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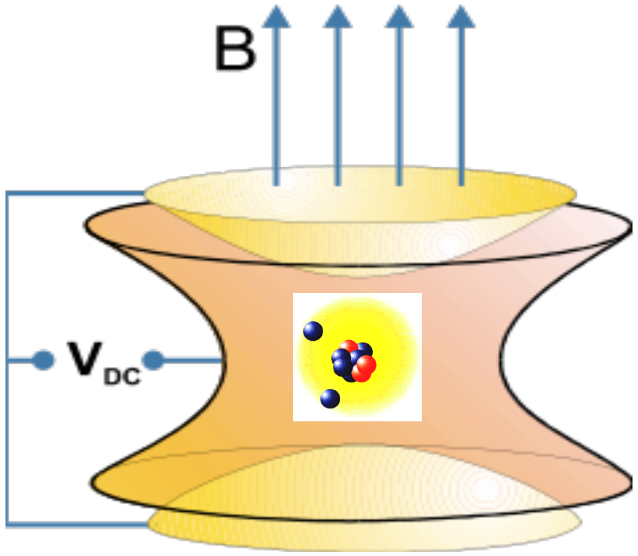
Precision mass measurement of neutron halo nuclei and first radioactive charge-bred ions using the TITAN Penning trap



Maxime Brodeur
for the TITAN collaboration

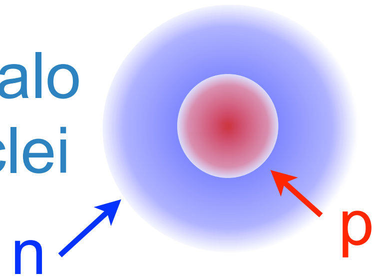
LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES
Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

Halo nuclei properties

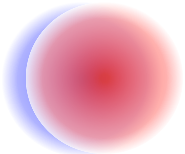
→ Halos are untypical nuclei characterized by:

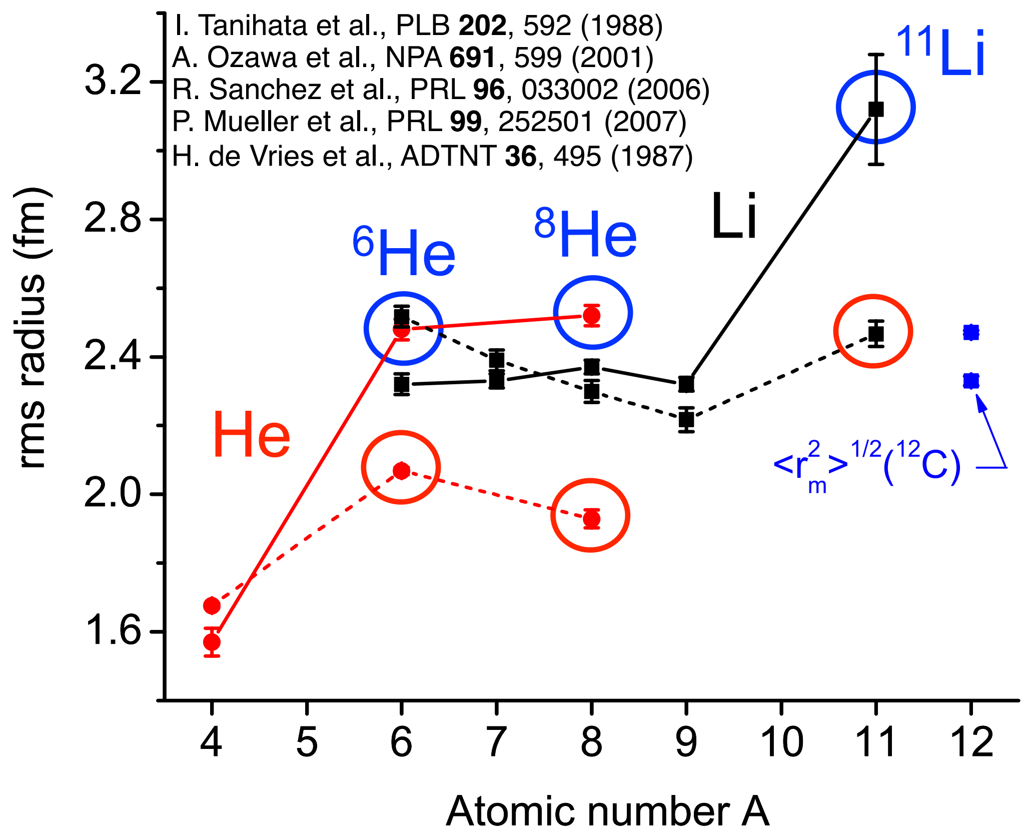
- Large matter distribution (larger than the usual $A^{1/3}$ dependence)
- Large difference in charge and matter radii

n-halo nuclei



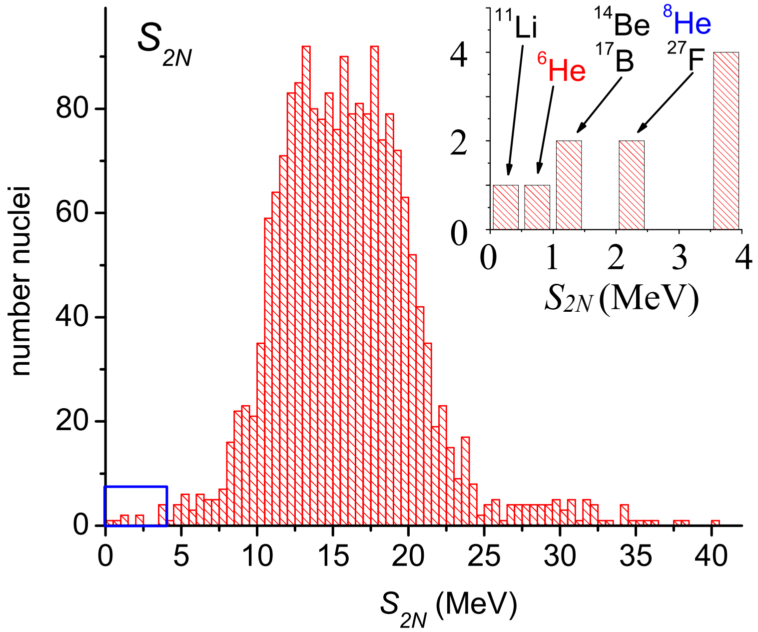
most nuclei

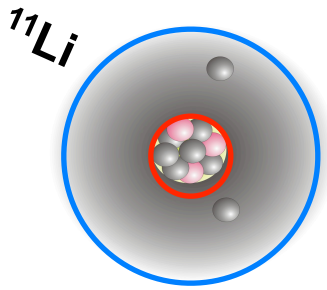


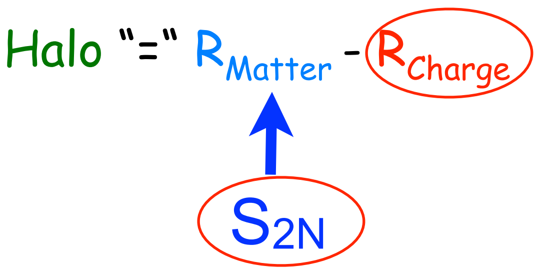


- Tiny one- or two- neutron separation energy

$$S_{xn} = m(Z,N-x) + x\,m_n - m(Z,N)$$

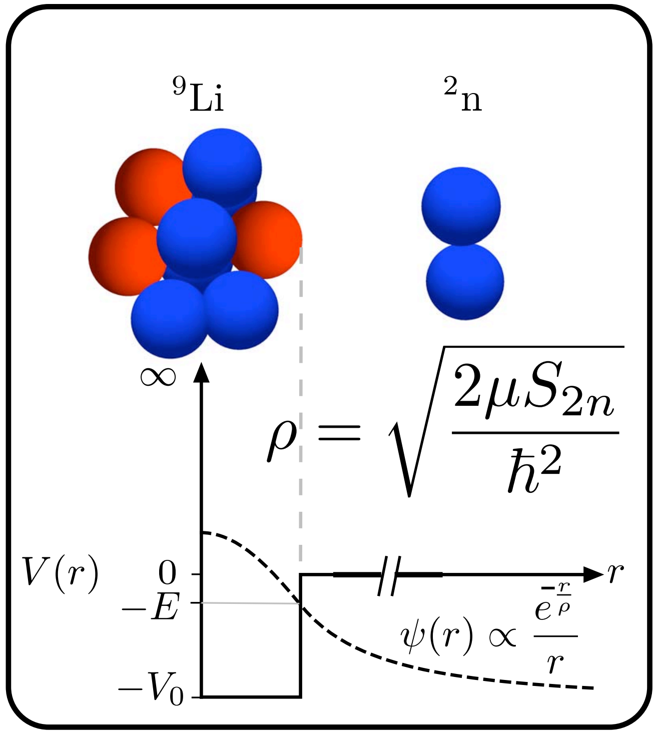






Halo "=" R_{Matter} - R_{Charge}

S_{2N}



P.G. Hansen and B. Jonson, Europhys. Lett., **4 (4)**, 409 (1987)

- Hansen & Jonson model for ^{11}Li: ^{9}Li core + 2n
- Halo formed by the valence neutrons QM leakage
- S_{2n} regulates extent of halo structure

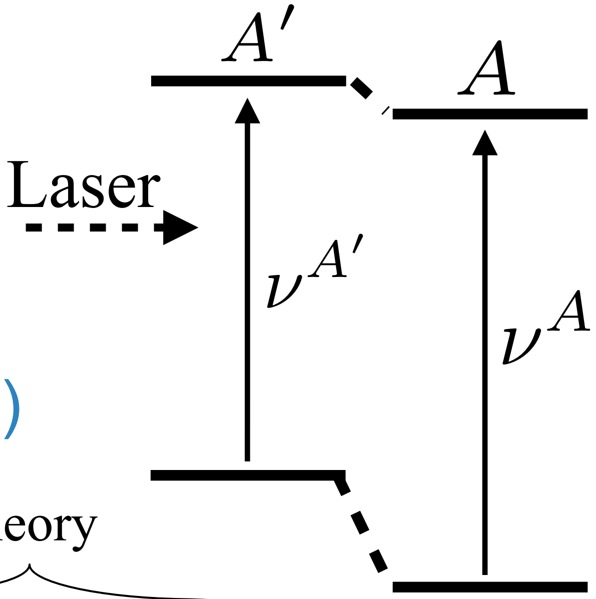
Relevance of the atomic mass

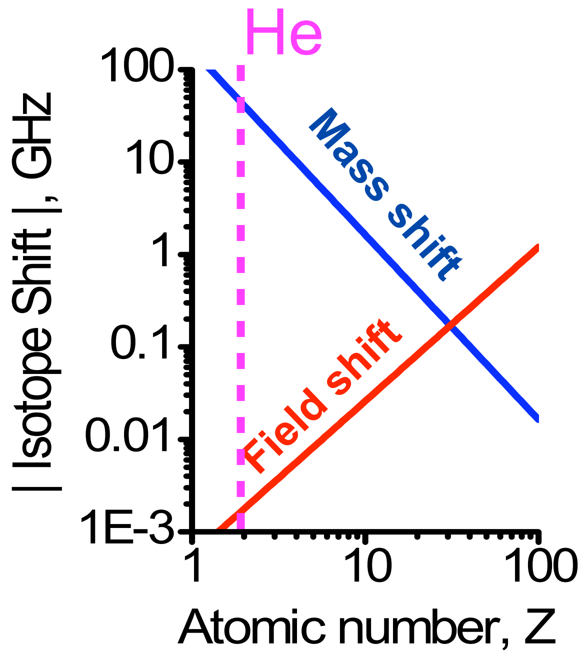
→ The atomic mass is involved in determination of both r_c and S_{2N}

Directly: neutron separation energies

$$S_n = \boxed{m(Z,N-1)} + m_n - \boxed{m(Z,N)}$$

Indirectly: relative charge radius δr_c determination via isotopic shifts measurement (of atomic energy levels)





$$\overbrace{\delta\nu^{A,A'} = \nu^{A} - \nu^{A'}}^{\text{Experiment}} = \overbrace{\underset{\text{Mass Shift}}{\underline{\delta\nu^{A,A'}_{MS}}} + \underset{\text{Field Shift}}{\underline{\delta\nu^{A,A'}_{FS}}}}^{\text{Theory}}$$

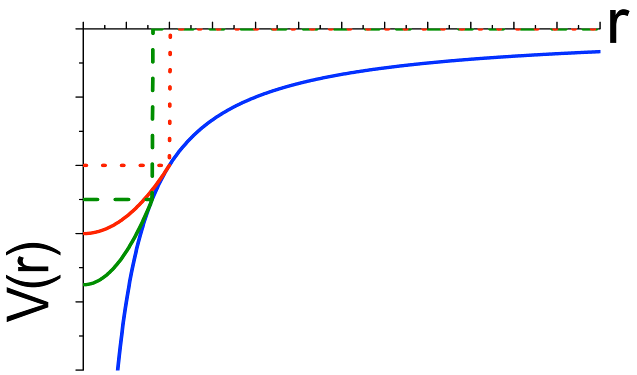
Change in mass of the nucleus $\propto \dfrac{M_A - M_{A'}}{M_A \cdot M_{A'}}$

This change the nucleus recoils

For ^{8}He, M.S. 72 000 times larger than F.S. and needs to be known at same precision

Change in nucleus size $= K_{FS} \cdot \boxed{\delta\langle r_c^2\rangle^{A,A'}}$

This change electrical potential



Importance of mass measurement

- Mass is the major contribution to the error on ^{8}He relative charge radius

Error budget on relative charge radii

Error	^{6}He (%)	^{8}He(%)
IS Statistical	6	18
Atomic mass	19	58
IS systematics	75	24

Error calculated from: P. Mueller et al., PRL **99,** 252501 (2007)

- Mass precision required < 350 eV for ^{6}He
  < 730 eV for ^{8}He

Tabulated mass excesses (M.E. = m - A)

Isotope	M.E. (keV)
^{6}He	17 595.11 ± 0.76
^{8}He	31 598.0 ± 6.9
^{8}He	31 593 ± 8
^{8}He	31 613 ± 17

G. Audi et al., NPA **729,** 337 (2003)

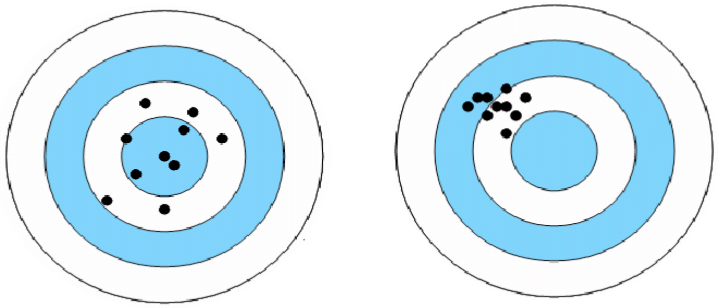
Need 2x more precise

Need 10x more precise

relative uncertainty of ~ $1\mathrm{x}10^{-7}$ on the mass needed

The two ^{8}He measurements differs by 20 (19) keV, which could lead to change in relative charge radius of 40%

... masses also need to be more accurate!



accurate, but not precise

precise, but not accurate

Motivation for mass measurement

Besides metrology, why do we need to increase charge radii precision?

- → Current experimental charge radii are at a similar level of precision as theory
- → Need more precise and accurate mass for reliable test of nuclear theory

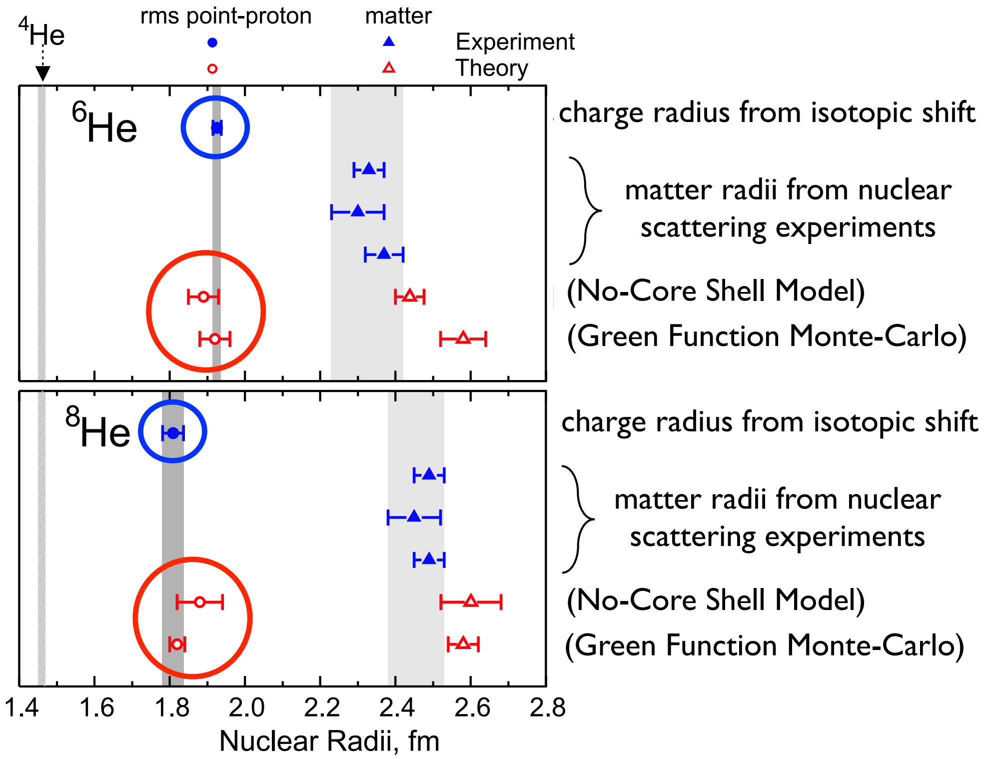
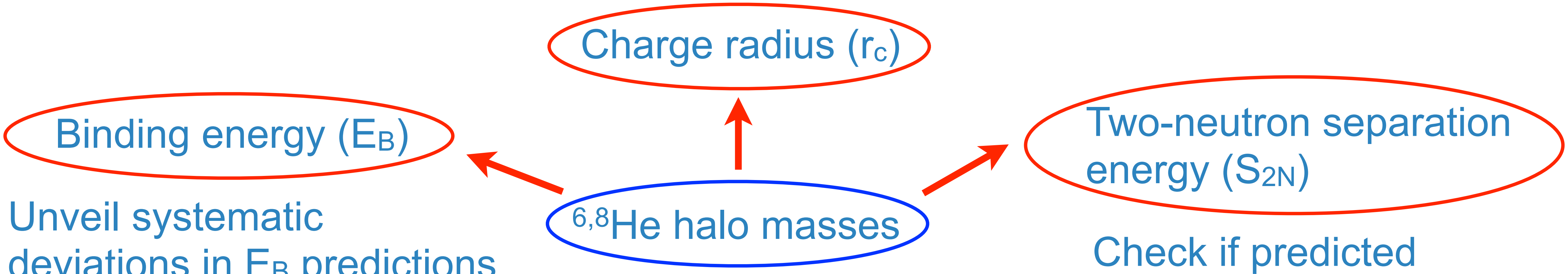


Figure from: P. Mueller et al., PRL **99,** 252501 (2007)

- → from Muller et al., ab-initio theories charge radius predictions for ^{6,8}He agree with value from isotopic shift measurement
- → Does it still hold using the more accurate & precise values obtained from the TITAN masses?
- → How well these methods predicts other observables?



Charge radius (r_C)

^{6,8}He halo masses

Binding energy (E_B)

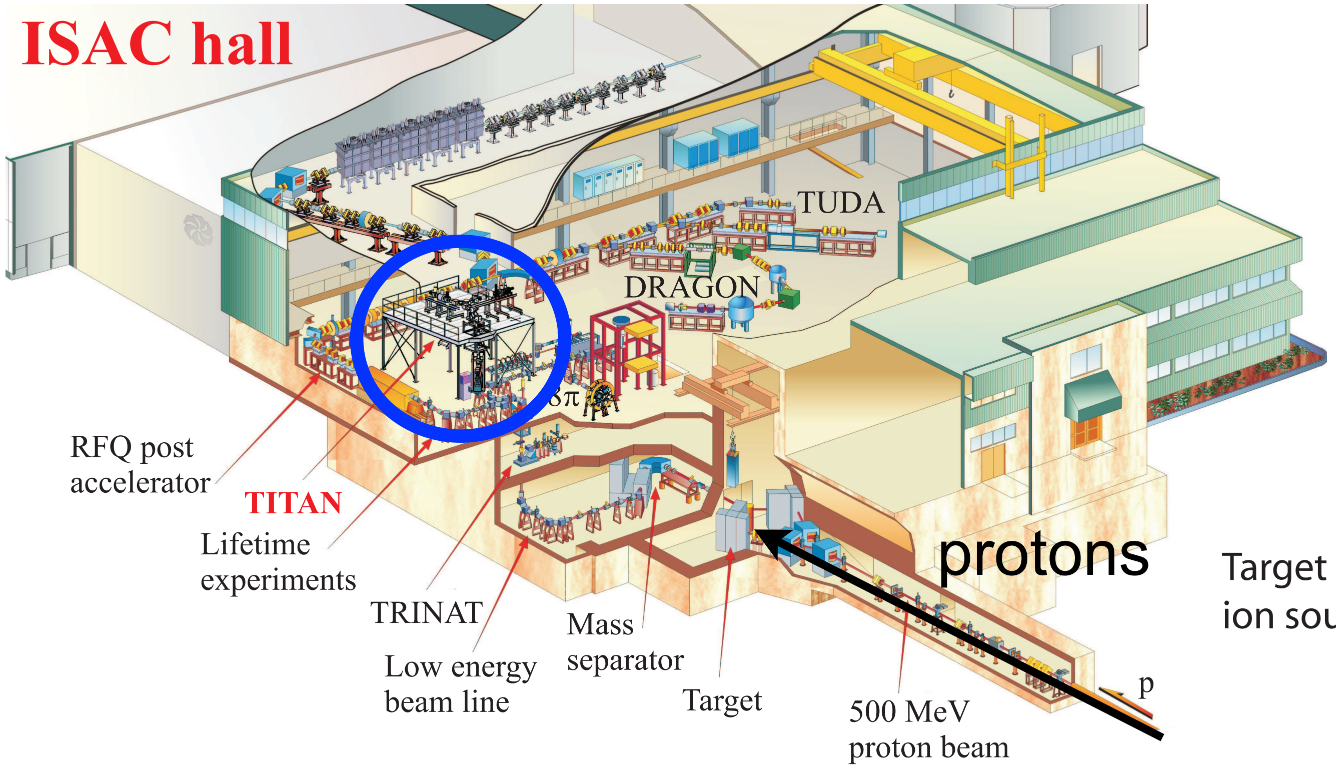
Unveil systematic deviations in E_B predictions

Two-neutron separation energy (S_{2N})

Check if predicted bound nuclei ($S_{2N} > 0$)

^{6,8}He production at ISAC

Location of the TITAN Penning trap at the TRIUMF ISAC facility



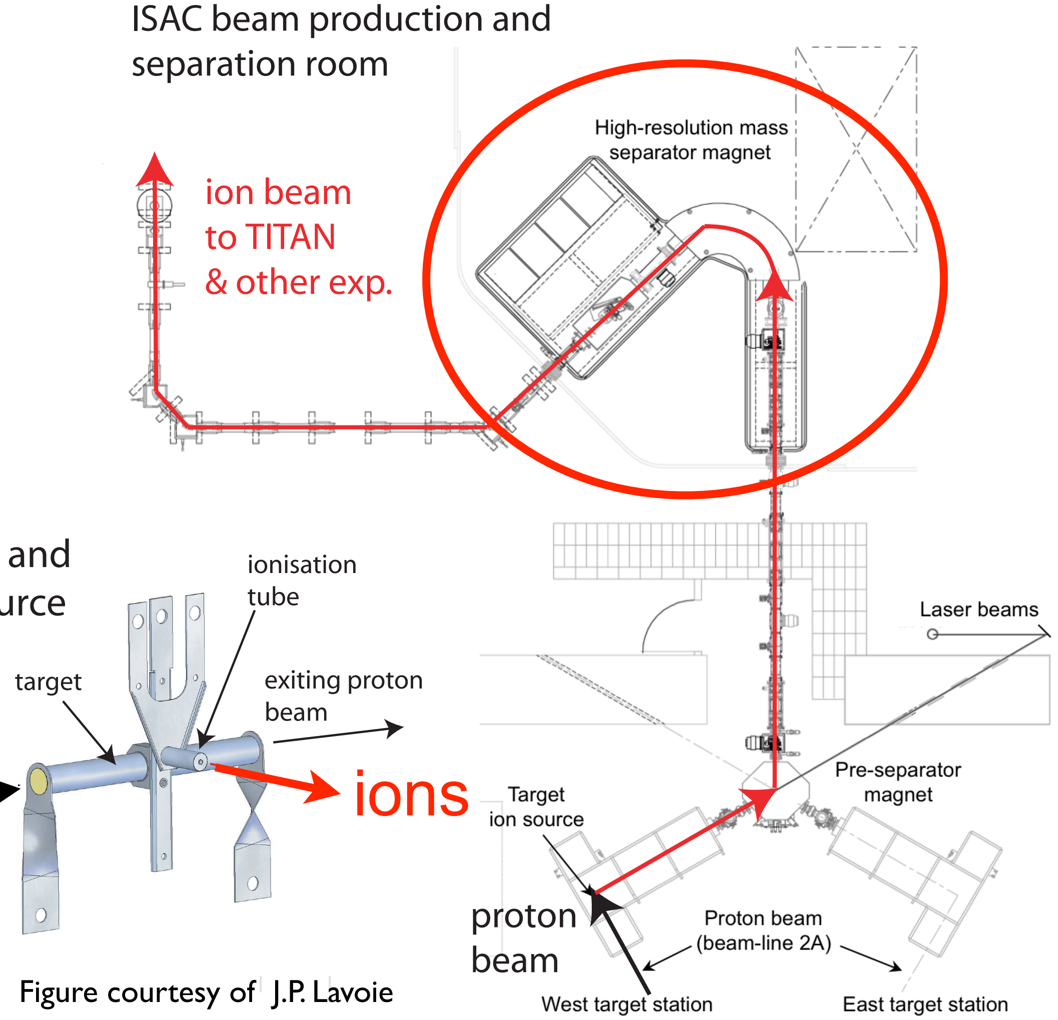


Figure courtesy of J.P. Lavoie

1) 500 MeV protons from cyclotron

2) protons hit thick target, unstable nuclei produced, diffuse, get ionized, extracted

3) contamination removed using mass separator (resolution: m/Δm = 3000)

Closest contaminants in mass to ^{6,8}He

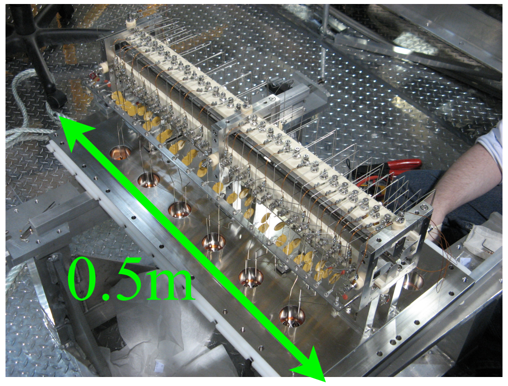
Isotope	Isotope Δ (keV)	contaminant	cont. Δ (keV)	$m/\Delta m$
^{6}He	17 592.09(6)	^{6}Li	14 086.88(2)	1600
^{8}He	31 609.74(12)	^{8}Li	20 945.80(11)	700

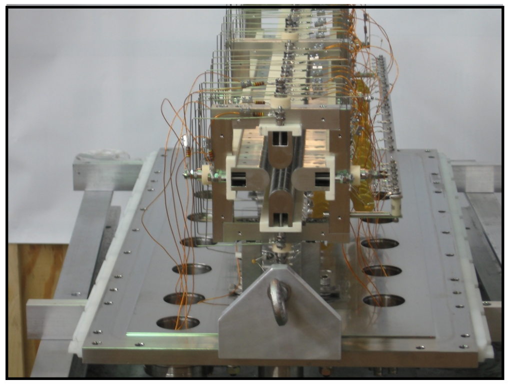
(mass excess: Δ = m - A)

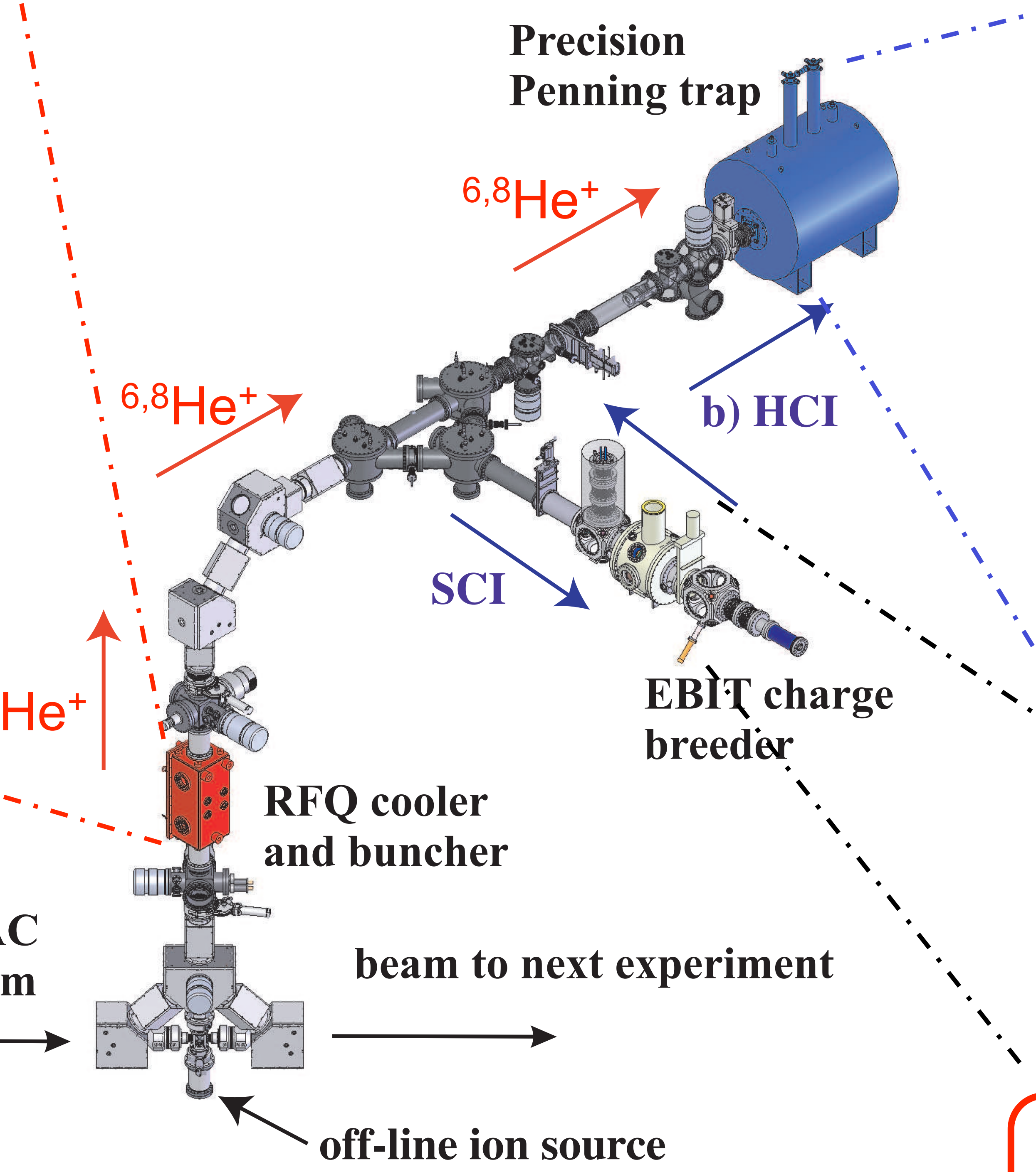
→ For all n-halo mass measurement, contamination was resolved

TITAN experimental set-up

TITAN: TRIUMF Ion Trap for Atomic and Nuclear science







Precision Penning trap

$^{6,8}He^{+}$

$^{6,8}He^{+}$

$^{6,8}He^{+}$

b) HCI

SCI

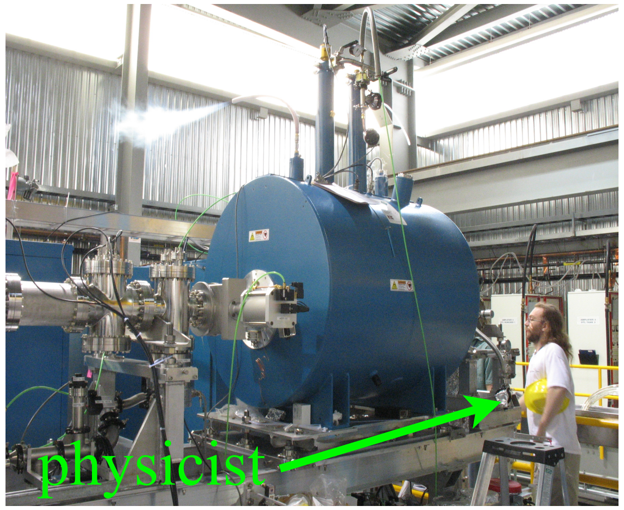
EBIT charge breeder

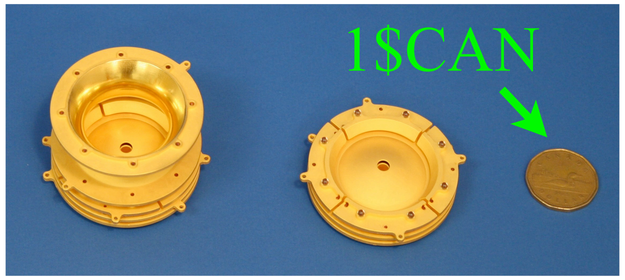
RFQ cooler and buncher

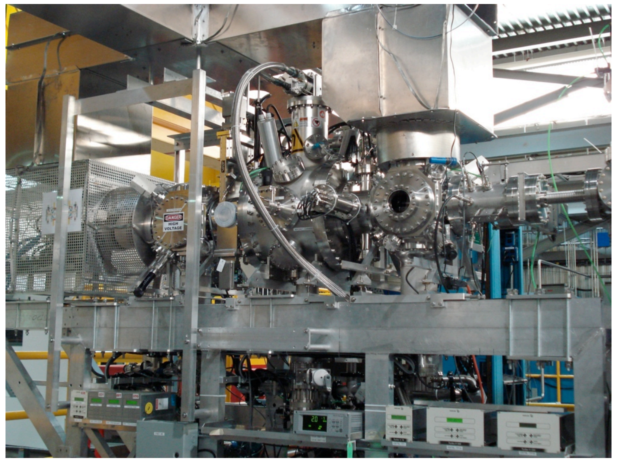
ISAC beam

beam to next experiment

off-line ion source







$$\frac{\delta m}{m} \approx \frac{m}{\boxed{q}\cdot B \cdot T_{RF} \cdot \sqrt{N_{ion}}}$$

Accuracy of the system

Depending on the count rate and excitation time, TITAN Penning trap can achieve precision in the ppb range for A < 10.

$$\frac{\delta m}{m} \approx \frac{m}{q \cdot B \cdot T_{RF} \cdot \sqrt{N_{ion}}}$$

→ But need to determine if the system is also accurate at this level!

→ To do so, several sources of systematic errors were investigated, including: (for the 3.6 V trap depth used for the halo mass measurements)

Recall: $R = \nu_{c,inter}/\nu_c$ $\qquad m = \overline{R} \cdot (m_{cal} - m_e + B_{e,cal}) + m_e - B_e$

Error	$\Delta R/R\ (\times\ 10^{-10})$
magnetic field inhomogeneities	$0.2 \cdot \Delta A$
misalignment and harmonic distortion	$4.2 \cdot \Delta A$
incomplete compensation	$0.5(5) \cdot \Delta A$
non-linear magnetic field fluctuation	$1.5 \cdot \Delta t$ (h)

(M. Brodeur Ph.D. thesis, UBC (2010))

As well as other sources of errors that can be minimized during the measurement:

→ Relativistic effects (adjusting ion radius such they have similar velocity)

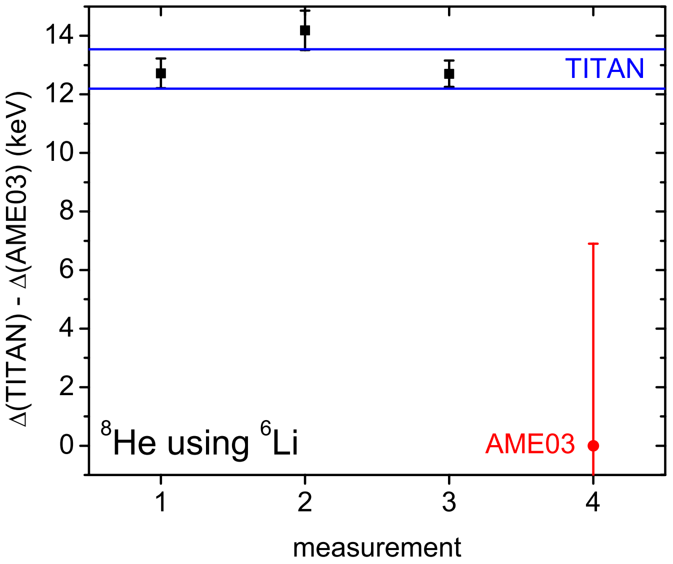
→ Ion-ion interaction (adjust count rate such as to have mainly one ion at the time)

^{6}He & ^{8}He mass measurements

TITAN mass excesses Δ compared to AME03

1st ^{8}He mass meas.

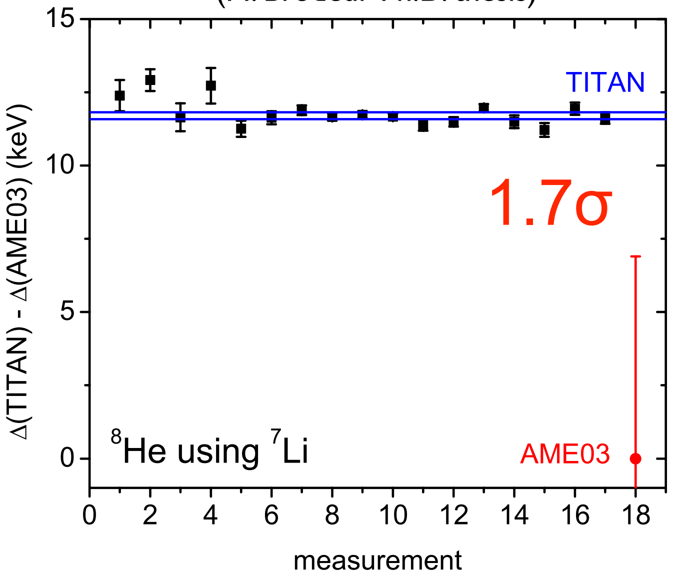
(V.L. Ryjkov et al., PRL **101**, 012501 (2008))



counts rate: ~3 ions/min

2nd ^{8}He mass meas.

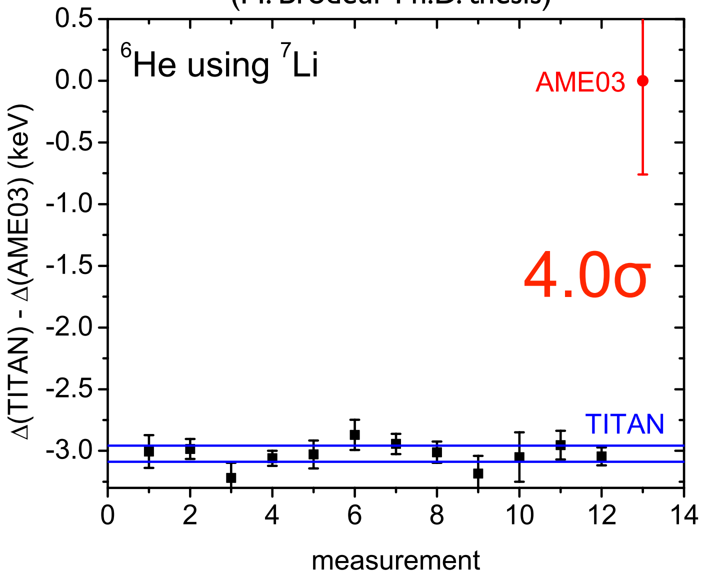
(M. Brodeur Ph.D. thesis)



~40 ions/min

^{6}He mass meas.

(M. Brodeur Ph.D. thesis)



~100 ions/min

Error budget (note: trapping potential V_0 = 3.6V)

Error	$\Delta R/R \times 10^{-9}$ (^{6}He)	$\Delta R/R \times 10^{-9}$ (^{8}He)
Statistical	4.9	5.9
Ion-ion interaction	8.1	13.3
Total	9.4	14.6

Upper limit on the error due to the interaction between ^{6,8}He and ionized background gas.

(conservative estimate obtained from count rate analysis)

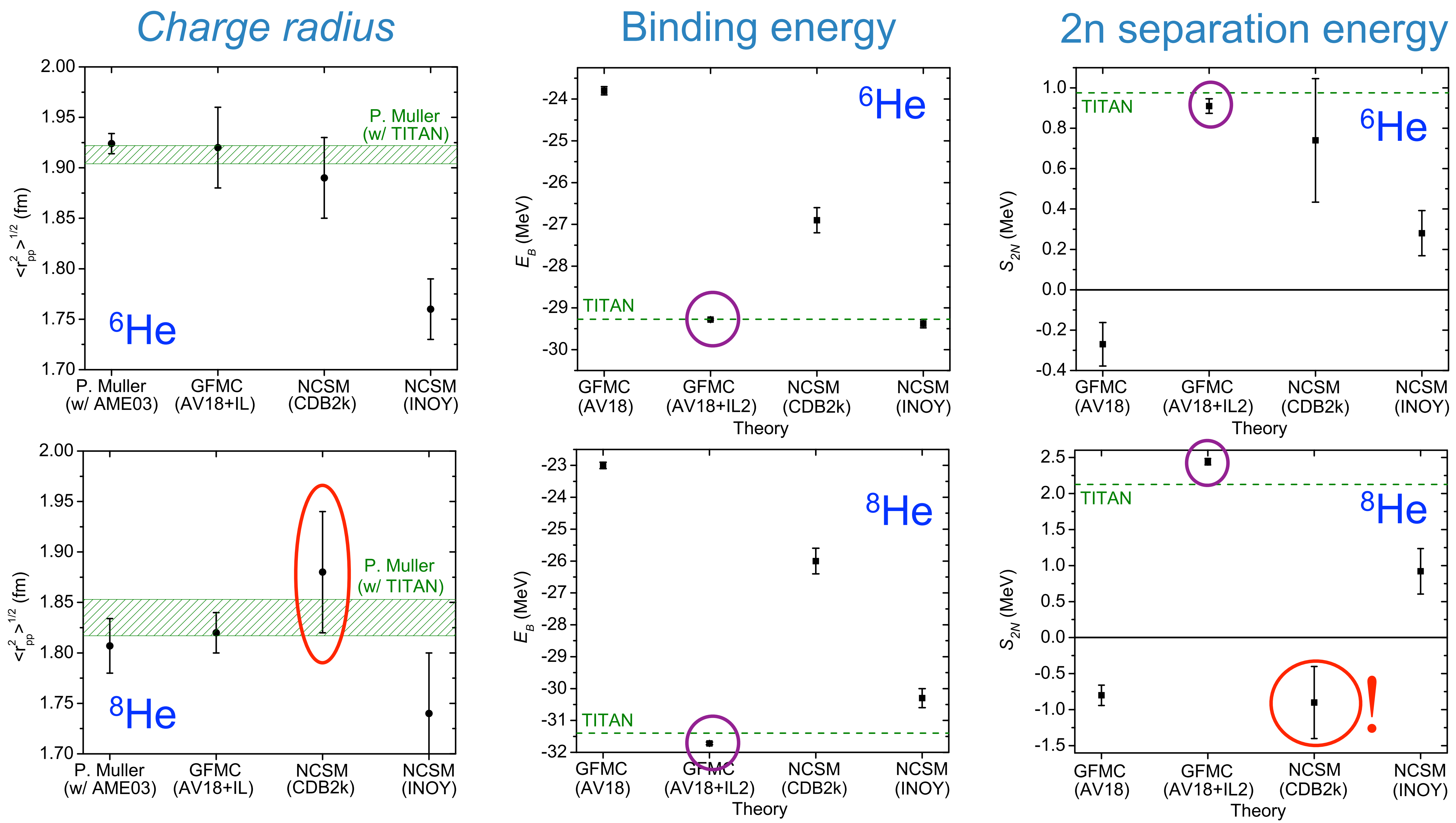
The other sources of systematic errors are < 1 ppb

Accuracy check: mass measurement of ^{6}Li and ^{4}He

Isotope	Δ(TITAN) (keV)	Δ(lit.) (keV)	δΔ (eV)
^{4}He	2 424.915(18)	2 424.915 65(6)	-1(18)
^{6}Li	14 086.867(9)	14 086.881(20)	-14(22)

Both results agrees with literature

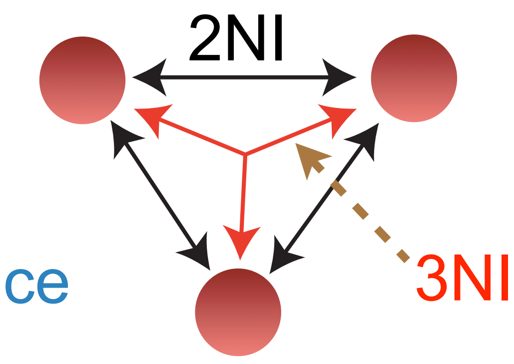
Comparison with theory



→ Both the GFMC & NCSM r_c agrees with new exp. ^{6,8}He r_c

GFMC (AV18+IL) → Method that provides the closest values to experiment
Only method that uses 3 nucleons interaction (3NI)

NCSM (CDB2k) → Produce a physical r_c for an unbound nuclei, consequence of using faster Gaussian fall-off and small model space.



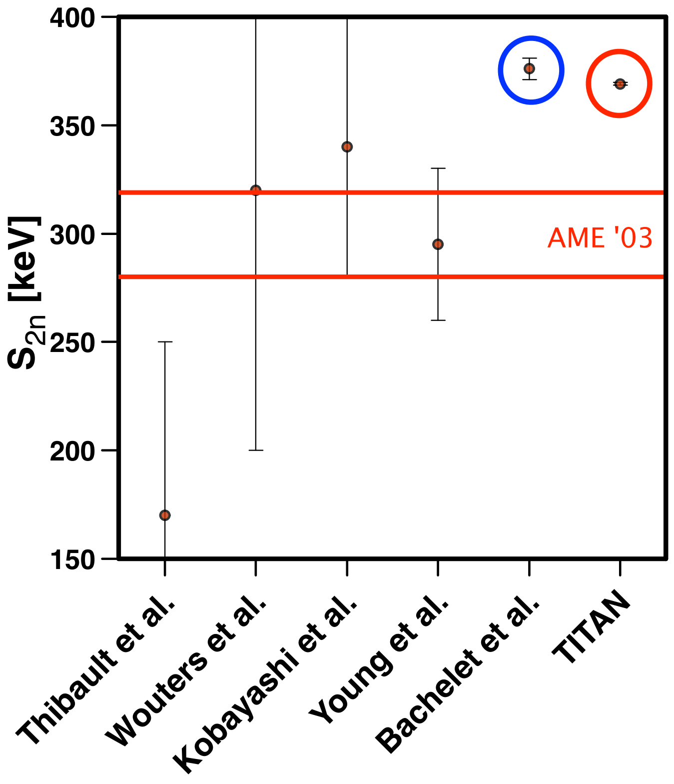
Mass measurement of ^{11}Li

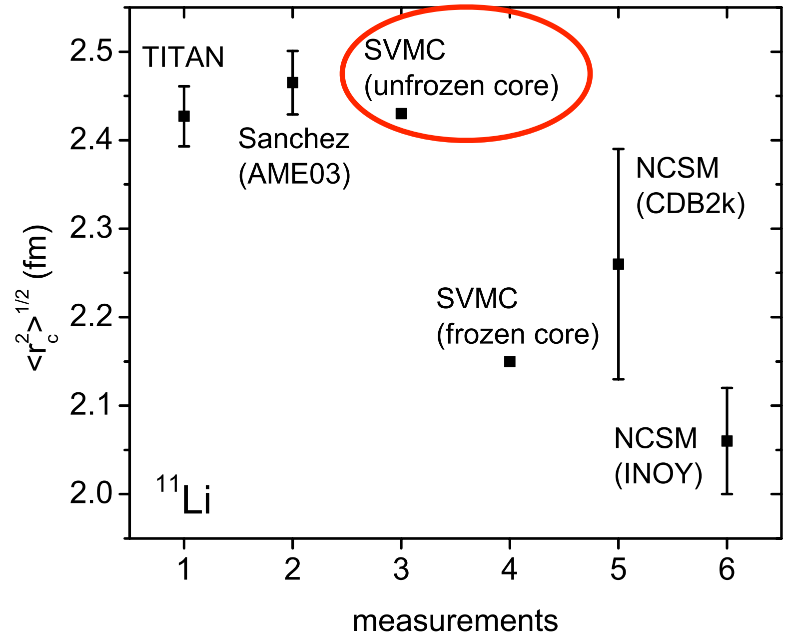
M. Smith et al., Phys. Rev. Lett. 101, 202501 (2008).

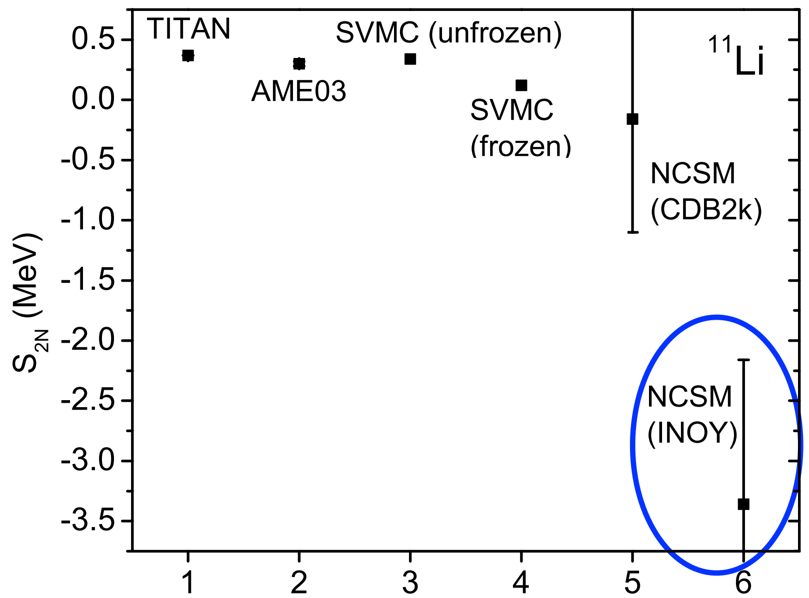
Bachelet et al. measurement shows 65 keV deviation with AME03

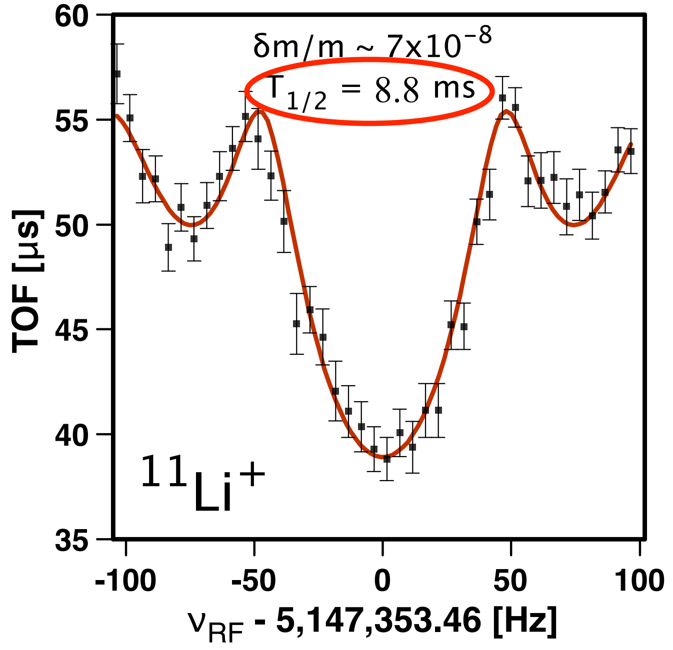
C. Bachelet et al., Phys. Rev. Lett. 100, 182501 (2008)

Confirmed by the TITAN shortest lived mass measurement using Penning trap





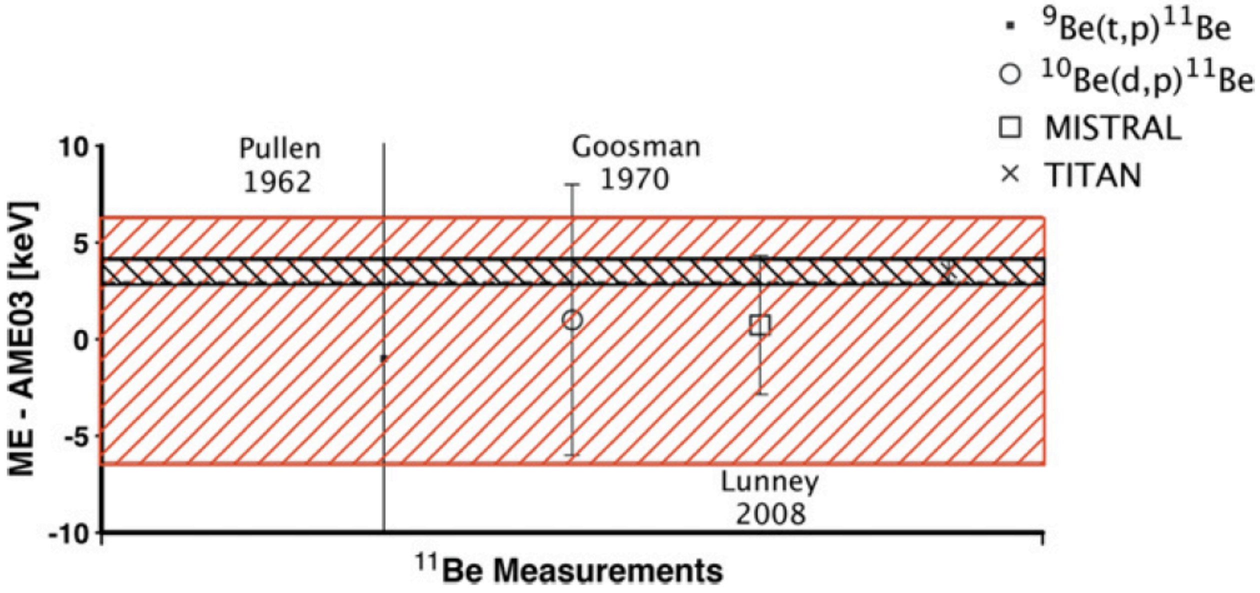


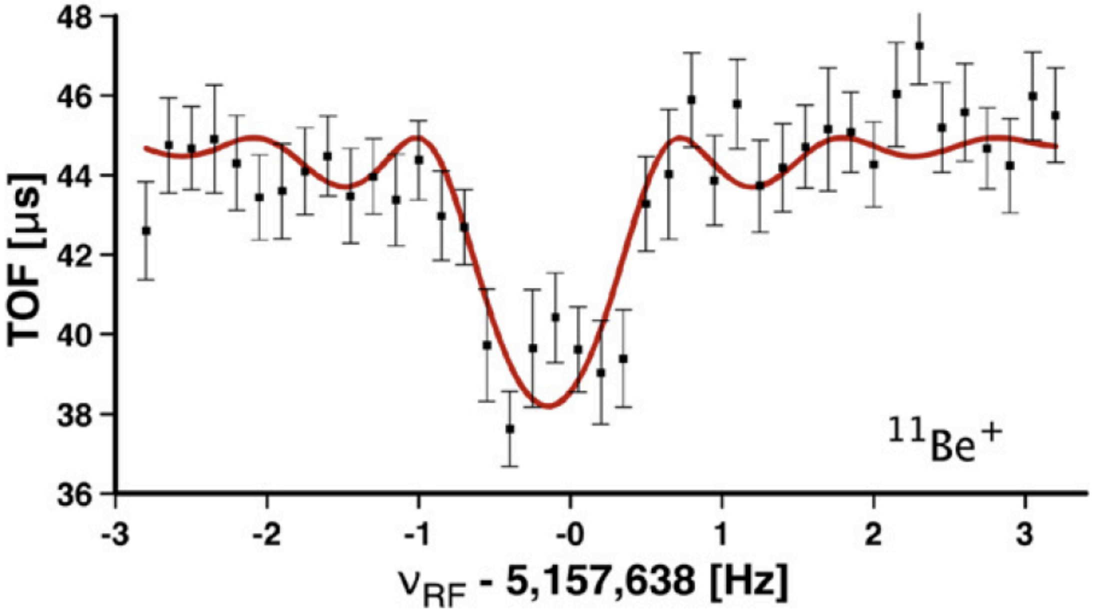


- → NCSM (INOY): unbound ^{11}Li with a physical r_c
- → Stochastic Variational Monte-Carlo cluster model (SVMC) with unfrozen core gives the best agreement for both r_c and S_{2N}
- → The ^{9}Li core should be seen as unfrozen, which means it is allowed to be deformed by the presence of the valence neutrons

Mass measurement of ^{11}Be

TITAN mass measurement of the one n-halo ^{11}Be

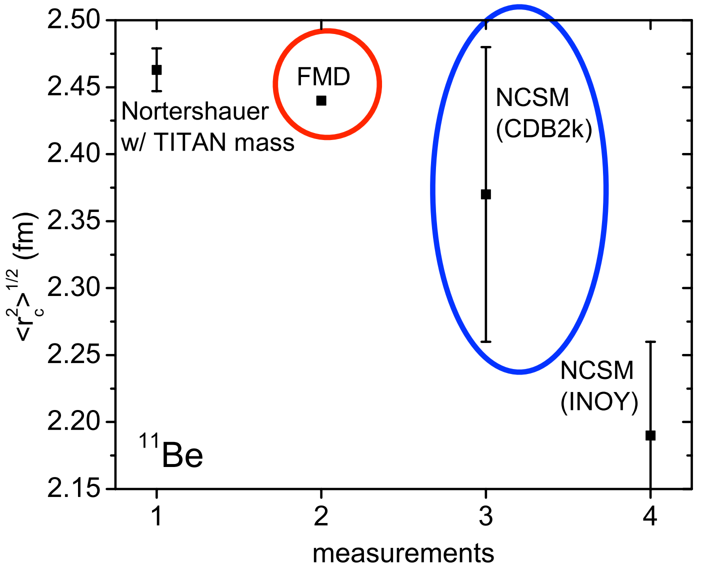


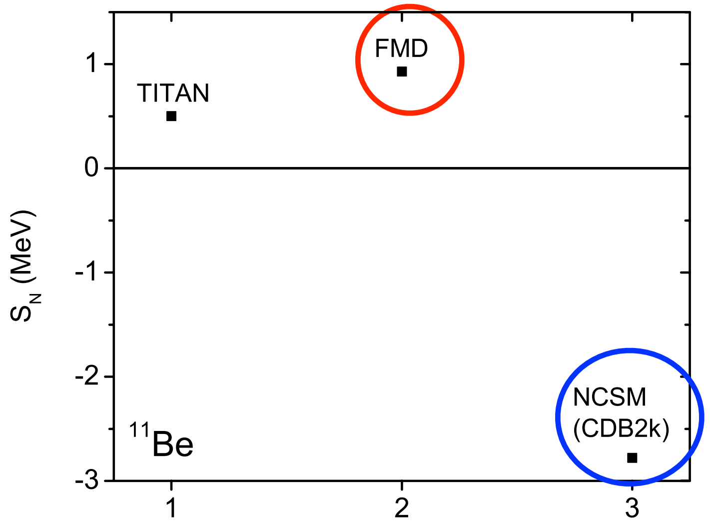


→ Improve precision on the mass by one order of magnitude

→ The latest charge radius determination uses the TITAN mass

(Nörtershäuser et. al., PRL **102** (2009) 062503)





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

FMD r_c and S_N ^{11}Be: B.R. Torobi Ph.D. thesis, Darmstadt (2010)

NCSM (CDB2k) S_N ^{11}Be: Quaglioni *et al.*, PRL **101** (2008) 092501

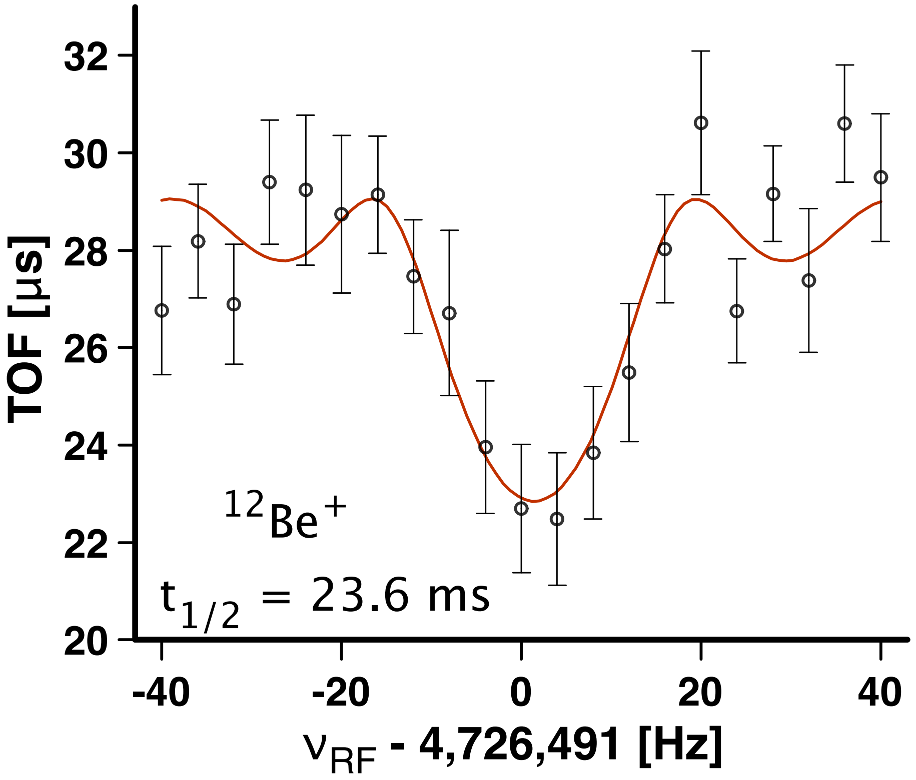
→ NCSM (CDB2k): unbound ^{11}Be with a physical r_c

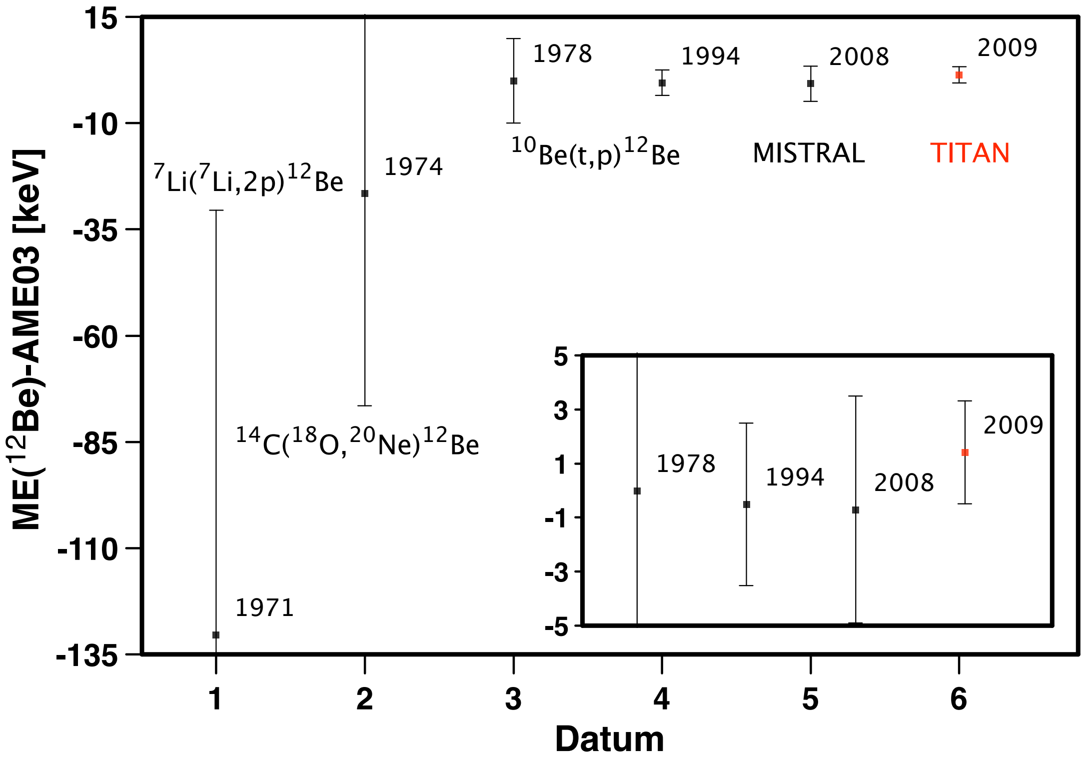
→ Fermionic Molecular Dynamic (FMD) gives the best agreement for r_c and S_N (potential used mimic 3 body interactions)

Mass measurement of ^{12}Be

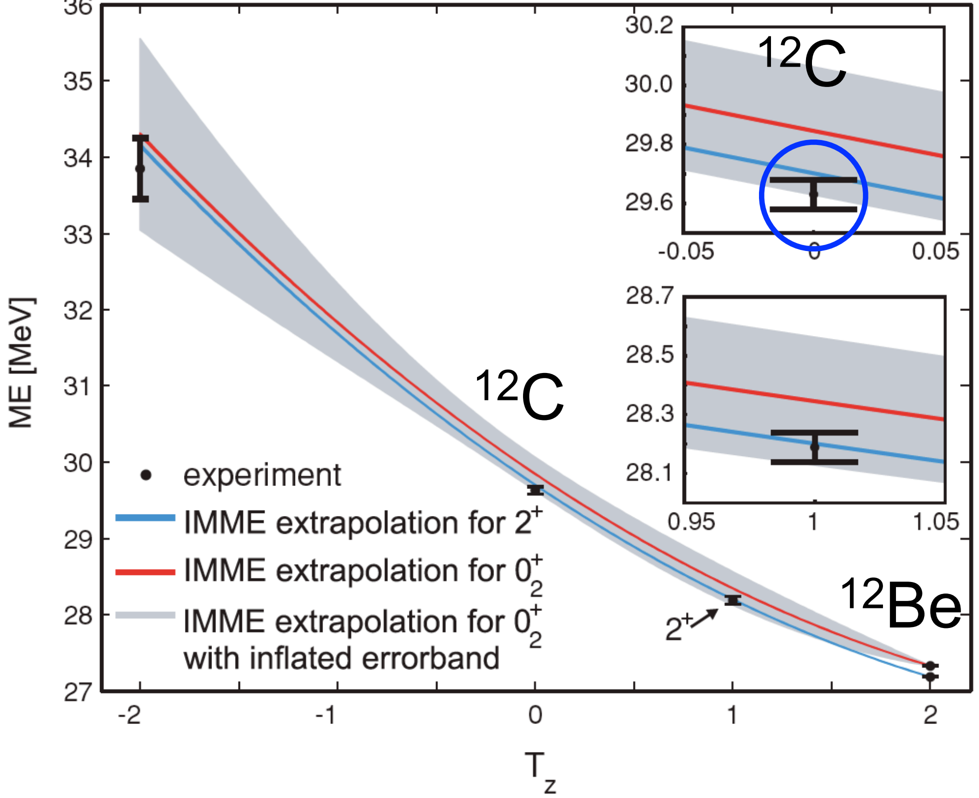
S. Ettenauer et. al, PRC **81** 024314 (2010)

First step towards the mass measurement of the 2n-halo ^{14}Be ($T_{1/2}$ = 4.4 ms)





IMME: $ME(A,T,T_z) = a + bT_z + cT_z^2$

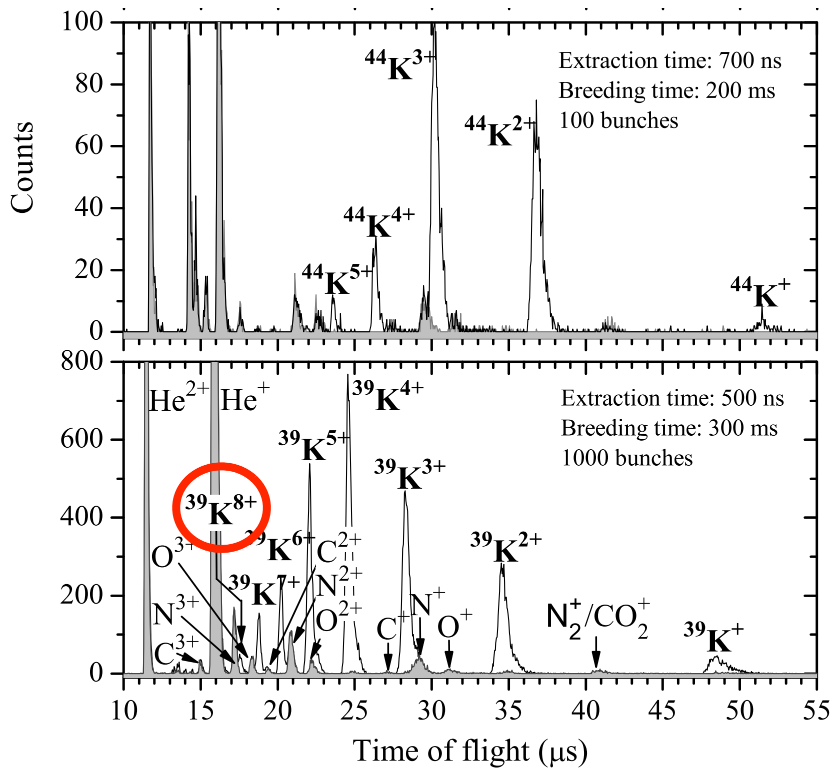


- ➞ Dispute regarding the J assignment of ^{12}C (either 0^+ or 2^+)
- ➞ Updated the A = 12 (for $J^p = 0^+$) IMME evaluation using the new TITAN ^{12}Be mass
- ➞ Using these fit parameters, made prediction that favours the $J^p = 0^+$ state

Ettenauer *et al.*, in prep.

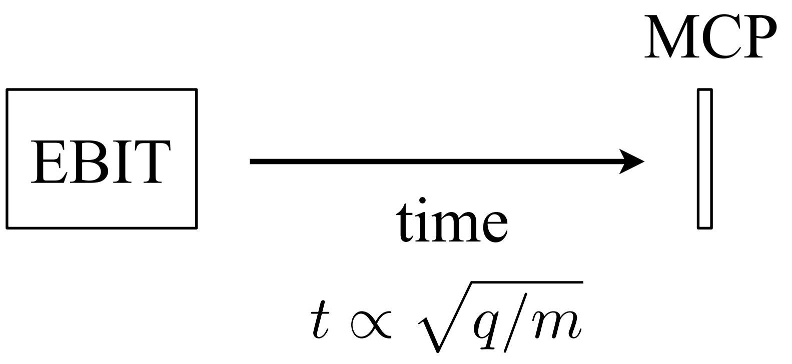
Charge-bred radioactive ion beam

Time-of-flight distribution of charge bred ions from the TITAN EBIT



injected beam: potassium

rest: charge bred residual gas



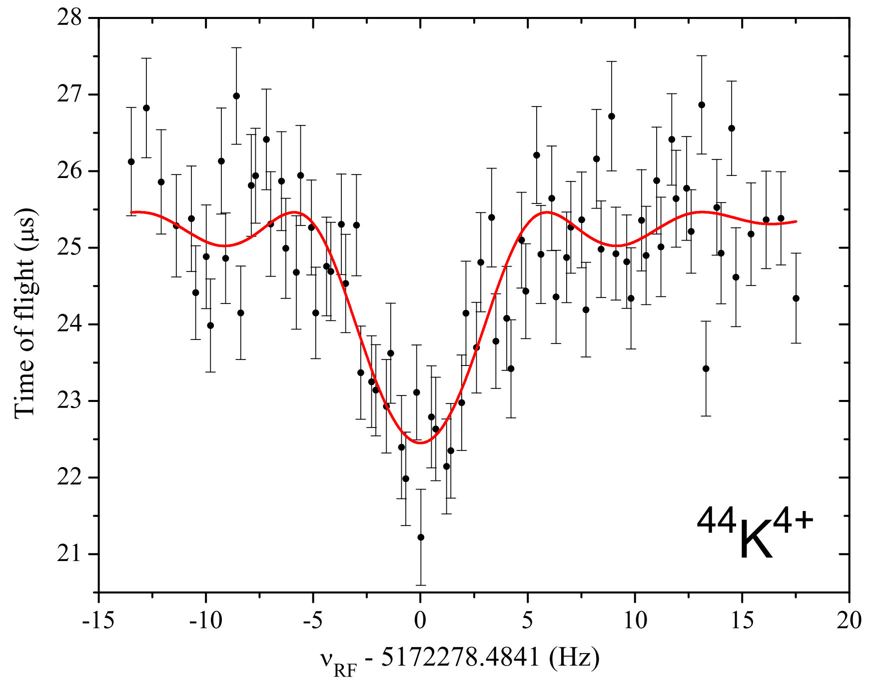
$$t \propto \sqrt{q/m}$$

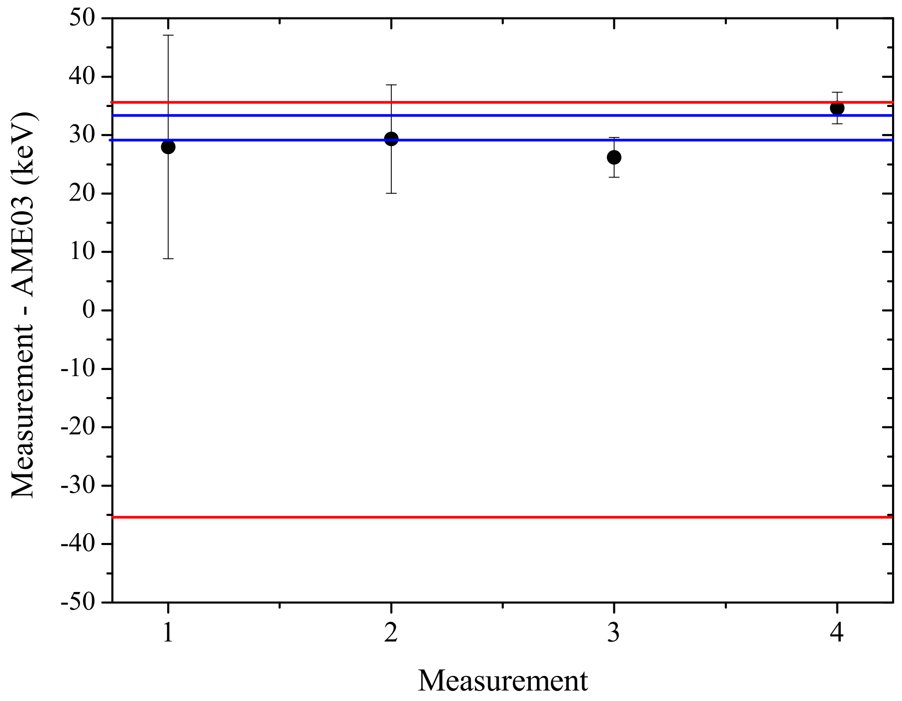
- → Observed up to 8+ charge state of ^{39}K for 2 keV e-beam energy
- → Charge breeding of the residual gas (O_2, N_2, H_2) and ^{4}He from RFQ makes it presently difficult to use higher charge states of injected ions for the Penning trap.
- → Total efficiency for injection/charge breeding and extraction of $^{44}K^{4+}$: 0.1%
- → Charge state 4+ is not the dominant one, but the easiest to resolve from residual gas contamination

First charge-bred RIB mass meas.

A. Lapierre et. al, in preparation

First Penning trap mass measurement using charge-bred ions: $^{44}K^{4+}$





Factor of 10 improvement on the AME03 mass

Future work needed for mass measurements using HCIs:

1) Improve EBIT efficiency for HCI production/transport

Plans: evaporative cooling in the EBIT
cooling using the cooling Penning trap (as discussed by V. Simon)
dipole cleaning in the EBIT (already demonstrated)
charge state ratio optimization

2) vacuum in the Penning trap

→ Excitation time limited to 200 ms due to Penning trap vacuum

Solution: baked the Penning trap (now we reached 4 x 10^{-11} torr)

Summary & Outlook

- → Accurate and precise mass measurements of halo nuclei allows to guide nuclear theory and refine our understanding of the nucleus
- → Ab-initio methods points to the need of 3-body interactions in order to explain both the binding energy and charge radius of halo nuclei.
- → Cluster models need to account for deformation of the core due to the presence of the halo.
- → We showed that using 2 observables involving the mass of halo nuclei, we can test the limitations of nuclear theories
- → Found deviations of 4 and 1.7 σ for the respective ^{6,8}He masses compared to tabulated values
- → The uncertainties on the new charges radii are now independent of the atomic mass
- → There are more halo mass measurements to come at TITAN, including ^{14}Be and ^{19}C.
- → Other mass measurements are planned at TITAN, including ^{46,48}Ar, ^{51,52}K, and towards ^{54}Ca to study change in the nuclear structure

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