TITAN

ISAC-TRIUMF

Experimental Program on
Halo Nuclei
with non-accelerated Beams at TRIUMF

stephan ettenauer
for the TITAN collaboration

UBC

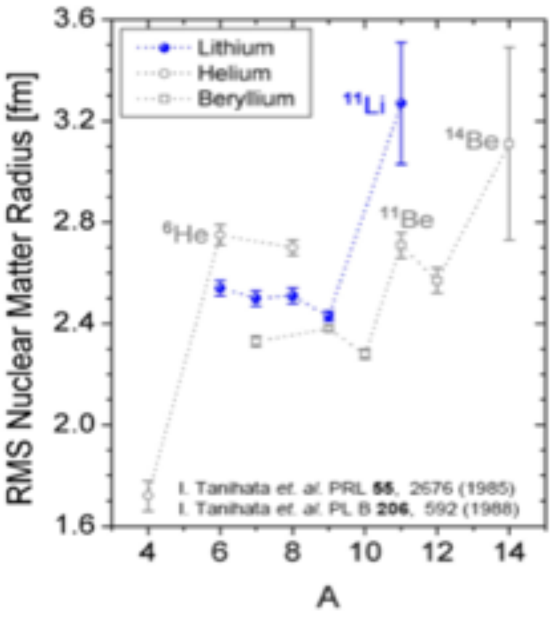
Weakly Bound Systems in Atomic and Nuclear Physics, March 2010

Outline

- Overview: Experimental Probes on Halo
- Production of Halo Nuclei
- non-accelerated Halos @ TRIUMF
  - Laser Spectroscopy
  - Mass Measurements in Penning Trap
- Conclusion & Outlook

TRIUMF

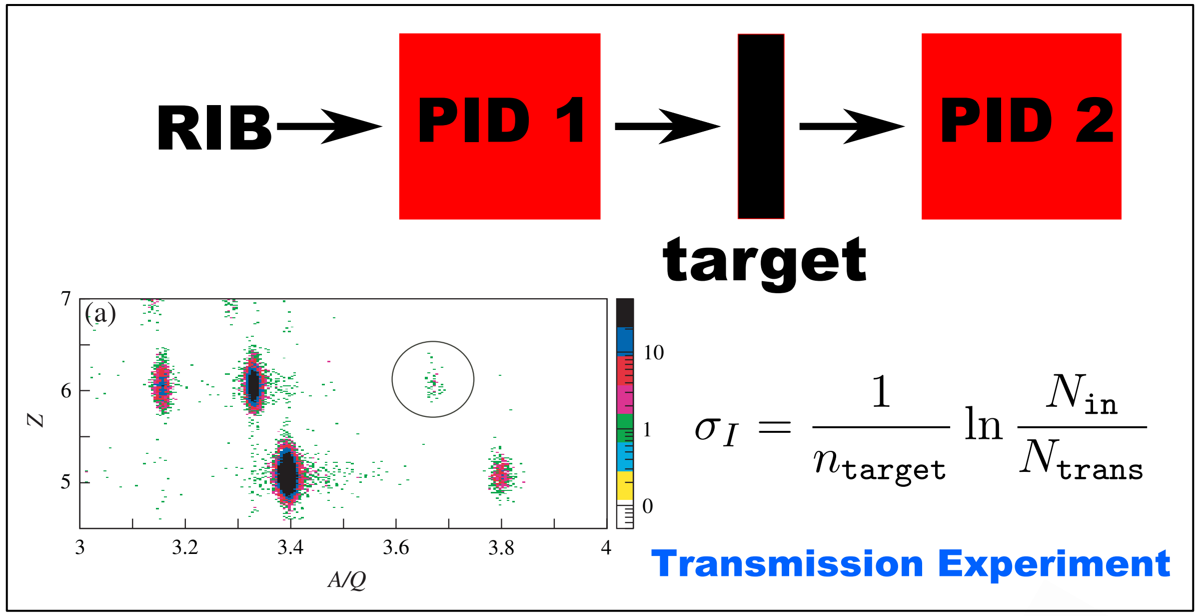
Halo Nuclei



In 1985 Tanihata et al.:

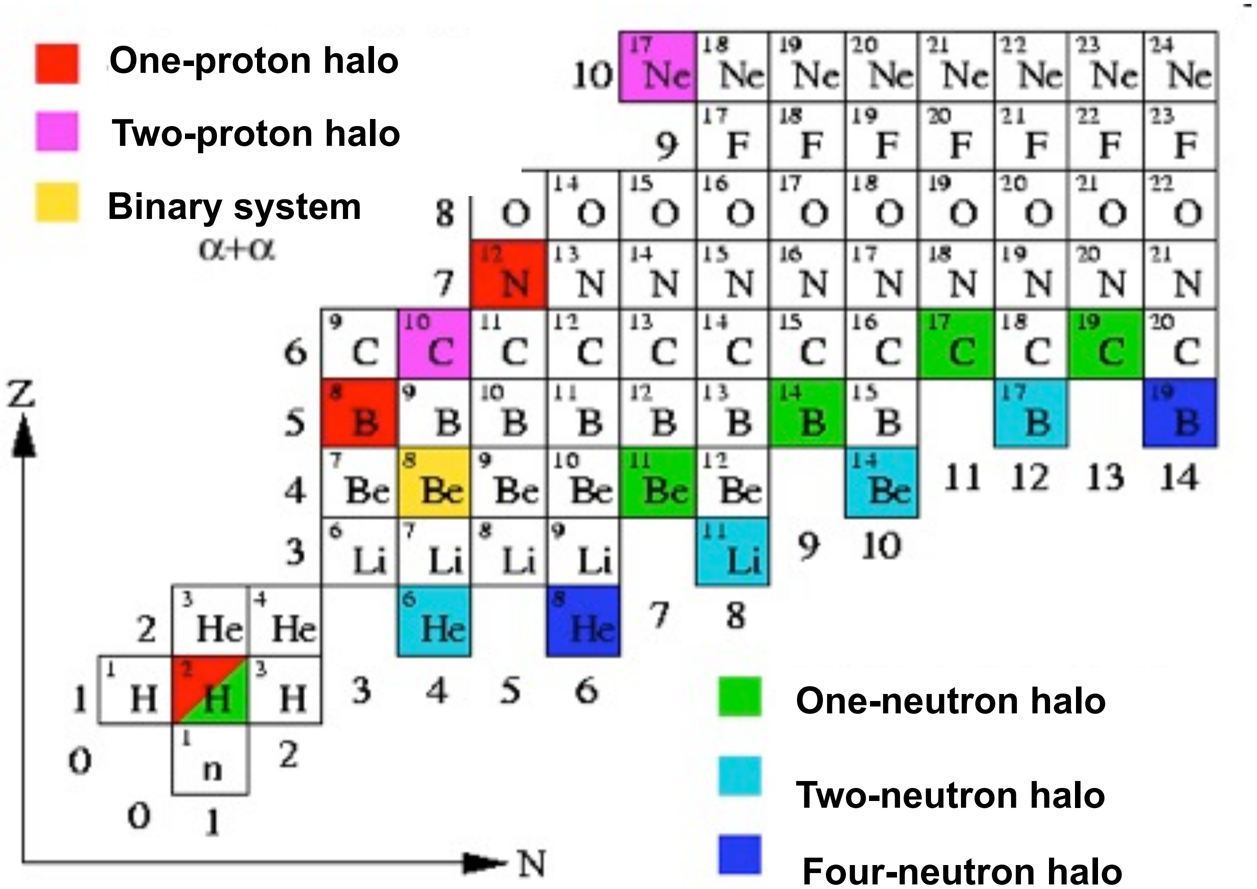
- interaction cross section measurements (transmission experiment)
- ^{11}Li much larger than expected from general rule of stables: $R_N \sim r_0\, A^{1/3}$
- extra neutrons (or protons) in classically forbidden region

I. Tanihata et al., PRL 55, 2676 (1985)

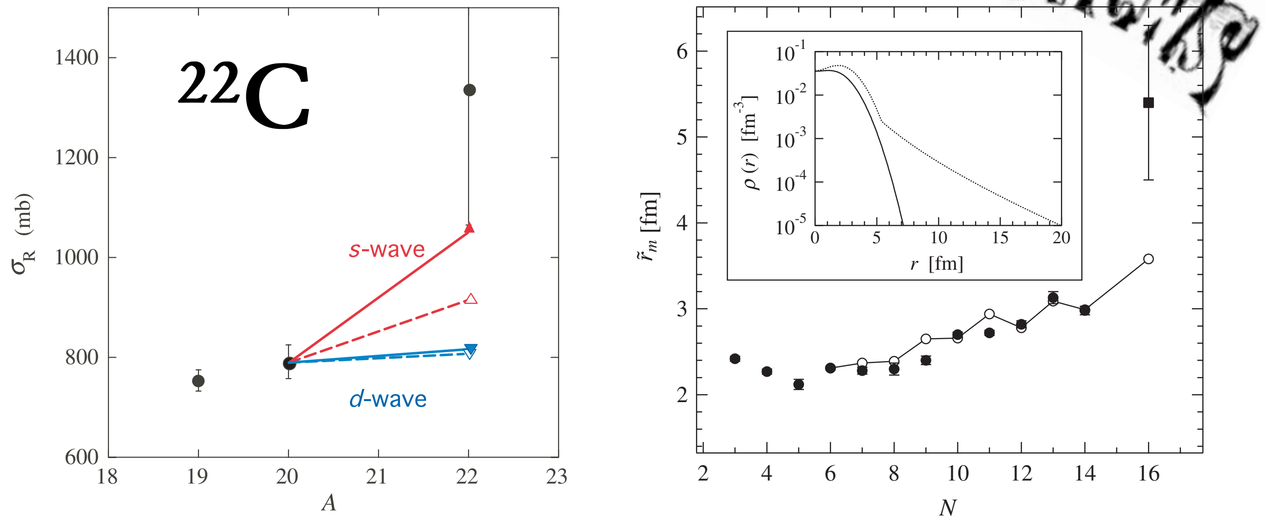


$$\sigma_I = \frac{1}{n_{\mathtt{target}}} \ln \frac{N_{\mathtt{in}}}{N_{\mathtt{trans}}}$$

Transmission Experiment



New Candidates:



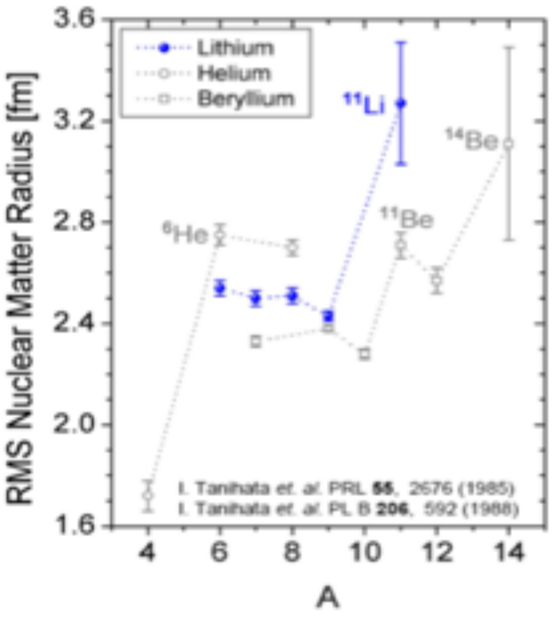
K. Tanaka et al., PRL 104, 062701 (2010)

……

^{31}Ne
- would be heaviest nuclear halo system
- possibly p - wave 1n halo

T. Nakamura et al., PRL 103, 262501 (2009)

Halo Nuclei



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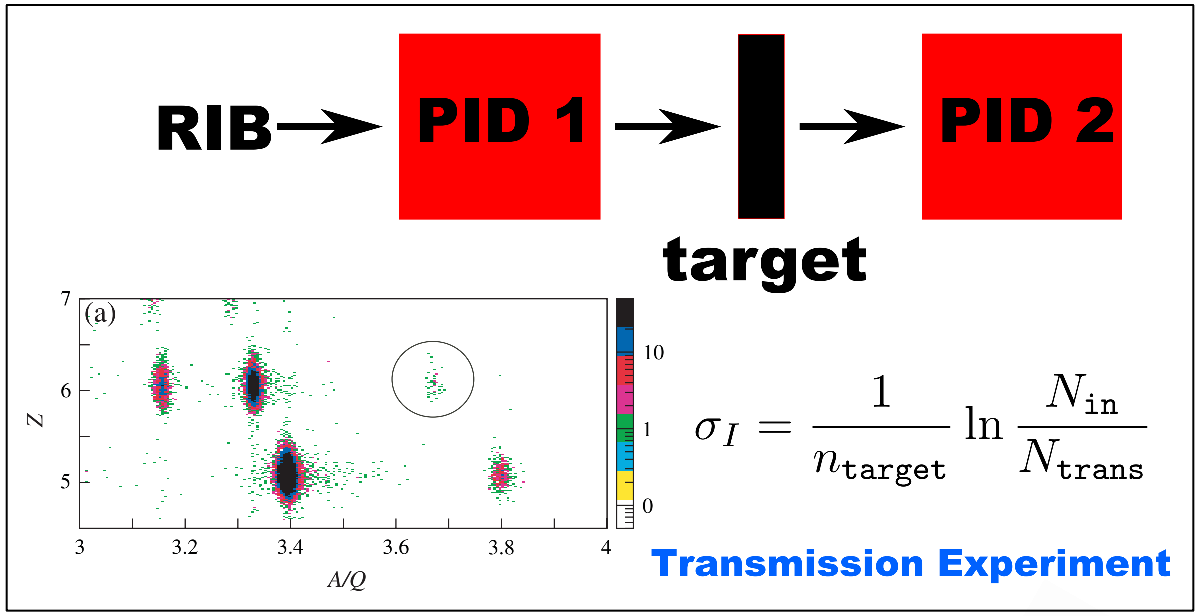

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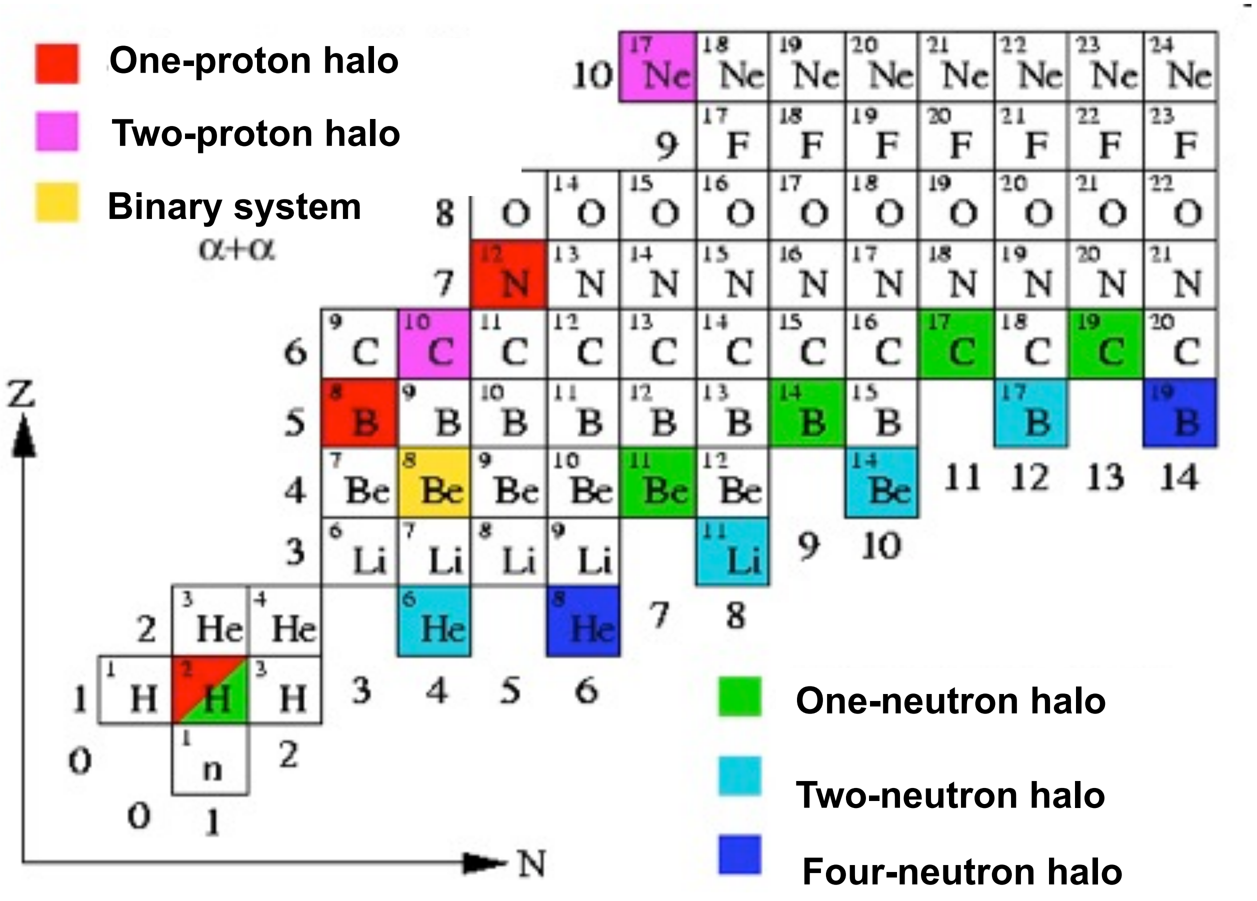
Transmission Experiment



🟥 One-proton halo

🟪 Two-proton halo

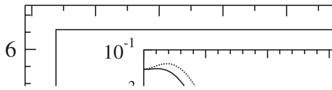
🟨 Binary system
α+α

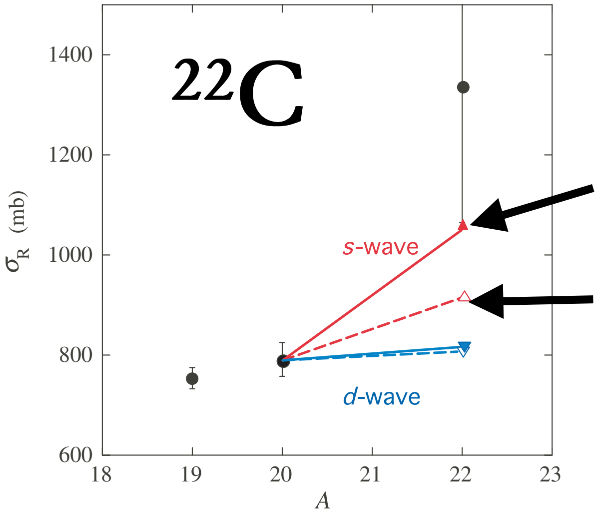
🟩 One-neutron halo

🟦 Two-neutron halo

🟦 Four-neutron halo

New Candidates:





S_{2n}=10 keV

S_{2n}=420 keV

⇒ **mass required**

N

K. Tanaka et al., PRL 104, 062701 (2010)

……

^{31}Ne

would be heaviest nuclear halo system

possibly p - wave 1n halo

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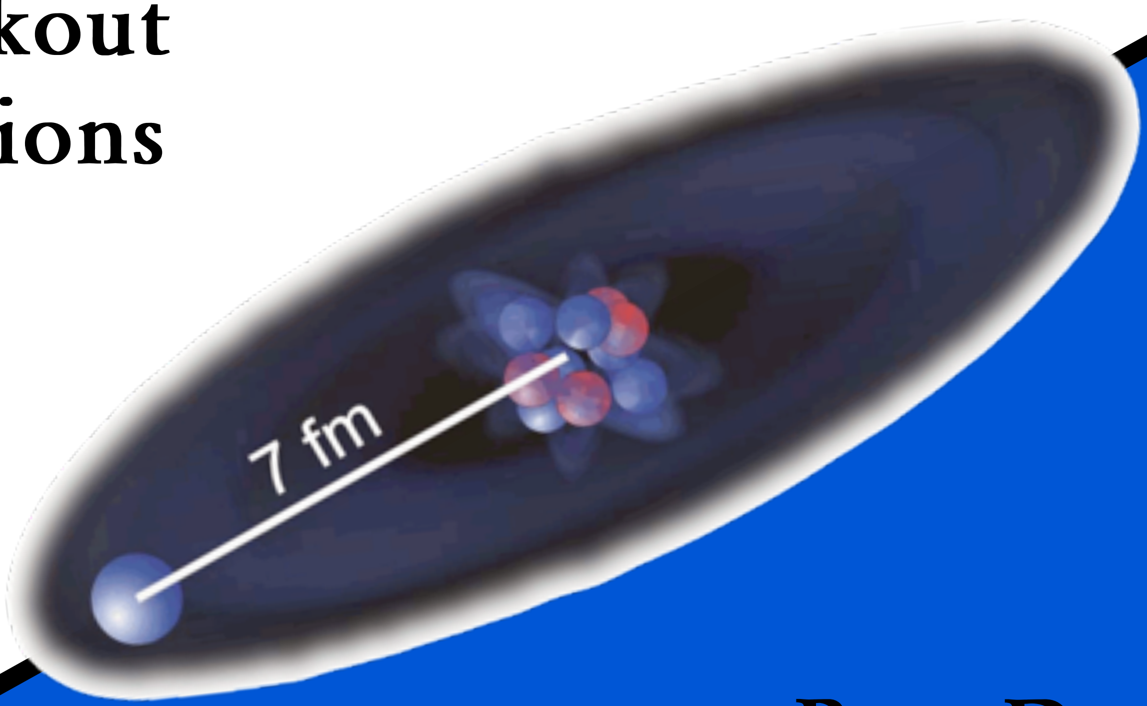
Experimental Probes for Halos



- accelerated beams
- model depend.

Elastic Scattering

Reaction Cross Sections

Knockout Reactions

Transfer Reaction

Breakup

Mass

Atomic Laser Spectroscopy

Beta Decay

Magnetic Moment

Beta Delayed Particle Emission

stopped or low E beam

TRIUMF ISAC

Experimental Probes for Halos

- accelerated beams
- model depend.

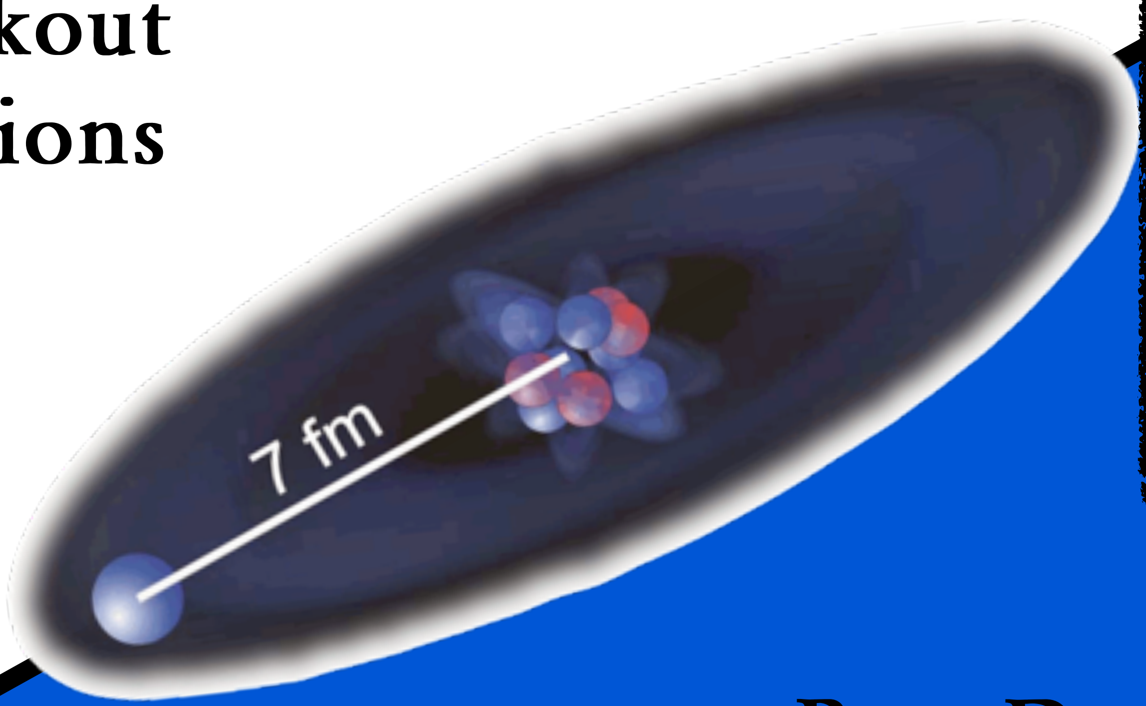
Elastic
Scattering

Reaction
Cross Sections

Knockout
Reactions

Transfer
Reaction

Breakup



Mass

this talk

Atomic Laser
Spectroscopy

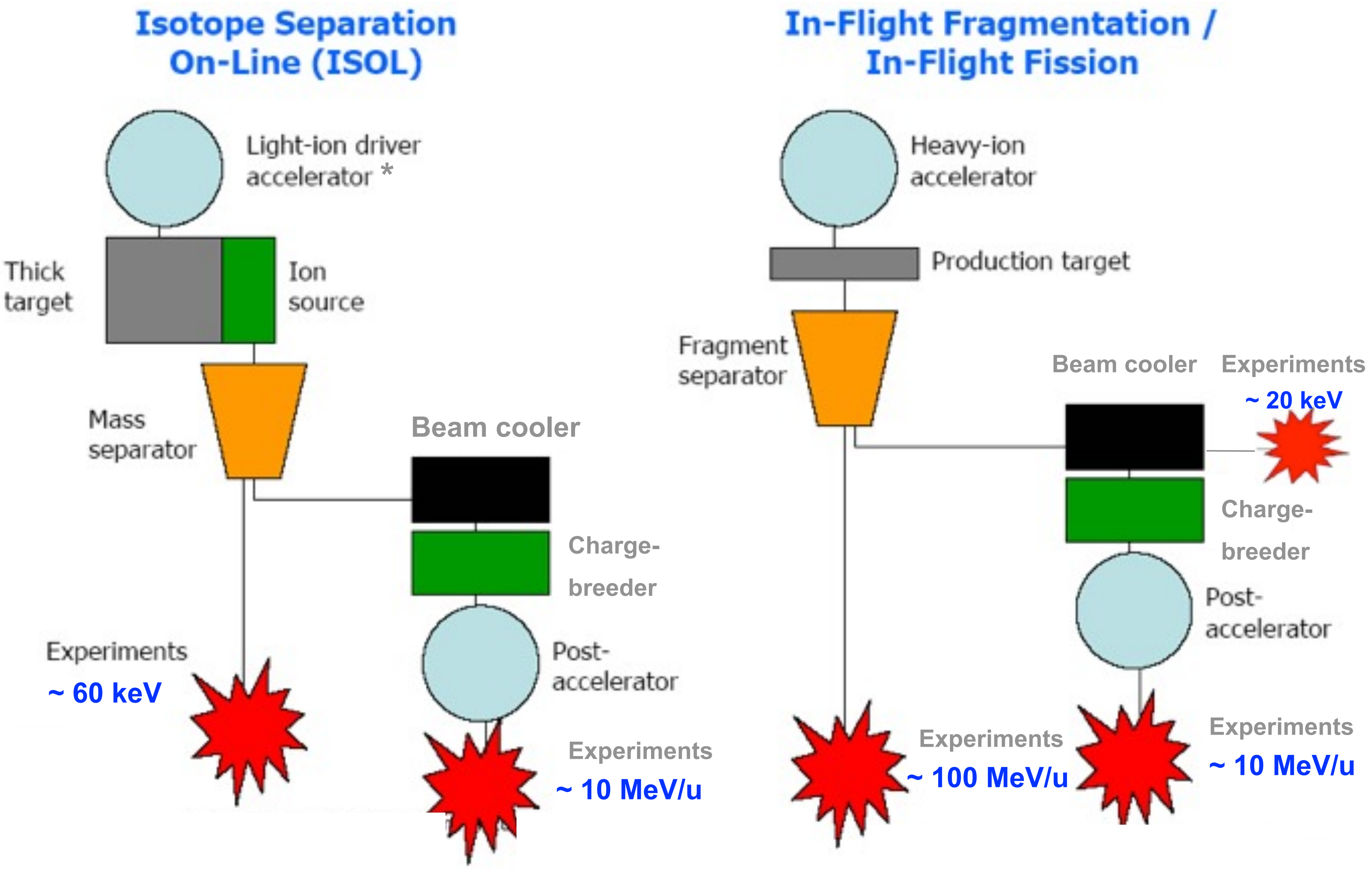
Beta Decay

Magnetic
Moment

Beta Delayed
Particle Emission

stopped or
low E beam

Rare Isotope Production



ISOL (TRIUMF, ISOLDE@CERN):

- Production: slow (~5 ms) BUT high intensity
- Low beam energy, ideal for decay and trap exp.
- Good beam quality (even cooled) & purity
- Post-acceleration for reaction studies
- BUT element selective ionization
  ⇒ some elements not possible!

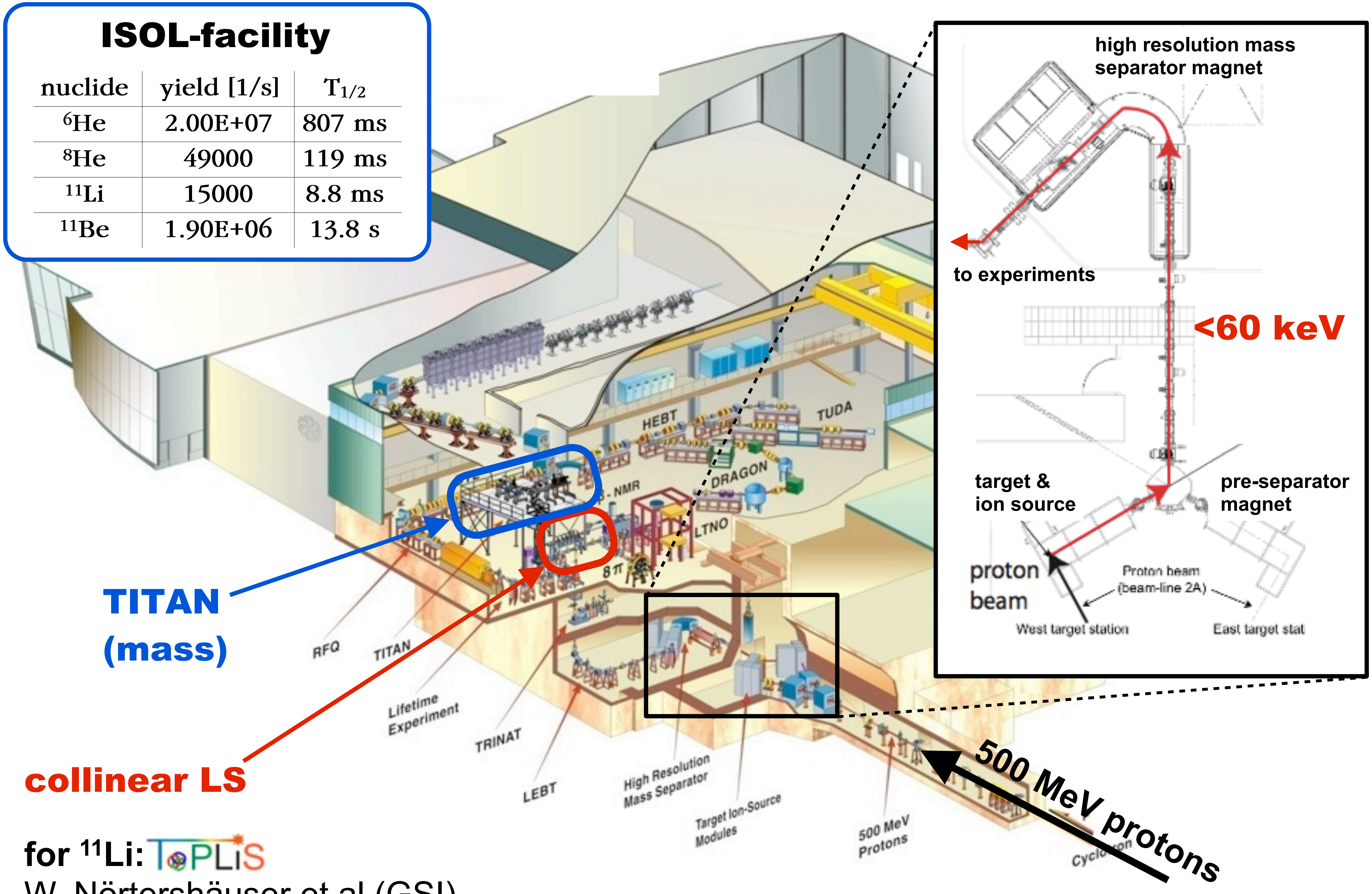
In-Flight (MSU, GSI, RIKEN, GANIL):

- Production: fast, no chemistry involved
- High beam energy, ideal for reaction exp.
- Life-time, masses, & basic discovery
- Low intensity, poor beam quality & purity

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



<60 keV

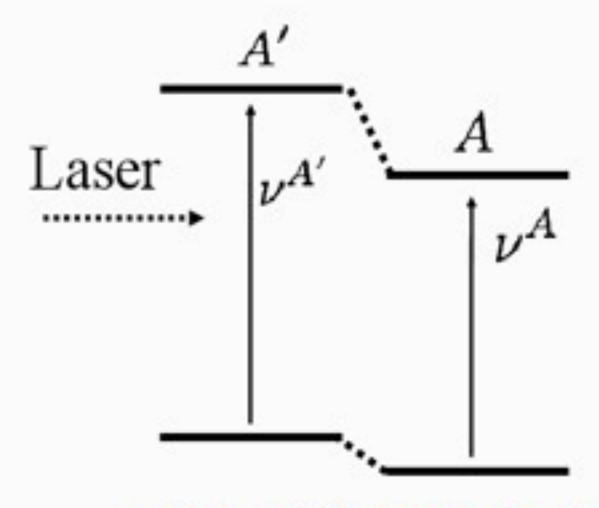
500 MeV protons

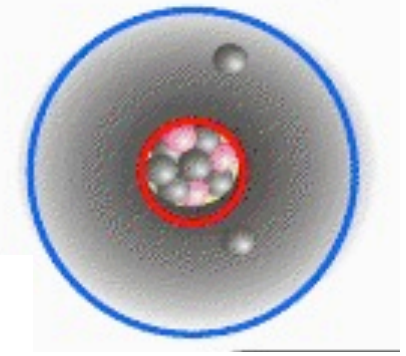
TITAN (mass)

collinear LS

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

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
- LS of individual atoms in MOT

$\left.\right\}$ in-beam

high precision atomic physics calculation

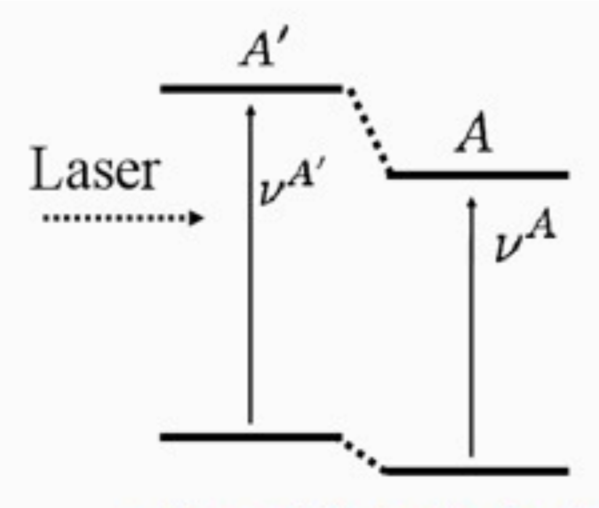
Z.-C. Yan et al., PRL 100, 243002 (2008)

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

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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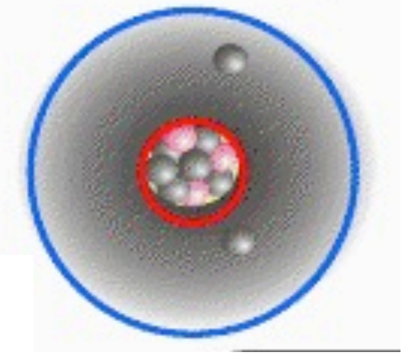

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$$\boxed{+\,\bar{r}_c^2(\mathcal{E}^{(0)}_{\mathrm{nuc}} + \lambda\mathcal{E}^{(1)}_{\mathrm{nuc}})} + \cdots$$

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

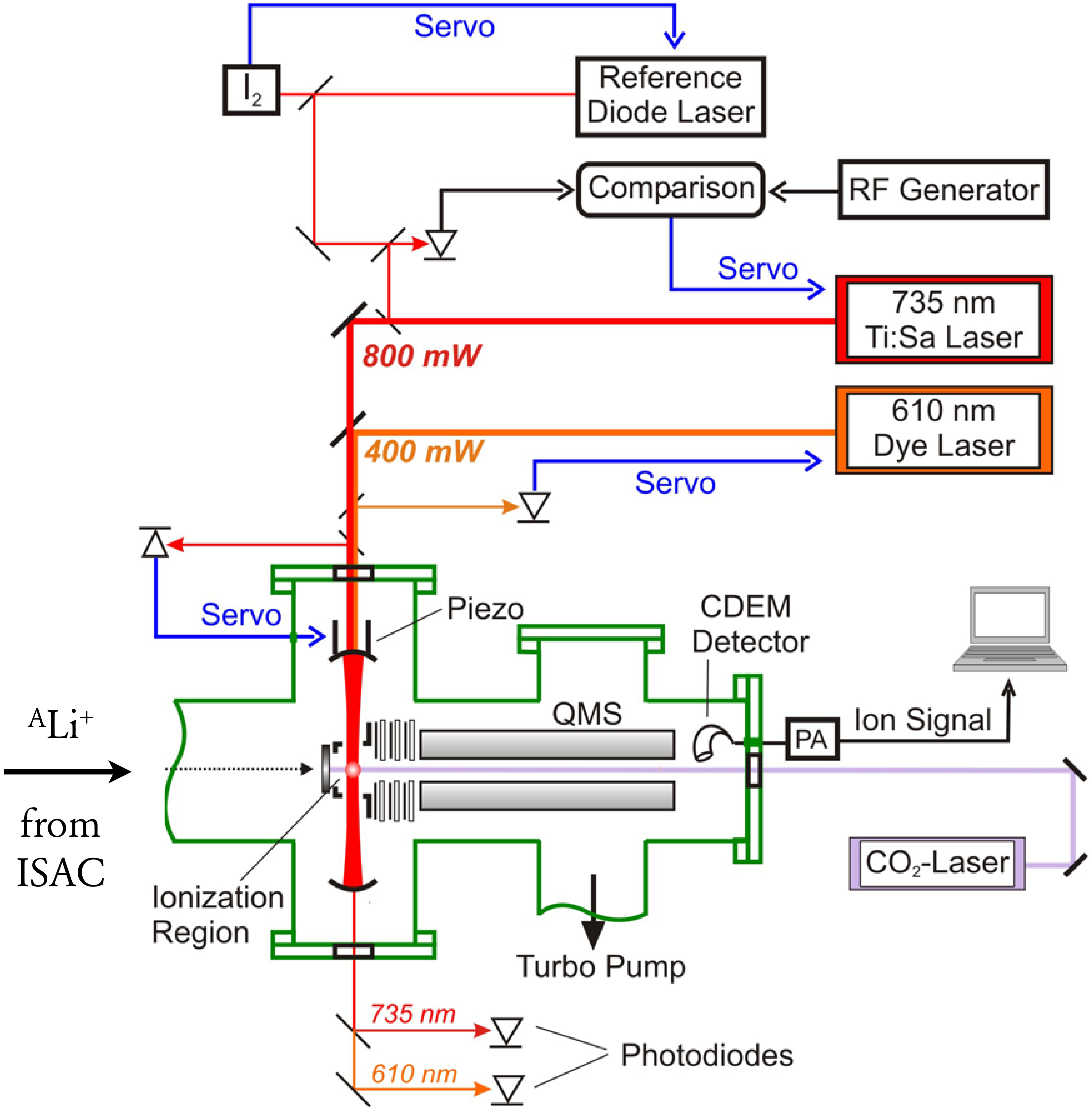
nuclear mass:

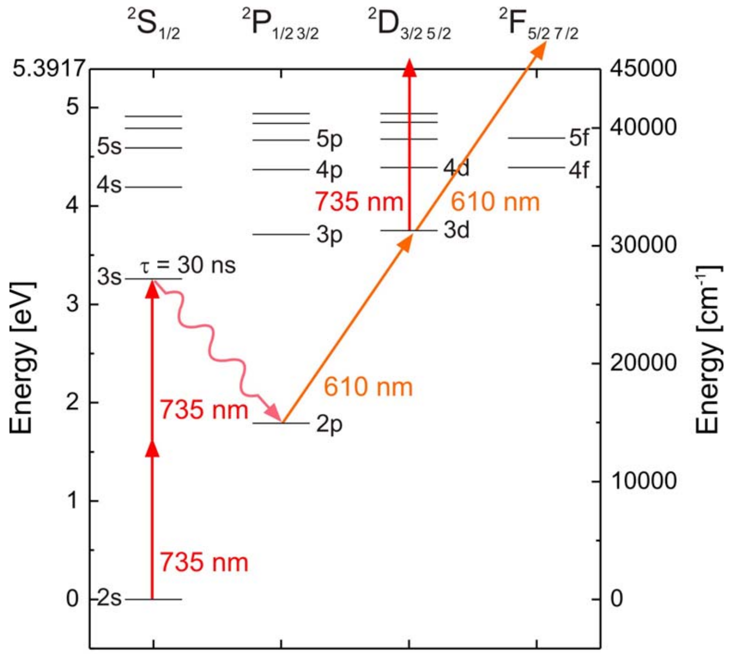
- need δm < 1keV
- short lived (<10 ms)

⇒ Penning Traps

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

Laser spectroscopy of ^{11}Li

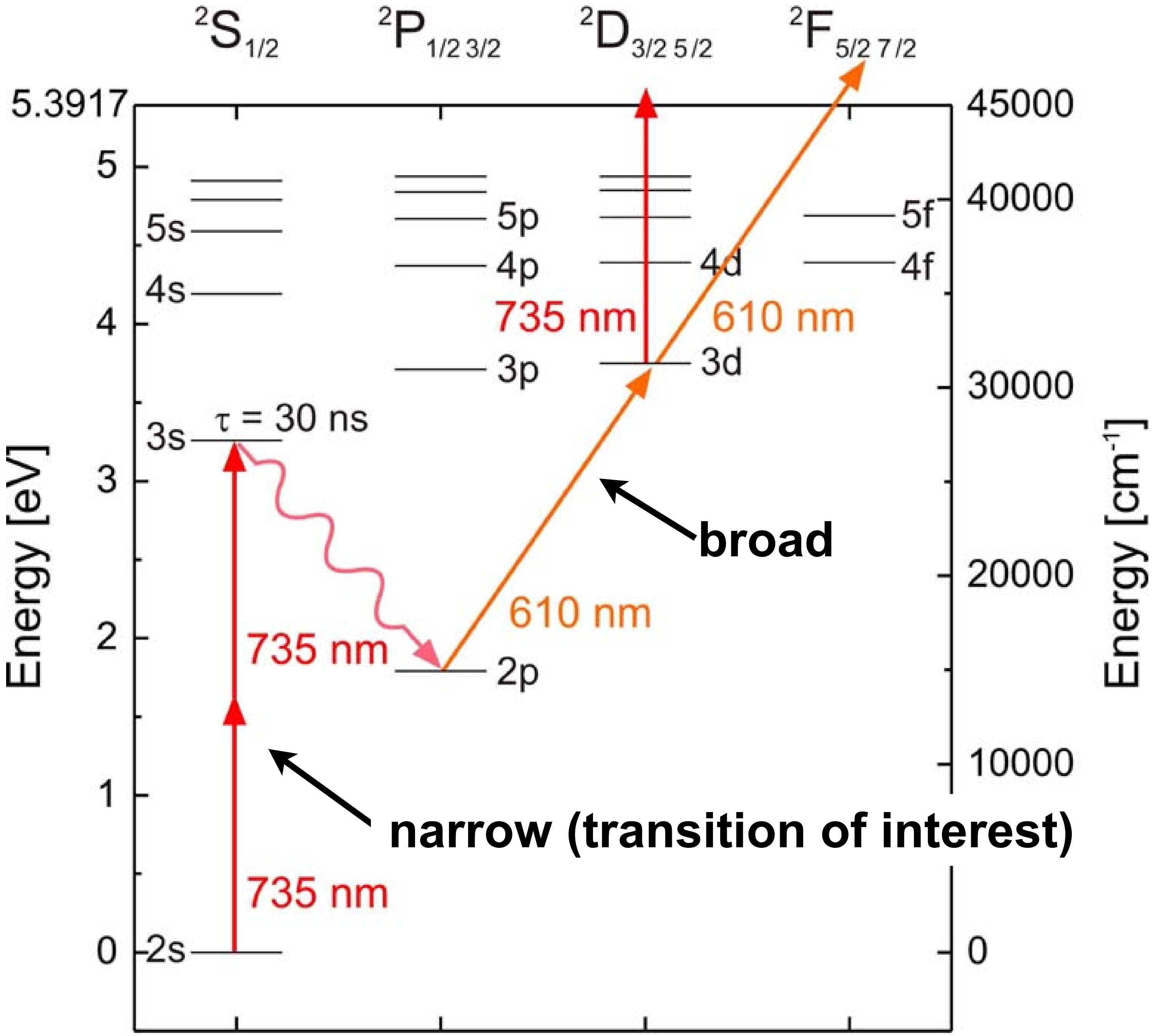




overall efficiency:
10^{-4}

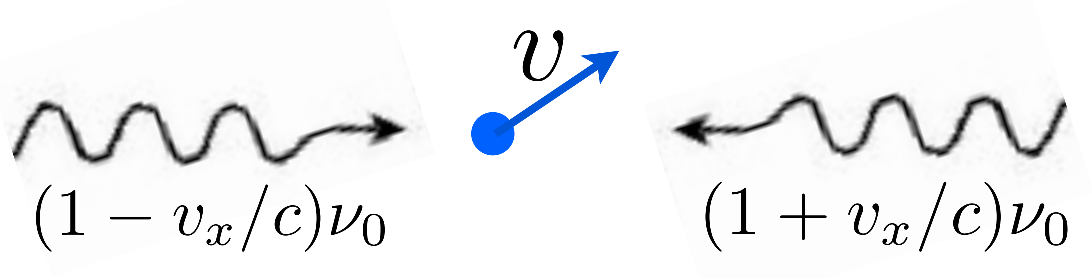
R. Sanchez et al., PRL 96, 033002 (2006)

Measurement Principle



atomic level scheme: Li

1) $^{11}Li^+$ from ISAC
2) neutralized in hot C - foil
3) two photon resonance 2s→3s



$(1 - v_x/c)\nu_0$ $(1 + v_x/c)\nu_0$

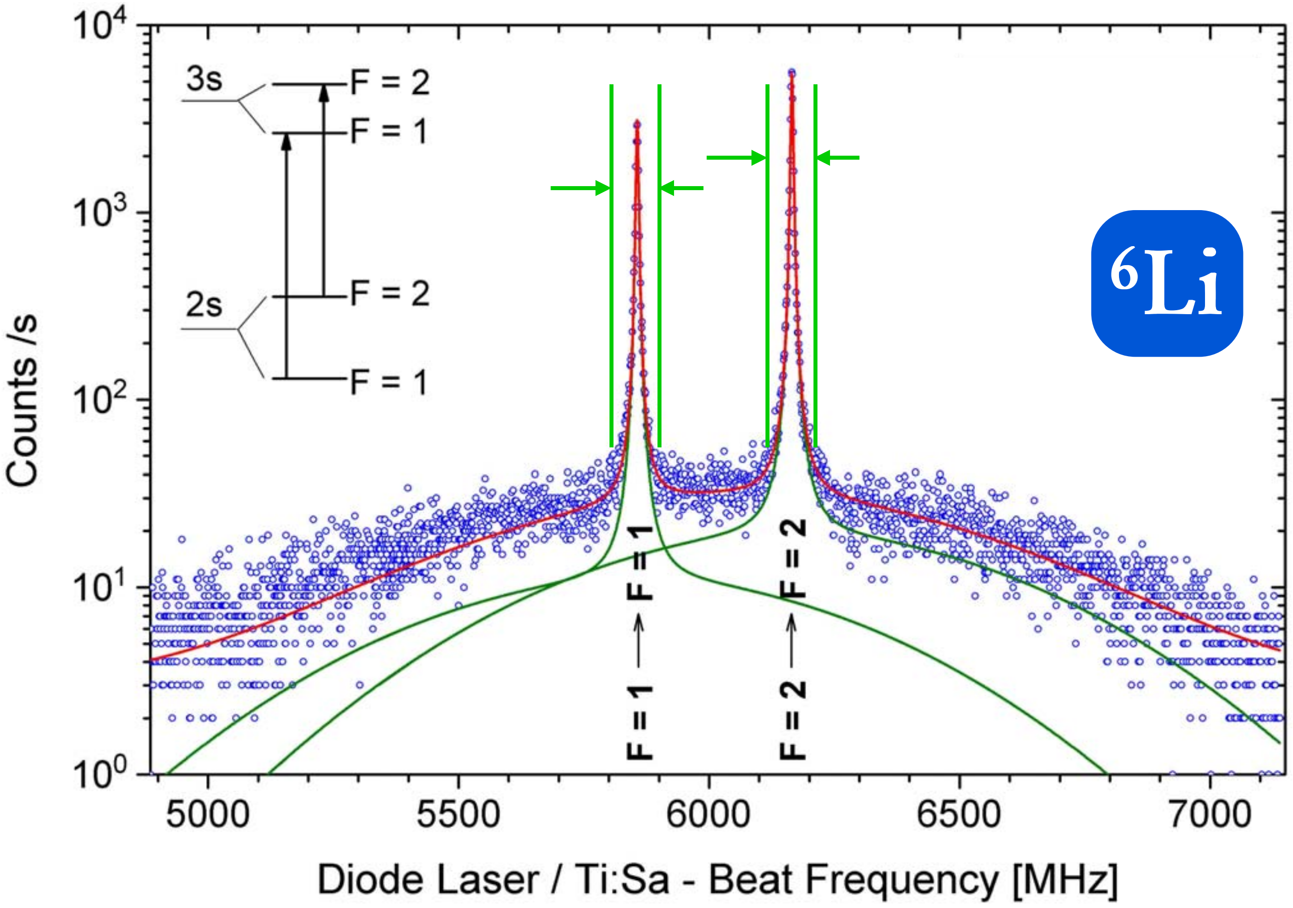
⇒ Doppler free

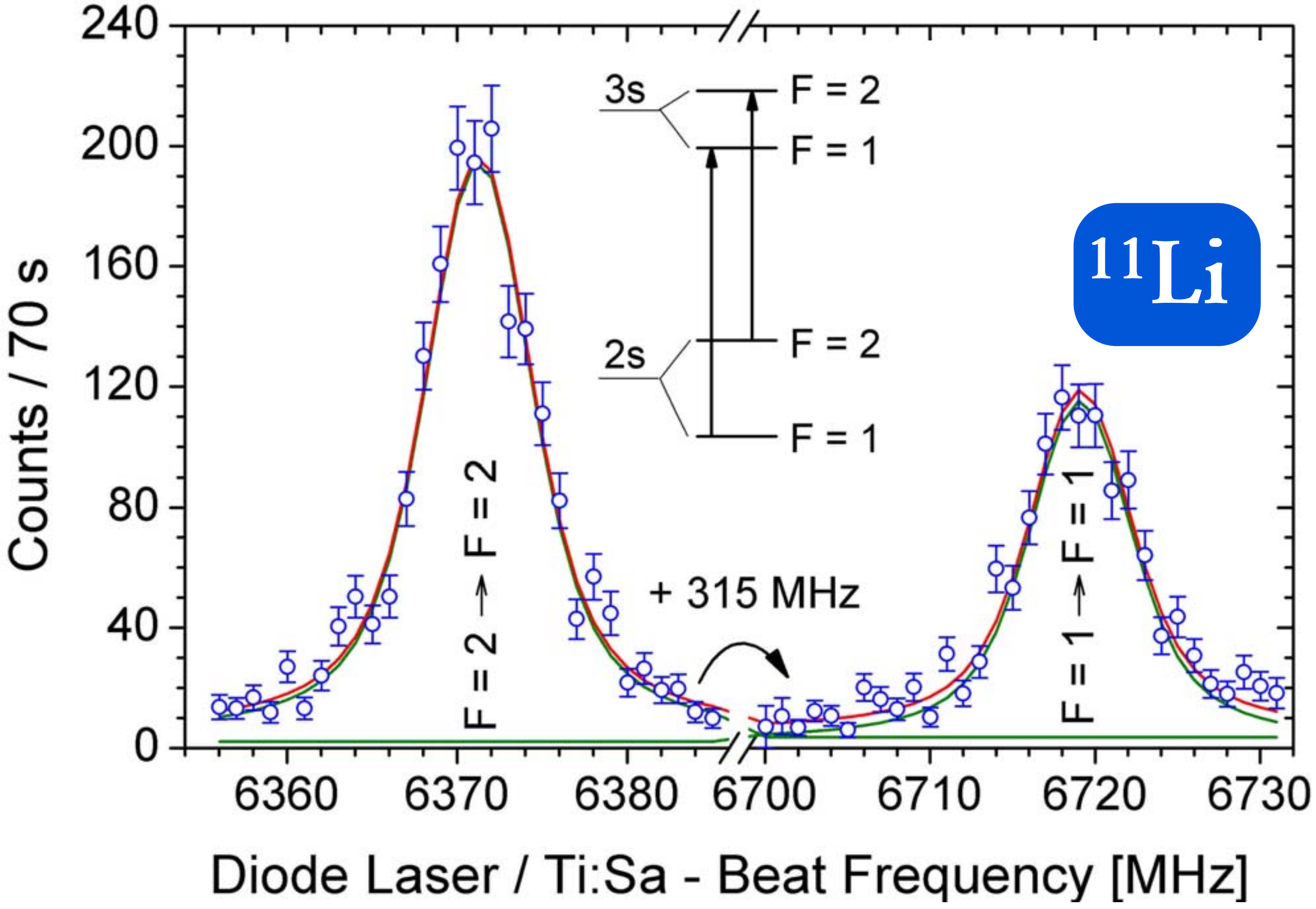
4) spontaneous decay 3s→2p
5) second laser: 2p→3d
6) ionization
7) detection of ions

⇒ scanν_0

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

Spectra





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

Results

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

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

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

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)

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

reference r_c

Results

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mass: MISTRAL (2005)

! need mass !

243002 (2008)

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

mass: AME'03

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

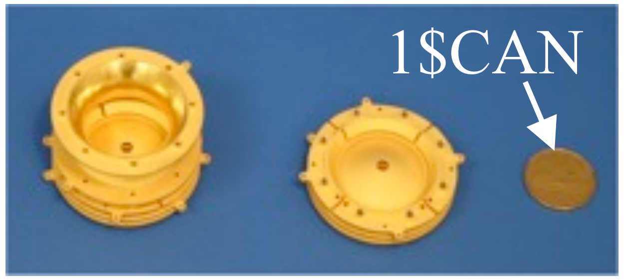
$r_c(^{11}\mathrm{Li})$ = 2.423(17)(30) fm

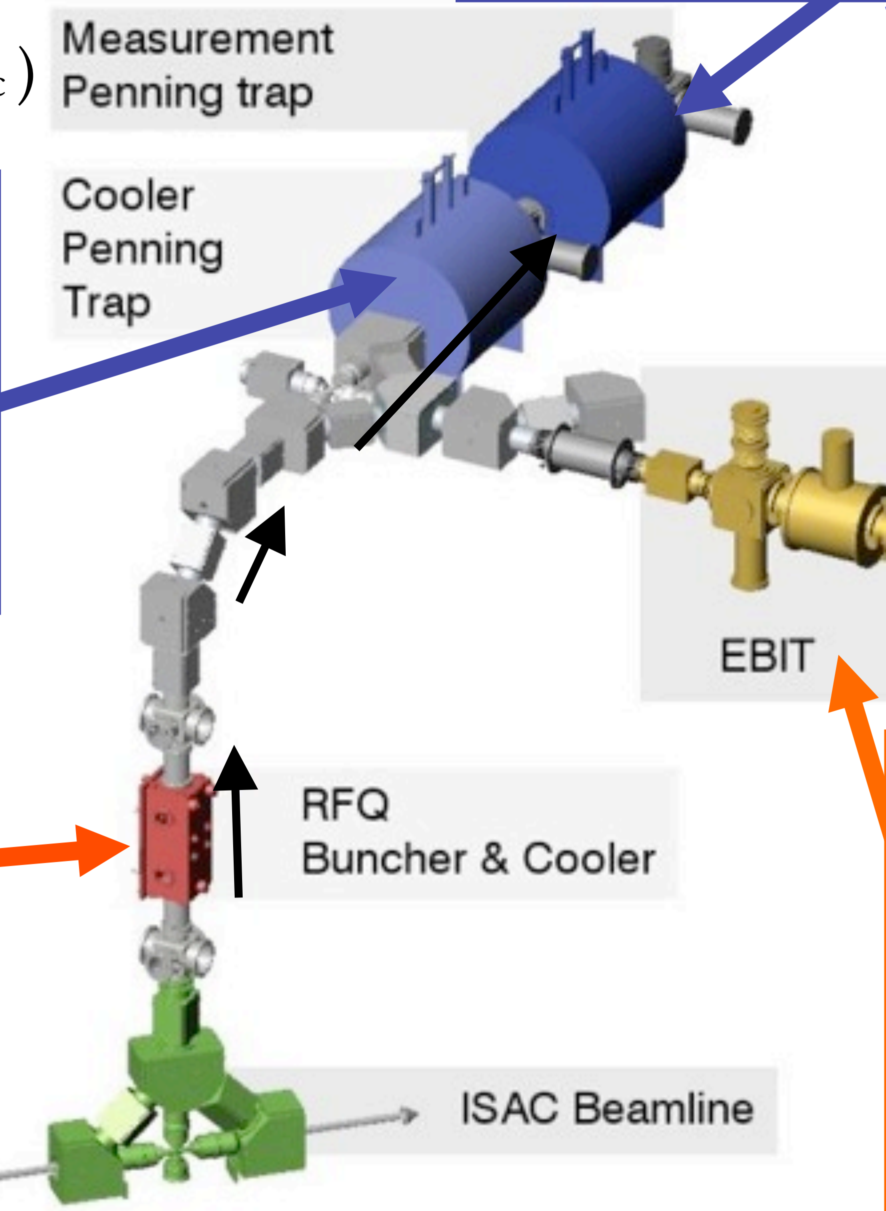
reference r_c

TITAN

masses of halos:

- reflect binding energy
- separation energy: S_n, Sp
- 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

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

Measurement Principle

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

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

- cyclotron frequency

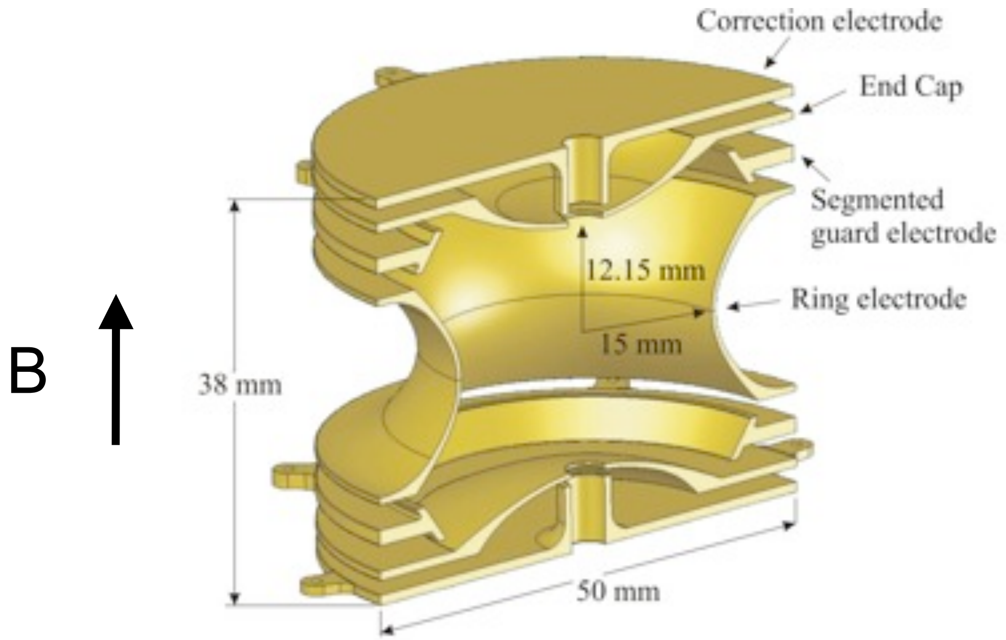
$$\nu_c = \nu_+ + \nu_- = \frac{1}{2\pi}\frac{q}{m}B$$

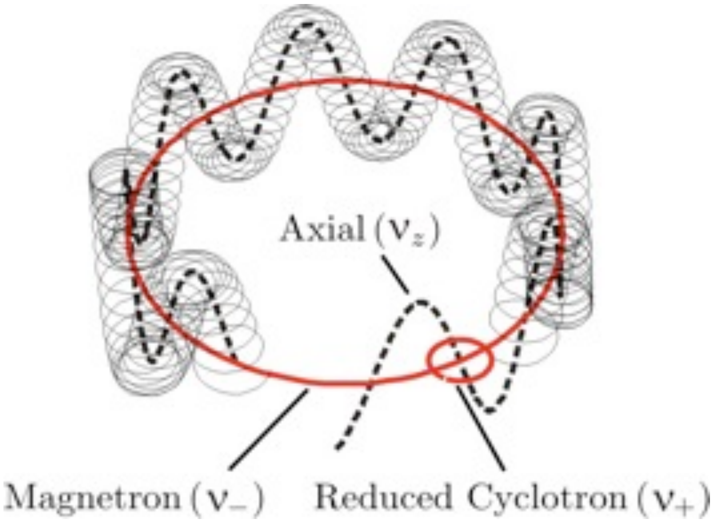
- quadrupolor rf- field (ring electrode) leads to conversion:

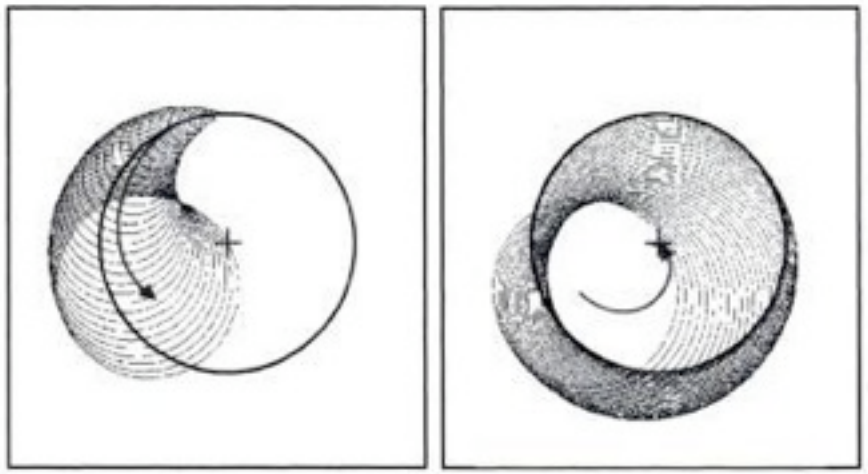
magnetron ↔ reduced cyclotron

- radial energy:

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

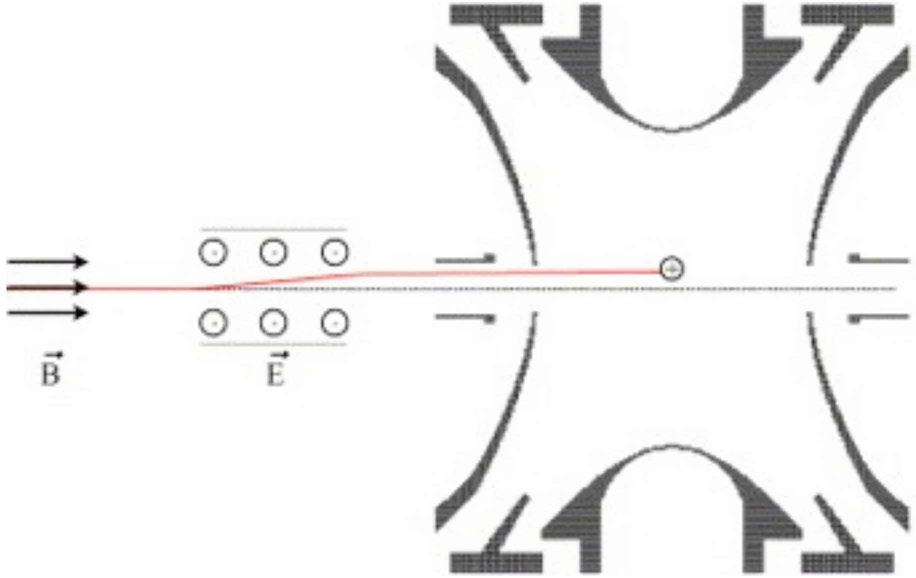


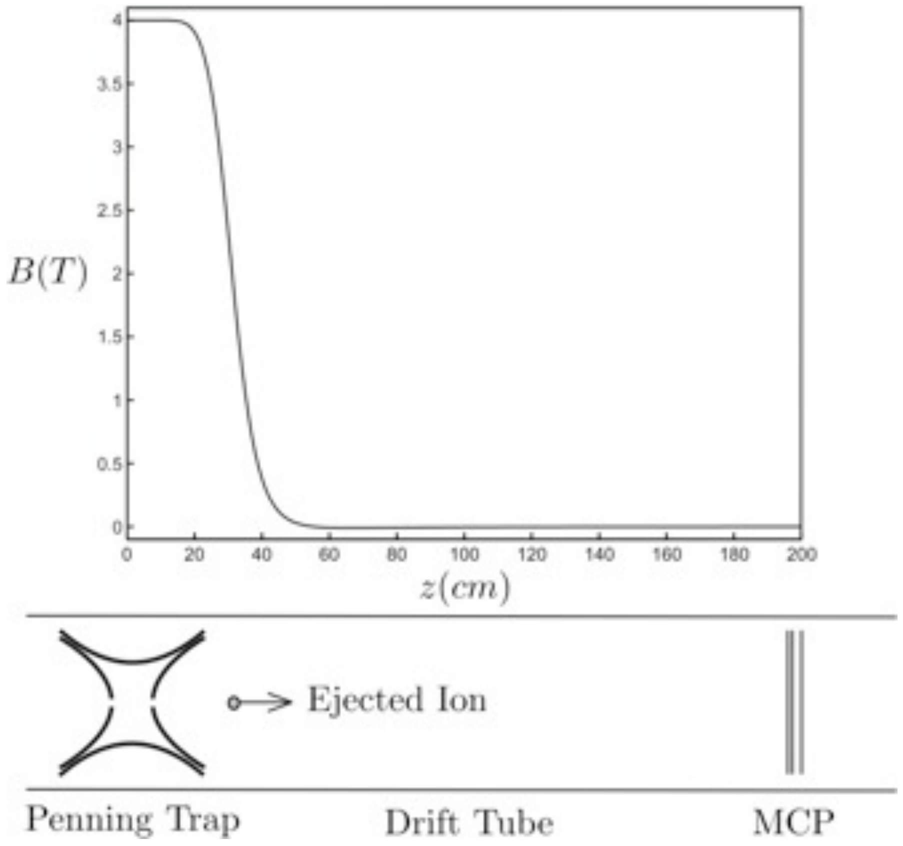


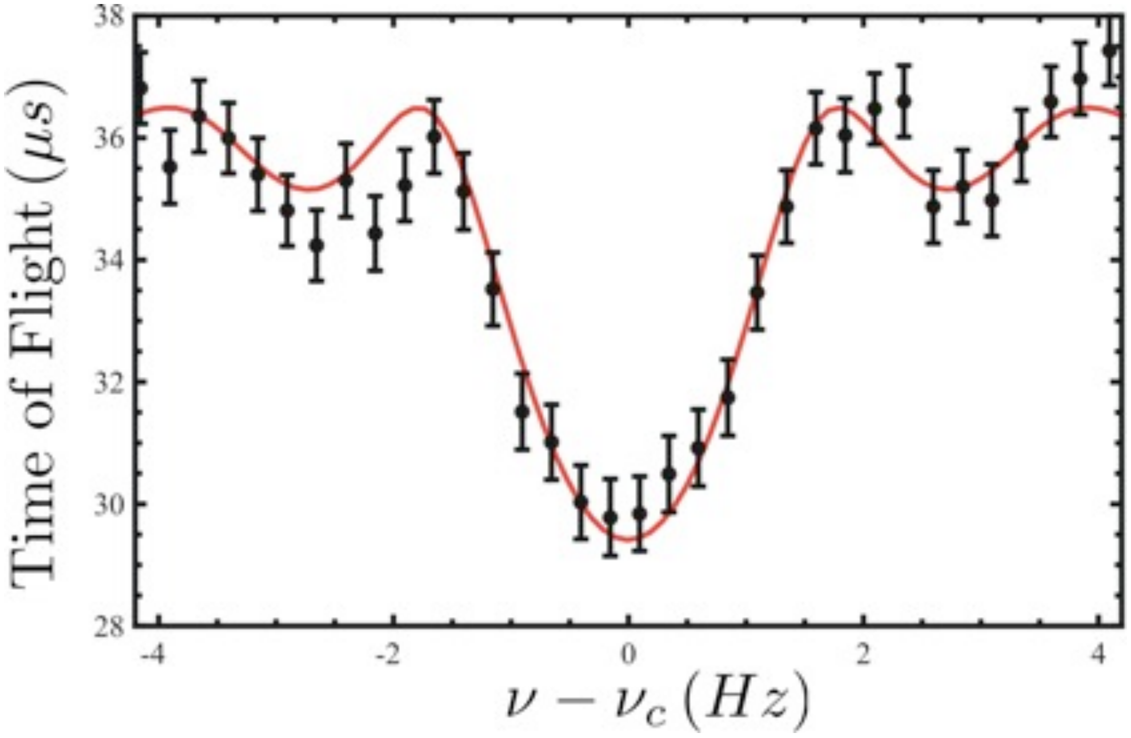


Mass measurements in the MPET

- 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):

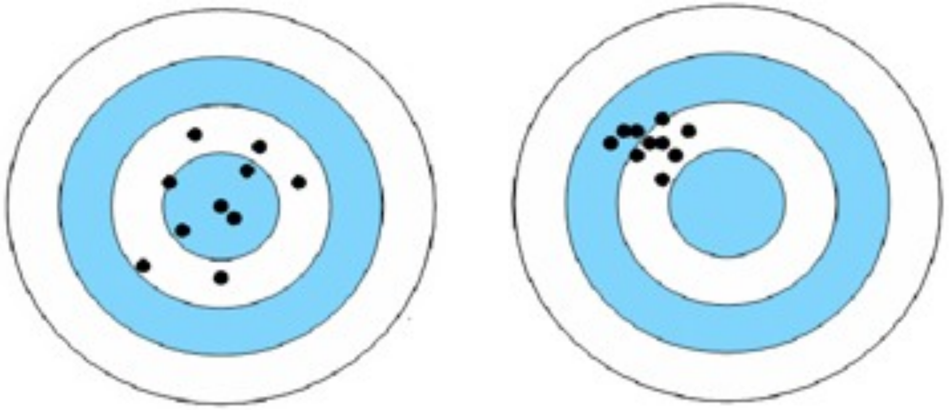
$$\Delta\nu \approx 1/T_{rf}$$

⇒ 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

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



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)

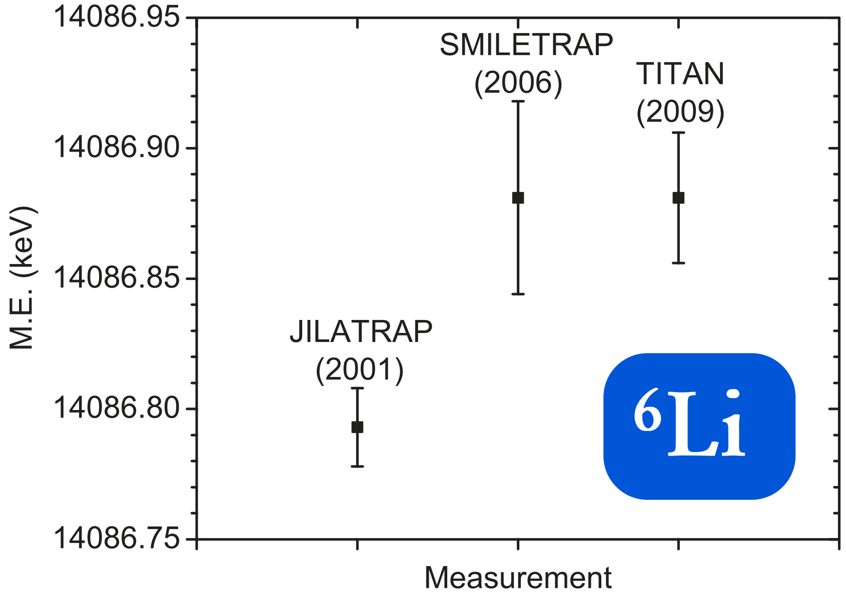
- even for non-ideal traps

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

- off-line tests with stables

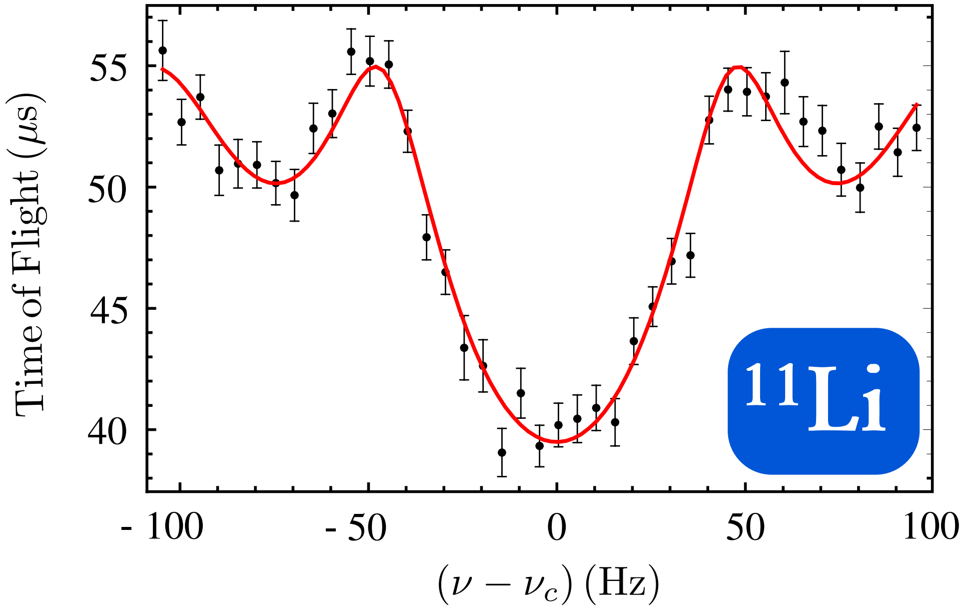
⇒ control over systematics

<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}Li) = 2.427(16)(30) fm

eliminates mass as source of uncertainty!

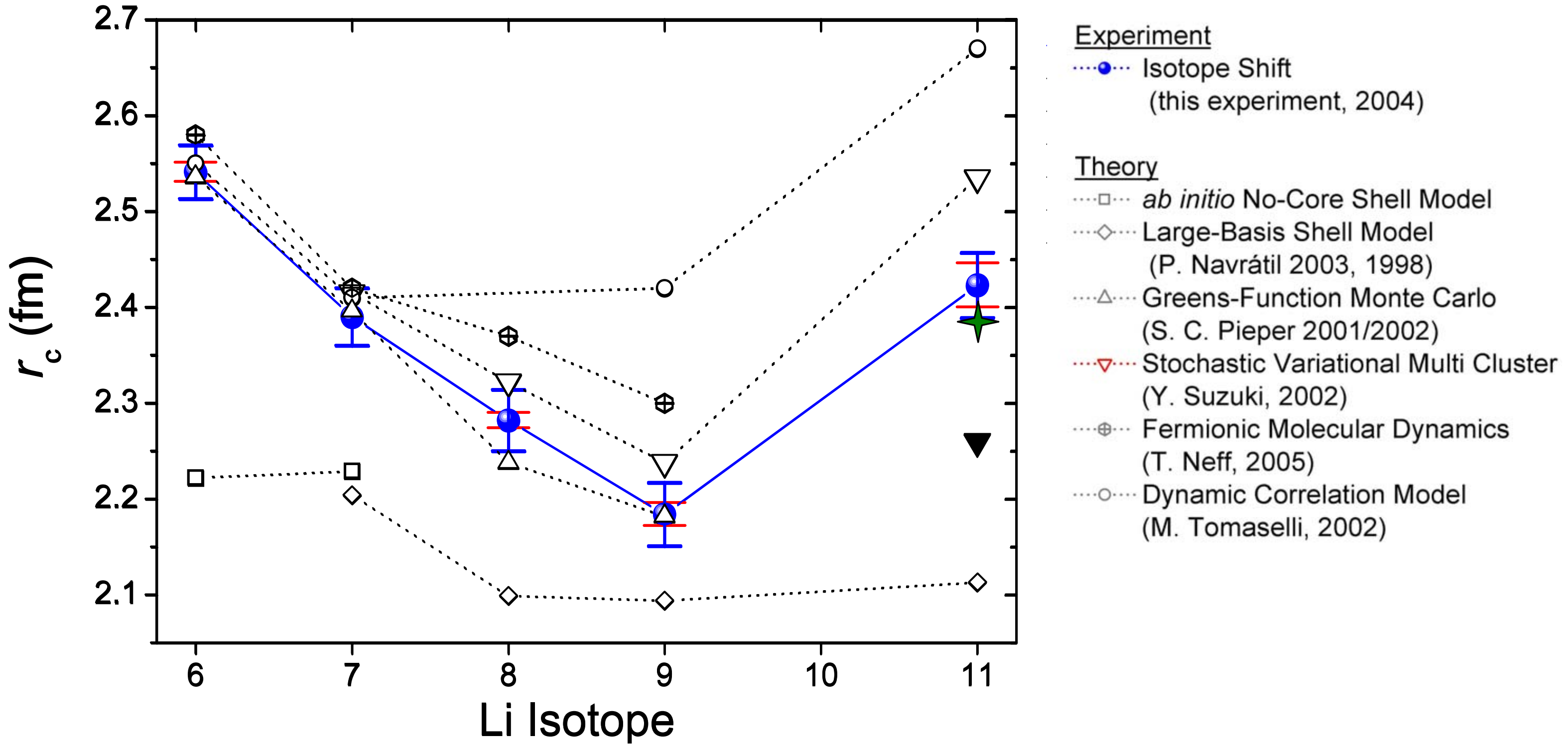
<u>two neutron separation energy:</u>

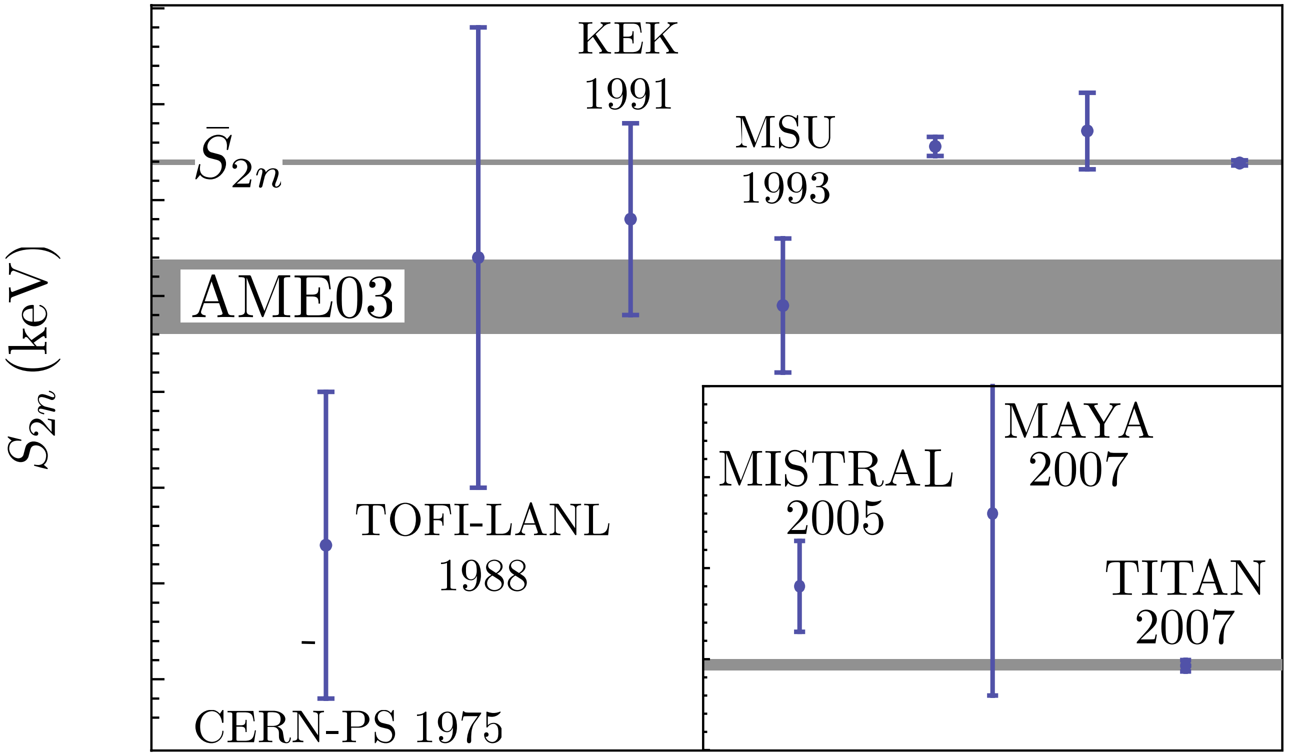
$$S_{2n} = -M(A,Z) + M(A-2,Z) + 2n$$

- 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

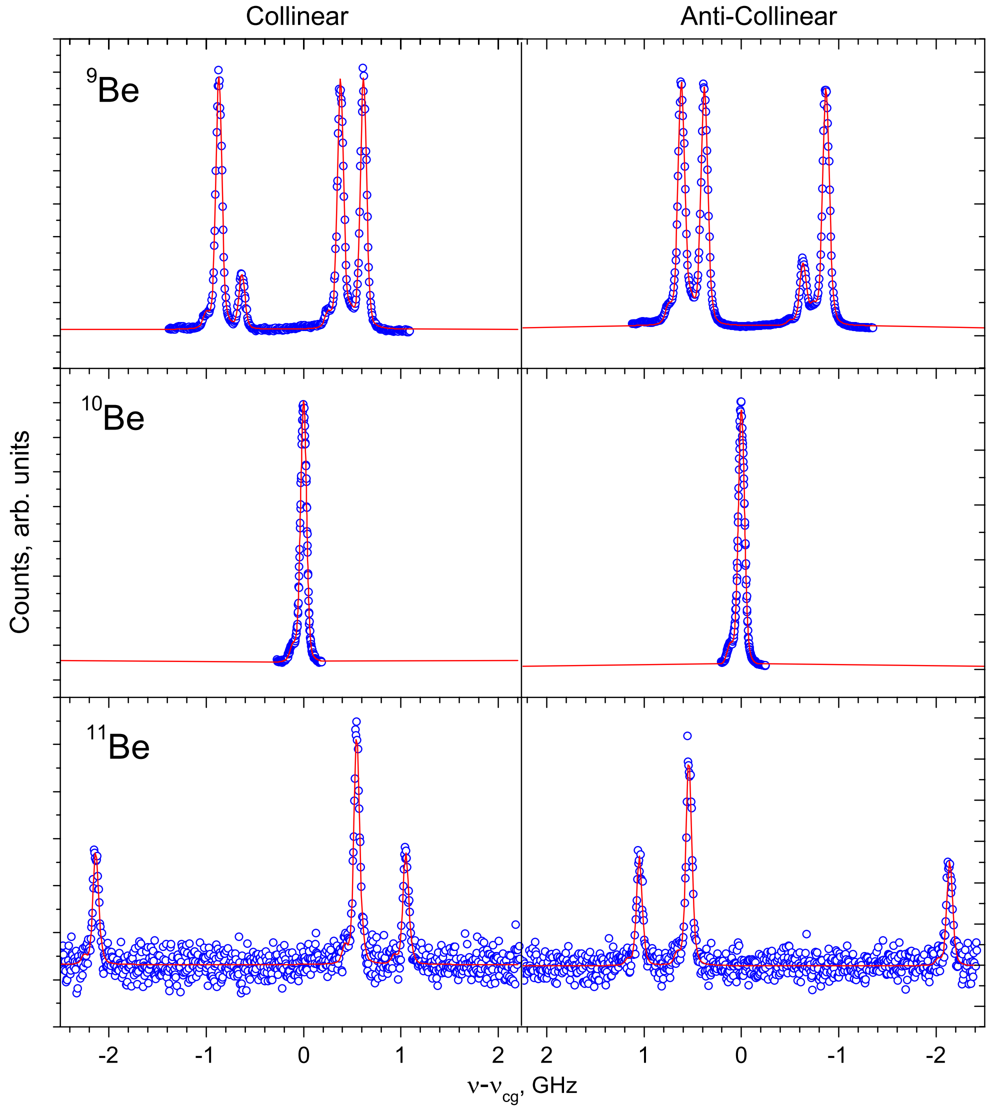
	^{6}He Value	^{6}He Error	^{8}He Value	^{8}He Error
Statistical				
Photon counting		0.008		0.032
Probing laser alignment		0.002		0.012
Reference laser drift		0.002		0.024
Systematic				
Probing power shift				0.015
Zeeman shift		0.030		0.045
Nuclear mass		0.015		0.074
Corrections				
Recoil effect	0.110	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)

^{811}Be:

- GSI
- collinear LS

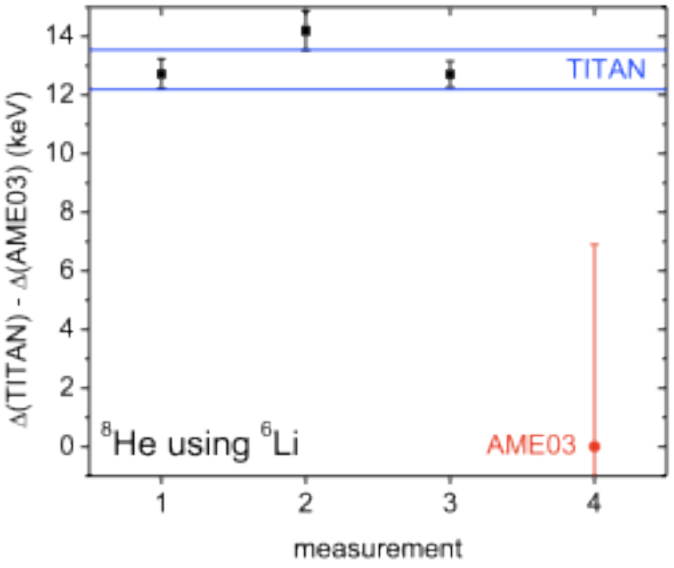


δm=6.4 keV (AME'03)

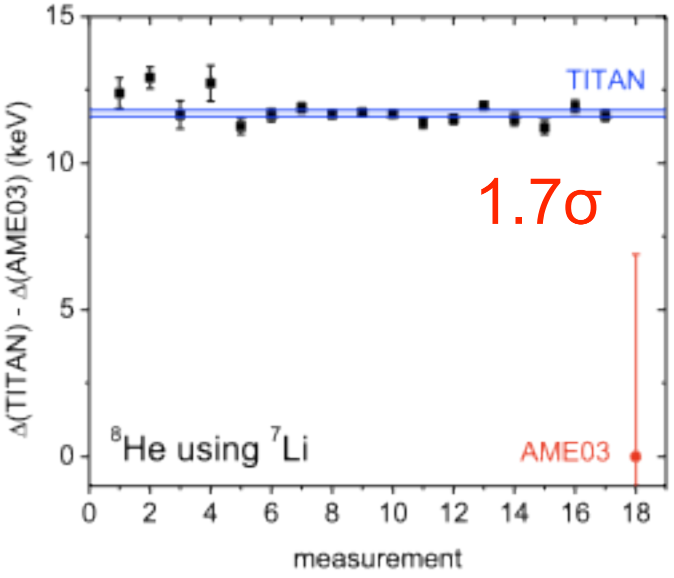
W. Nörtershäuseret al., PRL 102, 062503 (2009)

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

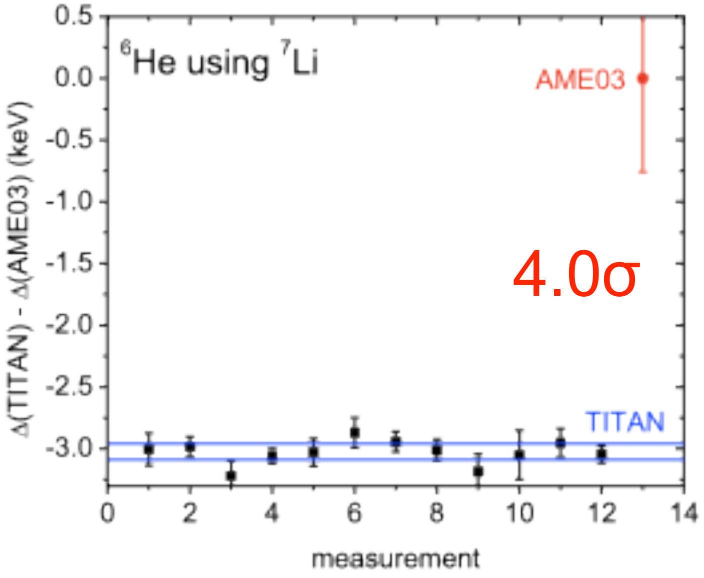
1st ^{8}He mass meas.



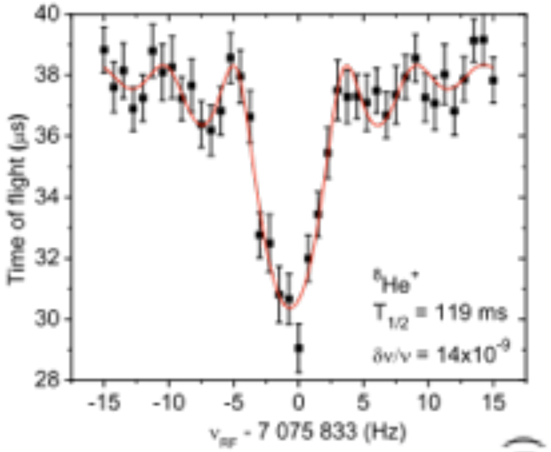
2nd ^{8}He mass meas.



^{6}He mass meas.



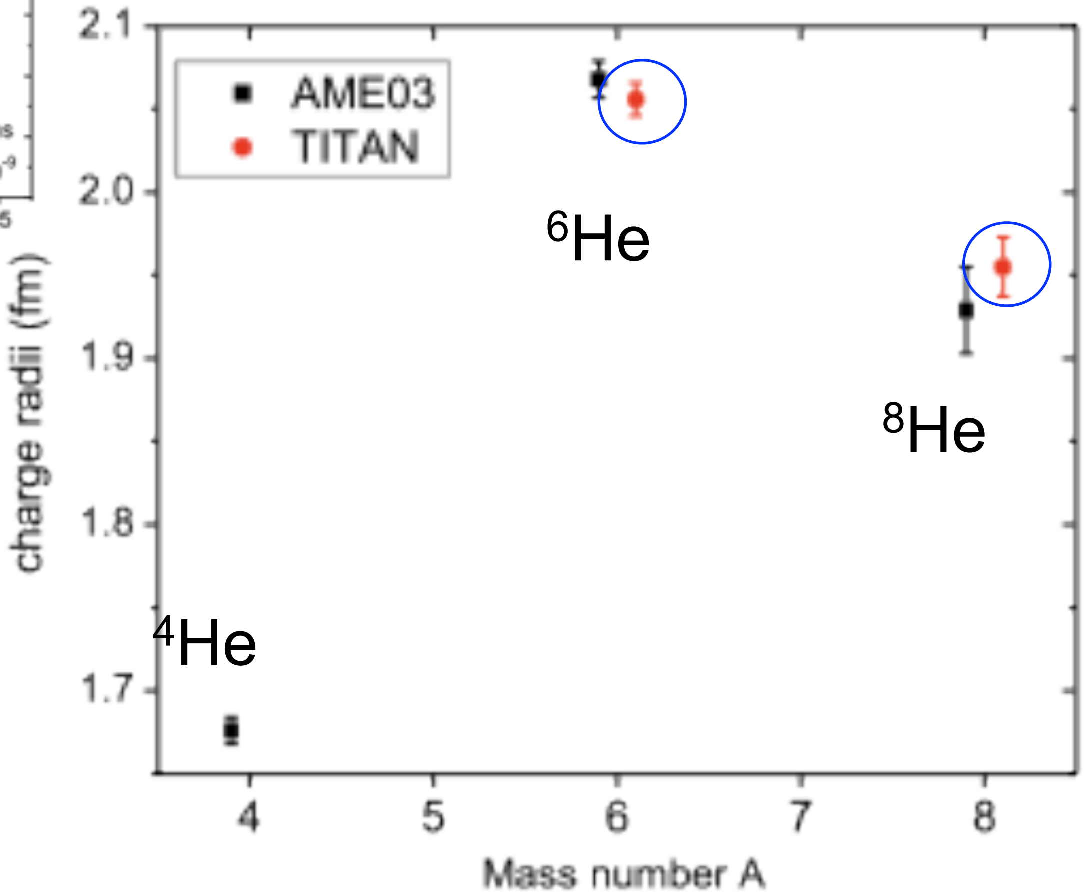
V. L. Ryjkov et al., PRL 101, 012501 (2008)



M. Brodeur et al., in prep.

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

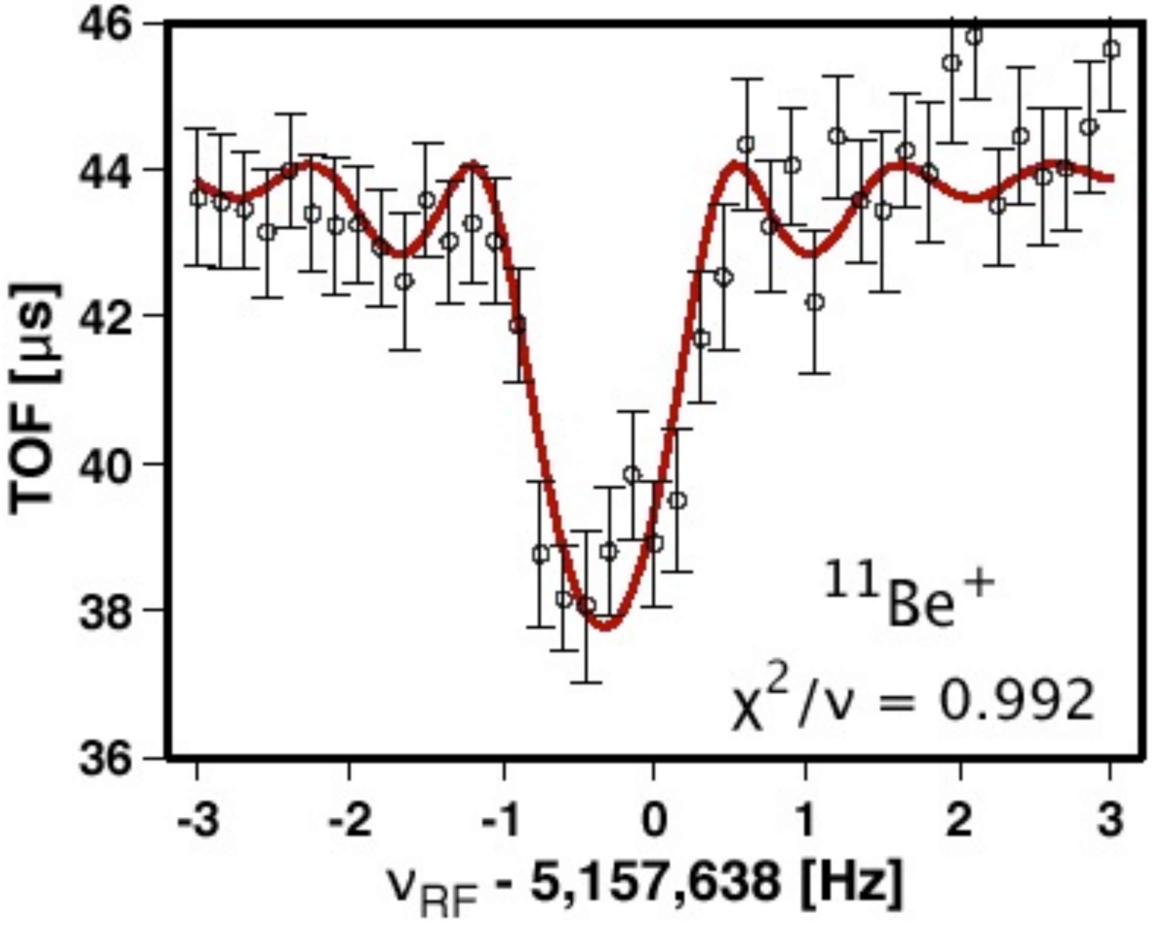
Isotope	mass (× 10^6 u)	M.E. (keV)
^{6}He	6 018 885.883(70)	17 592.087(65)
^{8}He (1st)	8.033 935 669(722)	31 610.872(673)
^{8}He (2nd)	8.033 934 410(128)	31 609.700(120)
^{8}He (average)	8.033 934 449(126)	31 609.736(118)

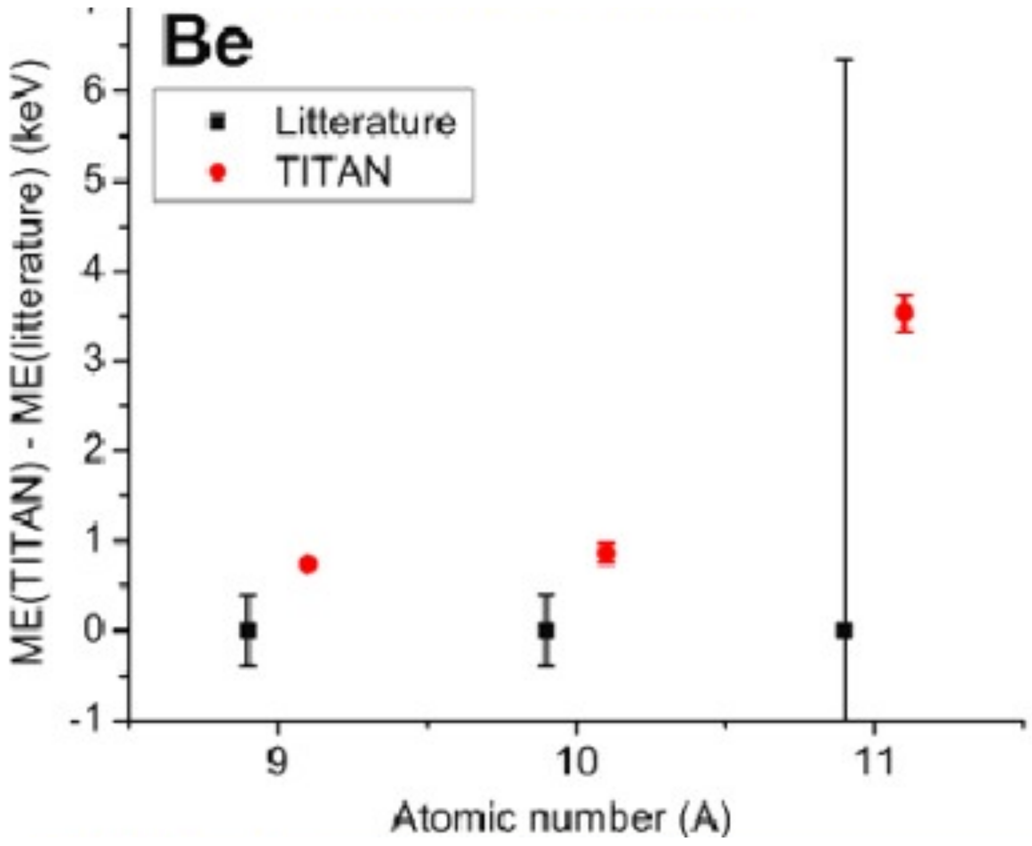


comparison to theory: need 3N interactions

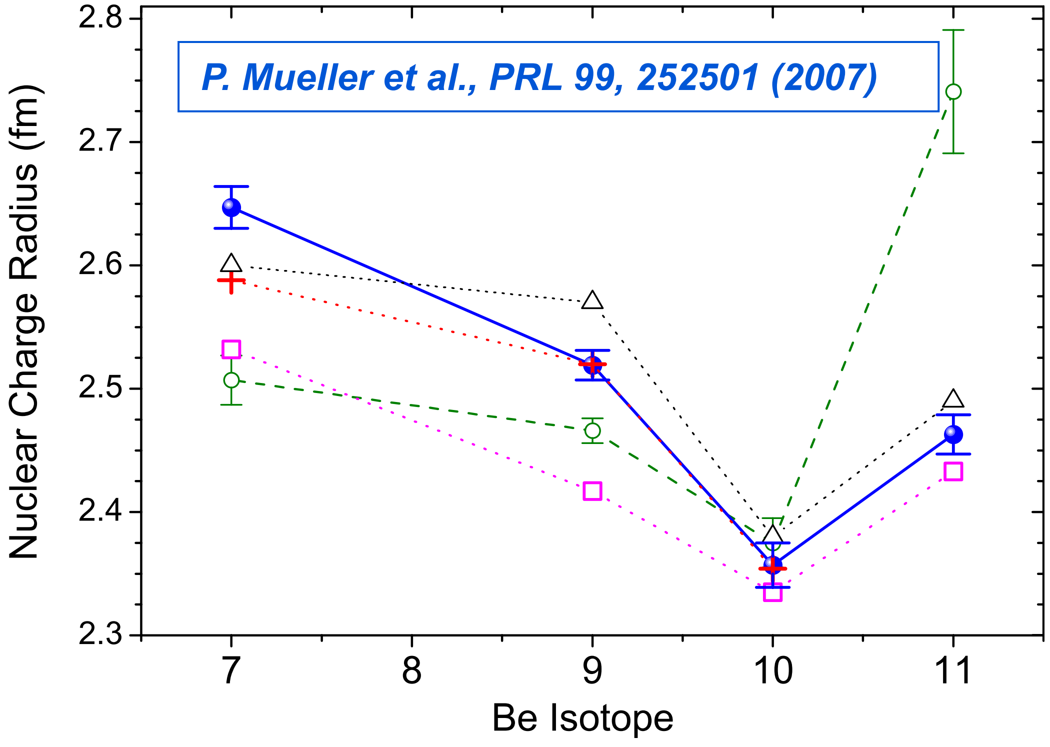
S. Bacca et al., Eur. Phys. J. A 42, 553 (2009)

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)



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

⇒confirms AME & improves precision

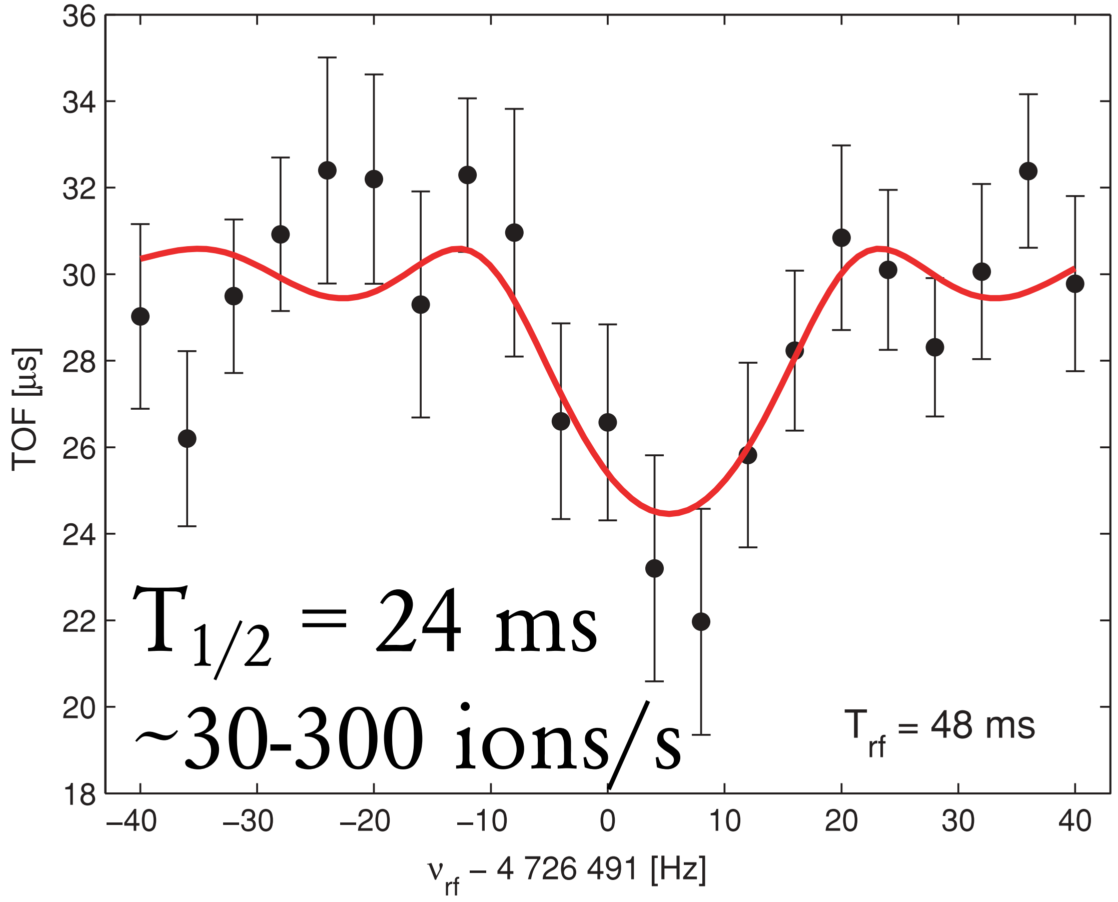
⇒uncertainty of mass negligible for r_c

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

^{12}Be

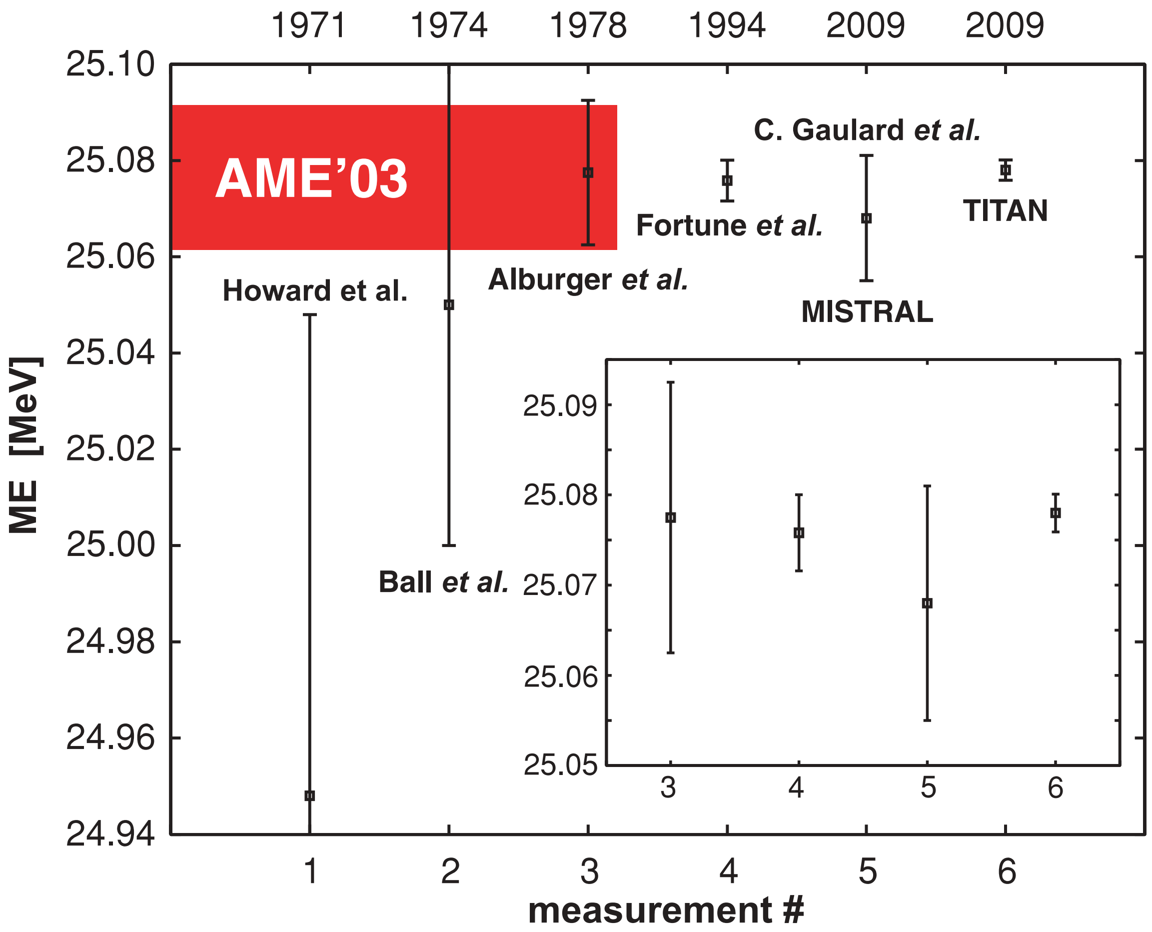
calculation & measurement of r_c in the near future

→ ***see talk of Thomas Neff***



$T_{1/2}$ = 24 ms

~30-300 ions/s



detectable at yield station

⇒ measurement possible

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

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

Conclusions

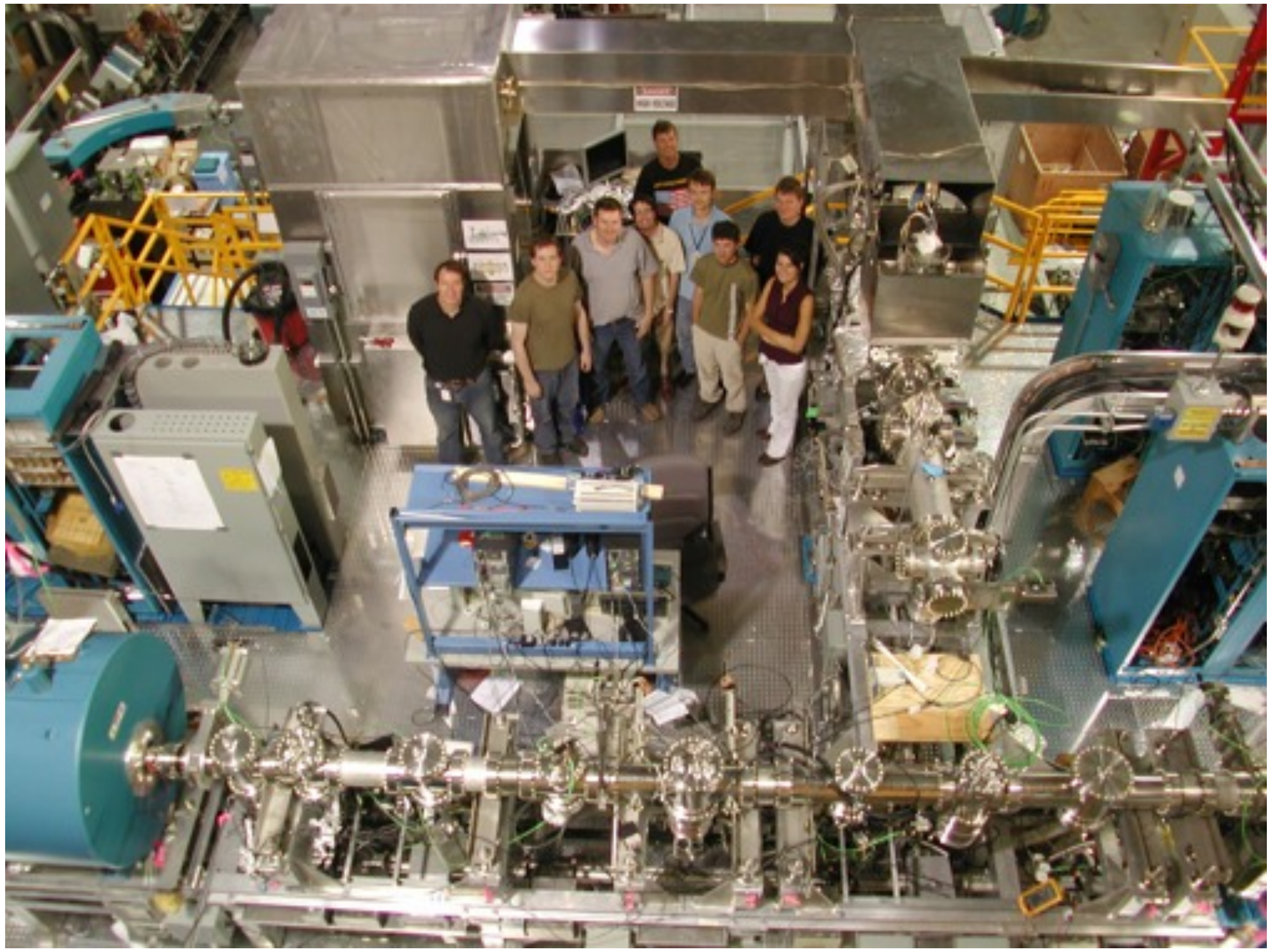
- Interplay of various experimental approaches allow to identify & probe nuclear halos
- Combination of high precision
  - laser spectroscopy
  - mass measurements
  - atomic physics calculation

  } ⇒ **charge radius**
- benchmark theoretical models (mass, matter/charge radius, ..)

Outlook (TRIUMF)

- later this year: electric quadrupole moment of ^{11}Li
- TITAN: masses
  - to investigate established halos ^{14}Be(2n), ^{19}C(1n), ^{17}Ne(1p)
  - needed to decide if halo structure in ^{22}C and ^{31}Ne

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

Backup Slides

^{11}Be: Comparison to Models

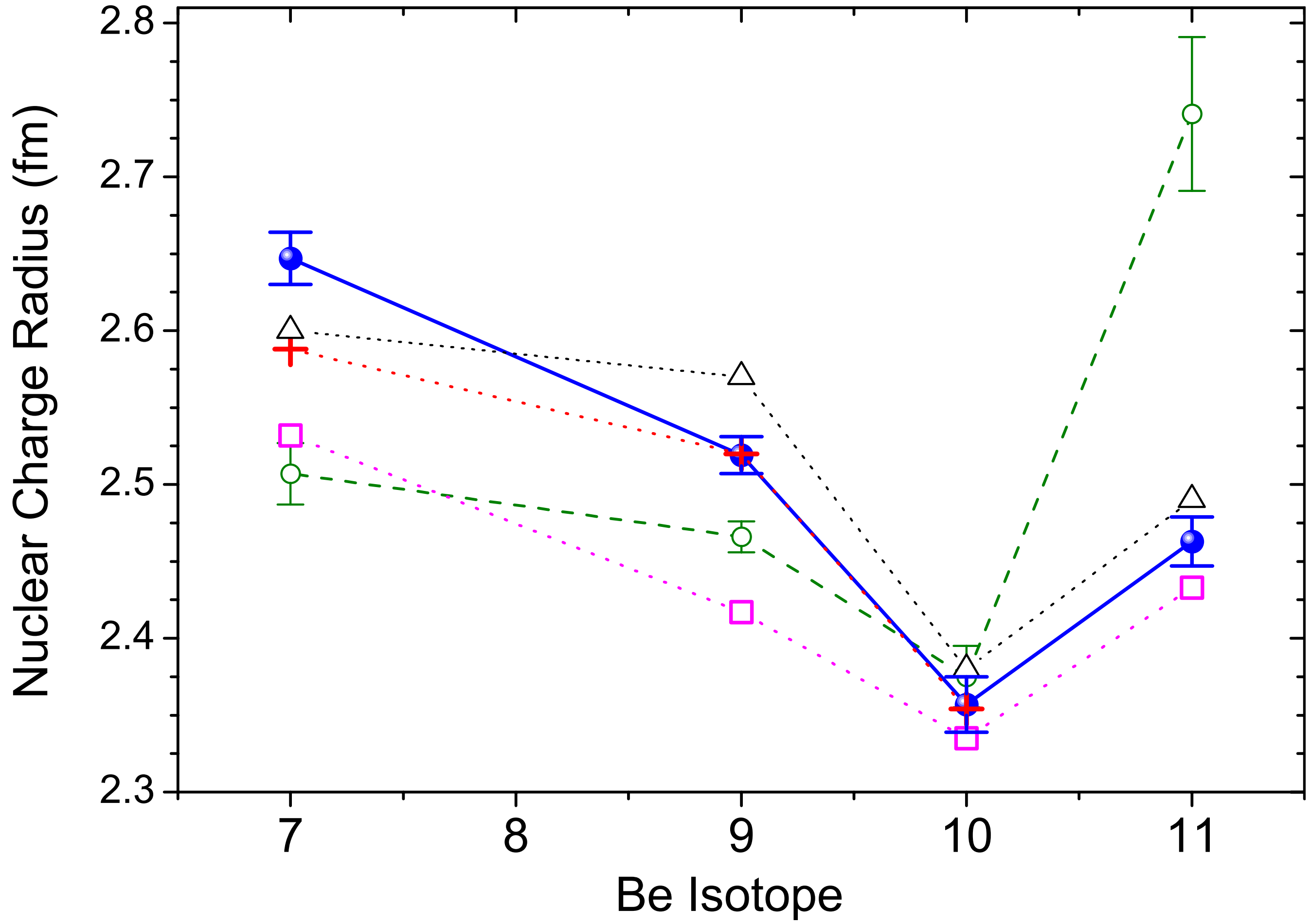


FIG. 3 (color online). Experimental charge radii of beryllium isotopes from isotope-shift measurements (●) compared with values from interaction cross-section measurements (○) and theoretical predictions: Greens-function Monte Carlo calculations (+) [2,24], fermionic molecular dynamics (△) [25], *ab initio* no-core shell model (□) [13,26,27].