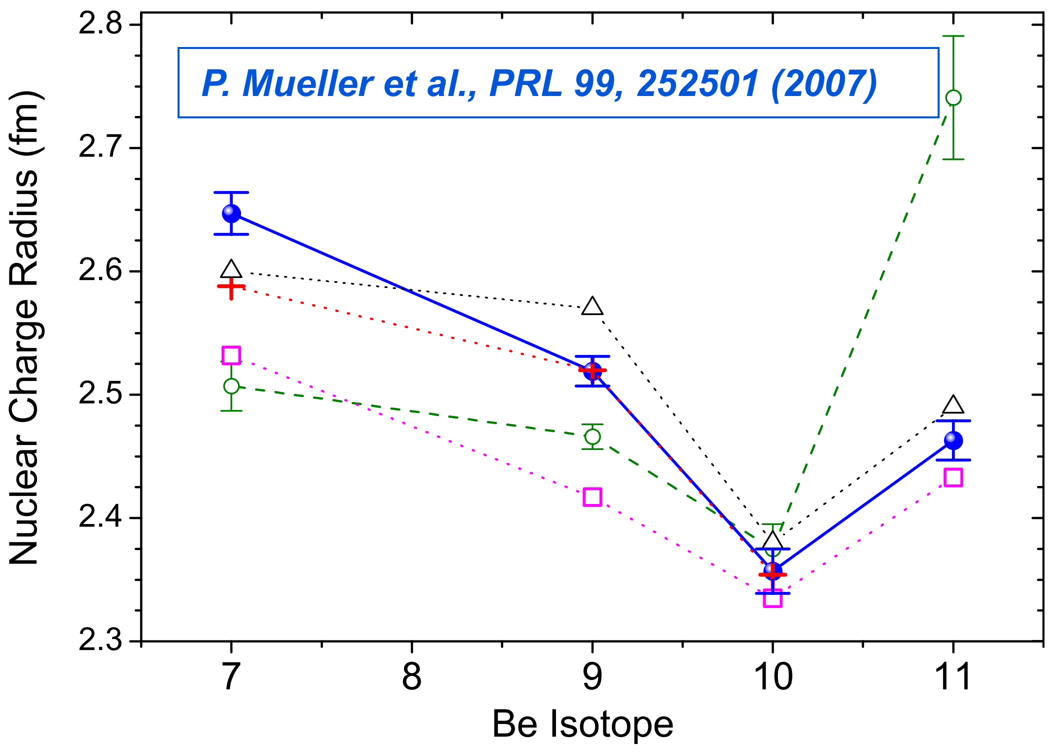


mass ref.	mass ex.[keV]	δ_{MS} (^{9}Be-^{11}Be) $2s_{1/2} \rightarrow 2p_{1/2}$
AME'03	20 174.1(6.4)	31 560.05(9)
TITAN'09	20 177.60(58)	31 560.086(13)

⇒confirms AME & improves precision

⇒uncertainty of mass negligible for r_c

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



^{12}Be: shell gap quenching

- one-neutron knockout reactions

A. Navin et al., Phys. Rev. Lett. 85, 266 (2000)

S. D. Pain et al., Phys. Rev. Lett. 96, 032502 (2006)

- inelastic scattering of ^{12}Be beams on various targets

H. Iwasaki et al., Phys. Lett. B481, 7 (2000)

H. Iwasaki et al., Phys. Lett. B491, 8 (2000)

N. Imai et al., Phys. Lett. B673, 179 (2009)

- discovery of a low-lying isomeric 0^+ state

S. Shimoura et al., Phys. Lett. B560, 31 (2003)

S. Shimoura et al., Phys. Lett. B654, 87 (2007)

interpretation:

- $\nu(1s,0d)^2$ intruder configuration
- pronounced admixture $\nu(1p)^2$

NEWS: ^{11}Be(d,p) @ TRIUMF:

- spec. factor for 2nd 0^+
- together with small S_n^{eff}

$\Rightarrow$ *neutron halo-like structure ?*

R. Kanungo et al., Phys. Lett. B682, 391 (2010)

^{12}Be: shell gap quenching

- one-neutron knockout reactions

A. Navin et al., Phys. Rev. Lett. 85, 266 (2000)

S. D. Pain et al., Phys. Rev. Lett. 96, 032502 (2006)

- inelastic scattering of ^{12}Be beams on various targets

H. Iwasaki et al., Phys. Lett. B481, 7 (2000)

H. Iwasaki et al., Phys. Lett. B491, 8 (2000)

N. Imai et al., Phys. Lett. B673, 179 (2009)

- discovery of a low-lying isomeric 0^+ state

S. Shimoura et al., Phys. Lett. B560, 31 (2003)

S. Shimoura et al., Phys. Lett. B654, 87 (2007)

interpretation:

- $\nu(1s,0d)^2$ intruder configuration
- pronounced admixture $\nu(1p)^2$

$$S_n^{eff} = S_n - E^*$$

mass

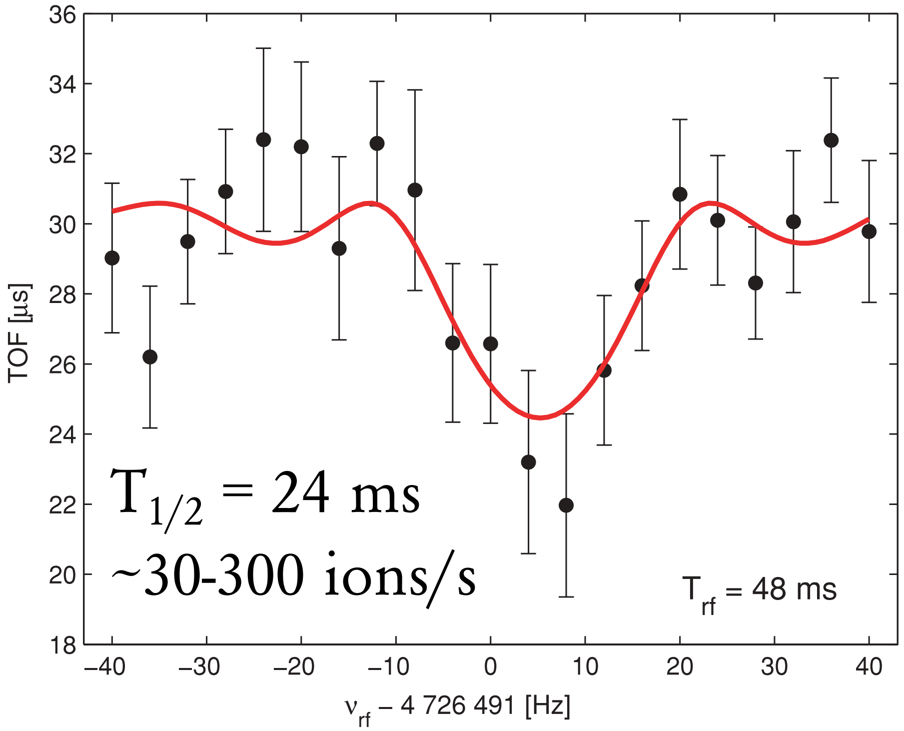
NEWS: ^{11}Be(d,p) @ TRIUMF:

- spec. factor for 2nd 0^+
- together with small S_n^{eff}

} ⇒ *neutron halo-like structure ?*

R. Kanungo et al., Phys. Lett. B682, 391 (2010)

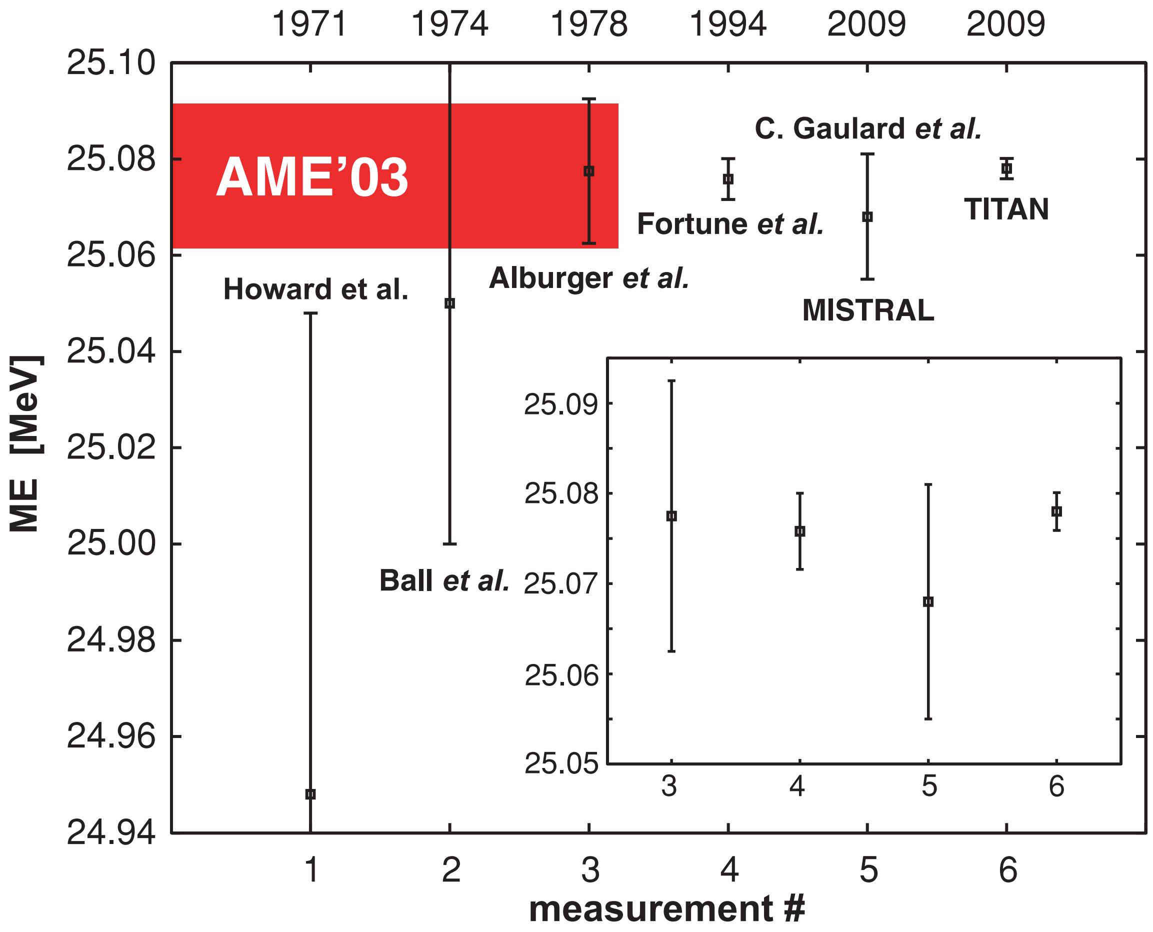
^{12}Be



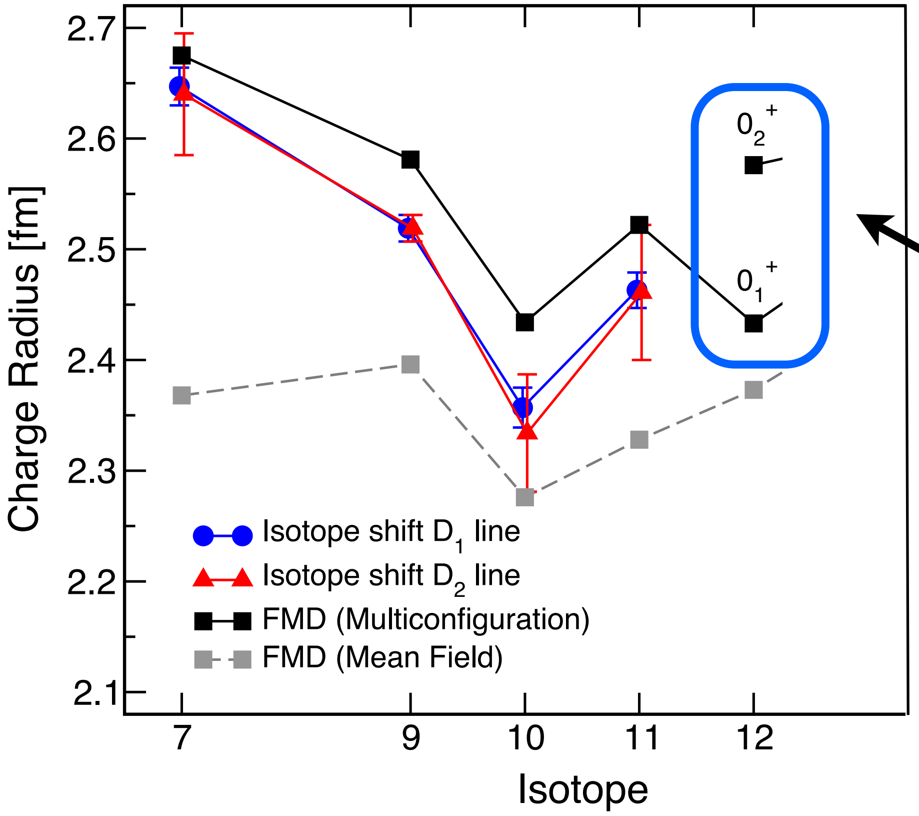
$T_{1/2}$ = 24 ms

~30-300 ions/s

TITAN: m.e.=25 078.0(2.1) keV



S. Ettenauer et al., PRC 81, 024314 (2010)



- Isotope Shift measurement in the near future
- will require mass

predictions by Fermionic Molecular Dynamics

M. Žáková et al., J. Phys. G: Nucl. Part. Phys. 37, 055107 (2010)
T. Neff et al., Niigata proceedings, in preparation

V_{ud} , Fundamental Symmetries and Highly Charged Ions

Quarks in the SM

Coupling to Higgs field $\Phi^T = (\Phi_1\ \Phi_2)$:

$$\sum G_{ij}^d L_i^+ \Phi d_{Rj} + \sum G_{ij}^u L_i^+ \varepsilon \Phi u_{Rj} + h.c \longleftarrow$$

Yukawa coupling

after symmetry breaking: mass term

⇒ weak ≠ mass eigenstates:

$$\boxed{\begin{array}{ll} d'_L = D_L d_L & u'_L = U_L u_L \\ d'_R = D_R d_R & u'_R = U_R u_R \end{array}}$$

interaction Lagrangian quarks - W⁺ and W⁻

$$g\,\bar{u}_{Li}\,\gamma^\mu d_{Li} W_\mu^+ + h.c. = g\,\bar{u}'_{Li} \boxed{U_L D_L^+} \gamma^\mu d'_{Li} W_\mu^+$$

$$V = U_L D_L^+ = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo–Kobayashi–Maskawa matrix:

Quarks in the SM

Coupling to Higgs field $\Phi^T = (\Phi_1\ \Phi_2)$:

$$\sum G^d_{ij} L^+_i \Phi d_{Rj} + \sum G^u_{ij} L^+_i \varepsilon \Phi u_{Rj} + h.c \longleftarrow$$ Yukawa coupling

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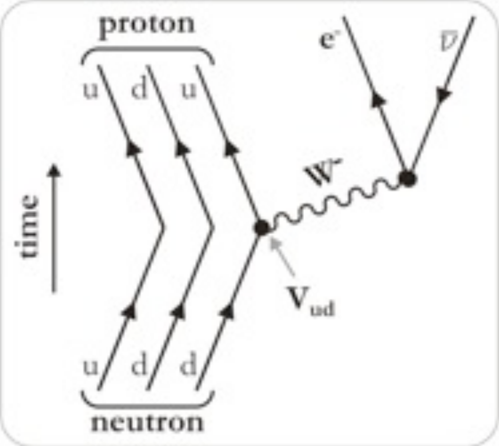

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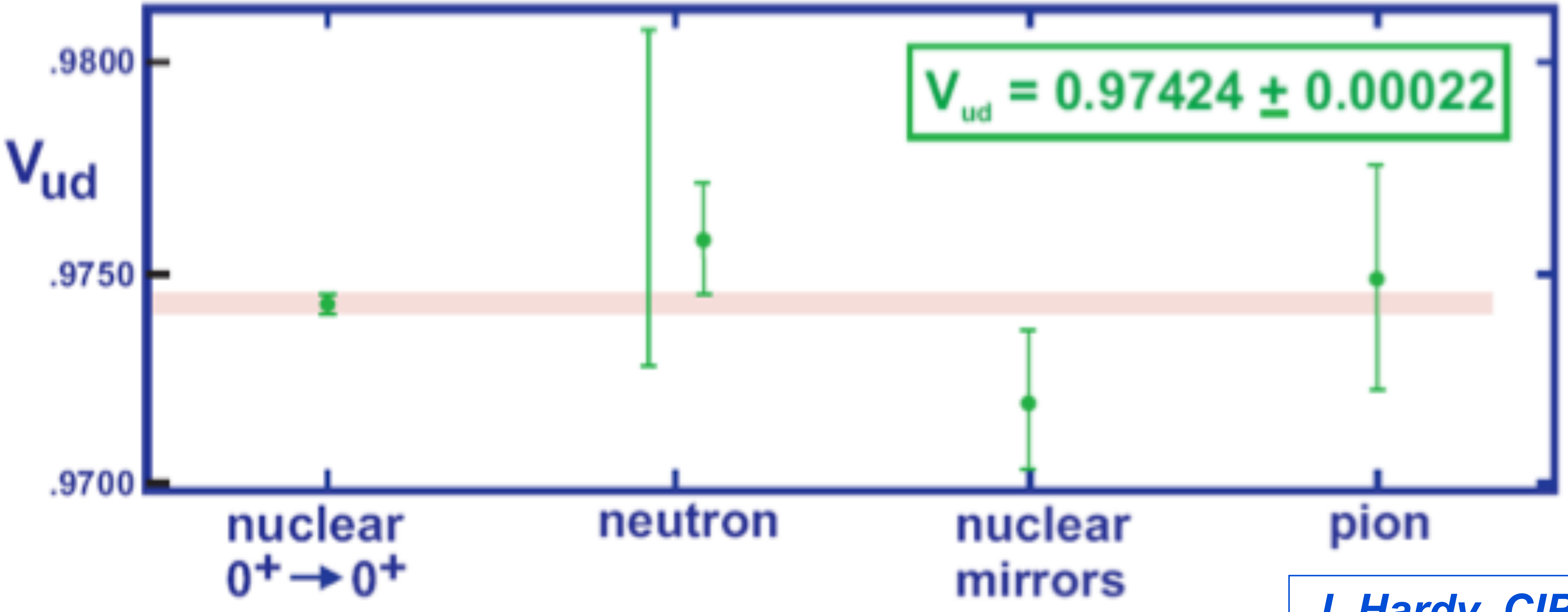
β - decay

Cabibbo–Kobayashi–Maskawa matrix:

V_{ud} measurements



J. Hardy, CIPANP 2009

⇒ superallowed $0^+ \rightarrow 0^+$ decays most precise way to extract V_{ud}

due to $\Delta J = \Delta T = \Delta L = \Delta S = 0$:

- pure Fermi decay (only vector part)
- transition between isobaric analog states
- only total Isospin Ladder Operator $T^{\pm}$ alters wave-function

⇒ for T = 1:
$$|\overline{M}|^2 = \frac{G_V^2}{g^2}|M(F)|^2 = \frac{2G_V^2}{g^2}$$

TRIUMF ISAC

ft- values, corrected Ft-value and V_{ud}

Combination to *ft*-values (T=1):

$$ft = \frac{K}{2G_V^2} = \text{const}$$

f … phase space integral (dep. on Q-value)

t … „partial halflife“ (dep on. BR and T)

K … numerical constant

<u>corrected *Ft* value:</u>

$$Ft = ft(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} = \text{const} \longrightarrow \boxed{|V_{ud}| = \frac{G_V}{G_F}}$$

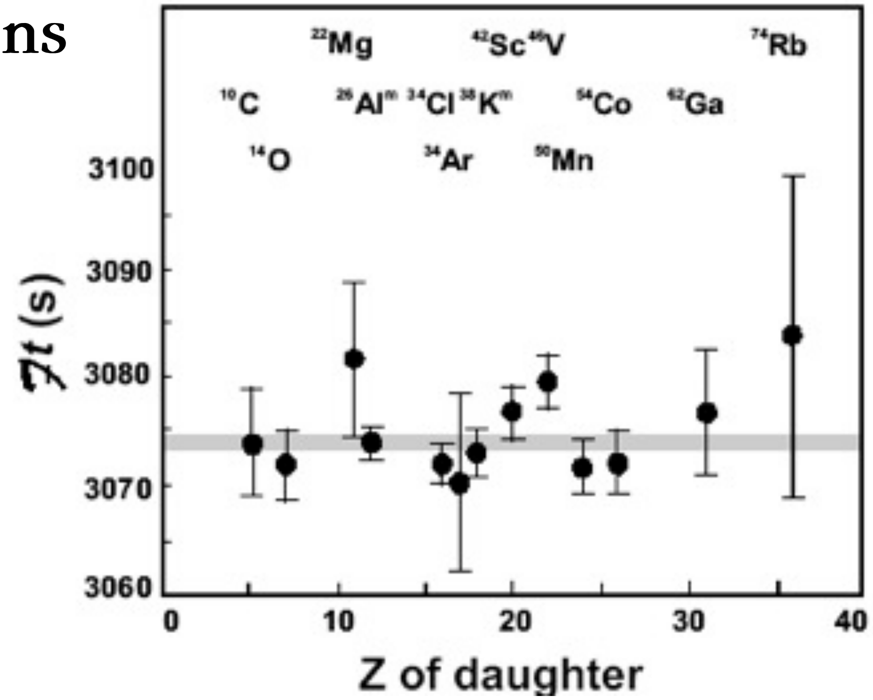
Δ^V_R … transition indep.

δ_R and δ_{NS} ….transition dep.

} radiative corrections

δ_c … isospin symmetry breaking (tans. dep.)

Corrections: small (about a few %),
BUT dominating uncertainty



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Experimental Input

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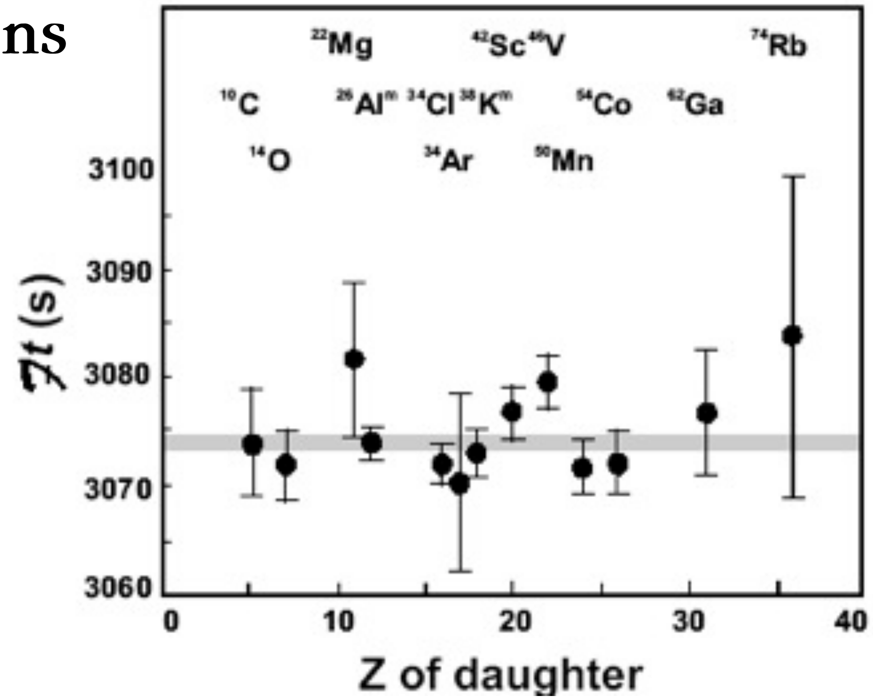

Corrections: small (about a few %),
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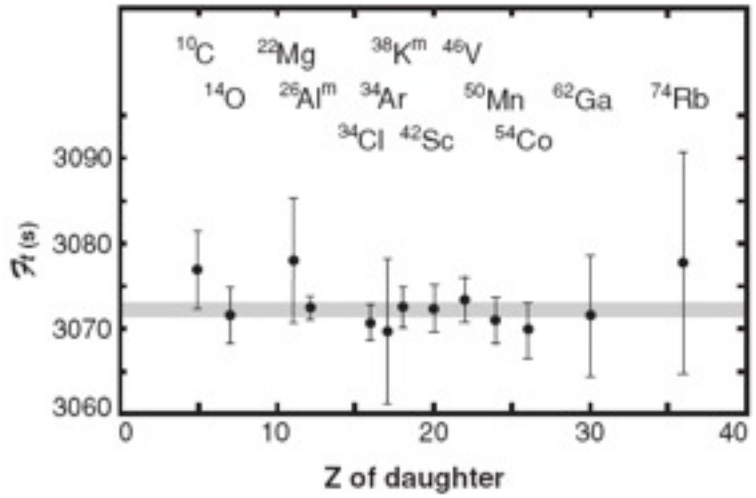
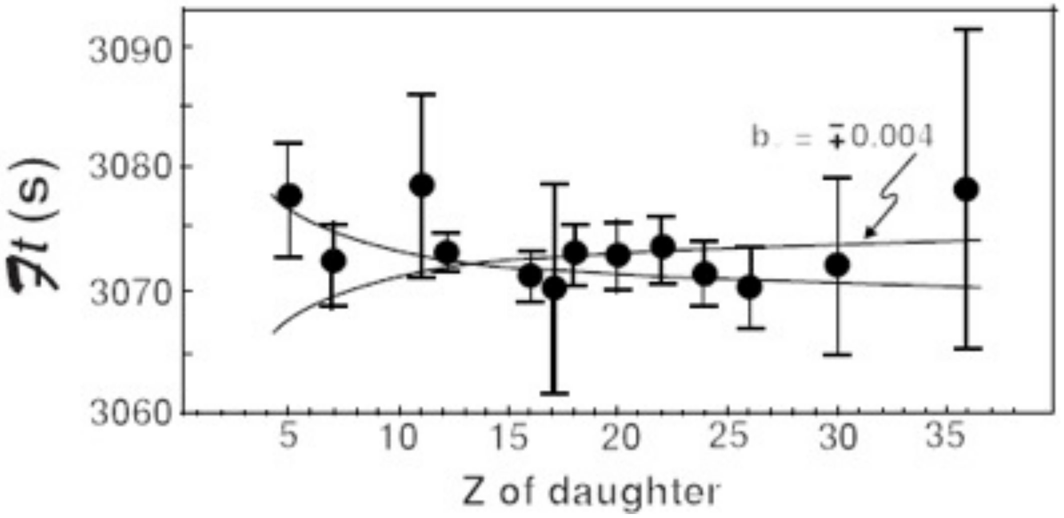
Tests of Fundamental Symmetries I

1) CVC



$\chi/\nu = 0.28$

2) Scalar Currents

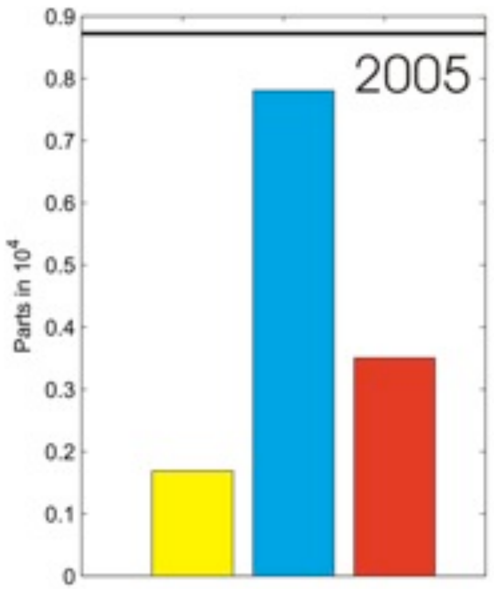


$$\frac{C_s}{C_V} = 0.0011(13)$$

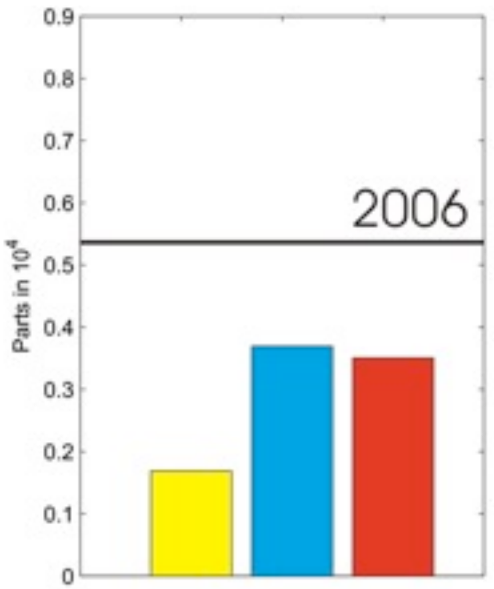
J. Hardy & I.S. Towner, Phys. Rev. C 79, 055502 (2009)

3) $|V_{ud}|^2$

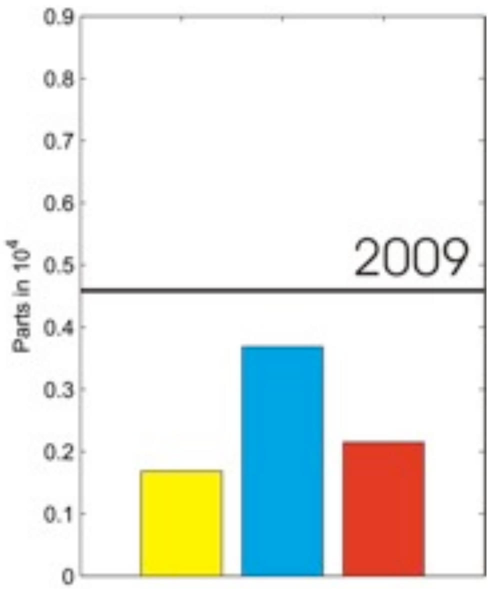
J. Hardy & I.S. Towner



W. J. Marciano et al.



J. Hardy & I.S. Towner



🟨 experimental 🟦 Δ_R 🟥 $\delta_{NS}, \delta_C,$ and δ_R

Tests of Fundamental Symmetries

4) CKM: basis transformation weak mass eigenstates

⇒Unitarity test of 1st row:

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ SM

$= 0.99995(61)$ Experiment

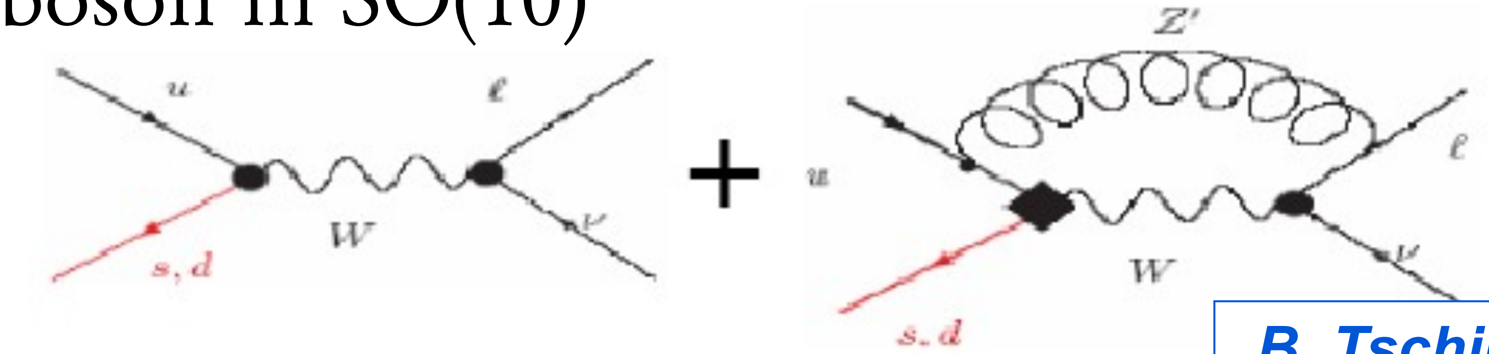
0.9491(4) 0.0508(4)

J. C. Hardy & I.S. Towner, Phys. Rev. C 79, 055502 (2009)

5) Coupling Universality:

$$G_F\,(|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) = G_\mu = G_\tau$$

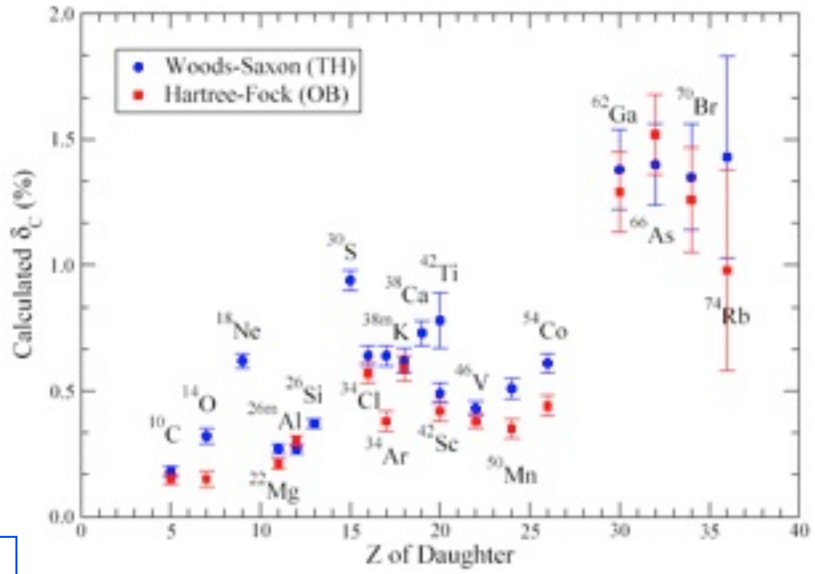
e.g. Z_χ boson in SO(10)



implies: $M(Z_\chi) > 750$ GeV at 95% CL

B. Tschirhart , CIPANP 2009

Developments for δ_c



J.C. Hardy and I.S. Towner, Phys. Rev. C66, 035501 (2002)
Phys. Rev. C71, 055501 (2005)
W. E. Ormond and B. A. Brown, Phys. Rev. C52, 2455 (1995)
Nucl. Phys. A 440, 274 (1985)

I.S. Towner & J. C. Hardy, Phys. Rev. C77, 025501 (2008)

new δ_c – calculations (including core orbitals)

G.A. Miller & A. Schwenk, Phys. Rev. C 78, 035501 (2008)

T&H's δ_c: use W^+-spin, not isospin τ^+

N. Auerbach, Phys. Rev. C 79, 035502 (2009)

New approach to δ_c (Coulomb force treated by perturbation theory)

results lower than T&H

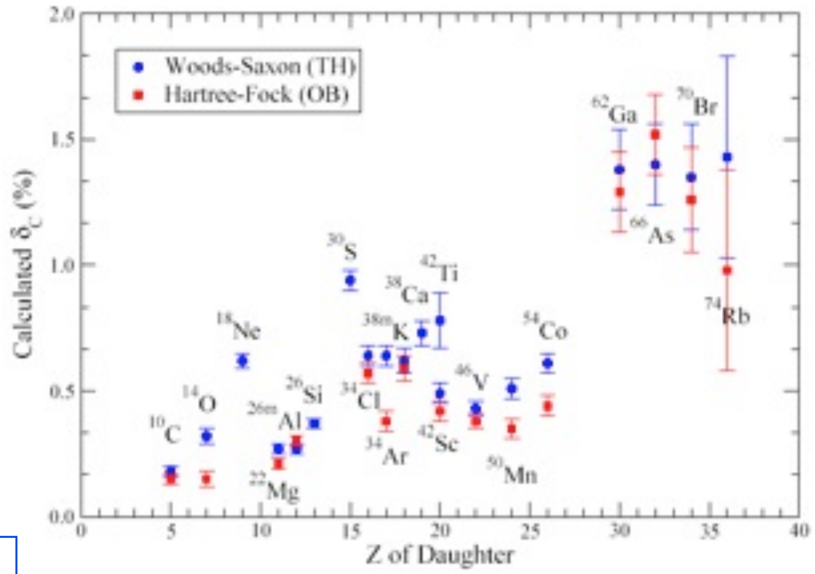
J. C. Hardy & I.S. Towner, Phys. Rev. C 79, 055502 (2009)

New Hartree-Fock (same model space as Woods-Saxon with core orbitals)

H. Liang et al., Phys. Rev. C, 064316 (2009)

δ_c accessed via self-consistent RPA in relativistic framework

Developments for δ_c



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G.A. Miller & A ***Rev. C 78, 035501 (2008)***

implemented differently

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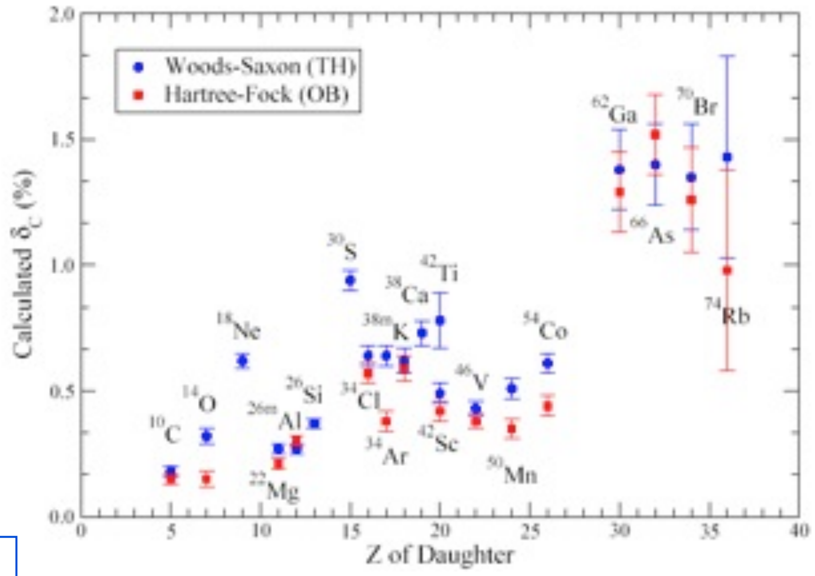

I.S. Towner & J. C. Hardy, Phys. Rev. C77, 025501 (2008)

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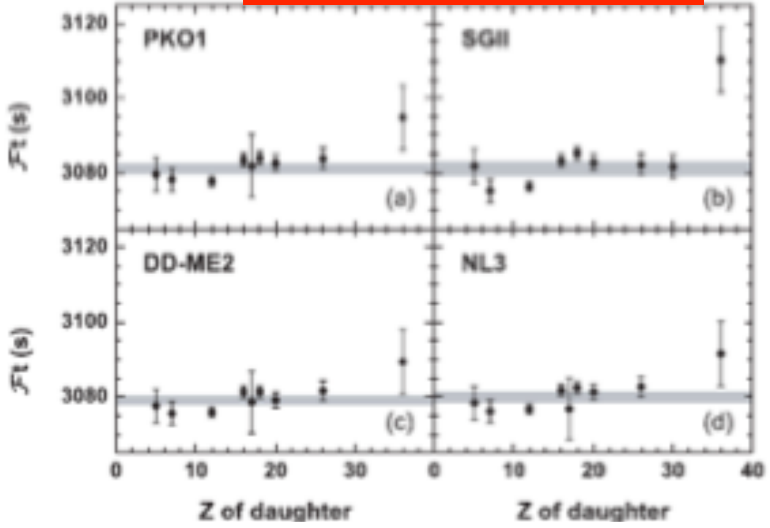
χ/ν = 1.0-1.1



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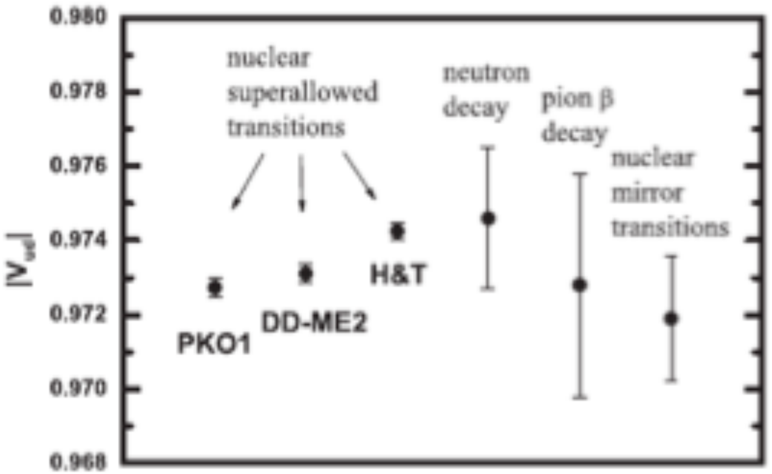

J. C. Hardy & I.S. Towner, Phys. Rev. C 79, 055502 (2009)

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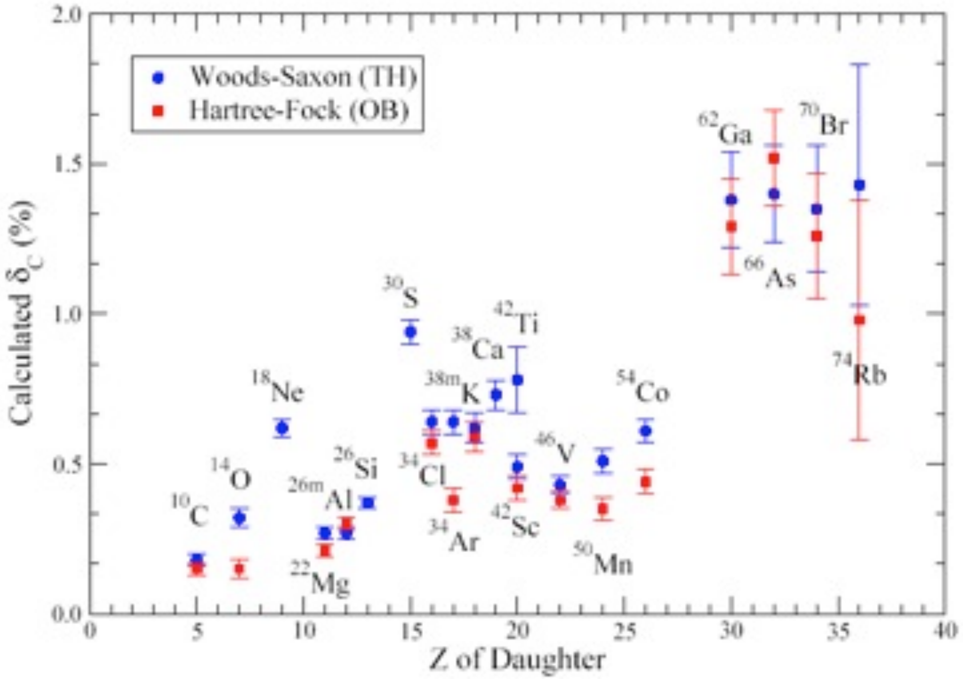
H. Liang et al., Phys. Rev. C, 064316 (2009)

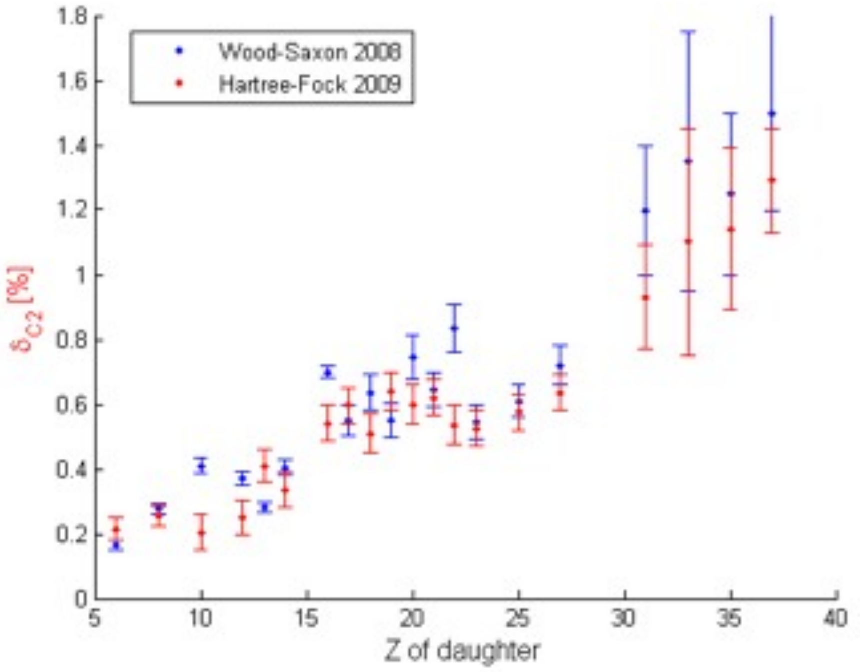
δ_c accessed via self-consistent RPA in relativistic framework

δ_c : comparisons between models

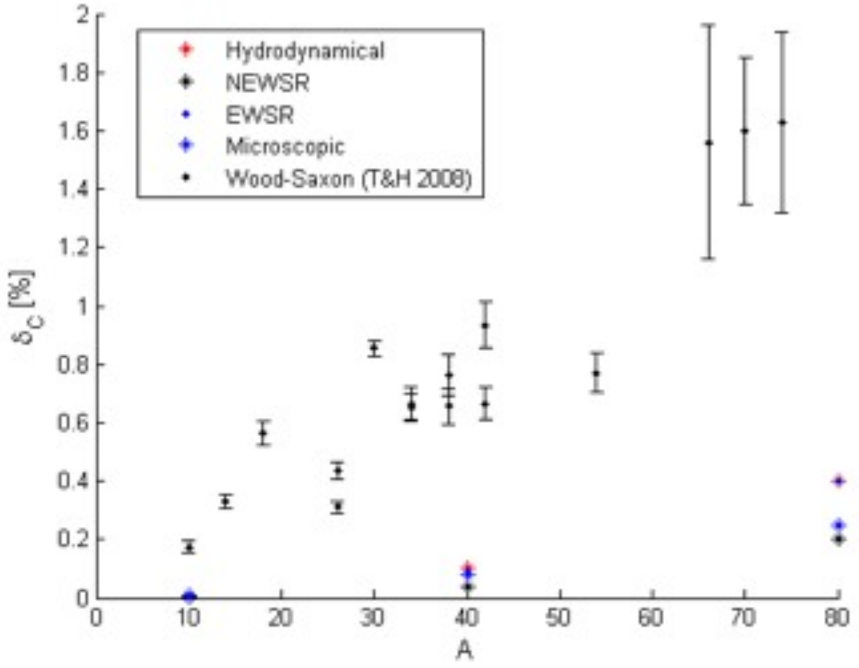
T&H (2005) ↔ O&B



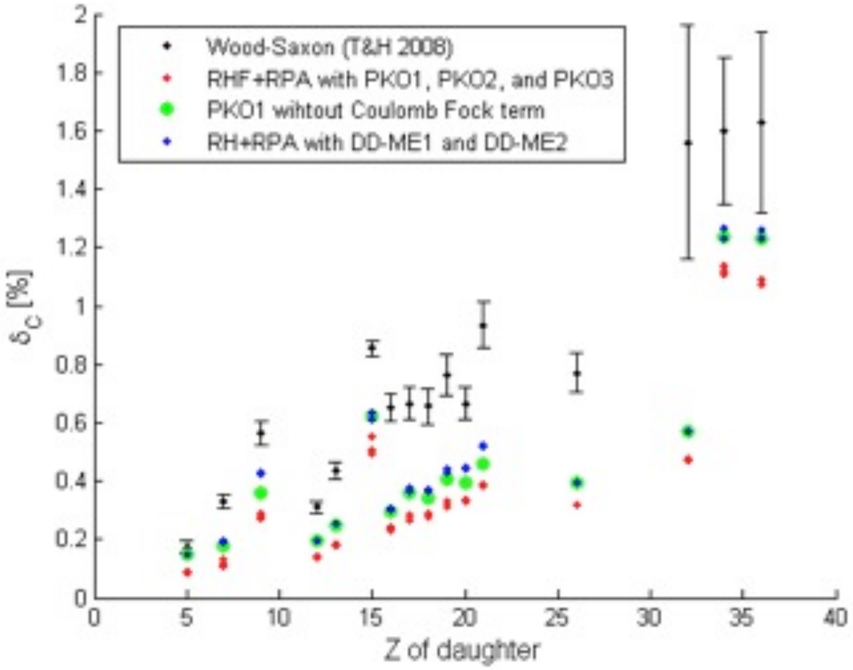
T&H: WS (2008) ↔ HF (2009)



T&H (2008) ↔ Perturbation theory



T&H (2008) ↔ RPA



Status of δ_c

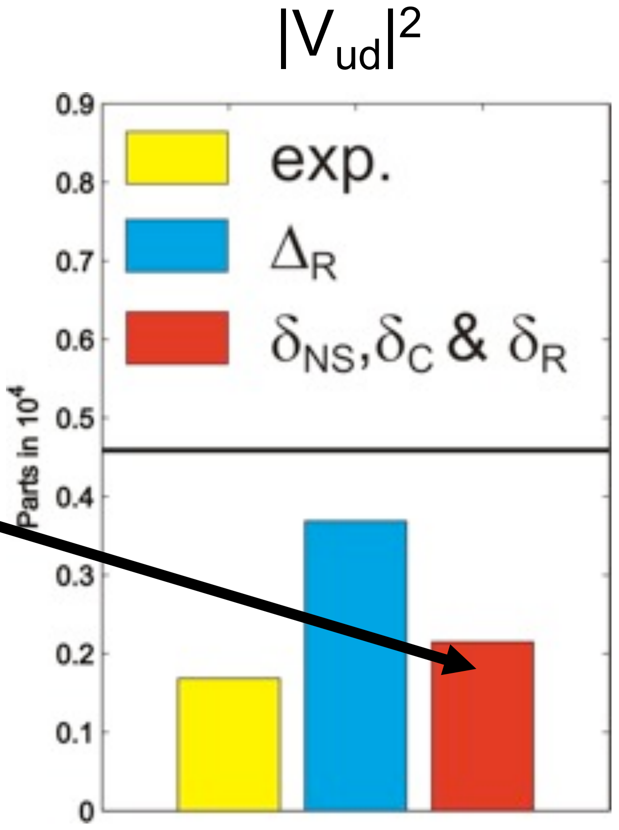
- **T&H:** currently best calculations
  - Wood Saxon & Hartree-Fock
  - same model space
  - good agreement with each other and CVC
- 4 other descriptions
  - 3 with numerical results
  - disagree with T&H (all lower δ_c)
  - but all need improvements

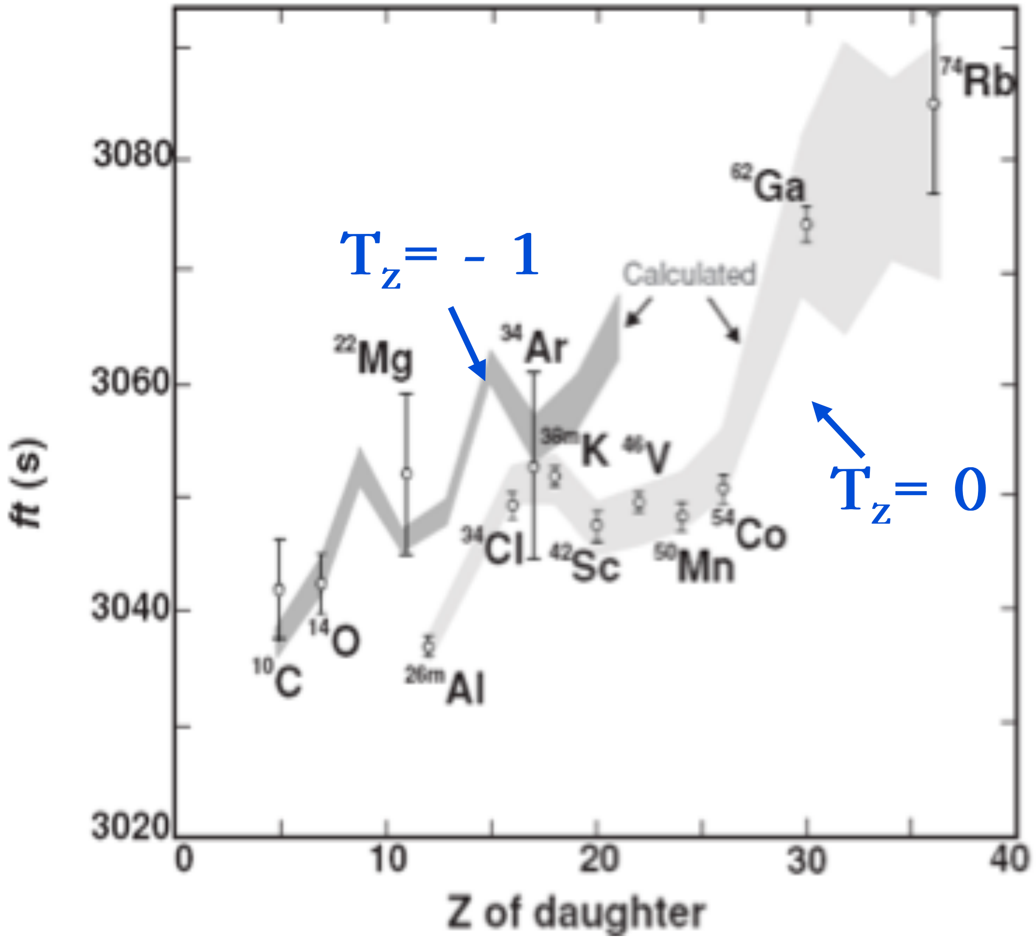
$\Rightarrow$ benchmark models / check $\Delta\delta_c$

- assume CVC
- use

$$ft = \frac{\overline{Ft}}{(1+\delta_R)(1-\delta_c+\delta_{NS})}$$

- compare with experiment
- new cases or/and cases with large δ_c





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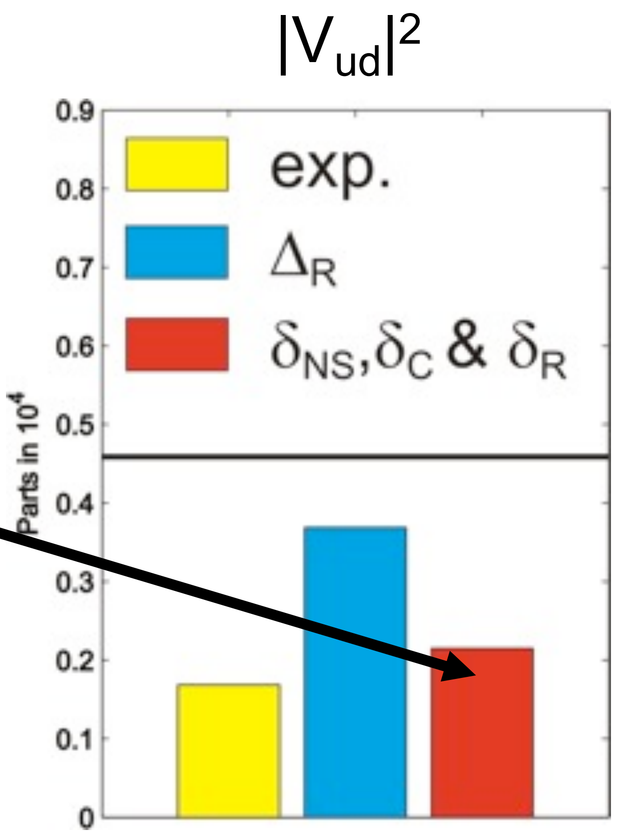
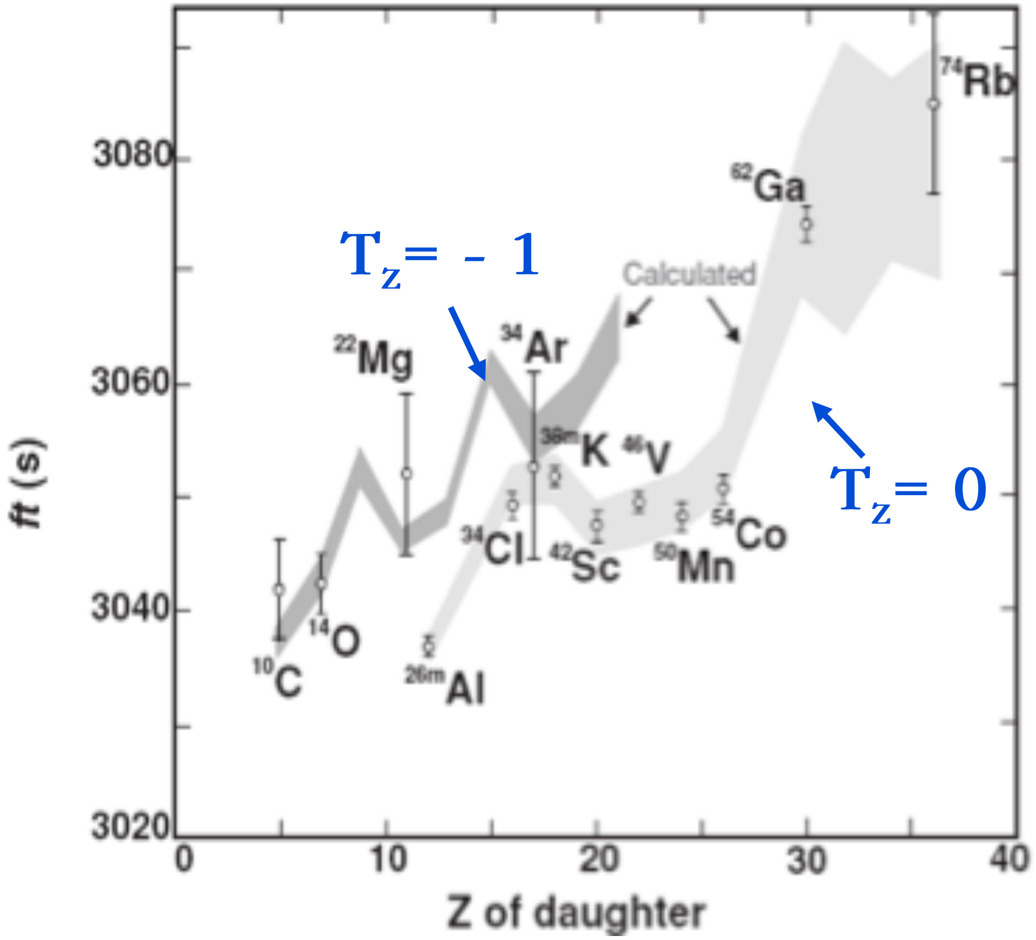
- compare with experiment
- new cases or/and cases with large δ_c

superallowed T=2 cases

TRIUMF S1242





ISAC & superallowed $0^+ \rightarrow 0^+$ β-decays

unique position: x) required beams available (high intensity)

x) experimental facilities in place

⇒ determine all 3 parameters at one place

<u>Q-value:</u> TITAN via direct mass measurements

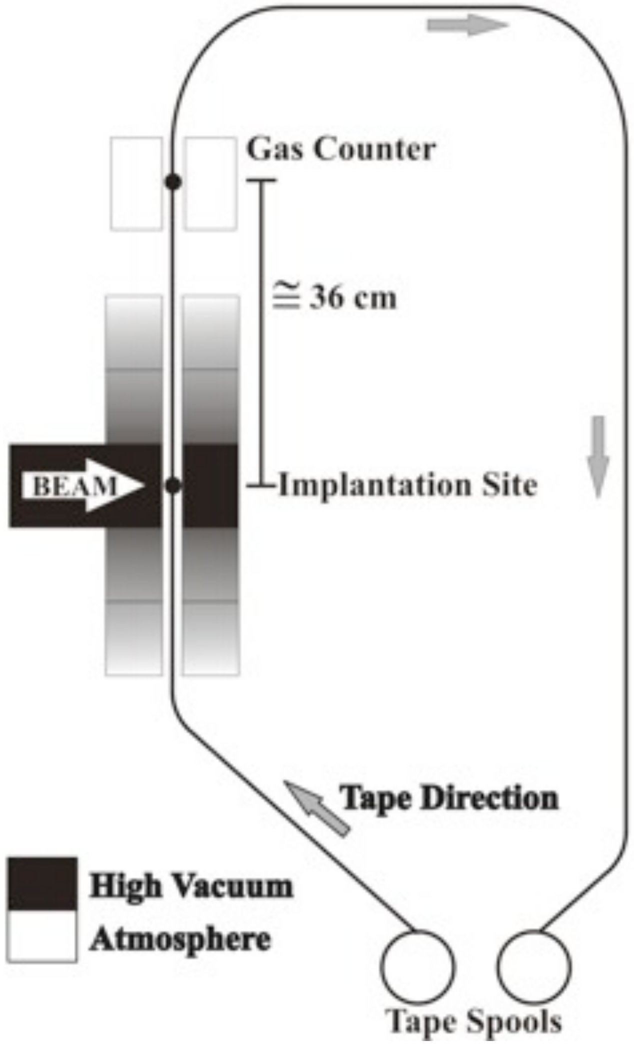
<u>Branching Ratio:</u> 8π (γ–rays) + SCEPTAR (β-particles)

<u>Recent Measurments at TRIUMF</u>:
<u>^{38m}K:</u> *K. G. Leach et al., Phys. Rev. Lett. 100, 192504 (2008)*
<u>^{26m}Al:</u> *data analysis in progress*

<u>Half-life:</u>

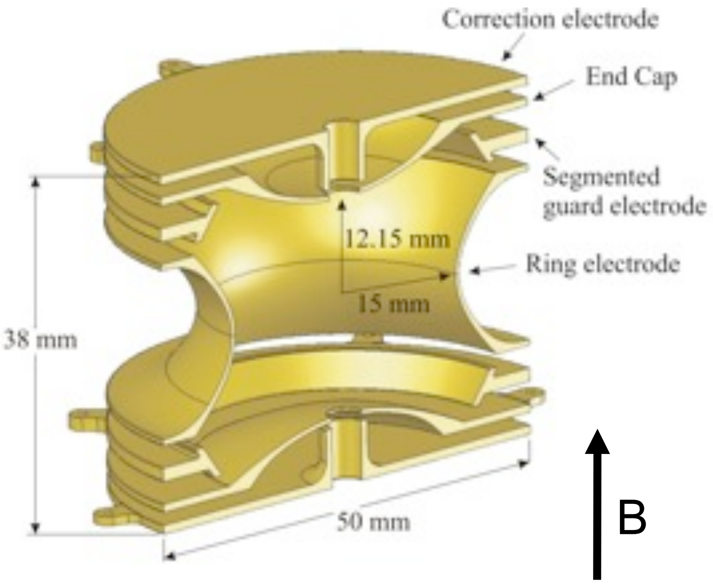
- Gas Proportional Counter
- Photo Peak Counting (8π)

<u>Recent Measurements at TRIUMF</u>:
<u>^{62}Ga:</u> *G. F. Grinyer et al., Phys. Rev. C 77, 015501 (2008)*
<u>^{26m}Al:</u> *most precise [superallowed] $T_{1/2}$ (0.012%)*
P. Finlay, S. Ettenauer et al., in preparation



gas proportional counter

Perspective for Q-values



- nuclei far away from stability (e.g. T=2 cases):
  - lower yields in RIB facilities
  - shorter half-lives
- improve precision of current ion trap measurements

⇒ new approach needed

resolution

$$\frac{\delta m}{m} \propto \frac{m}{\boxed{q}} \frac{1}{BTN^{1/2}}$$

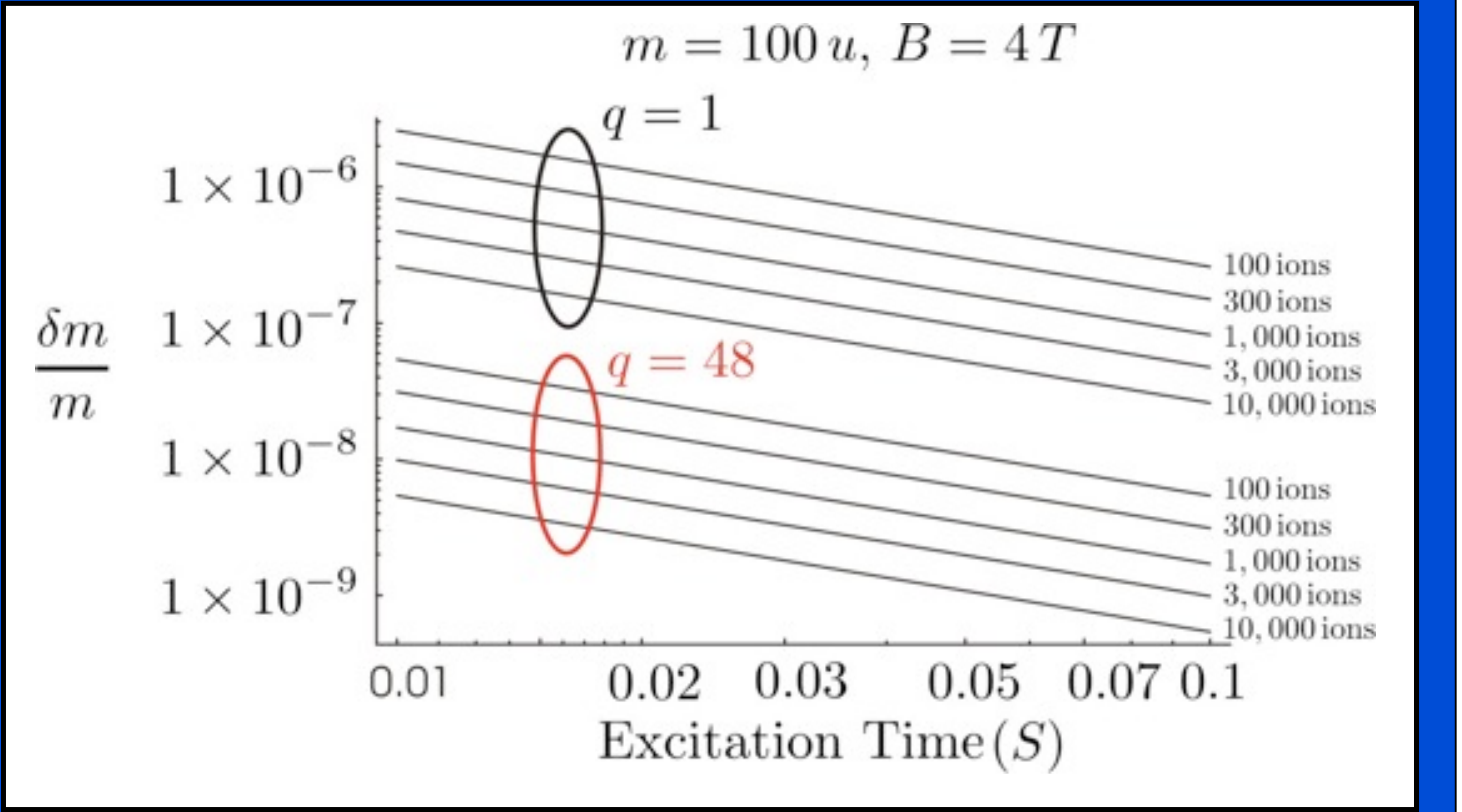
⇒ longer excitation time

⇒ larger B

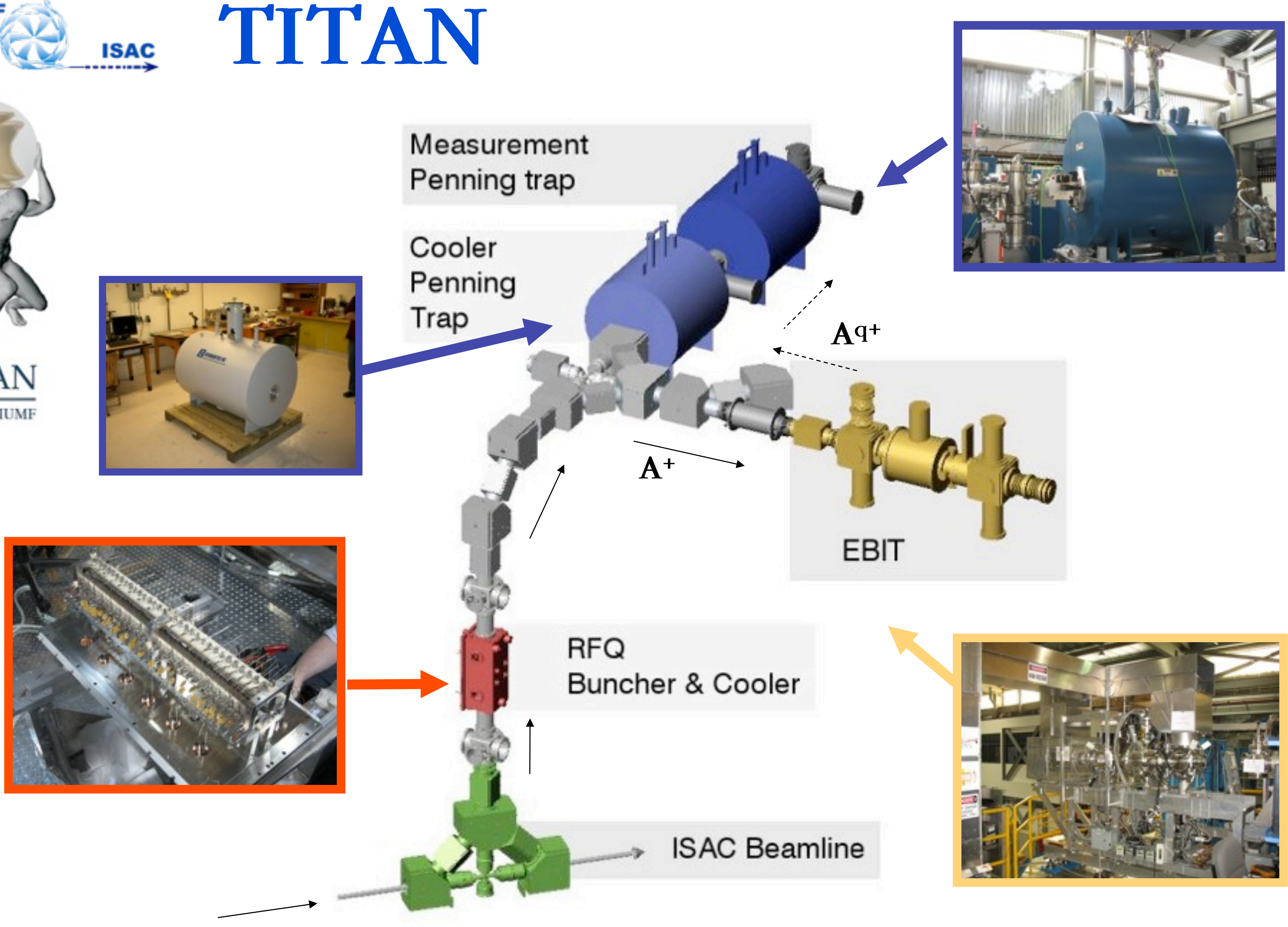
⇒ more ions

⇒ highly charged ions

⇒ CHARGE BREEDING



TITAN



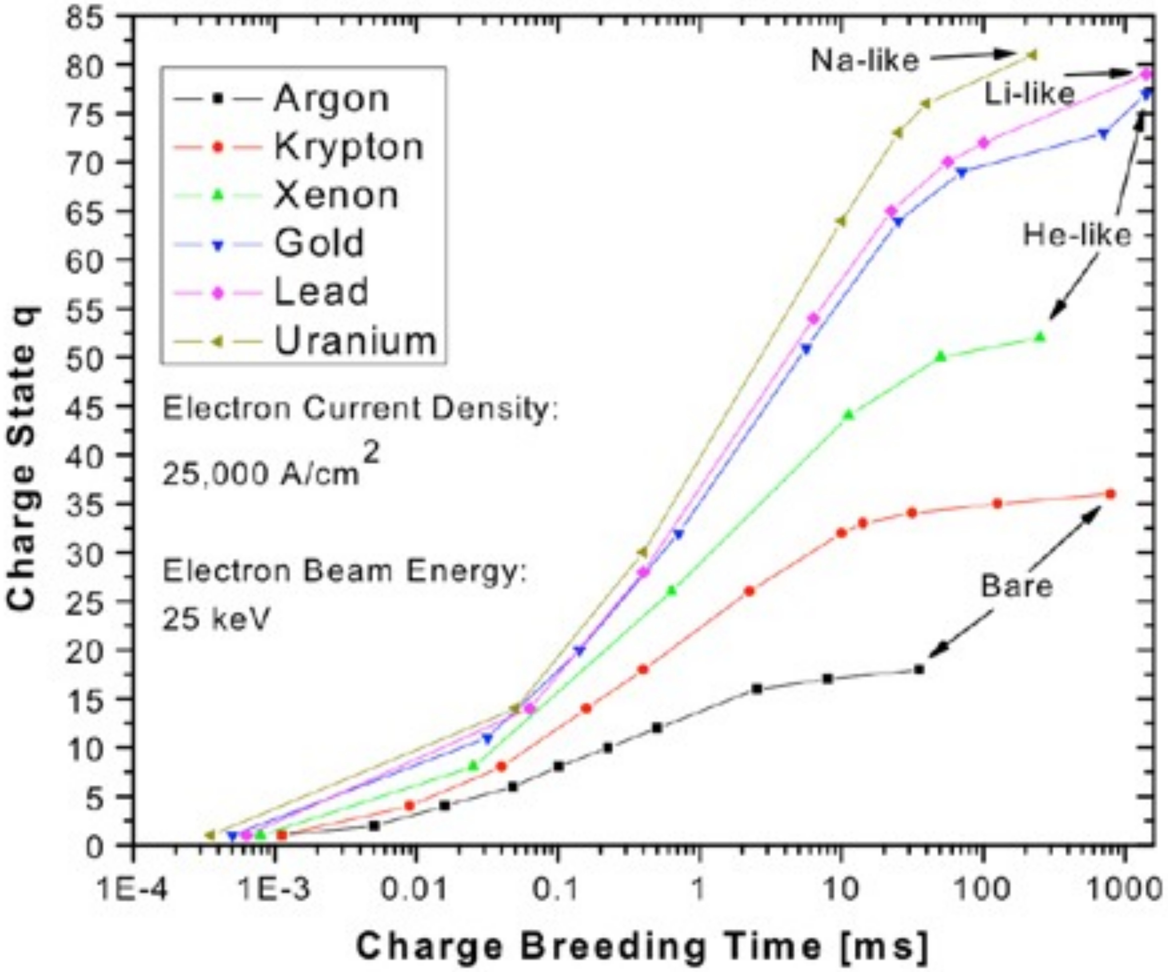
ISAC beam: A^{+}

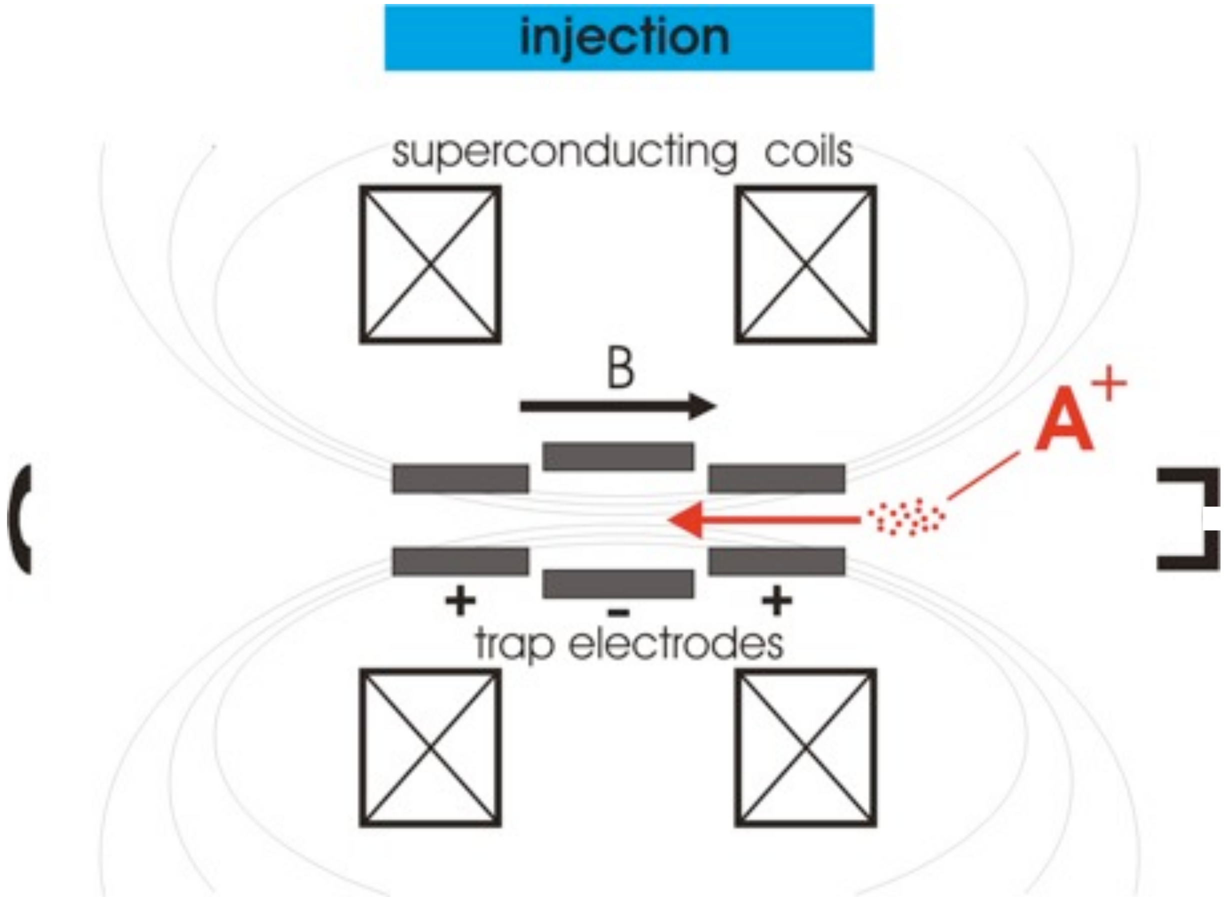
Electron Beam Ion Trap (EBIT)

confinement:

- axial by electrostatic field
- radial by electron beam + B- field

B-field (6 T) compresses e^- beam





requirements for charge breeding:

- efficient
- fast

<u>example: ^{74}Rb</u>
half-life: 65 ms
He-like CB:~10ms
Bare CB: ~100 ms

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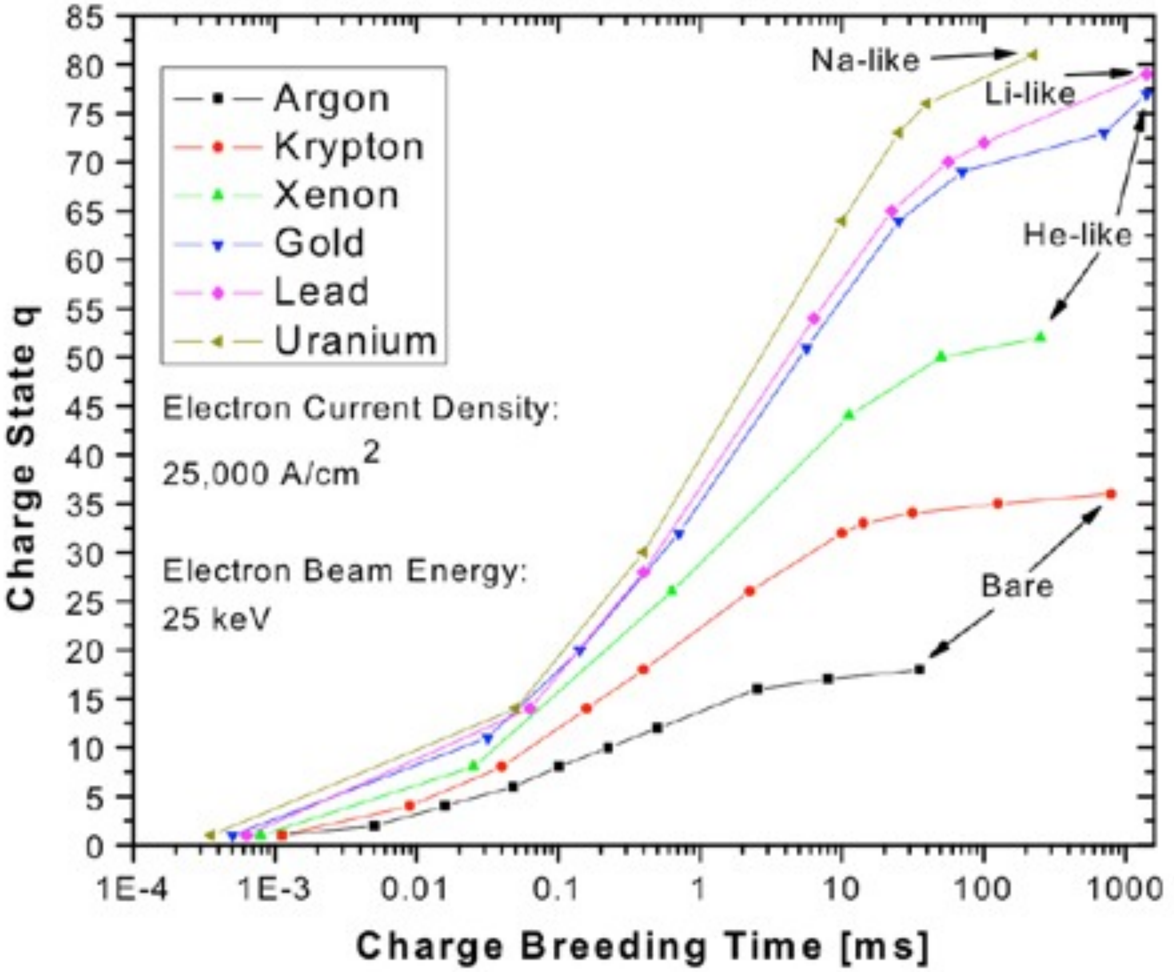

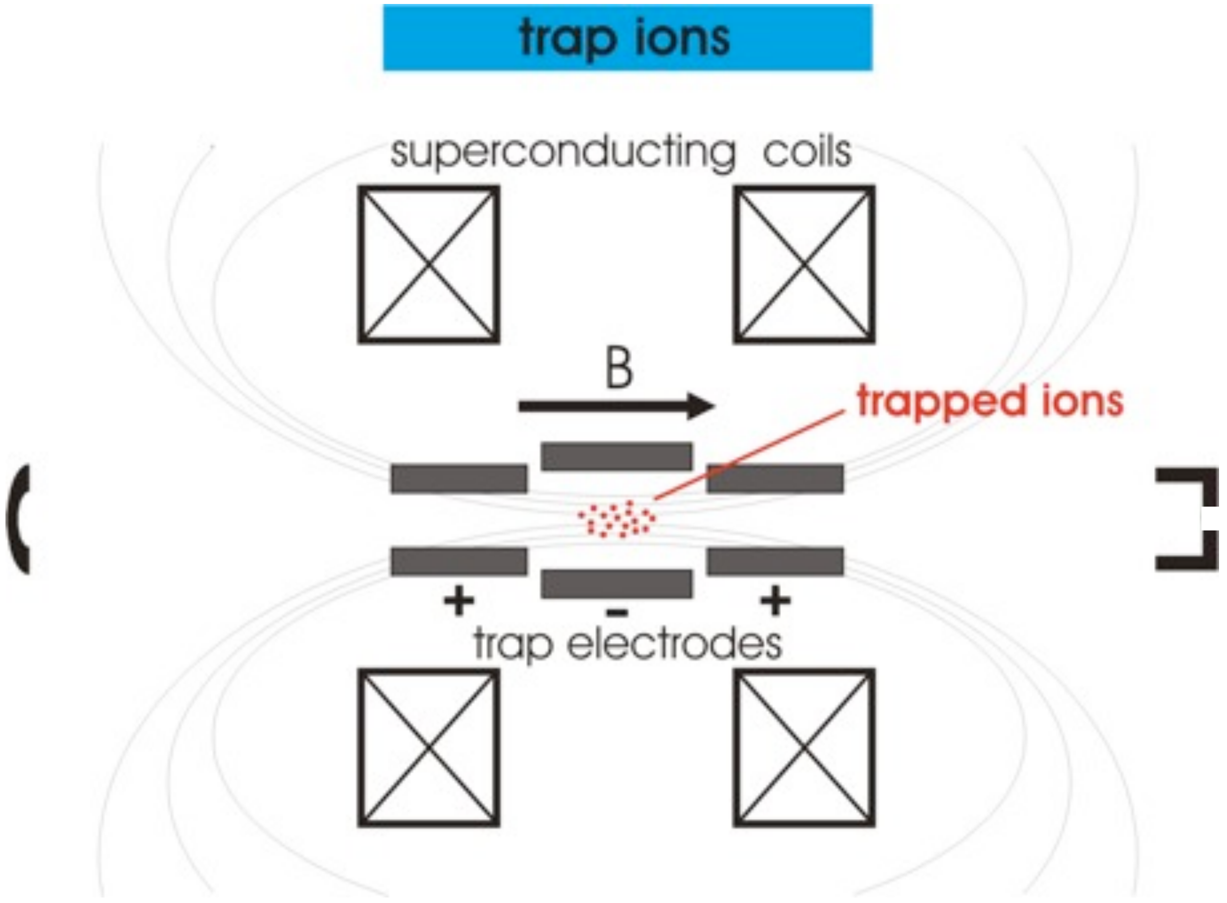

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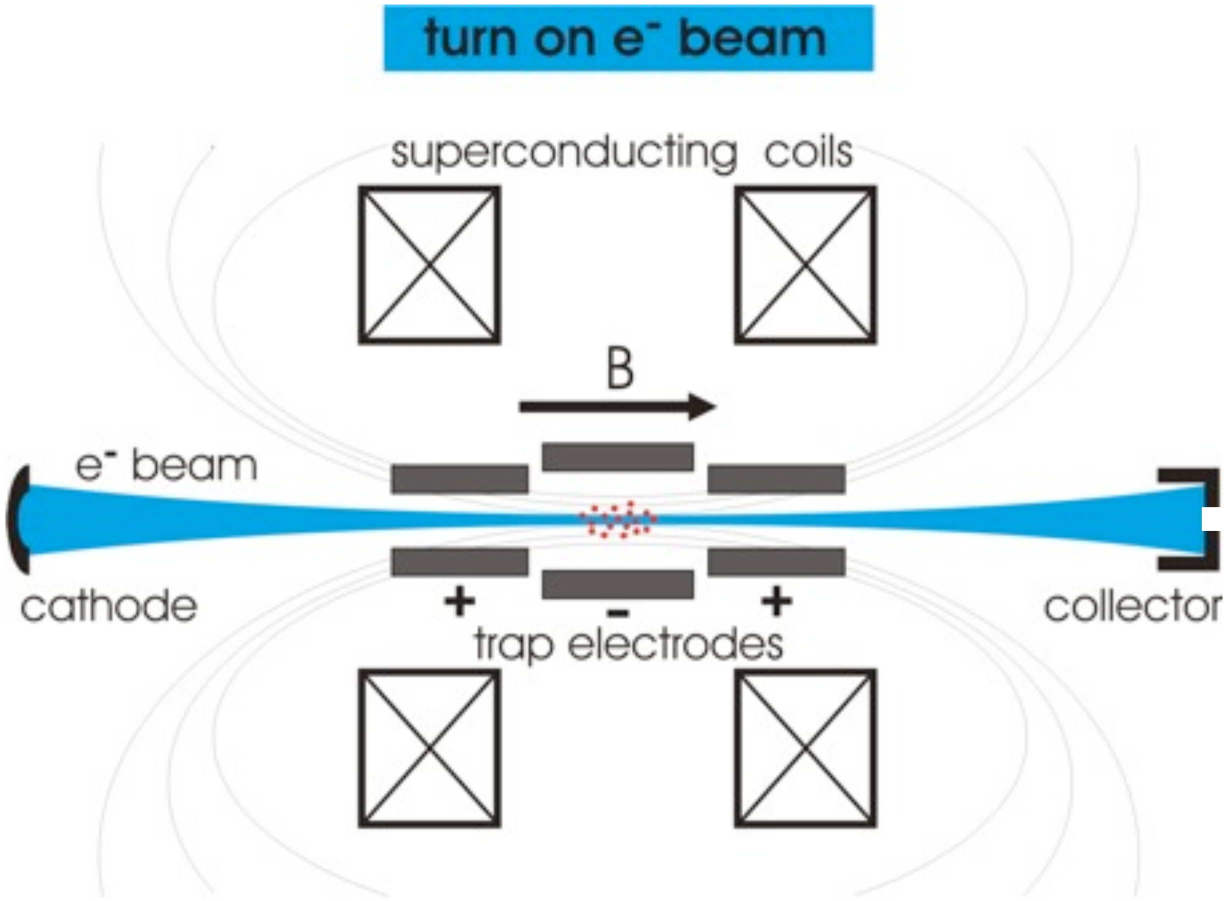

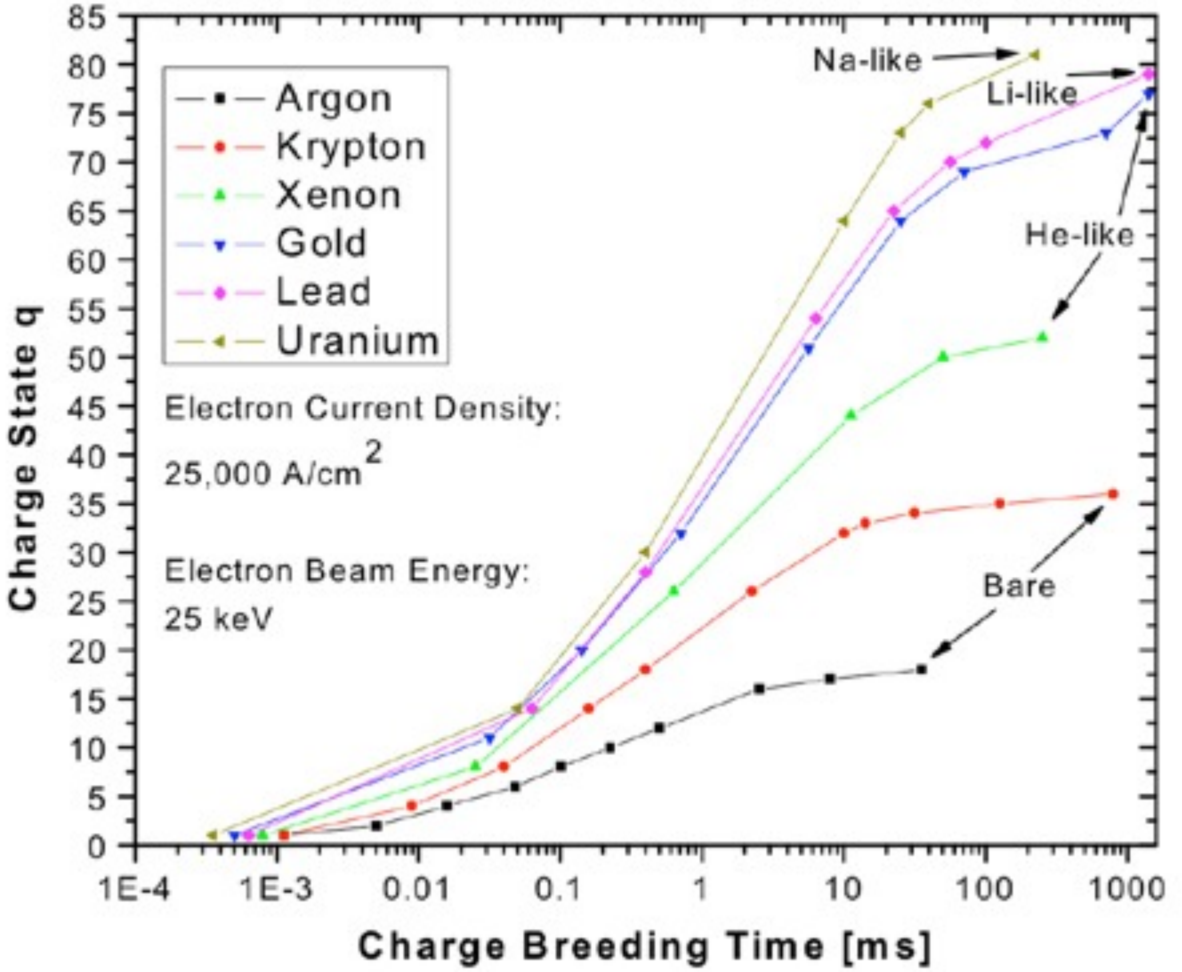

requirements for charge breeding:

- efficient
- fast

example: ^{74}Rb

half-life: 65 ms

He-like CB:~10ms

Bare CB: ~100 ms

Electron Beam Ion Trap (EBIT)

confinement:

- axial by electrostatic field
- radial by electron beam + B- field

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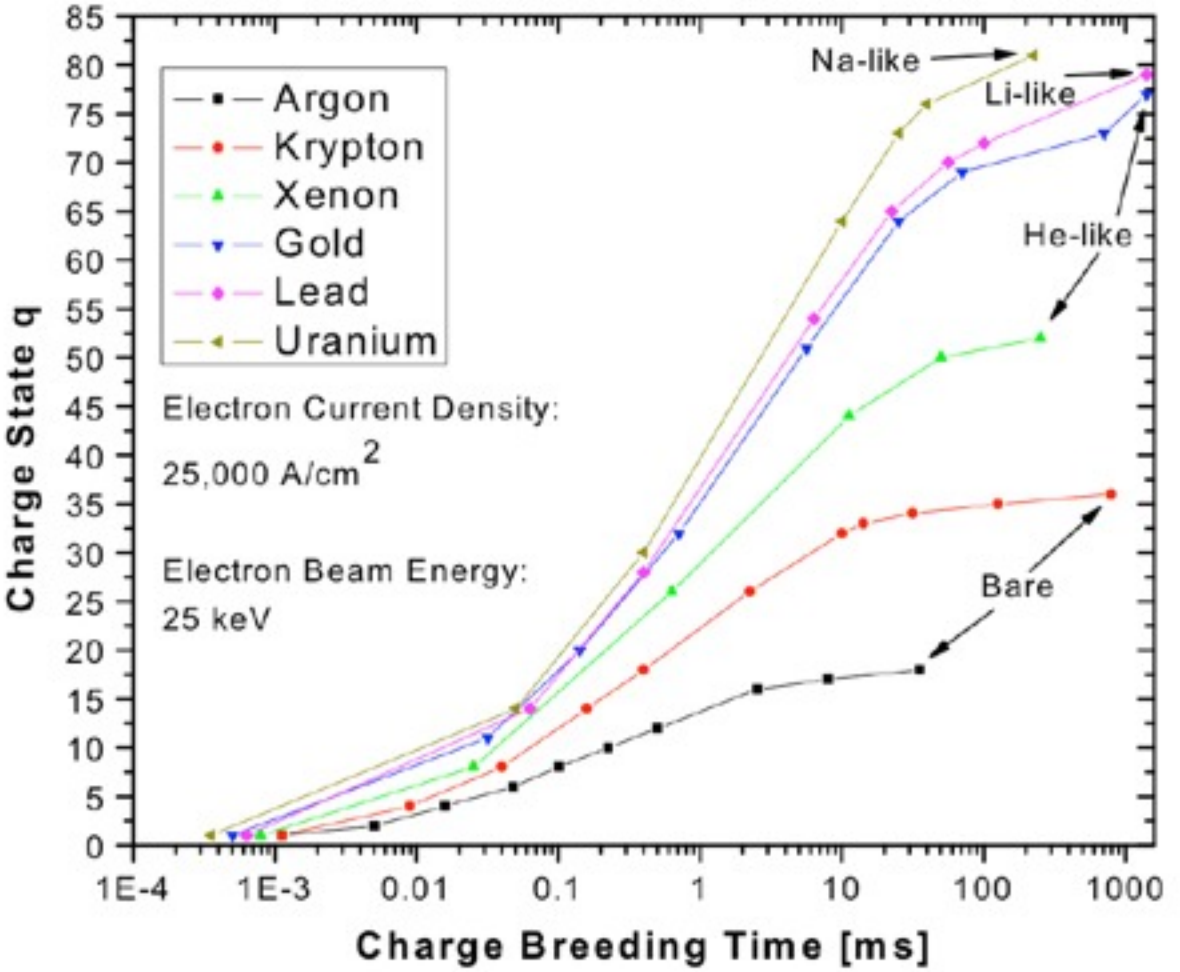

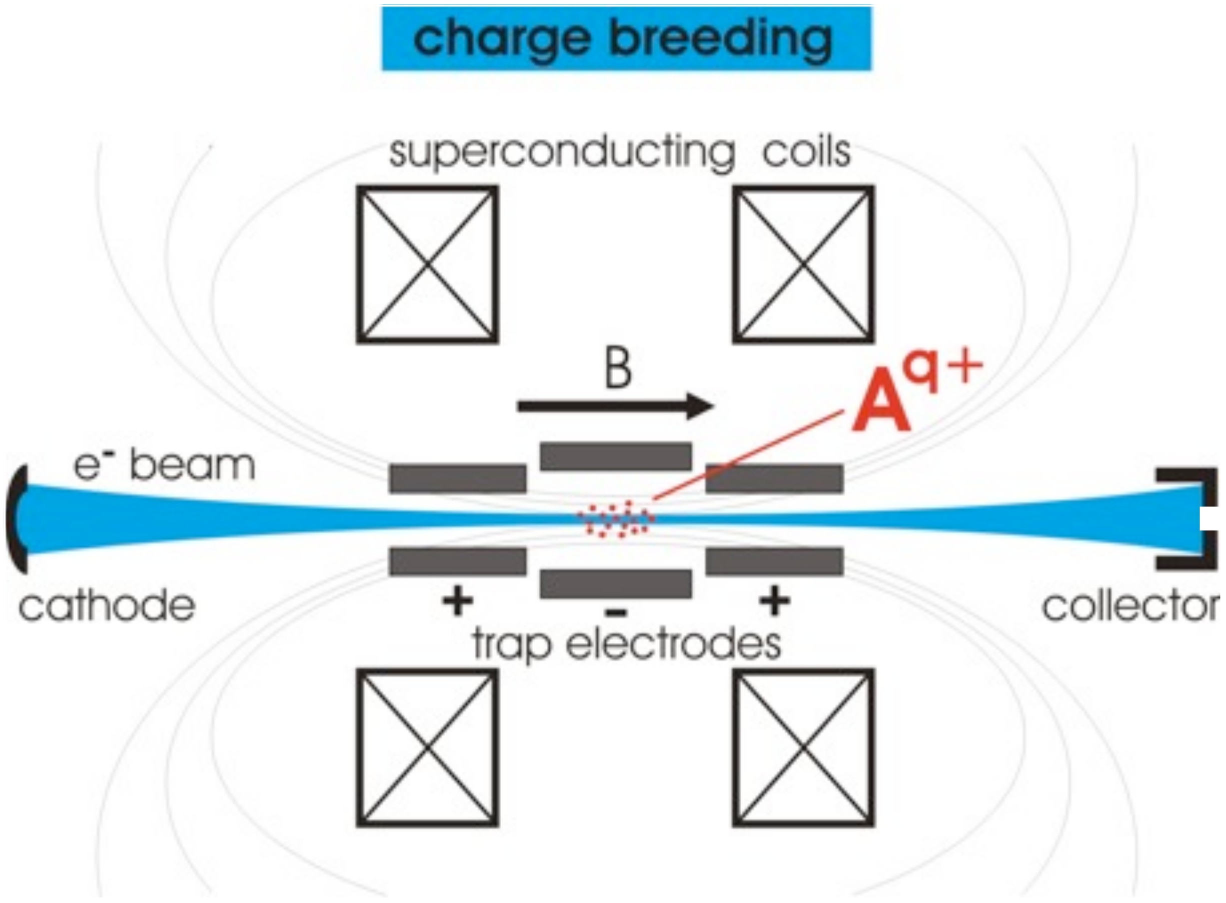

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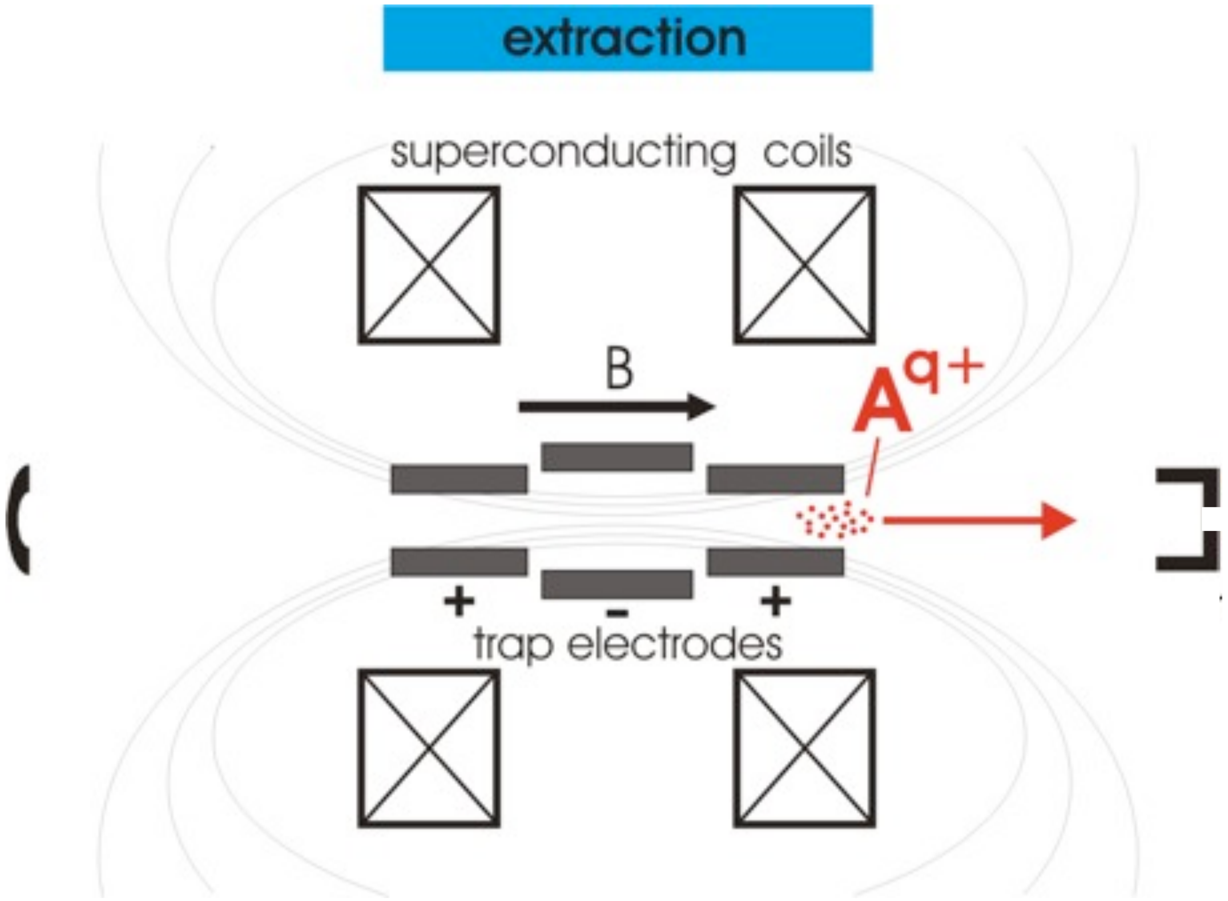

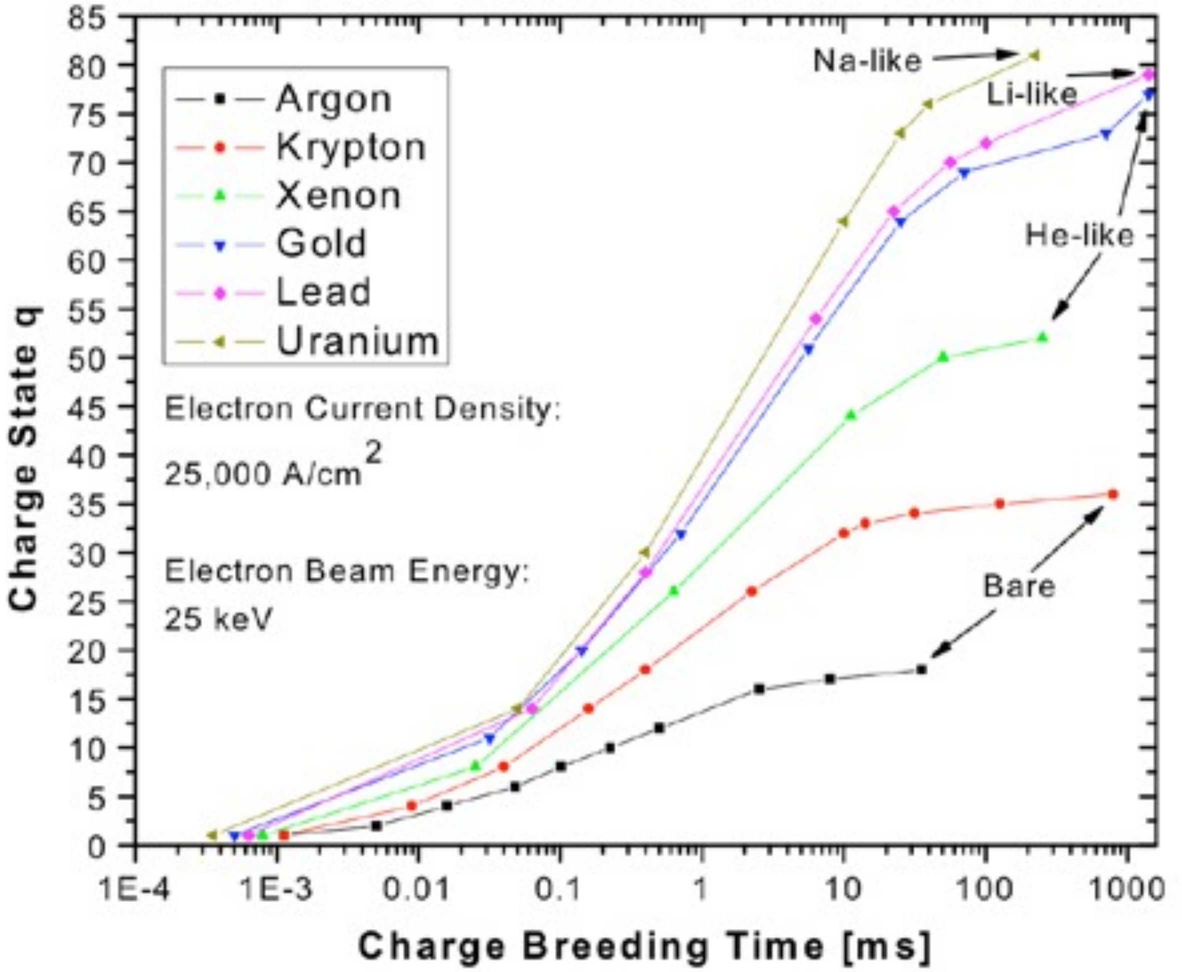

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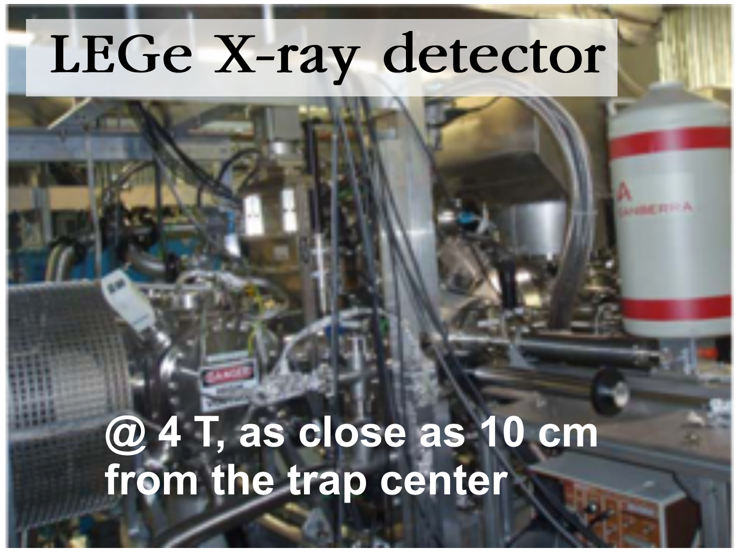
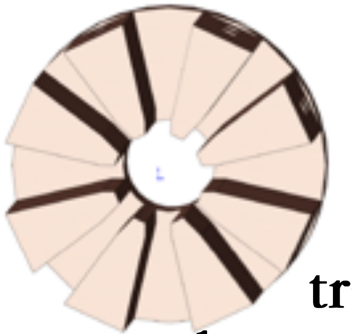
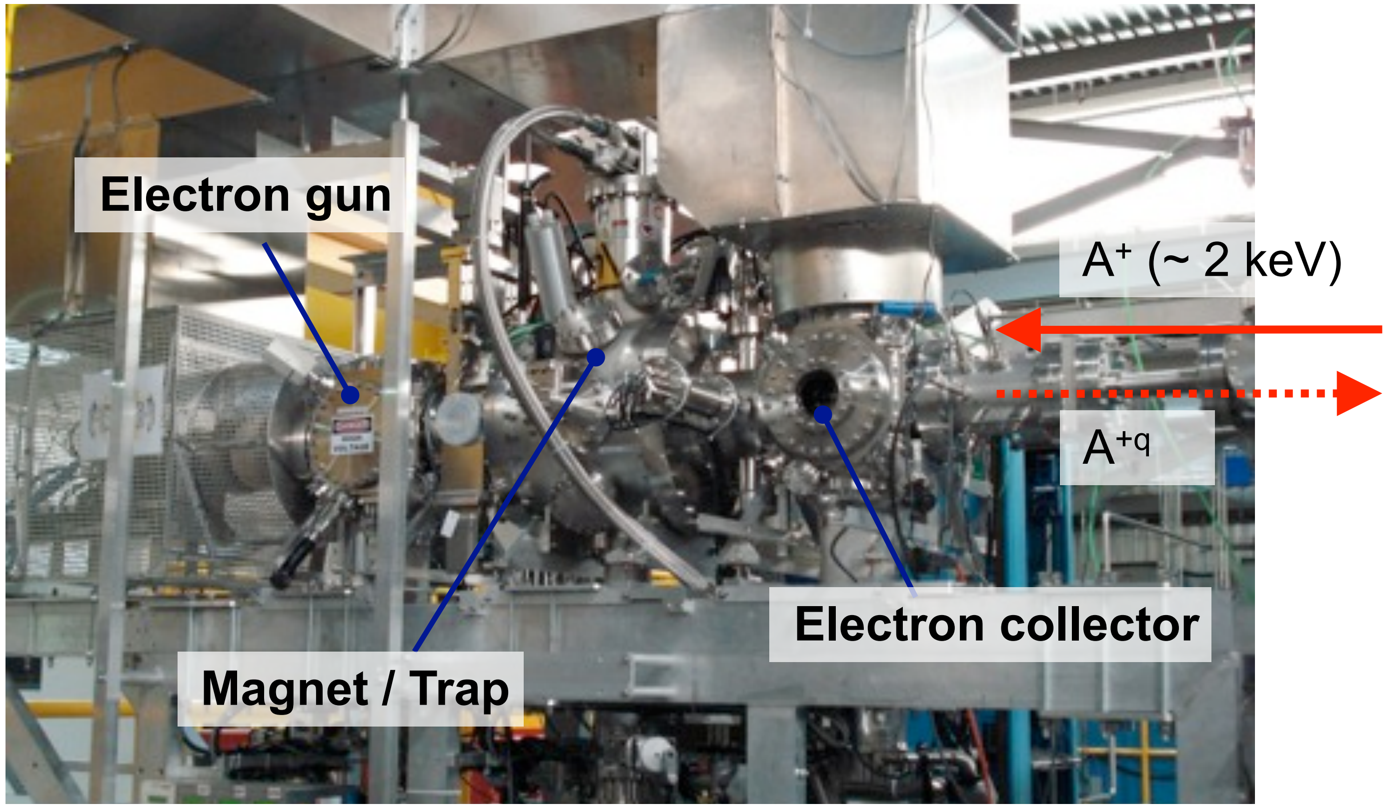
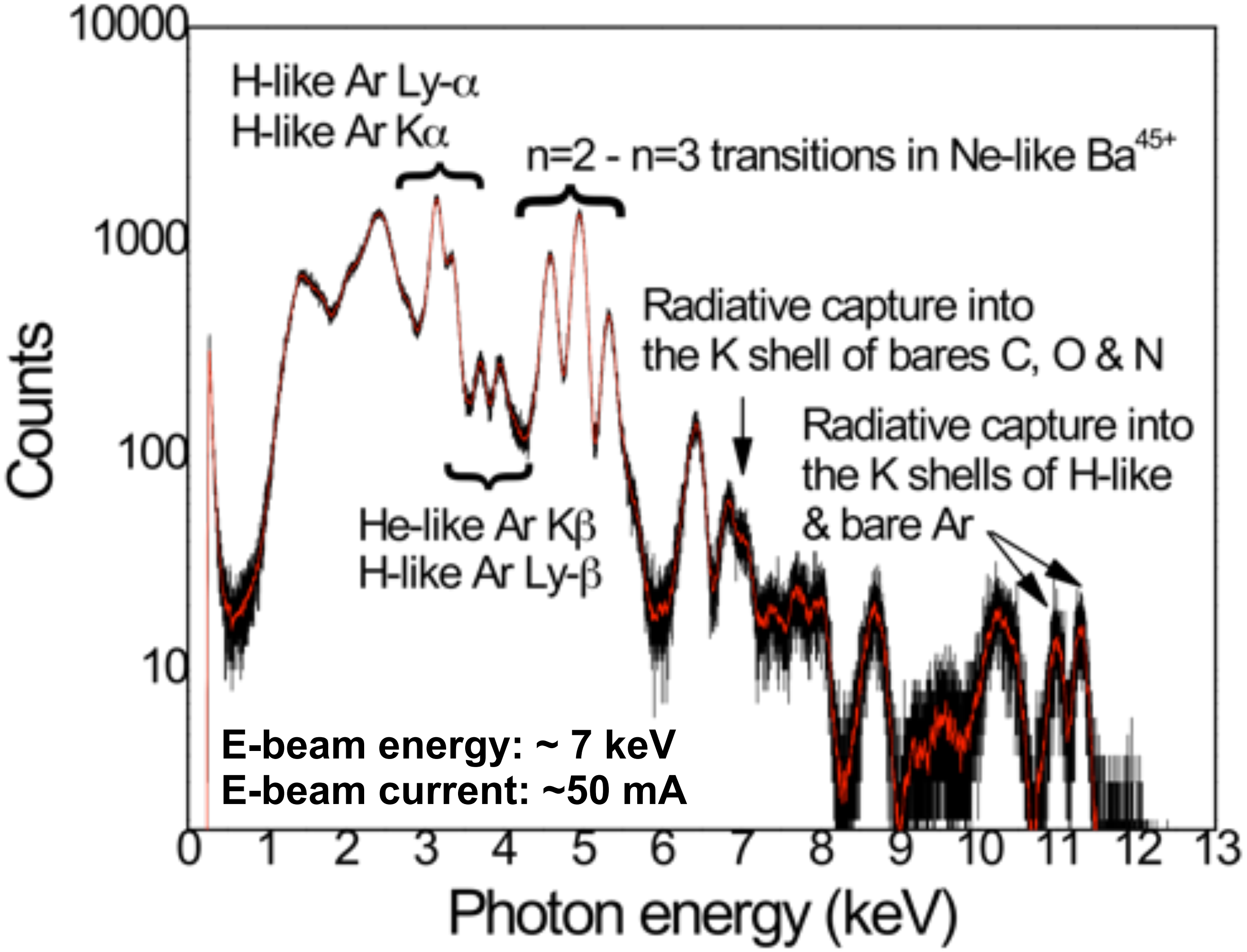
TRIUMF ISAC

TITAN's EBIT





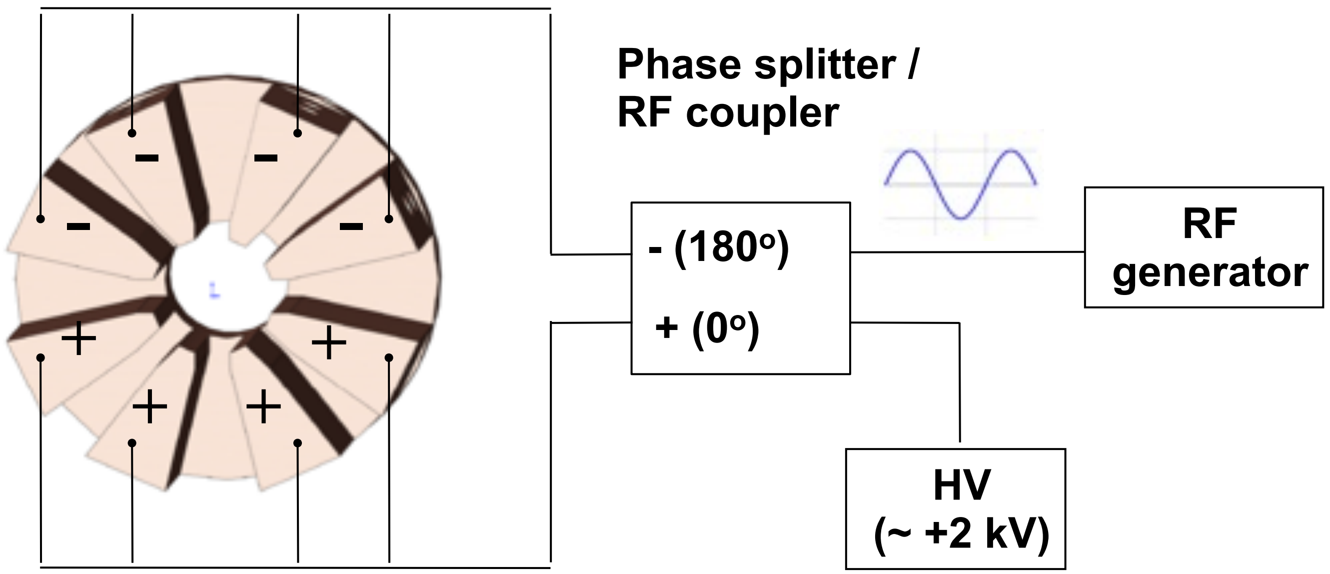




X-ray spectroscopy:

- diagnostics tool for charge breeding
- EC-BR measurement

Dipole Cleaning in EBIT


Phase splitter /
RF coupler

- (180°)

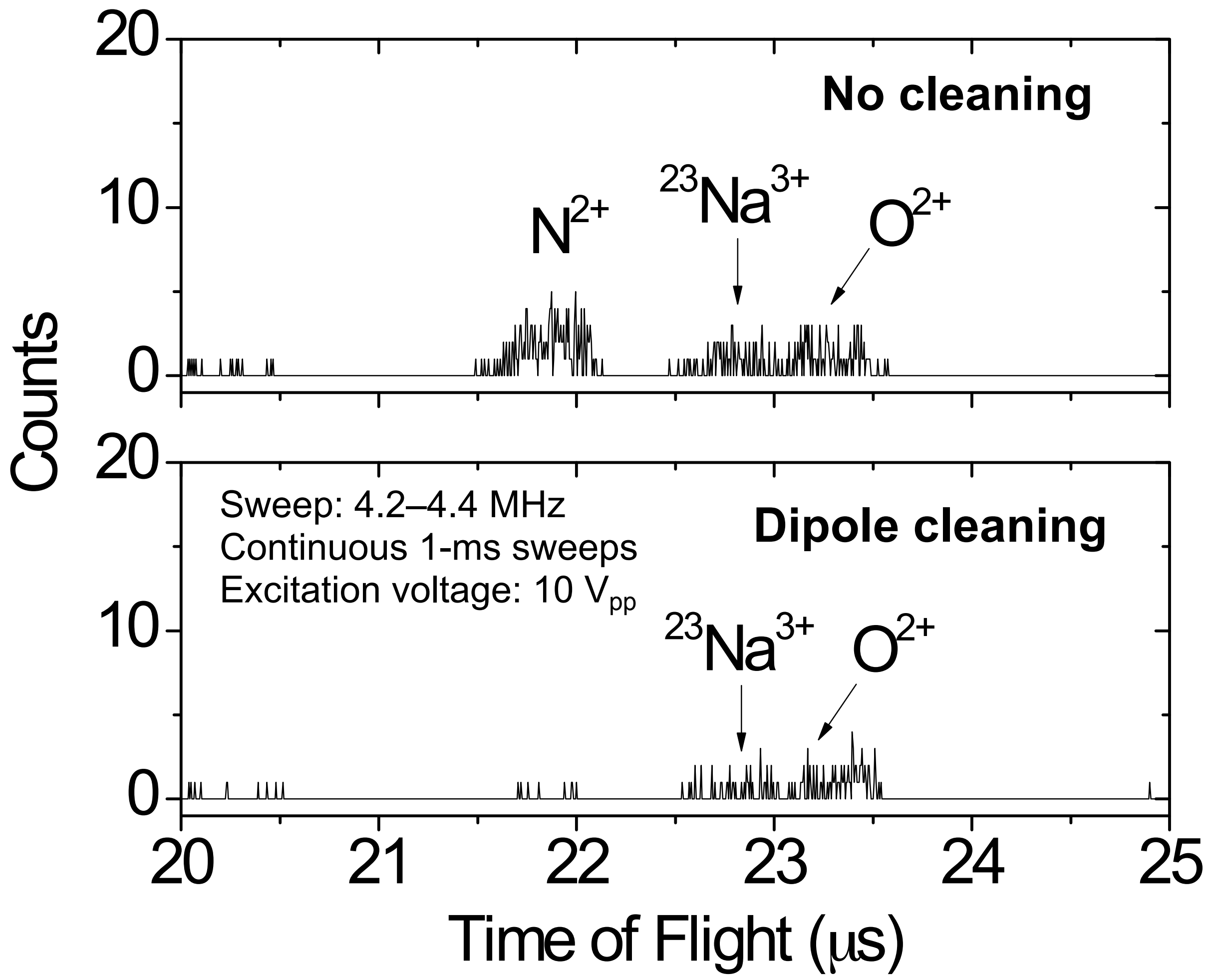
+ (0°)

RF
generator

HV
(~ +2 kV)

<u>ion trap technique to get rid of unwanted species:</u>

- apply RF at reduced cyclotron frequency of species (eigen-motion)
- increases radius until ions leave the trap

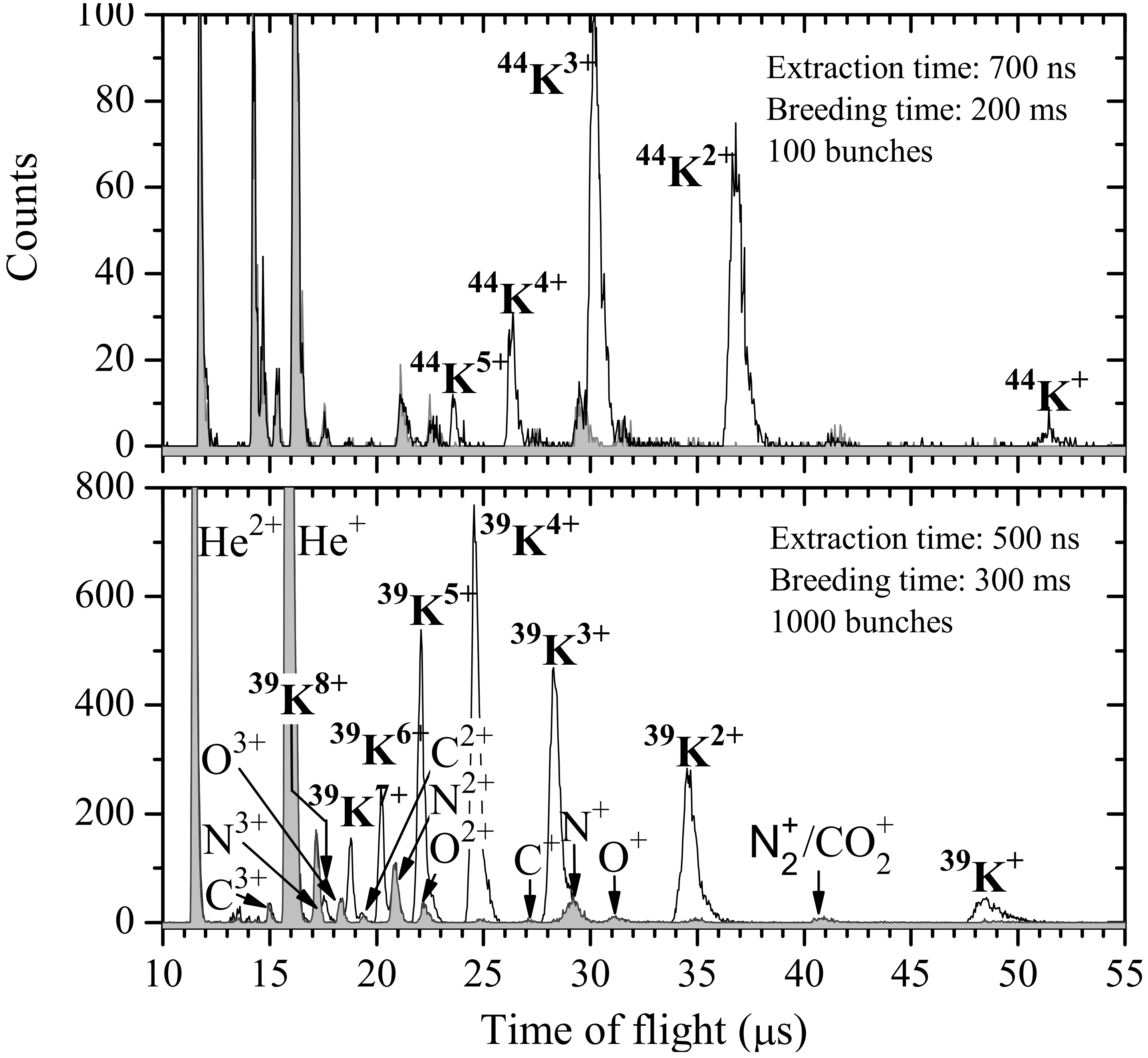


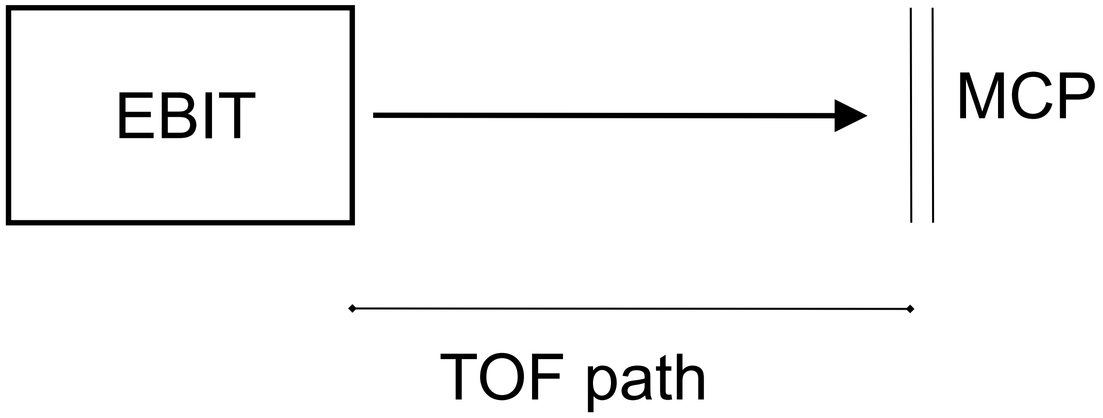
Sweep: 4.2–4.4 MHz
Continuous 1-ms sweeps
Excitation voltage: 10 V_{pp}

E-beam energy: 3.880 keV
E-beam current: ~5 mA
Breeding time: 100 ms
Extraction (dump) time: 1 ms
(E-beam switched)

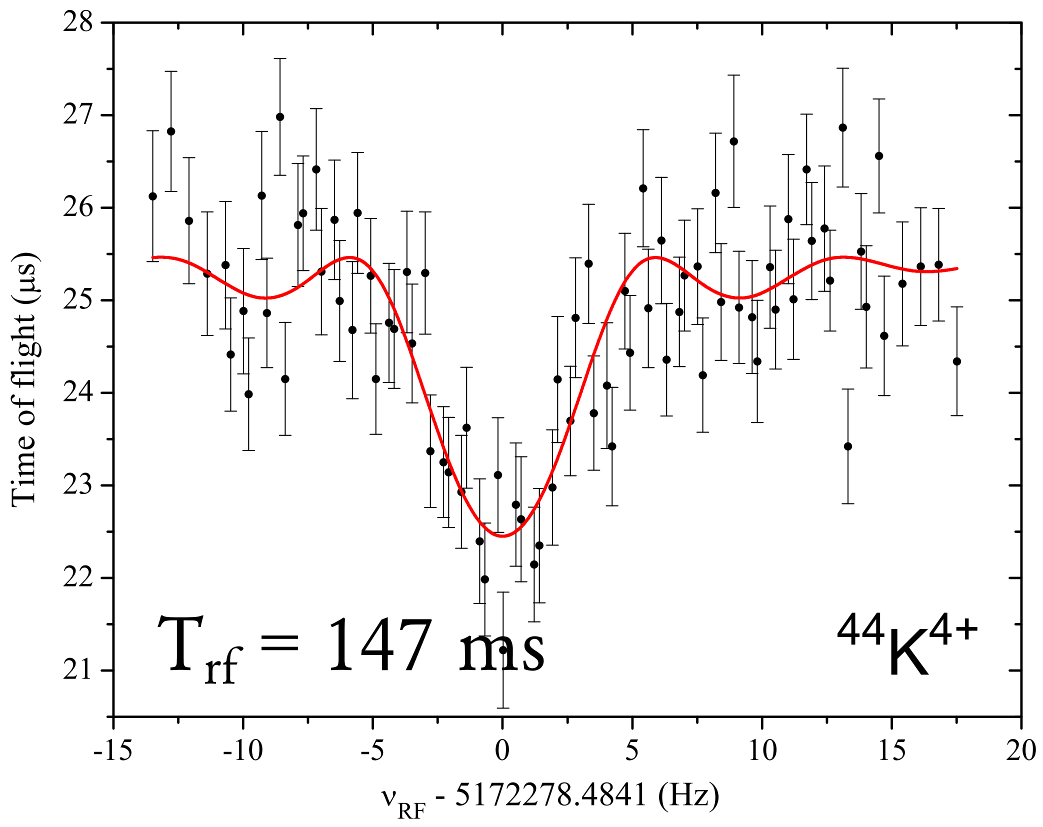
Milestone in Charge Breeding

TITAN: only facility with online charge bred ions (HCI) worldwide





TOF: starts with extraction from EBIT



A. Lapierre et al., in preparation

Milestone in Charge Breeding

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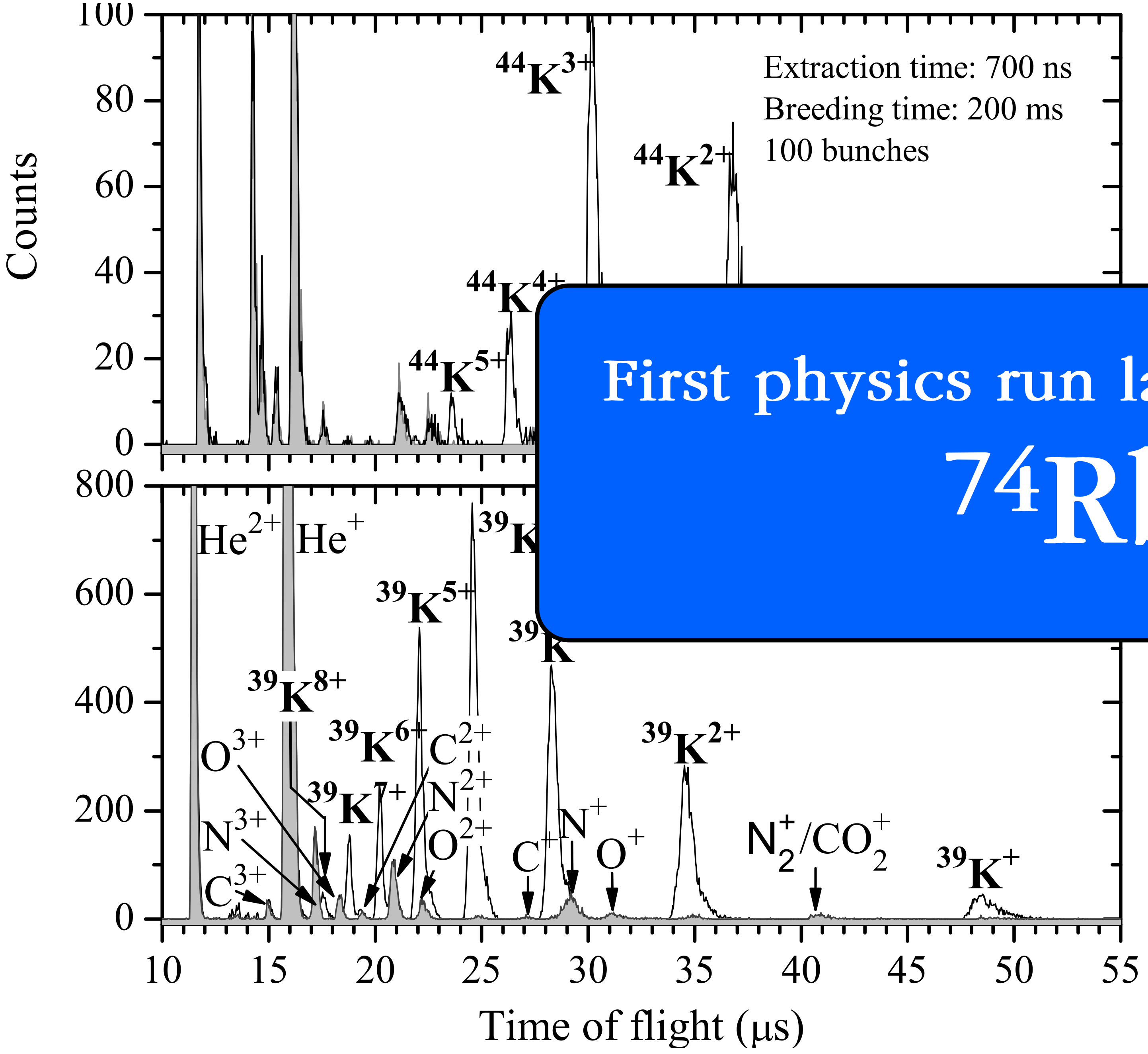
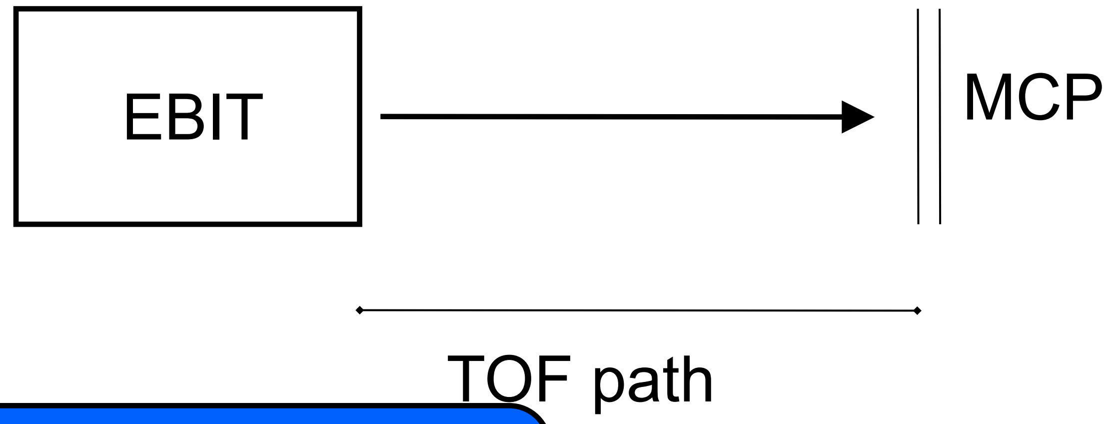
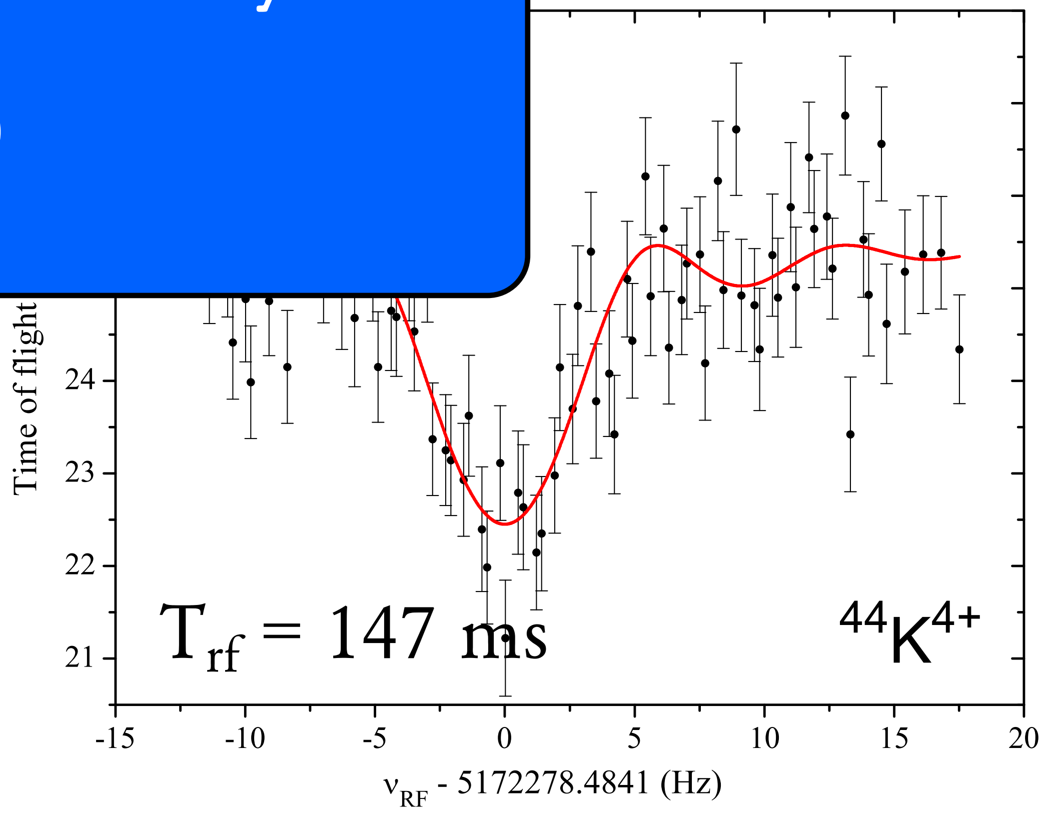




extraction from EBIT



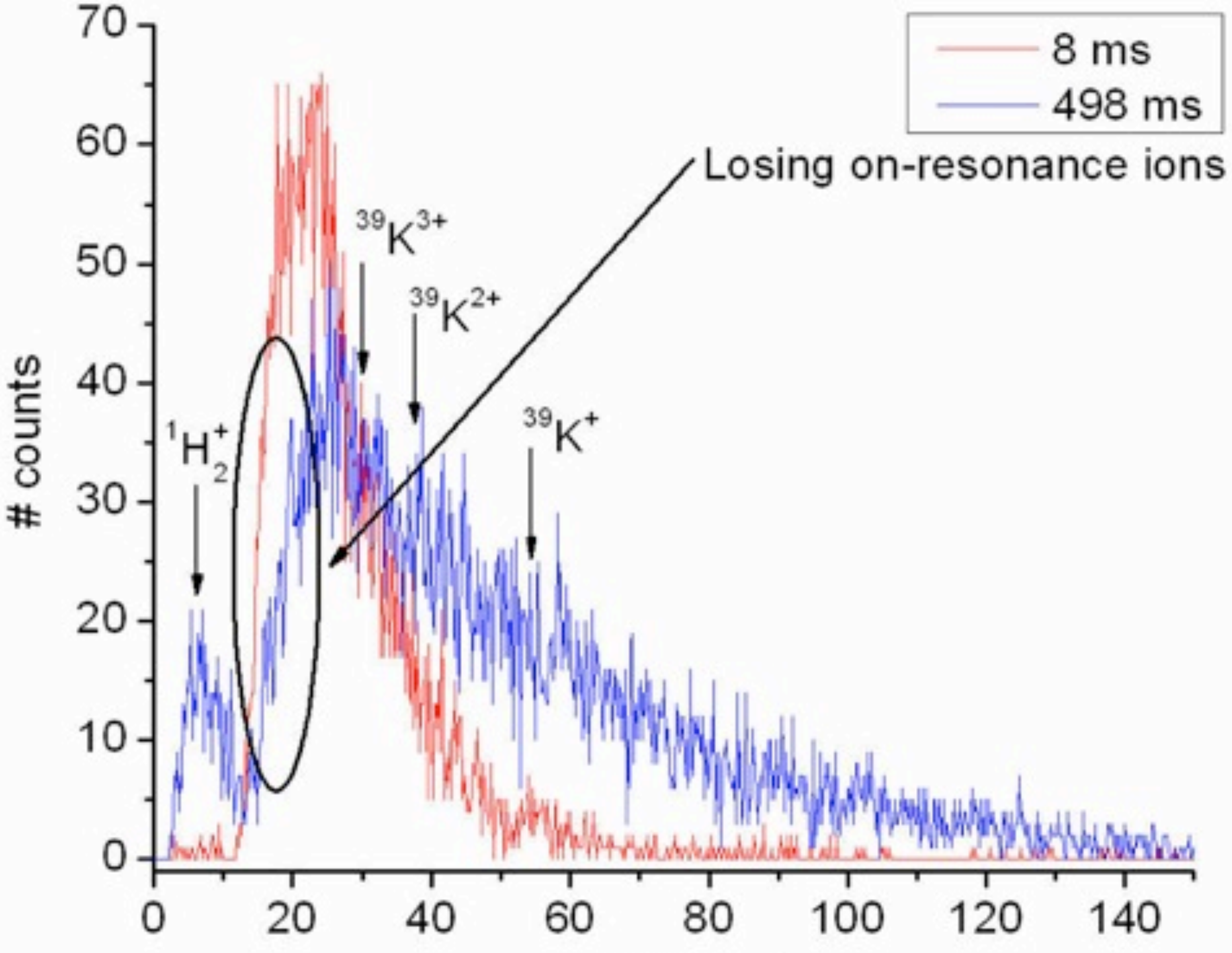
First physics run later this year:

^{74}Rb

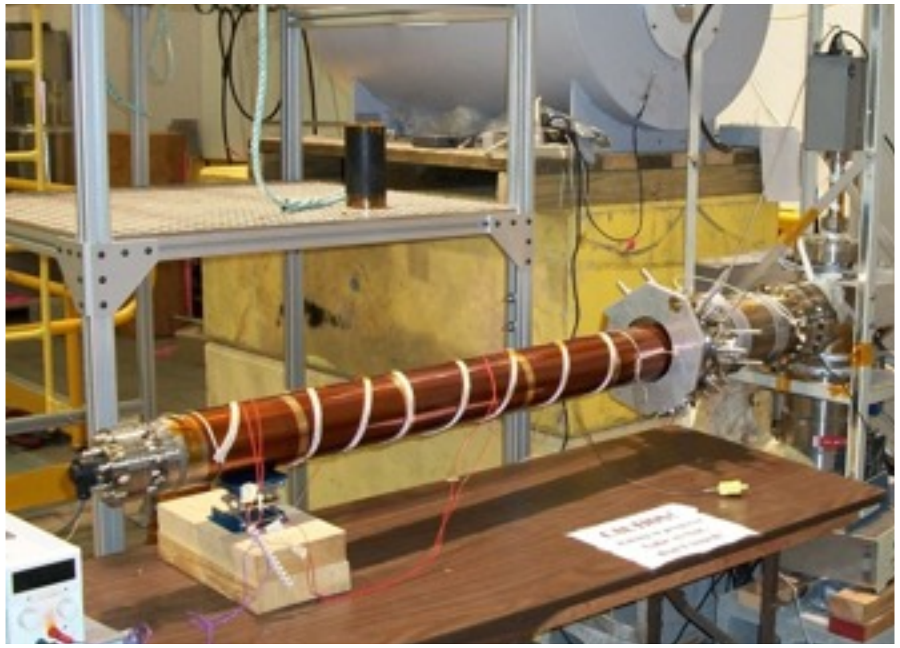
A. Lapierre et al., in preparation

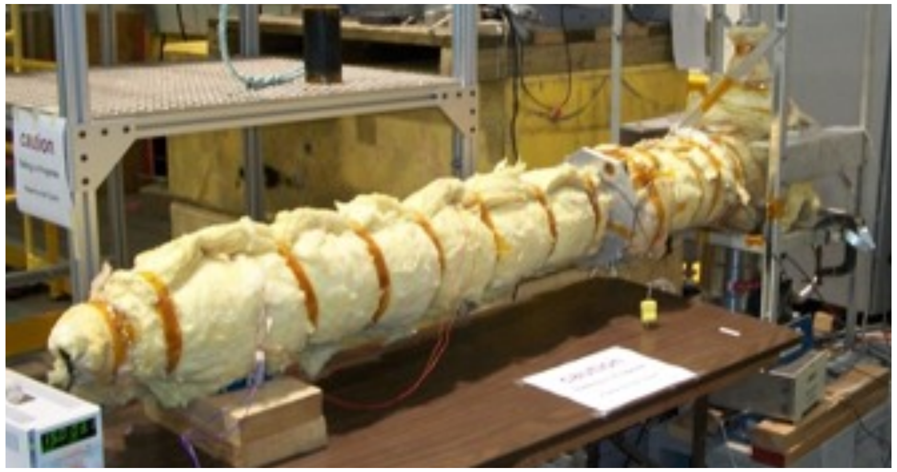
MPET Vacuum

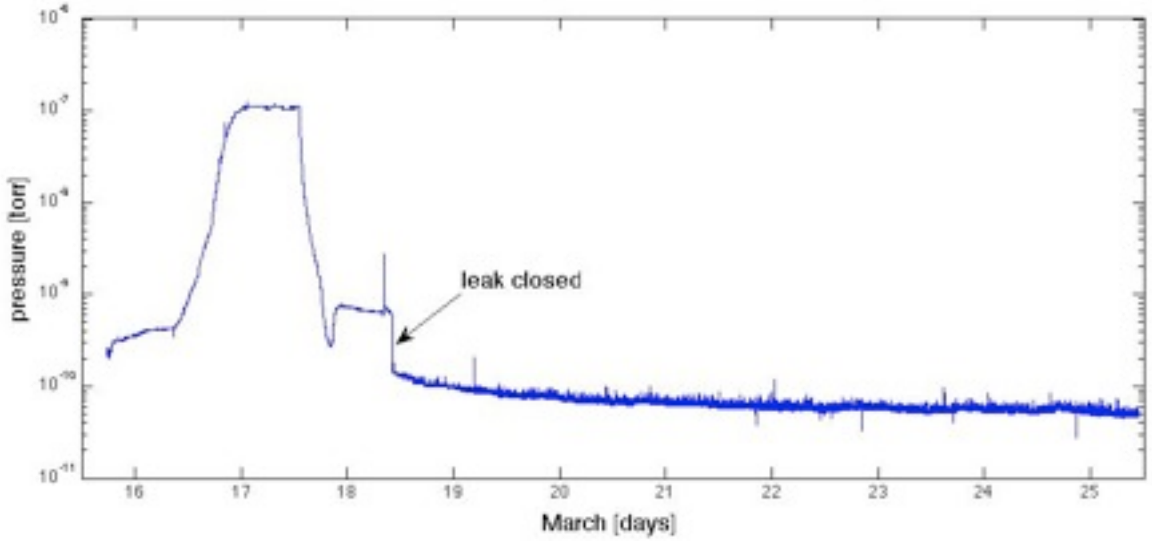
$^{39}K^{4+}$ @$1.2 \cdot 10^{-9}$ Torr



(after extraction)







EC-BR measurements
and
$2\nu\beta\beta$ Matrix Elements

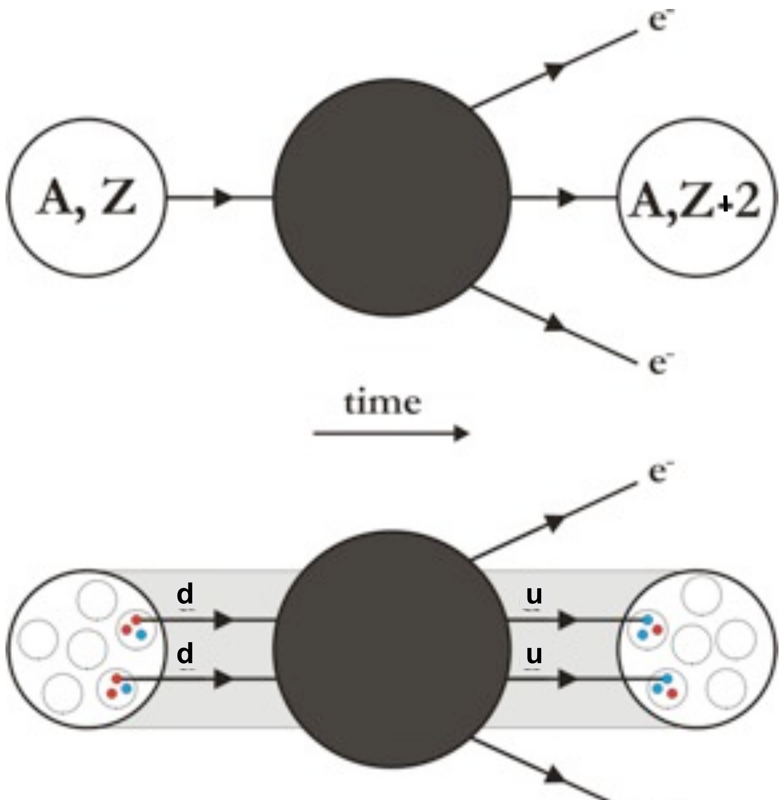
Scientific Motivation

neutrino oscillation experiments:

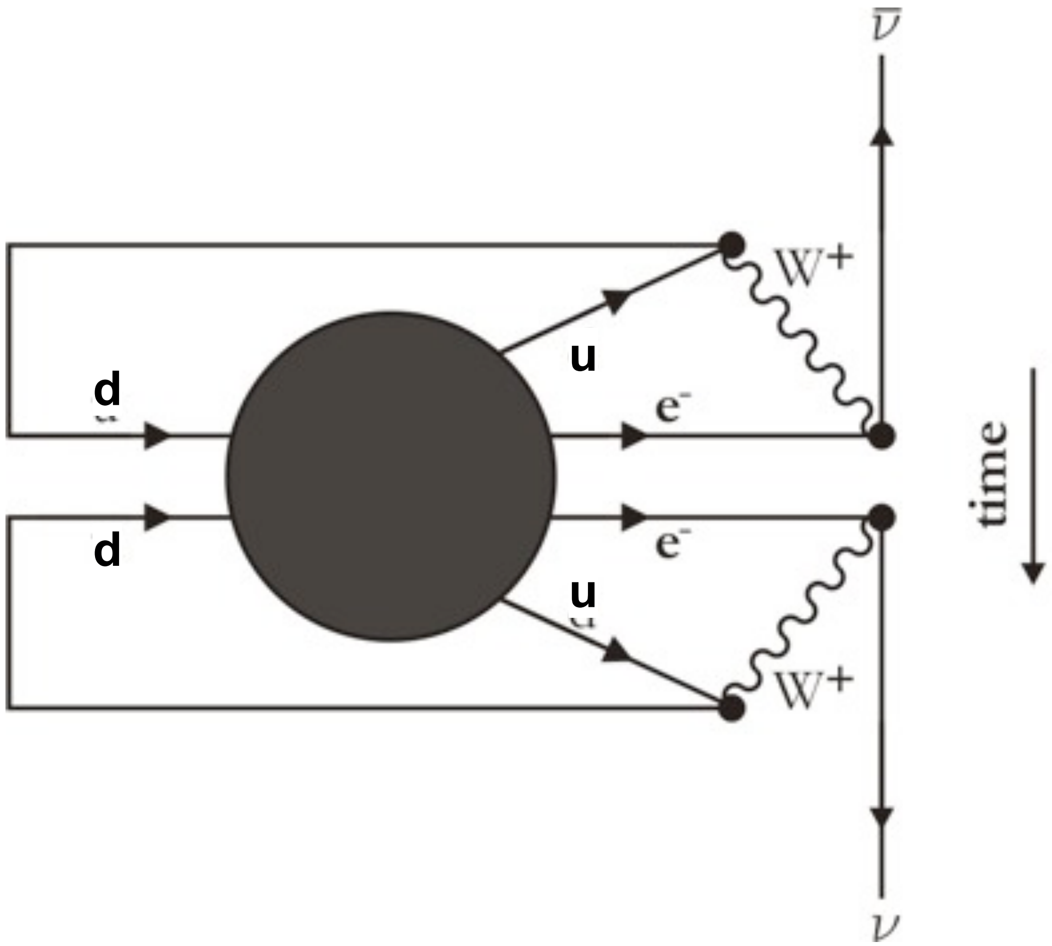
- neutrino massive
- BUT: no information about absolute mass scale & type of mass

absolute scale:

- electron endpoint energy in beta decay
- astrophysical limit
- 0νββ decay



0νββ decay



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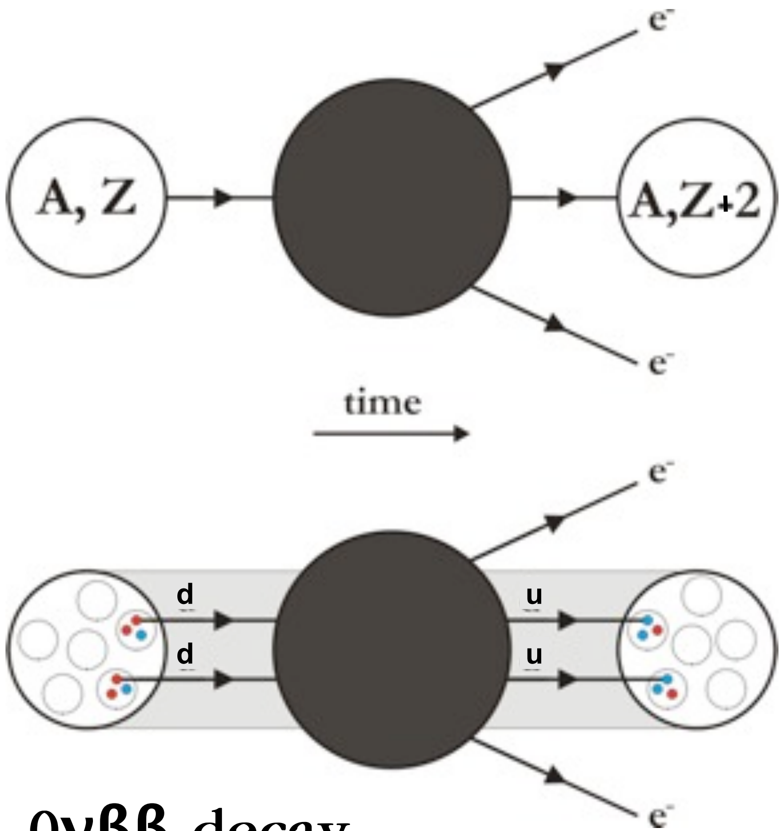
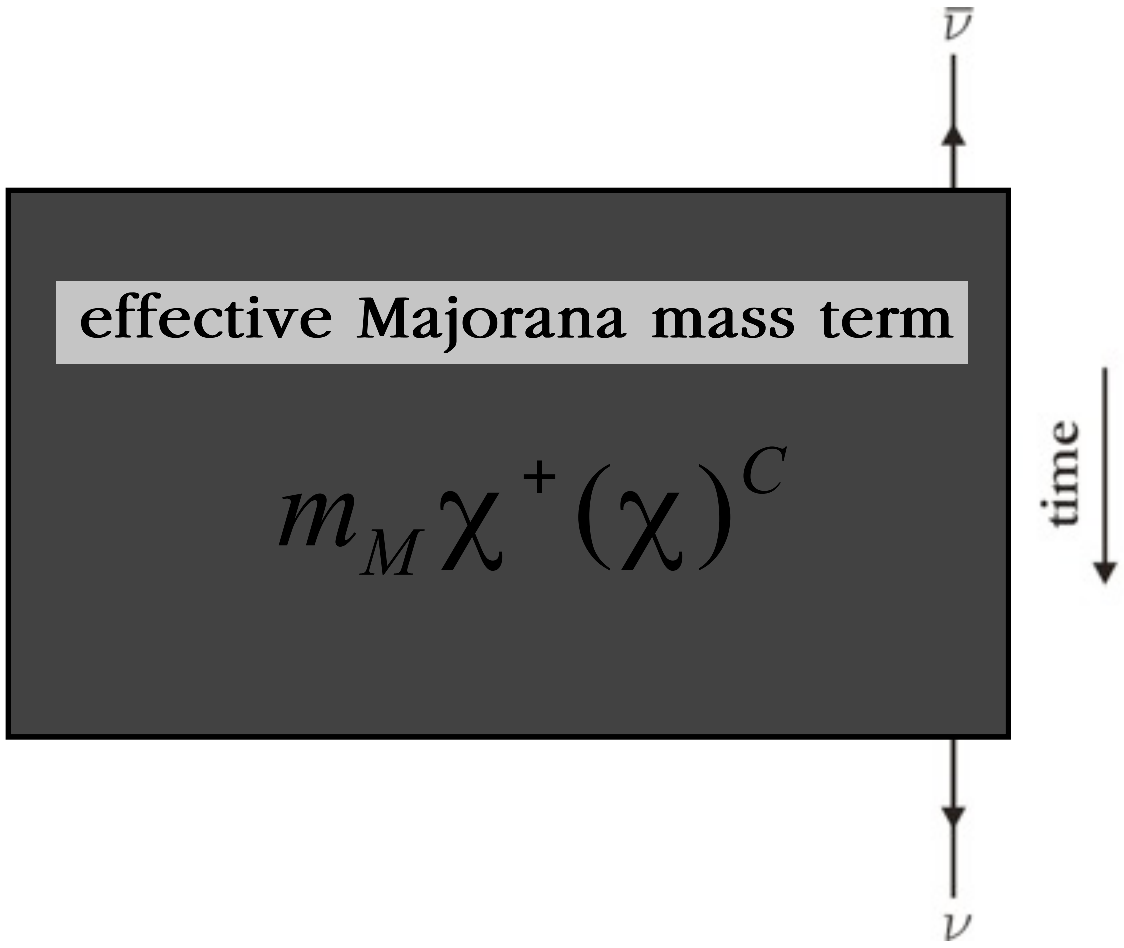


0νββ decay



effective Majorana mass term

$$m_M \chi^{+} (\chi)^{C}$$

Nuclear Matrix Element

0νββ decay rate: $\Gamma = G\,|M|^2 \left\langle m_{\nu e} \right\rangle^2$

phase space factor

effective Majorana mass $\left\langle m_{\nu e} \right\rangle = \left| \sum_i U_{ei}^2 m_i \right|$

nuclear matrix element:

<u>theoretical models:</u>

- proton-neutron Quasiparticle Random Phase Approximation (pnQRPA)
- nuclear shell model
- interacting boson model

Nuclear Matrix Element

$0\nu\beta\beta$ decay rate: $\Gamma = G\,|M|^2 \langle m_{\nu e}\rangle^2$

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effective Majorana mass

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theoretical models:

- proton-neutron Quasiparticle Random Phase Approximation (pnQRPA)
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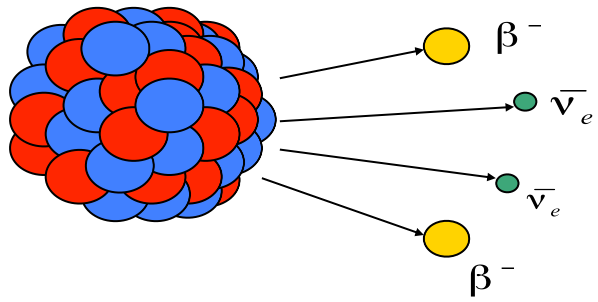
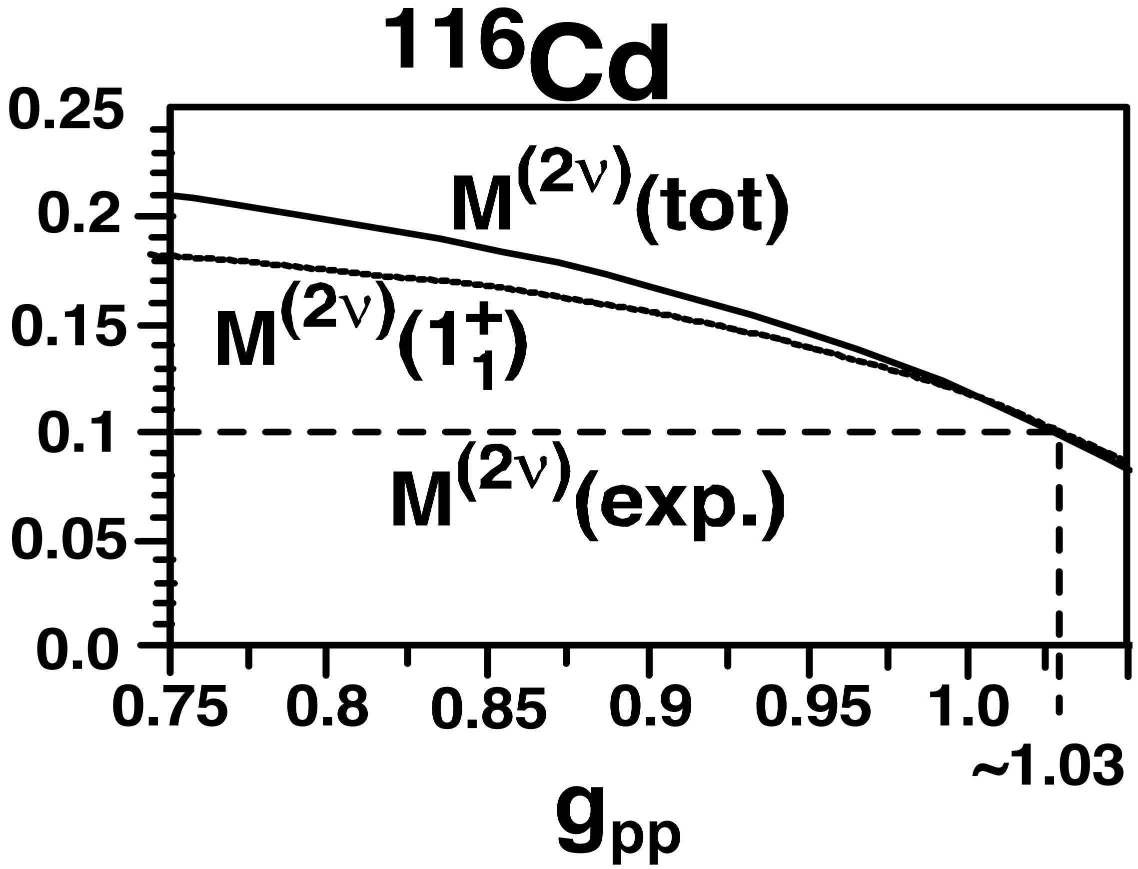
- adjustable particle-particle parameter g_{pp}
- fix g_{pp} with $2\nu\beta\beta$ decay (very sensitive on g_{pp})





- $0\nu\beta\beta$ decay much less dependent on g_{pp}

Nuclear Matrix Element

0νββ decay rate: $\Gamma = G\,|M|^2 \left\langle m_{\nu e} \right\rangle^2$

phase space factor

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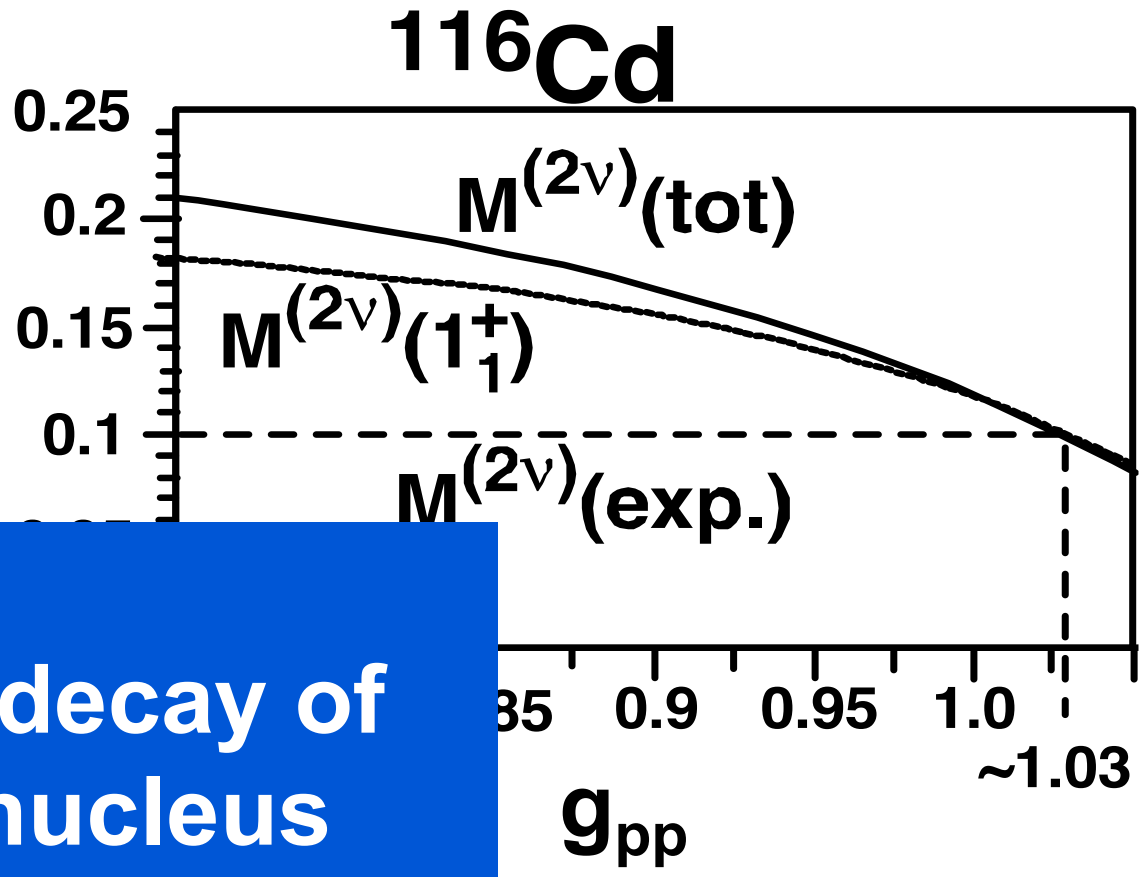
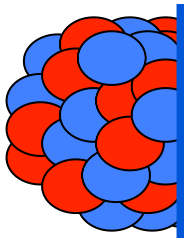




BUT:
problems with decay of intermediate nucleus

- 0νββ decay much less dependent on g_{pp}

New Approach for ECBR

EBIT in Penning trap mode

confinement:

- axial by electrostatic field
- B-field (6 T)

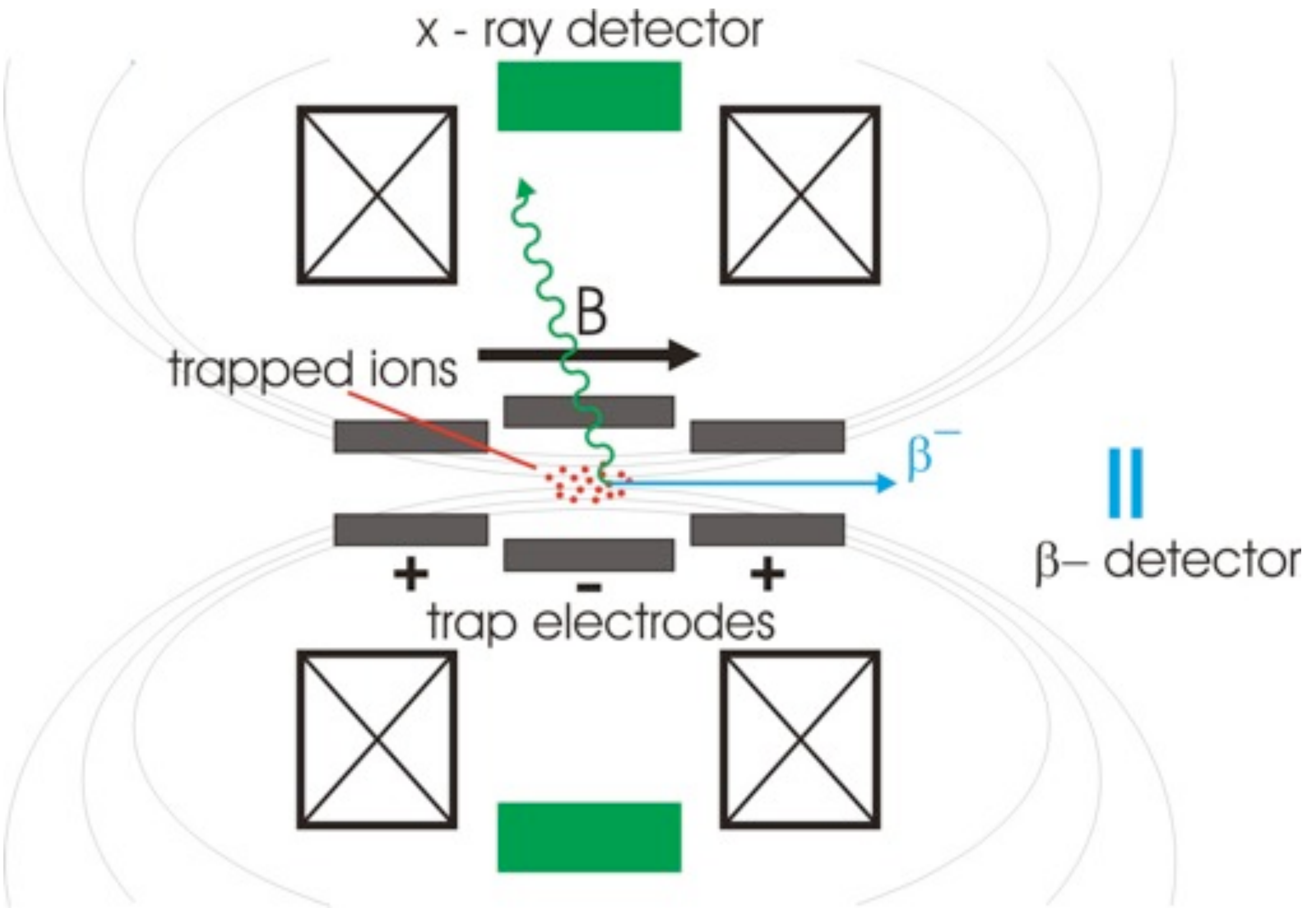
in-trap spectroscopy:

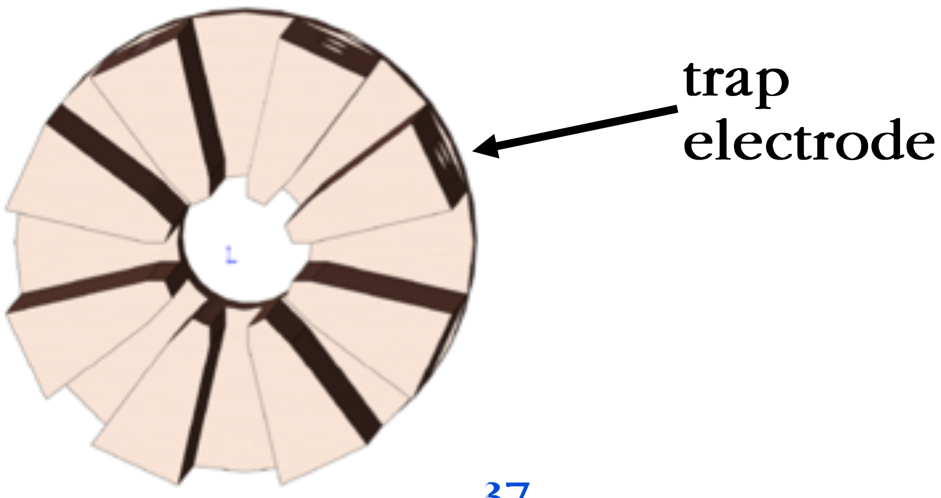
- strong B field spatial separation of X-ray and β-particles
- segmented trapping electrodes → close placement of X-ray detectors
- extract ions after observation time low background
- β-dectector: anti-coincidence

no β - background
no absorption in backing material

J. Dilling et al., Can. J. Phys. 85, 57 (2007)

T. Brunner et al., NIM B 266, 4643 (2008)

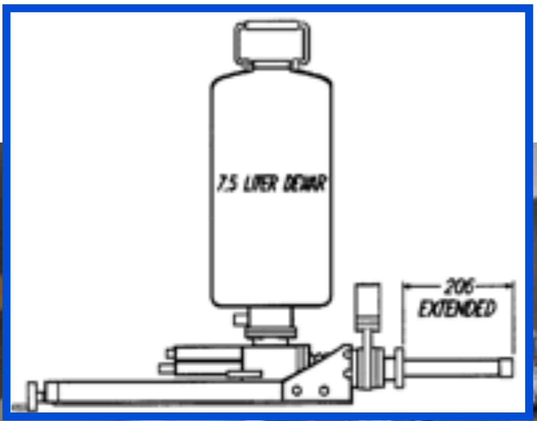




Detector Positions

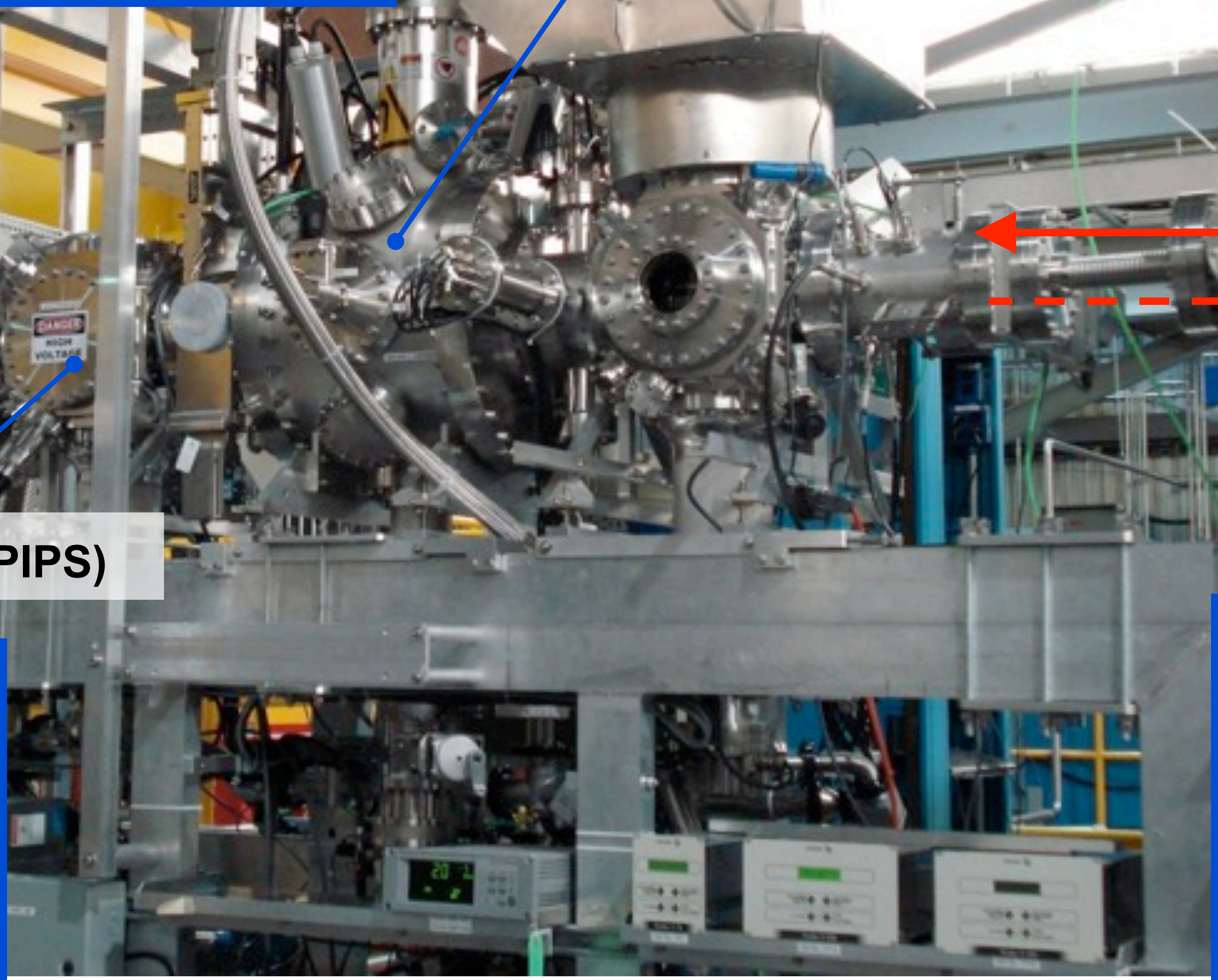
LEGe X-ray detector
in vacuum

@ 4 T, as close as 10 cm away from the trap center



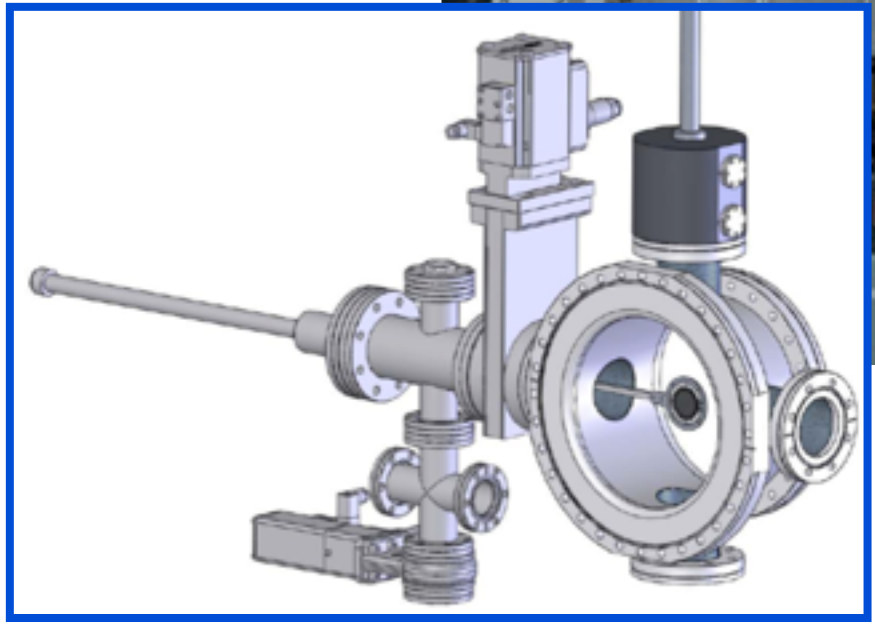
total solid angle: 0.7 %

final: 2.1 %



Injection

Extraction



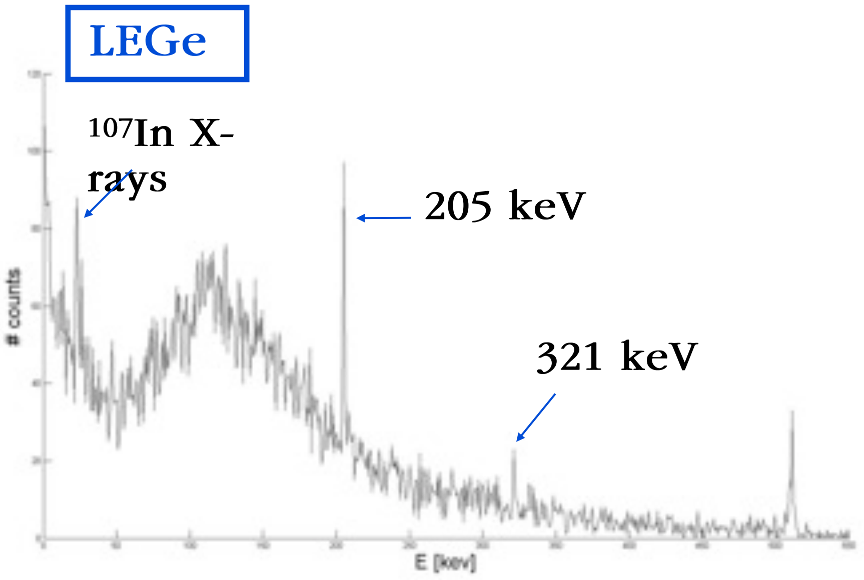
20 % **Coax Ge** external

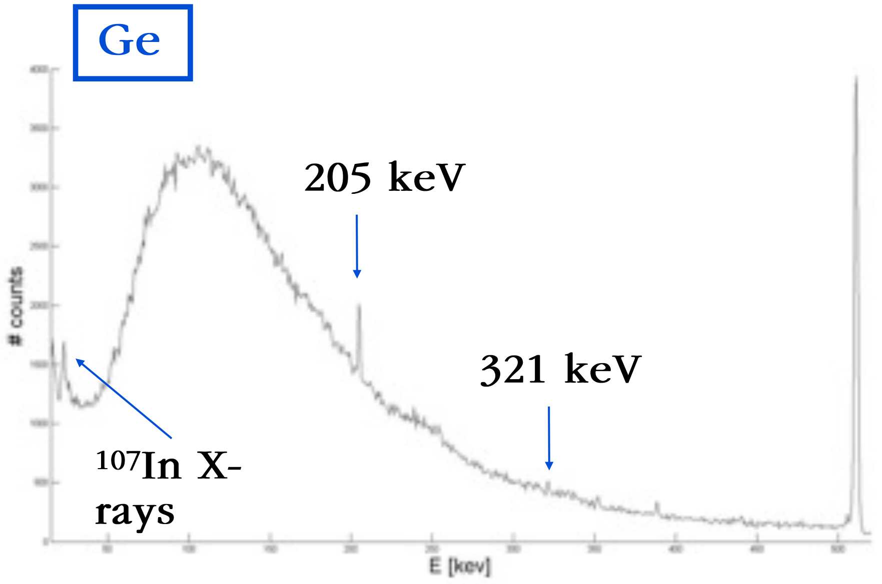
Proof-of-Principle

^{107}In

BR(EC)=(55 ± 20) %
lit =(64 ± 3) %

but problems with ion losses in trap





S. Ettenauer et al., AIP Conf. Proc. 1182(2009)100

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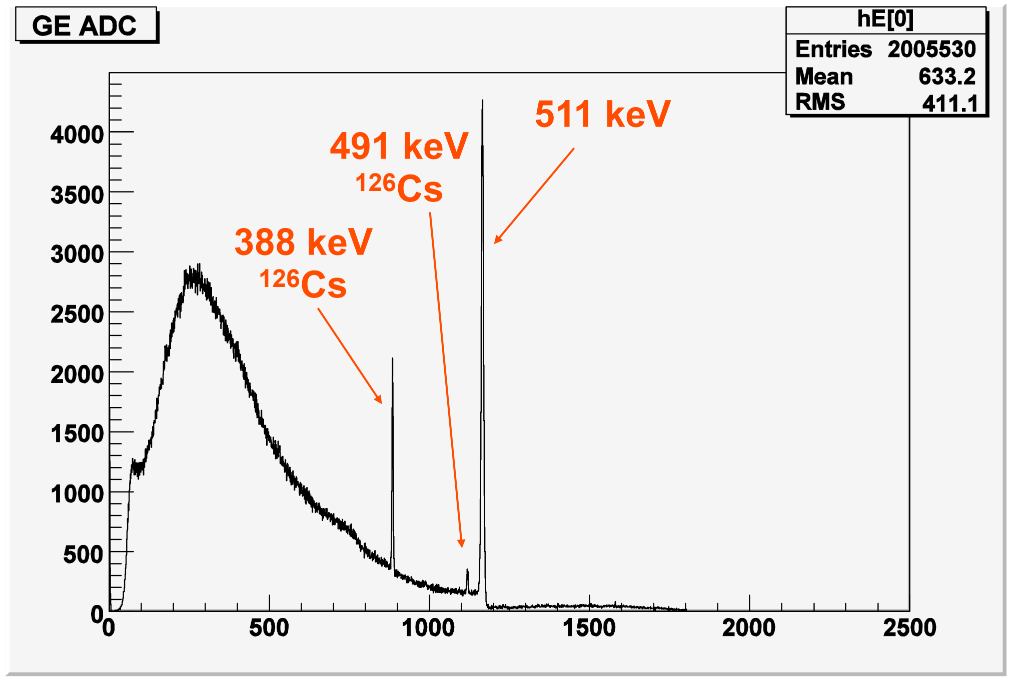
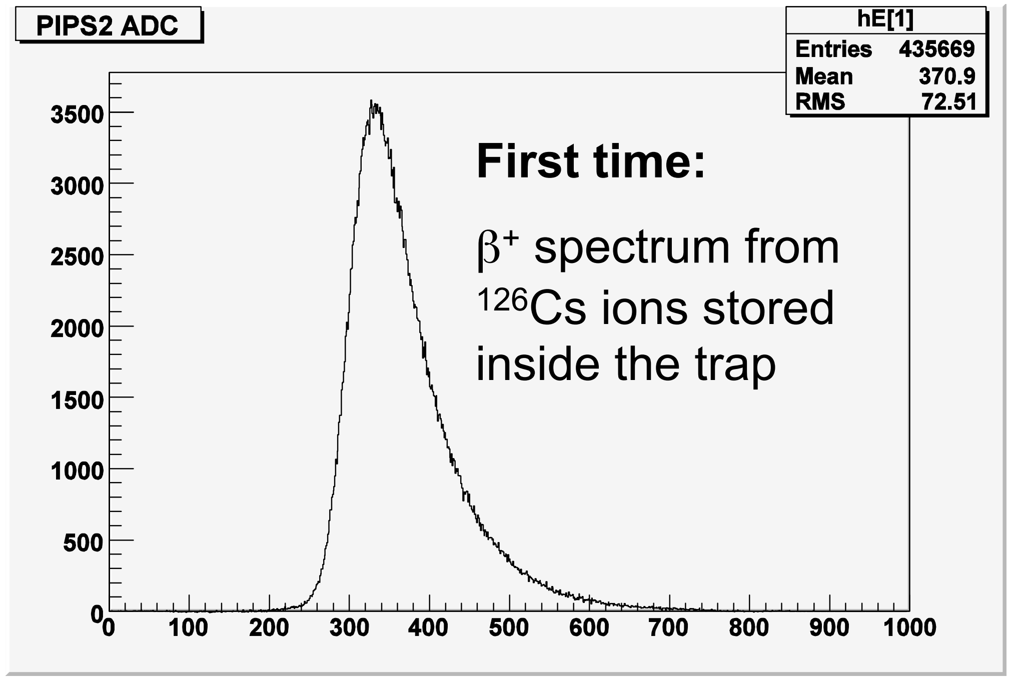
^{126}Cs





First time:

β^+ spectrum from ^{126}Cs ions stored inside the trap

preliminary

Proof-of-Principle

^{107}In

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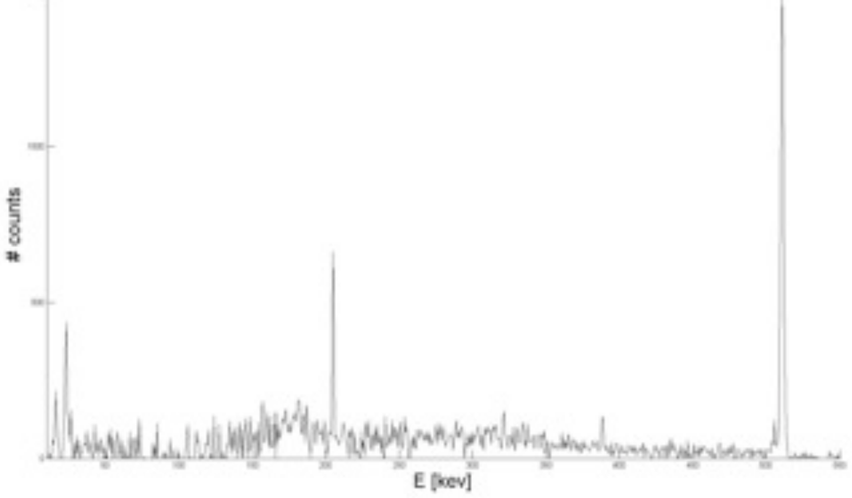
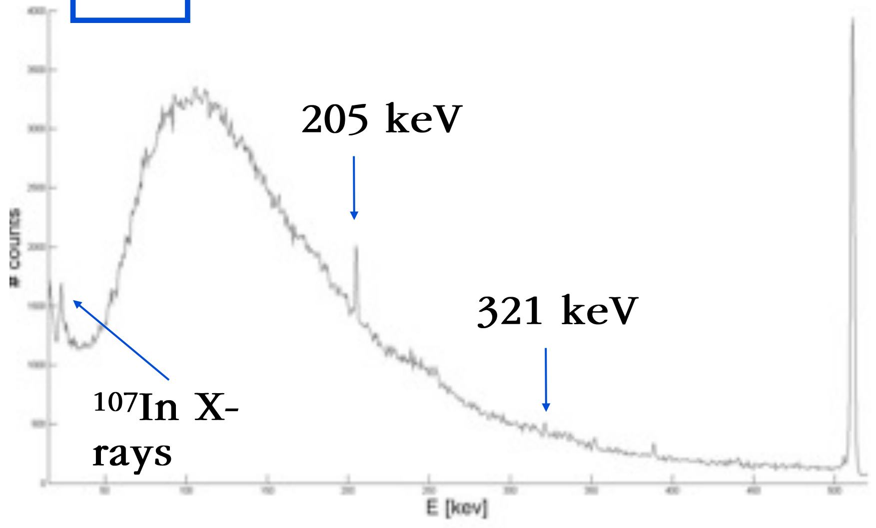
lit =(64 ± 3) %

but problems with ion losses in trap

Ge 'Background' subtracted



Ge



S. Ettenauer et al., AIP Conf. Proc. 1182(2009)100

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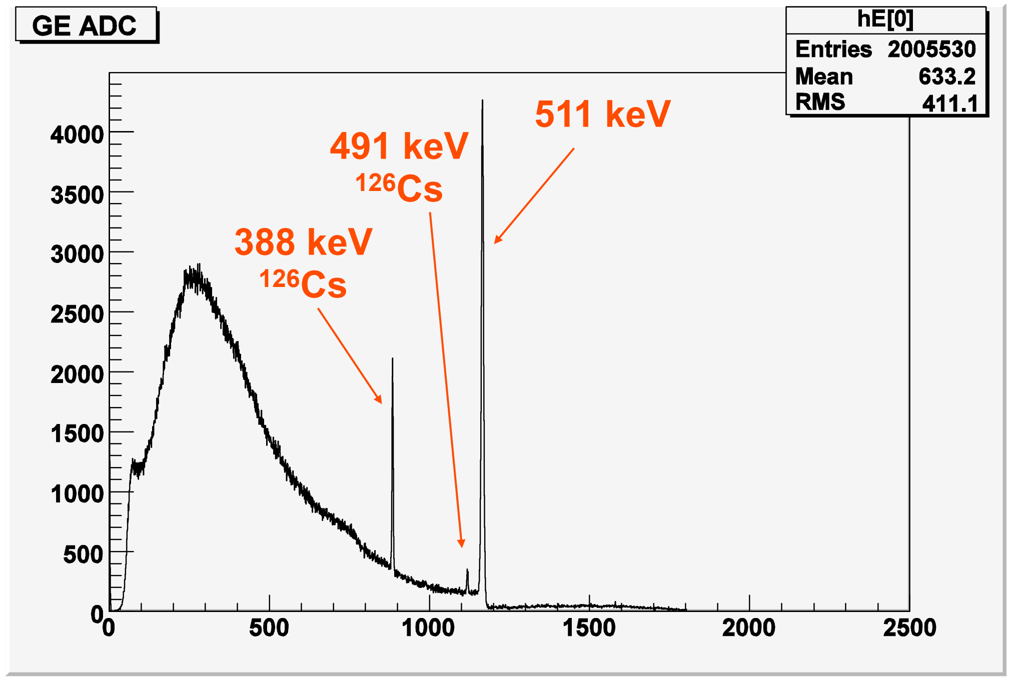

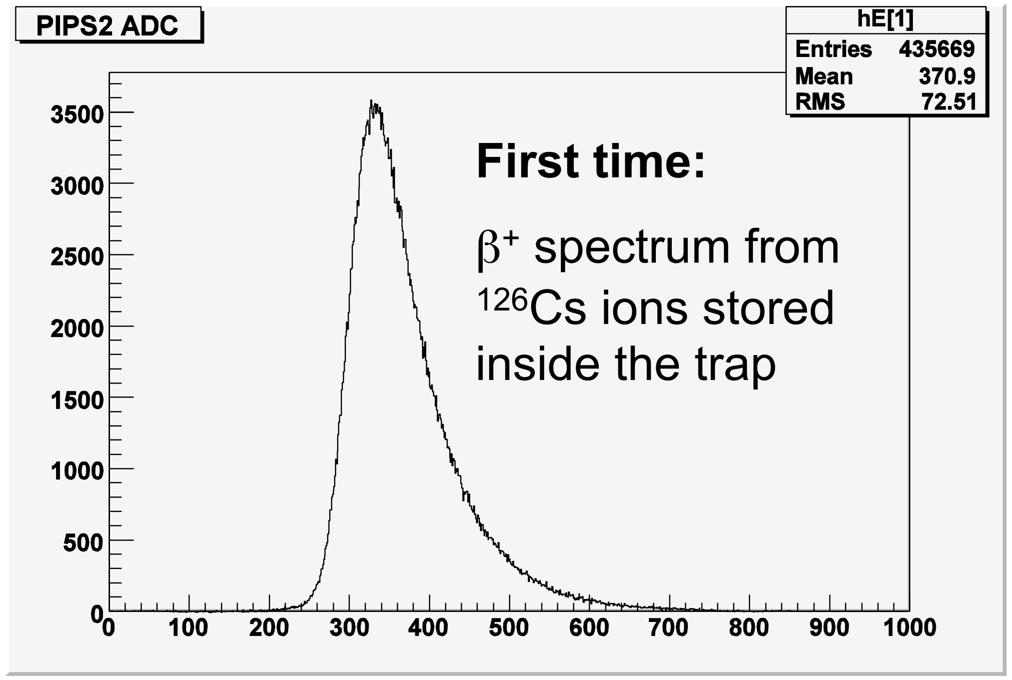

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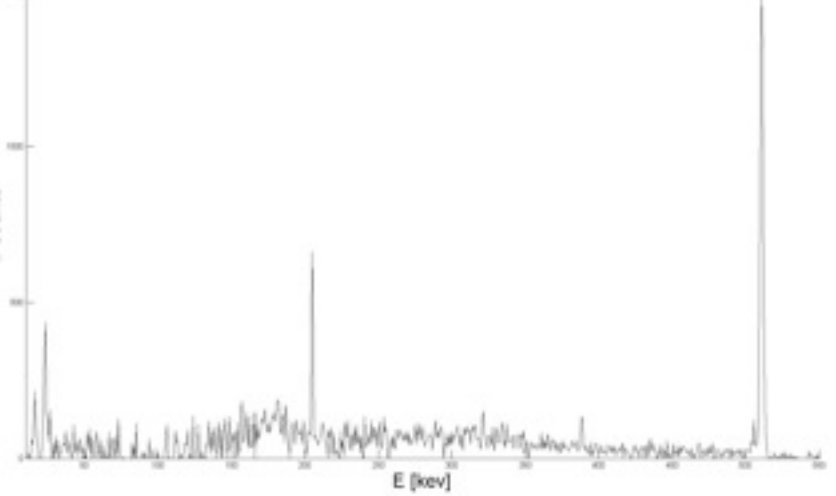
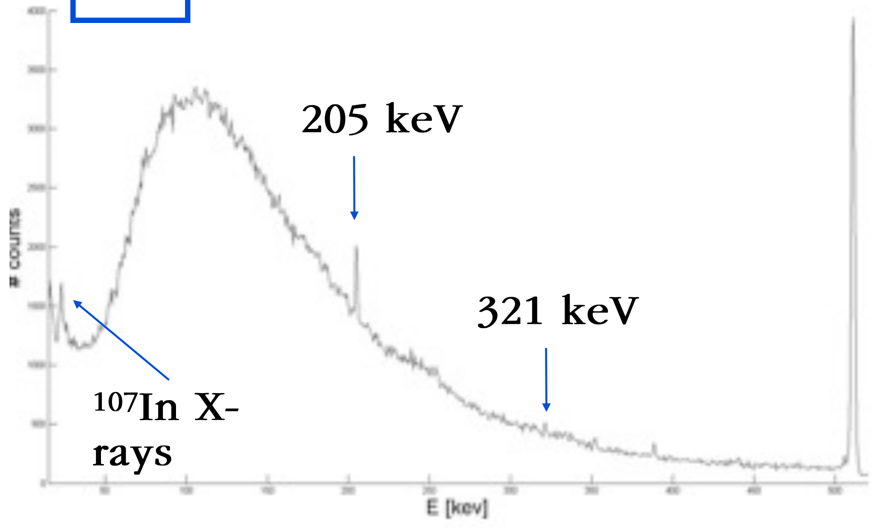


Ge



205 keV

321 keV

^{107}In X-rays

S. Ettenauer et al., AIP Conf. Proc. 1182(2009)100

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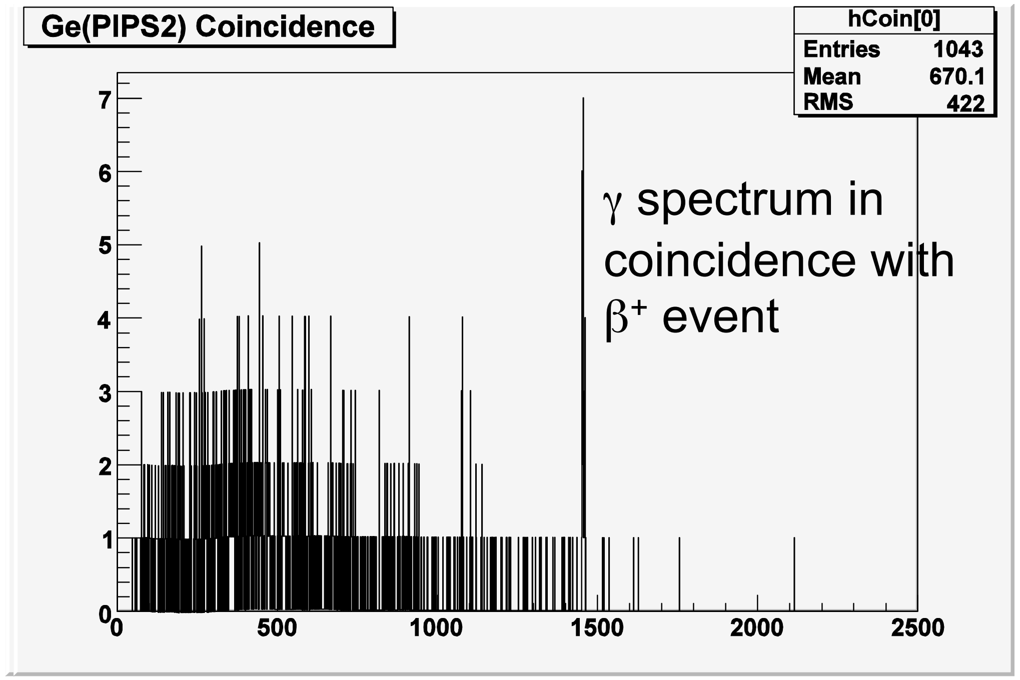
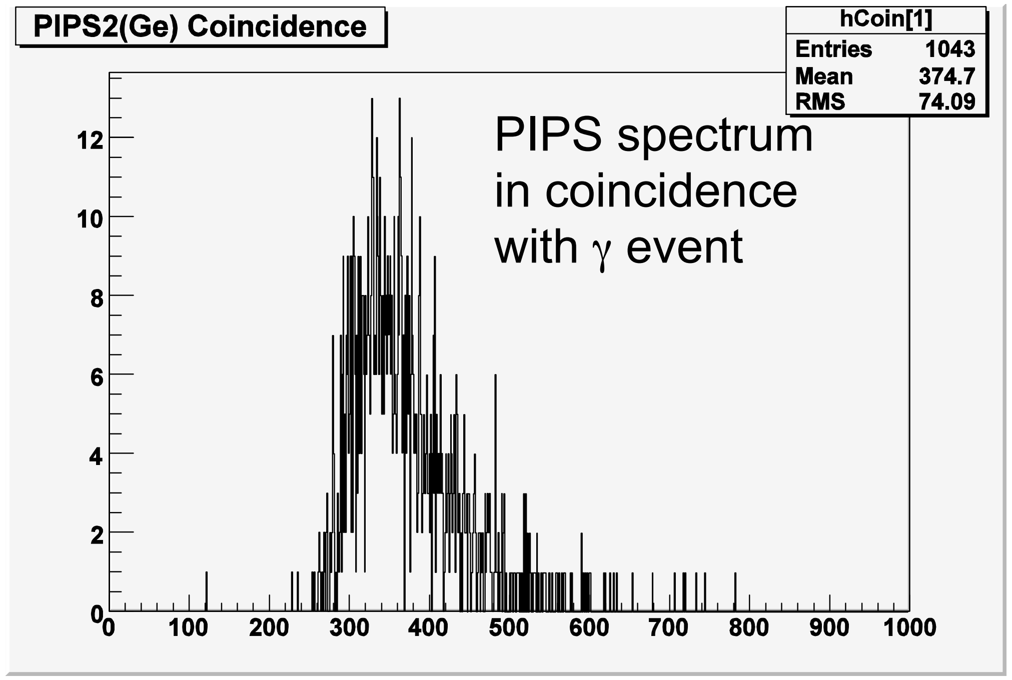
^{126}Cs



γ spectrum in coincidence with β⁺ event



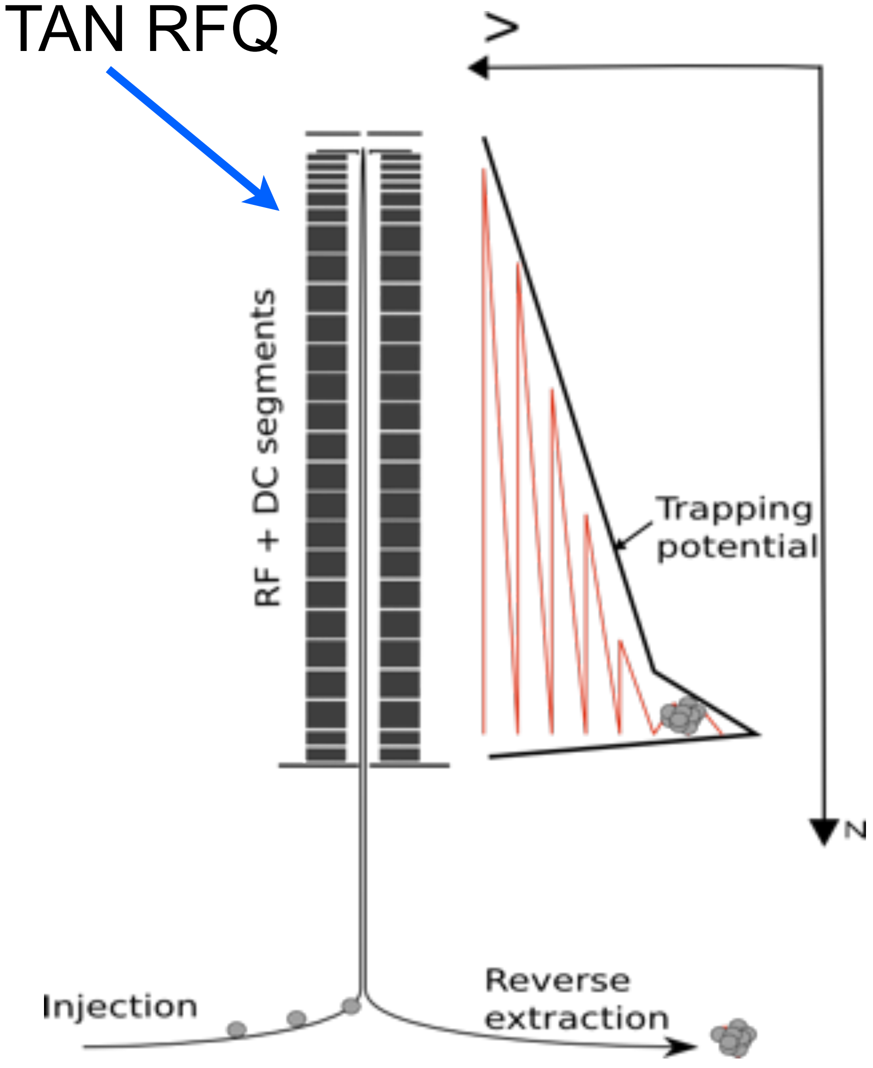
PIPS spectrum in coincidence with γ event

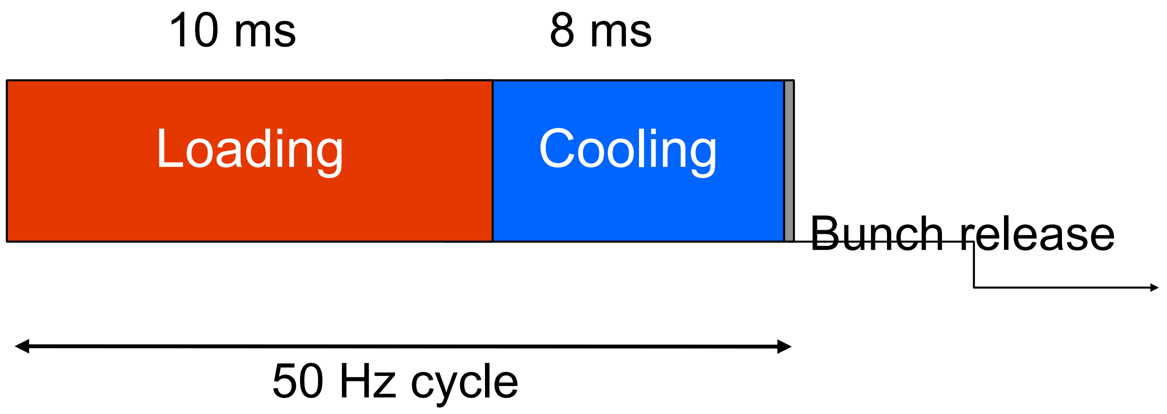
preliminary

Laser Spectroscopy on Bunched Beams

Test Run with ^{78,78m}Rb

TITAN RFQ





10 ms

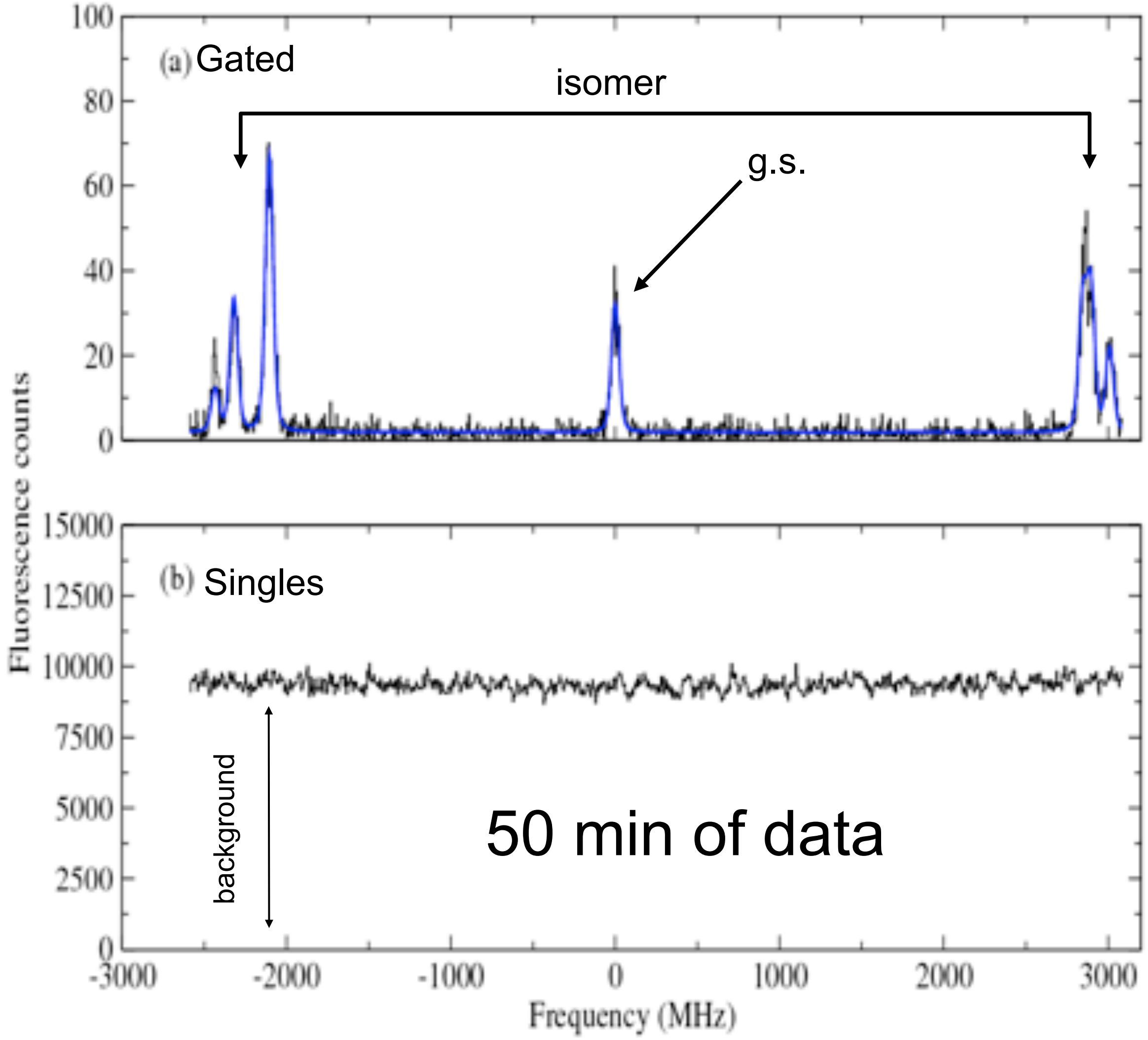
8 ms

Loading

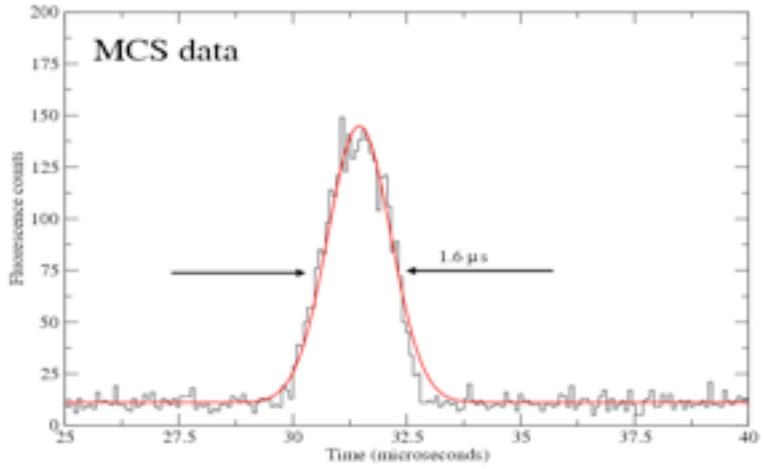
Cooling

Bunch release

50 Hz cycle



50 min of data



~ 10^5 ions/bunch, 50 Hz cycle

E. Mané et al., in preparation

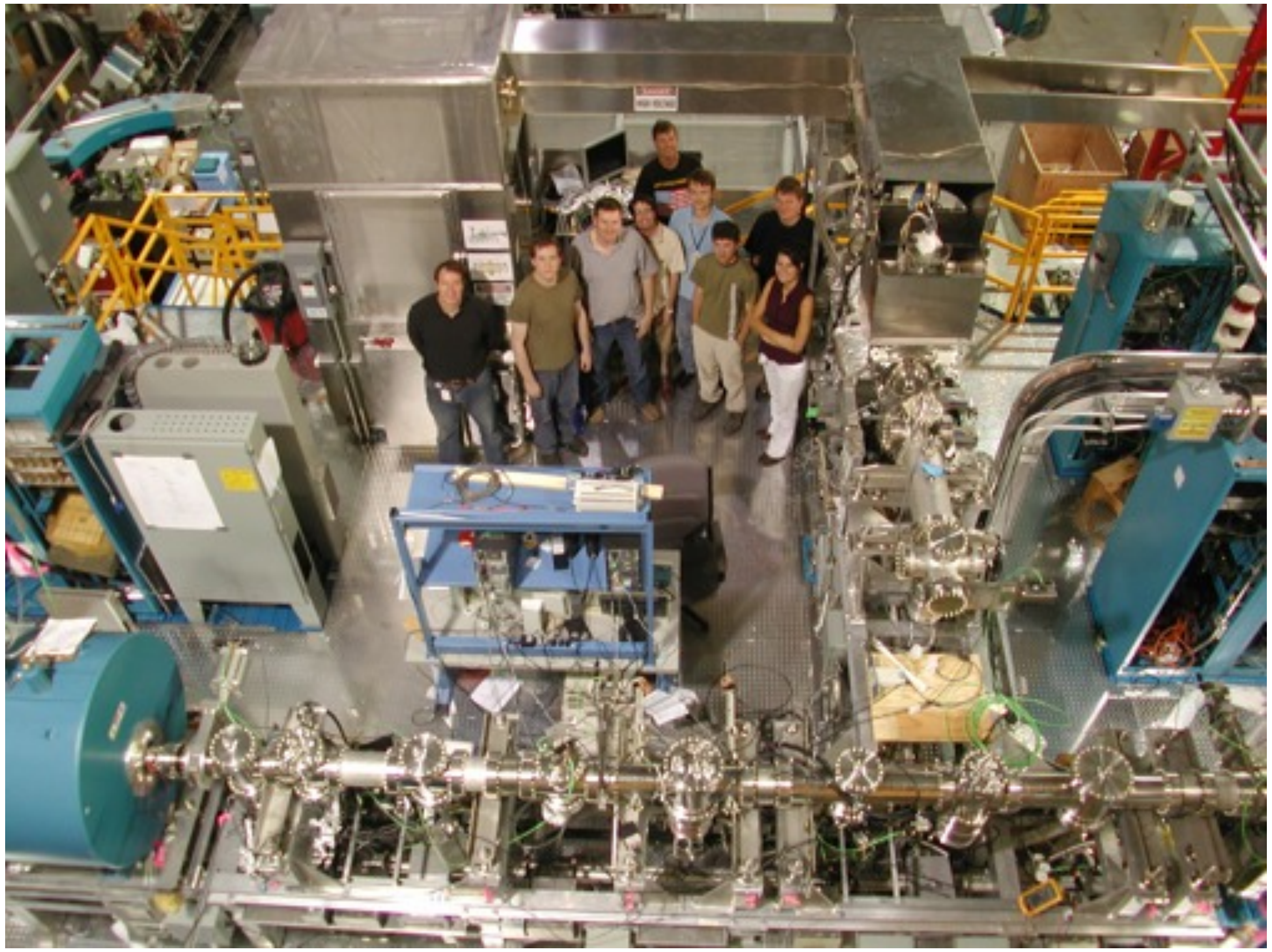
Conclusions

- precise TITAN masses for halo-nuclides
  - binding energy
  - eliminates uncertainty from mass on r_c
- first successful measurements with charge bred ions
- other TITAN programs
  - EC-BR - provide bunched ions for LS

Outlook

- nuclear structure
  - investigate established halos ^{14}Be(2n), ^{19}C(1n), ^{17}Ne(1p)
  - needed to decide on halo structure in ^{22}C and ^{31}Ne
- mass measurements on HCI for fundamental symmetries later this year

TITAN collaboration



M. Brodeur, T. Brunner, S. Ettenauer, A. Gallant, V. Simon, M. Smith,
A. Lapierre, R. Ringle, V. Ryjkov, M. Simon,
M. Good, P. Delheij, D. Lunney, and J. Dilling
for the TITAN collaboration

U. of Manitoba	U. of Calgary
McGill U.	U. of Windsor
Muenster U.,	Colorado School of Mines
Max Plank Inst. of Heidelberg	TRIUMF
GANIL	UBC