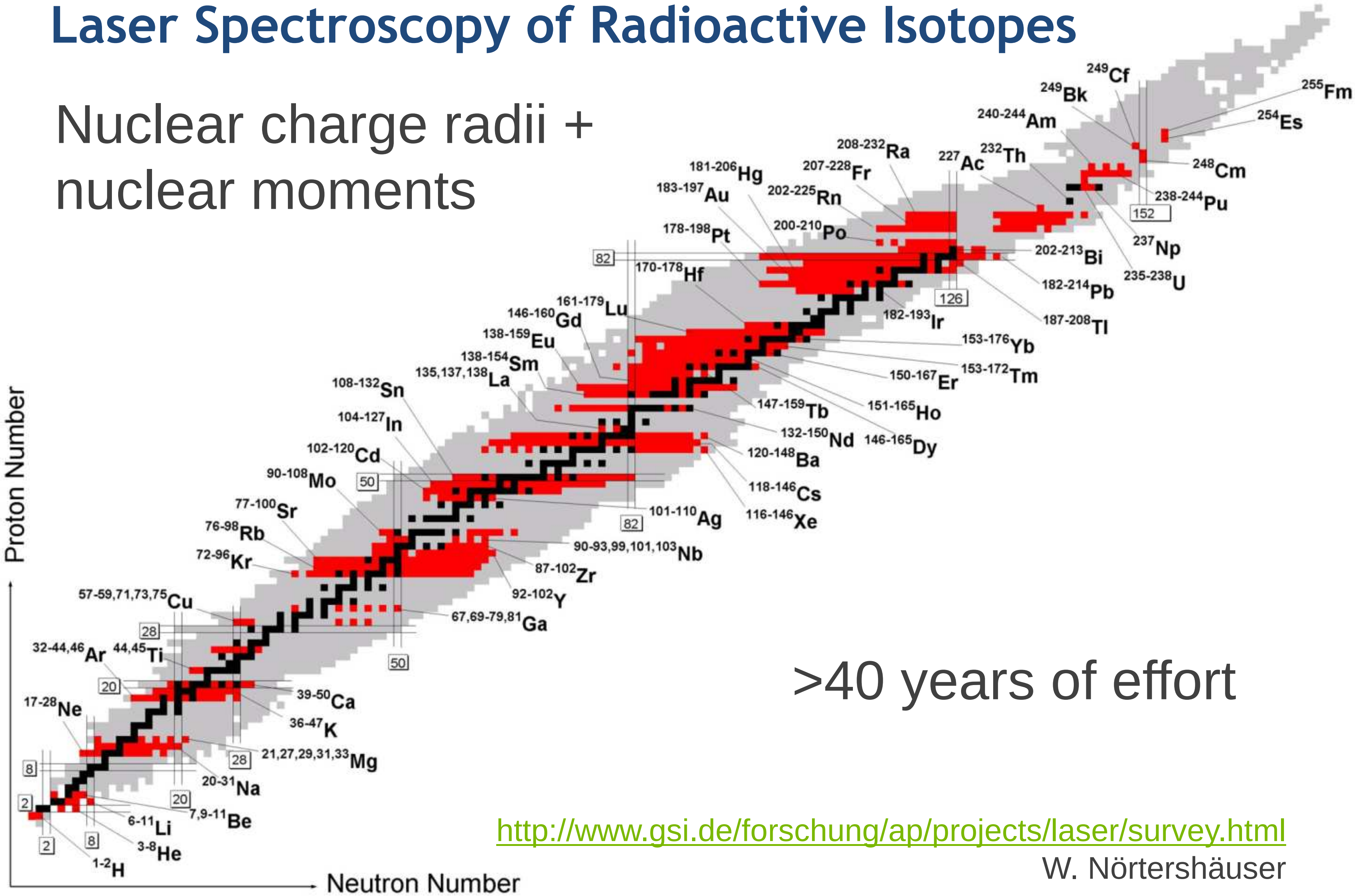
Precision Nuclear Ground State Property Measurements of Light Isotopes

Peter Müller

Laser Spectroscopy of Radioactive Isotopes

Nuclear charge radii +
nuclear moments

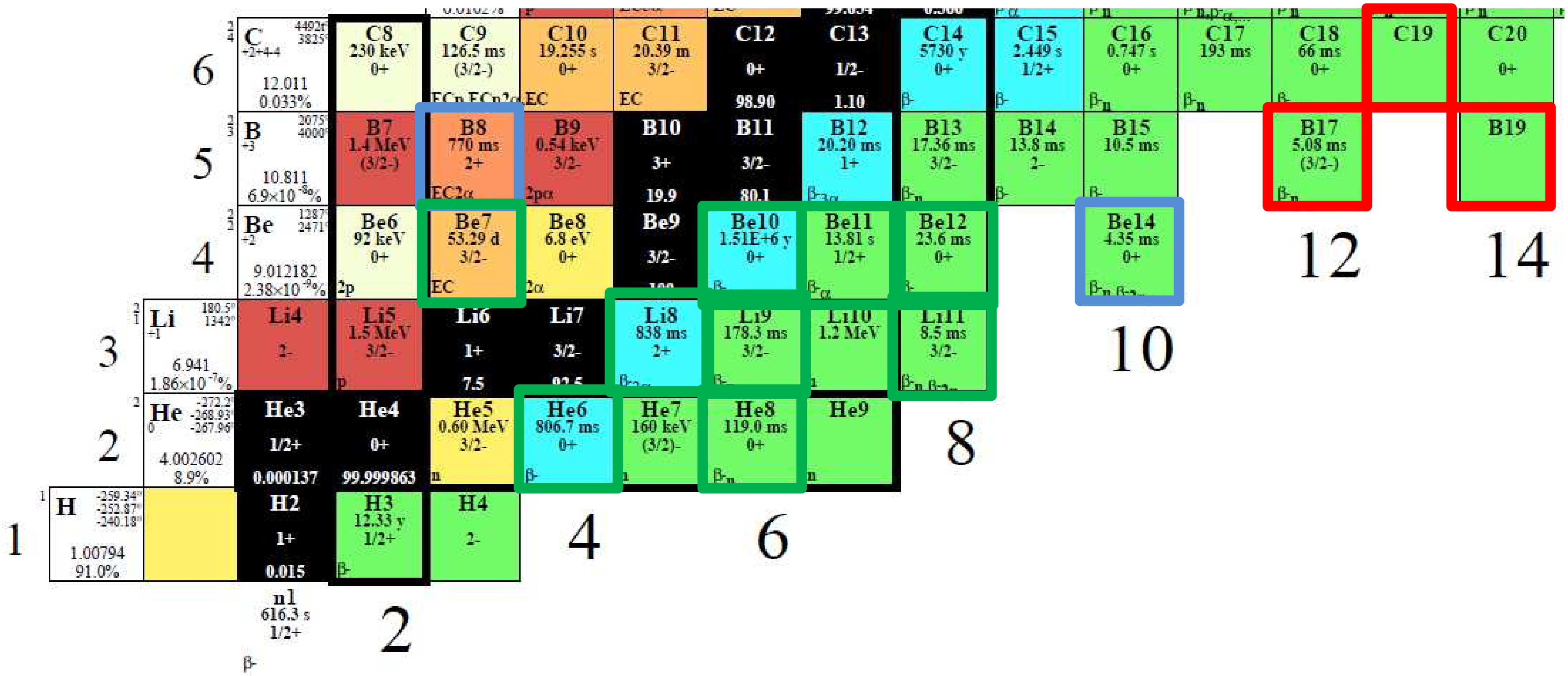


>40 years of effort

http://www.gsi.de/forschung/ap/projects/laser/survey.html

W. Nörtershäuser

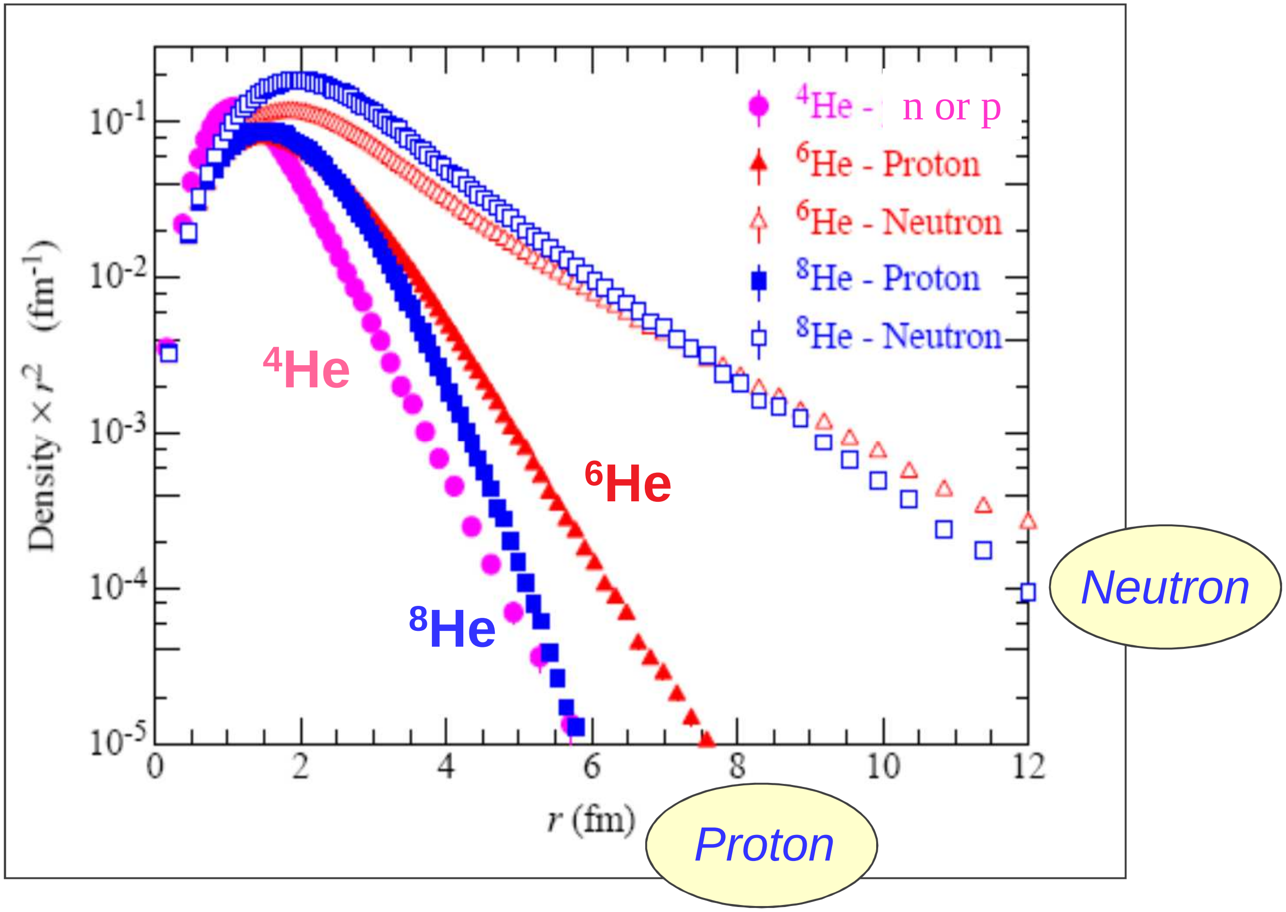
Light Isotopes



- ^{6,8}He Charge Radii
- ^{6}He Weak Interaction Studies + Lifetime Measurement
- Lithium + Beryllium Charge Radii
- Charge Radii of Boron and Carbon ?

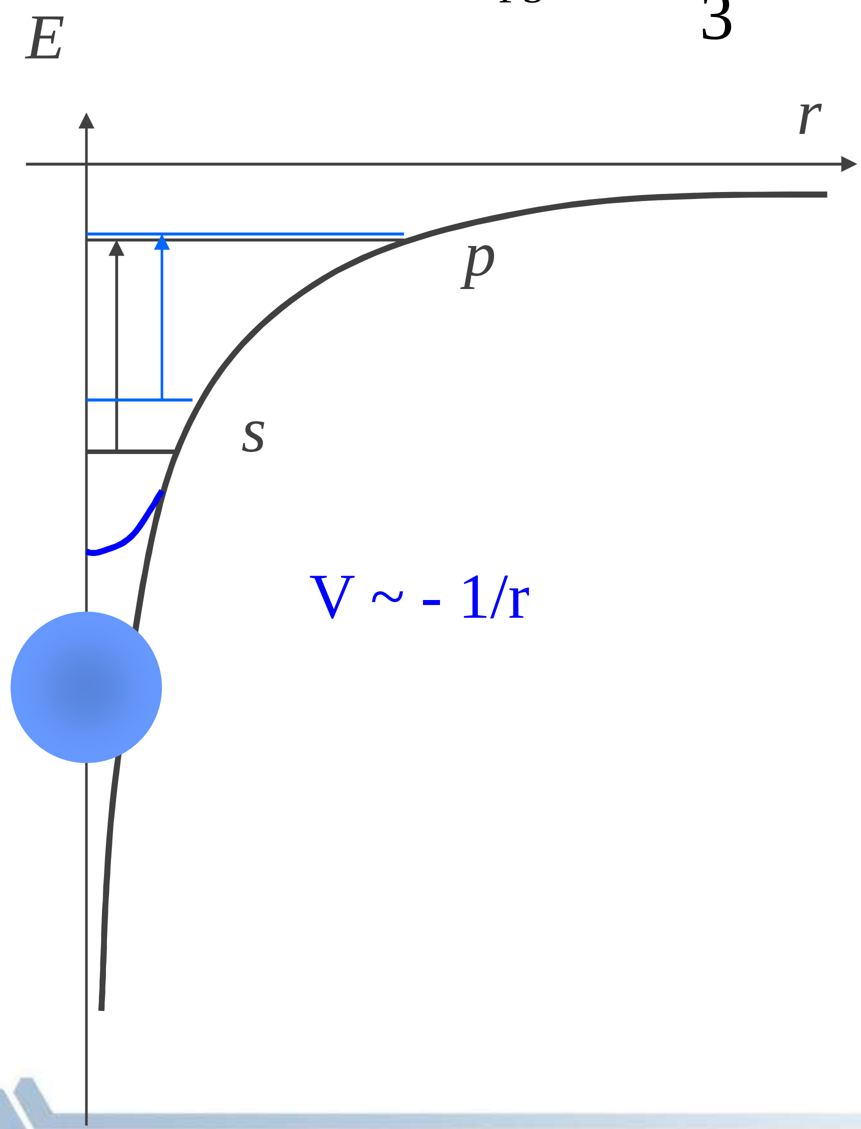
GFMC – Neutron and Proton Densities in ^{4,6,8}He

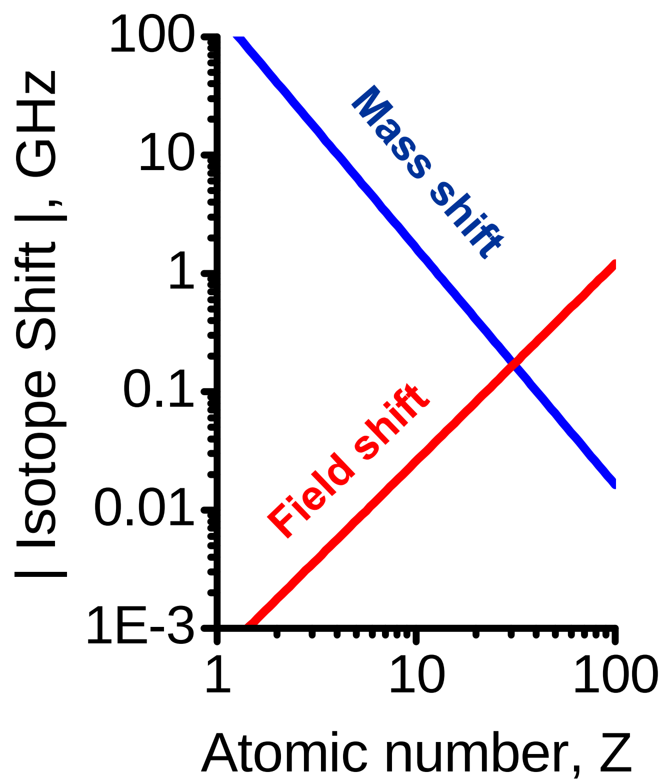
Steve Pieper, Bob Wiringa



Field (Volume) Shift

$$\delta\nu_{FS} = -\frac{2\pi}{3} Ze^2 \cdot \Delta|\Psi(0)|^2 \cdot \delta\langle r^2 \rangle^{AA'}$$



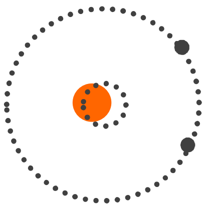


Atomic Isotope Shift

Isotope Shift $\delta\nu = \delta\nu_{MS} + \delta\nu_{FS}$

Mass shift:

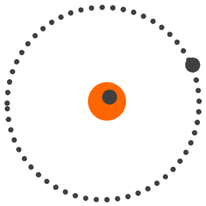
due to nucleus recoil



$$\delta\nu_{MS} \propto \frac{A - A'}{AA'}$$

Field shift:

due to nucleus size



$$\delta\nu_{FS} \propto Z \times \Delta[\Psi(0)]^2 \times \delta\langle r^2 \rangle$$

For $2^3S_1 - 3^3P_2$ transition @ 389 nm:

$$\delta\nu = \delta\nu_{MS} + C_{FS} \; \delta\langle r^2 \rangle$$

^{6}He - ^{4}He : $\delta\nu_{6,4}$ = 43196.202(16) MHz + 1.008 ($\langle r^2 \rangle_{He4}$ - $\langle r^2 \rangle_{He6}$) MHz/fm^2

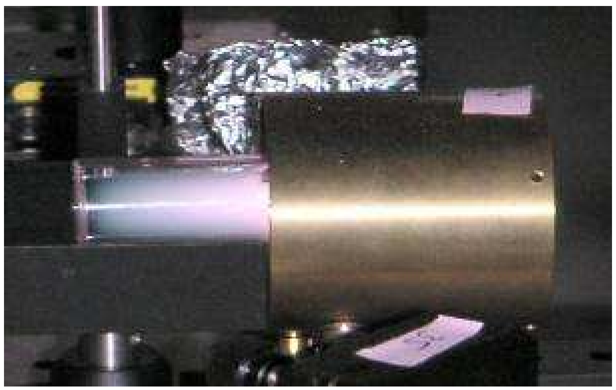
^{8}He - ^{4}He : $\delta\nu_{8,4}$ = 64702.519(70) MHz + 1.008 ($\langle r^2 \rangle_{He4}$ - $\langle r^2 \rangle_{He8}$) MHz/fm^2

G.W.F. Drake, Univ. of Windsor, *Nucl. Phys. A737c, 25 (2004)*

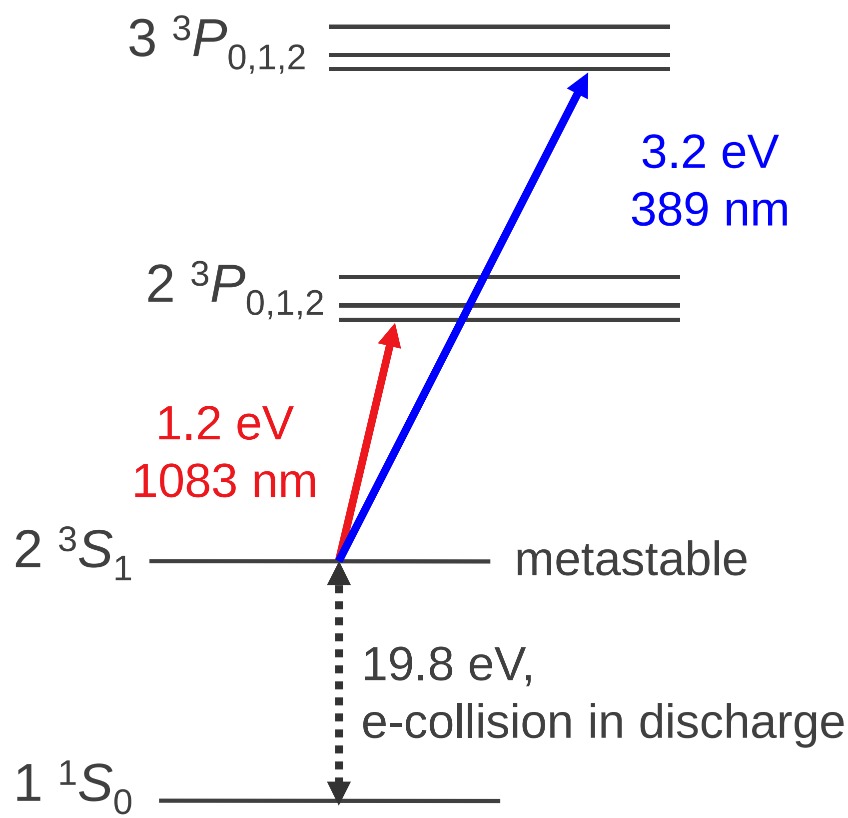
100 kHz error in IS ←→ ~ 1% error in radius

Atomic Energy Levels of Helium

He discharge



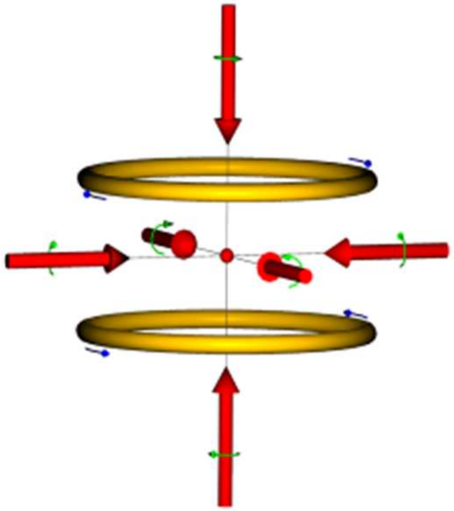
He energy level diagram



Laser Cooling and Trapping

Technical challenges:

- Short lifetime, small samples (<10^6 atoms/s available)
- Low metastable population efficiency (~ one in 100.000)
- Precision requirement (100 kHz = Doppler shift @ 4 cm/s)

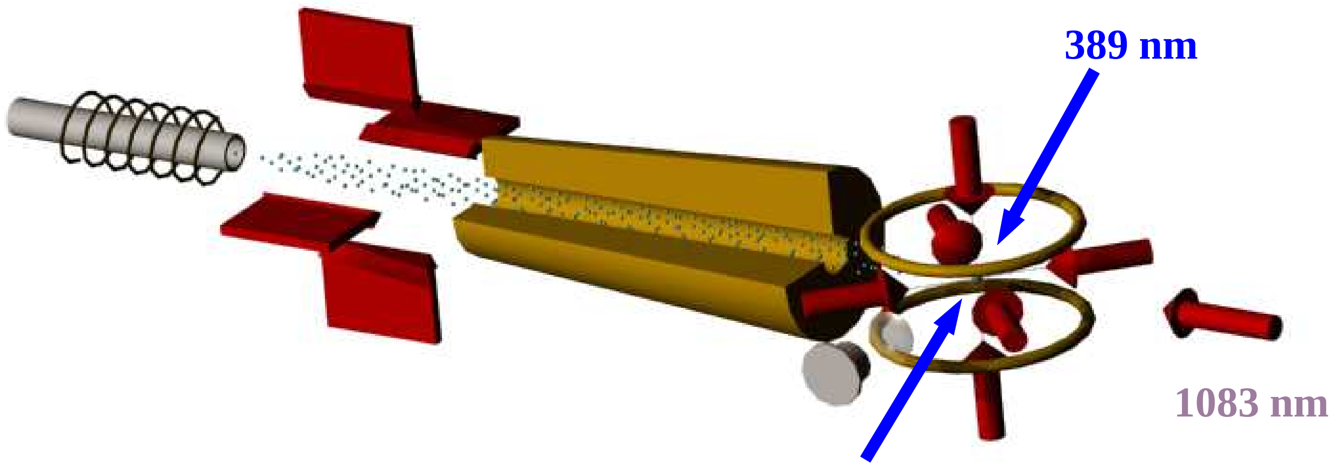


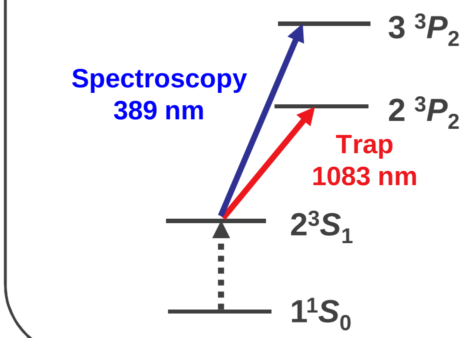
Magneto-Optical Trap (MOT)

- Cooling: Temperature ~ 1 mK,
  → avoid Doppler shift / width
- Long observation time: 100 ms
- Spatial confinement: trap size < 1 mm
  → single atom sensitivity
- Selectivity: → no isotopic / isobaric interference

Atom Trapping of ^{6}He & ^{8}He at GANIL

Atom Trap Setup

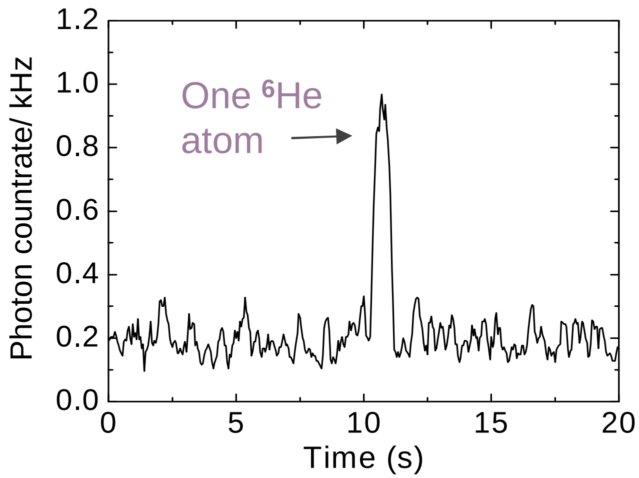




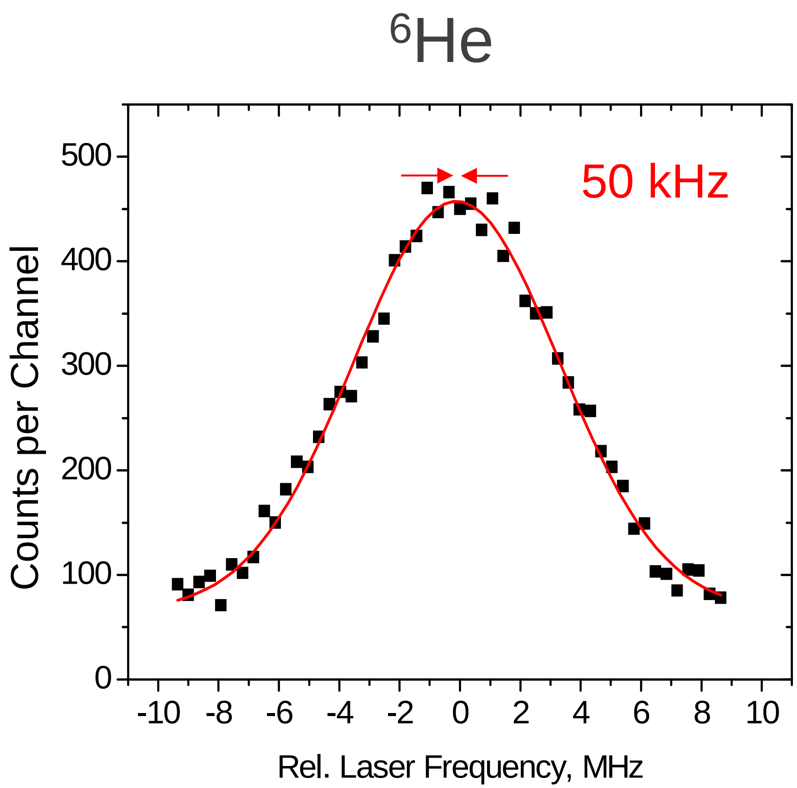
Helium Rates

	^{6}He	^{8}He
@ source	5×10^7 s^{-1}	1×10^5 s^{-1}
Efficiency = 1×10^{-7}		
@ trap	5 s^{-1}	30 hr^{-1}

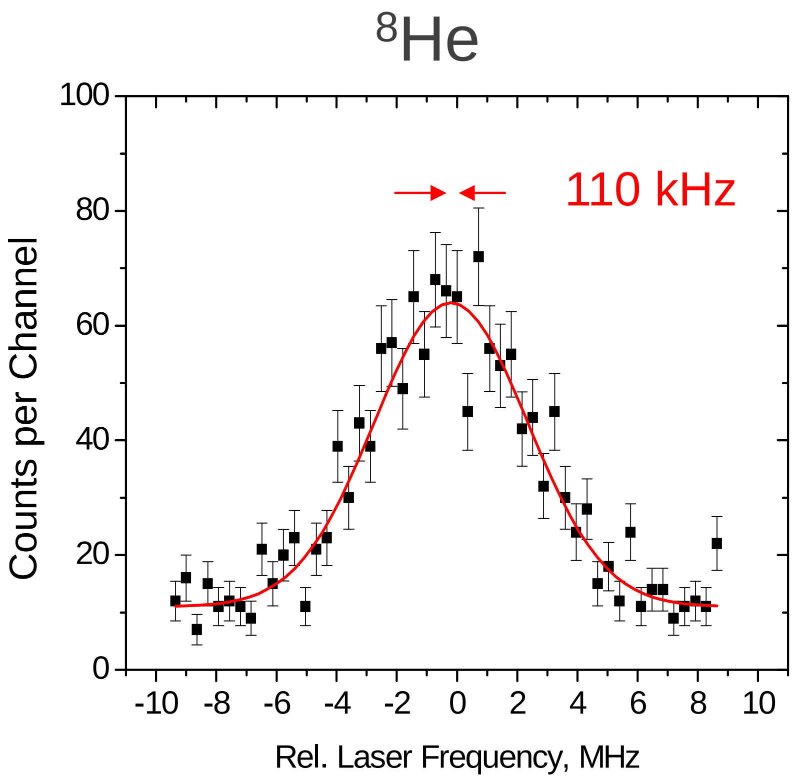
Single atom signal



$^{6}He + ^{8}He$ Sample Spectra

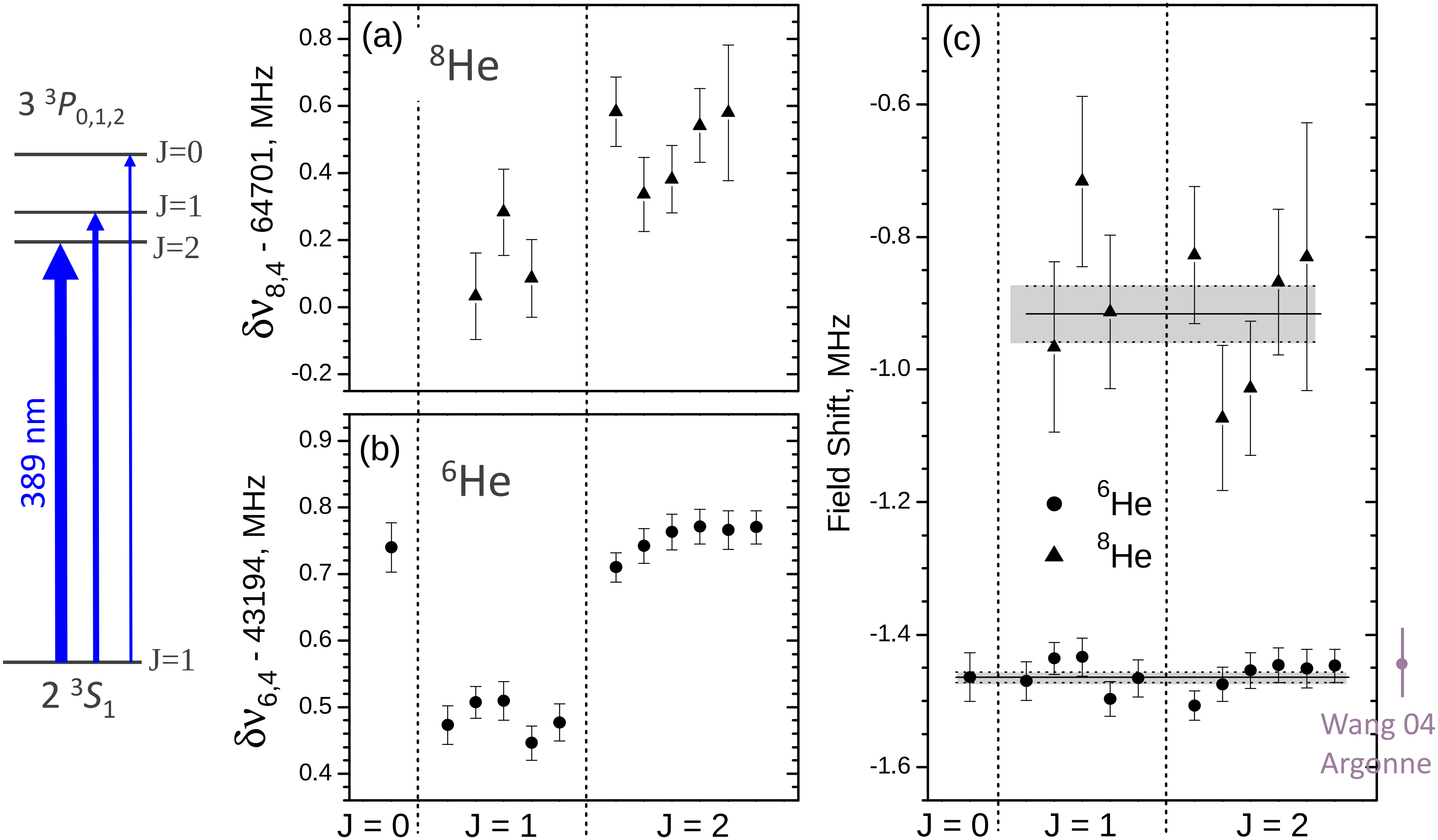


~ 5 ^{6}He atoms/s
2 minutes



~ 30 ^{8}He atoms/hr
2 hours

Isotope Shift and Field Shift : J - Dependence



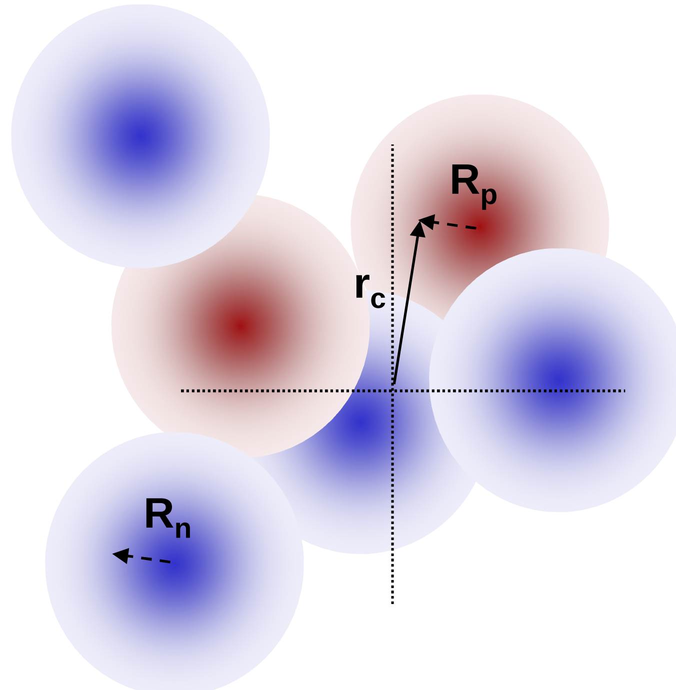
Experimental Uncertainties and Corrections

		^6He	^8He
Statistical	Photon Counting	8 kHz	32 kHz
	Laser Alignment	2 kHz	12 kHz
	Reference Laser	2 kHz	24 kHz
Systematic	Probing Power Shift	0 kHz	15 kHz
	Zeeman Shift	**30 kHz**	45 kHz
	Nuclear Mass	15 kHz	**74 kHz**
	TOTAL	**35 kHz**	**97 kHz**

Corrections	Recoil Effect	+110(0) kHz	+165(0) kHz
	Nuclear Polarization	-14(3) kHz	-2(1) kHz

^{6}He & ^{8}He RMS Charge Radii

	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-1.026(63)
RMS R_{CH}, fm	**2.060(8)**	**1.959(16)**
Total Uncertainty	**0.4 %**	**0.9 %**
- Statistical	*0.1 %*	*0.6 %*
- Trap Systematics	*0.3 %*	*0.6 %*
- Mass Systematics	*0.1 %*	*0.0 %*
- He-4: 1.681(4) fm	*0.1 %*	*0.1 %*



$$\langle r^2\rangle_{pp} = \langle r^2\rangle_{ch} - \langle R_p^2\rangle - \frac{3}{4M_p^2} - \frac{N}{Z}\langle R_n^2\rangle$$

$$- \langle r^2\rangle_{SO} - MEC$$

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

\+ M. Brodeur *et al.*, PRL **108**, 052504 (2012): He-6,8 mass

\+ I. Sick PRC **77**, 041302(R) (2008): He-4 Charge Radius

\+ A. Ong, J.C. Berengut, V.V. Flambaum, PRC **82**, 014320 (2010)

$\langle R_P^2\rangle = 0.766(12)\ \text{fm}^2$

$\langle R_N^2\rangle = -0.120(5)\ \text{fm}^2$

$\langle r^2\rangle_{SO} = -0.08 / -0.17\ \text{fm}^2$

^{6}He & ^{8}He RMS Charge Radii

	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-1.026(63)
RMS R_{CH}, fm	**2.060(8)**	**1.959(16)**
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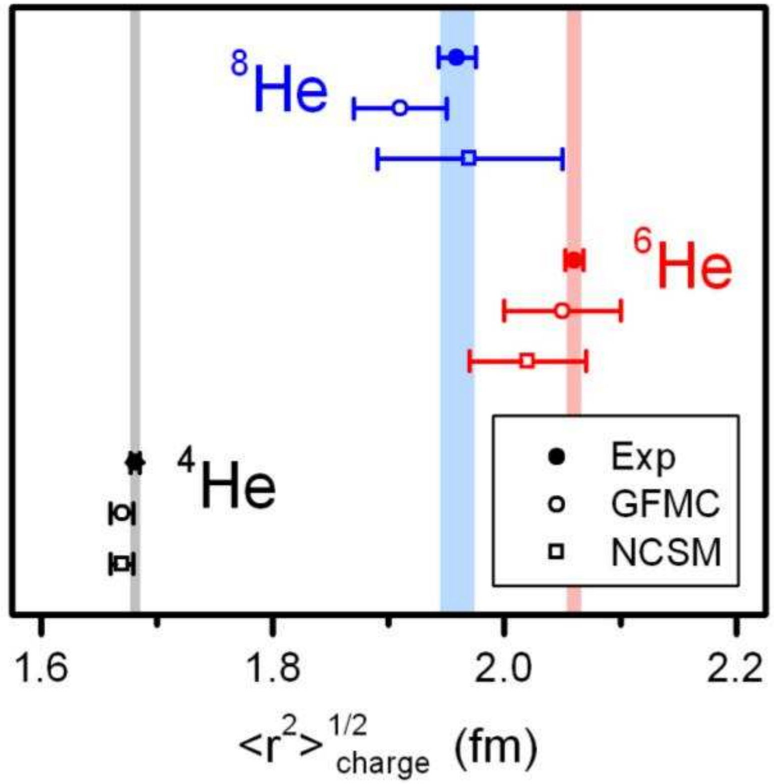
- He-4: 1.681(4) fm	*0.1 %*	*0.1 %*



CODATA 2010: R_p = 0.8775(51) fm

NCSM with CD Bonn 2000

G. Papadimitriou, *et al.* PRC **84**, 051304 (2011)

$\langle r^2 \rangle_{SO}$ = -0.072 / -0.158 fm^2

Helium Charge Radii "Over Time"

2004: ^{6}He @ ATLAS, L.-B. Wang, *et al.* PRL **93**, 142501 (2004)

^{6}He: 2.054(14) fm	^{4}He: 1.673(1) fm from muonic He
	^{6}He mass from AME93

2007: ^{6}He & ^{8}He @ GANIL, P. Mueller, *et al.*, PRL **99**, 252501 (2007)

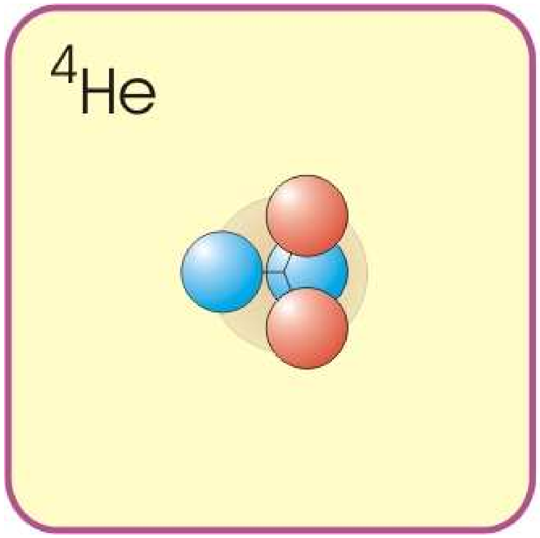
^{6}He: 2.068(11) fm	^{4}He: 1.676(8) fm from e-scattering
^{8}He: 1.93(3) fm	masses from AME2003

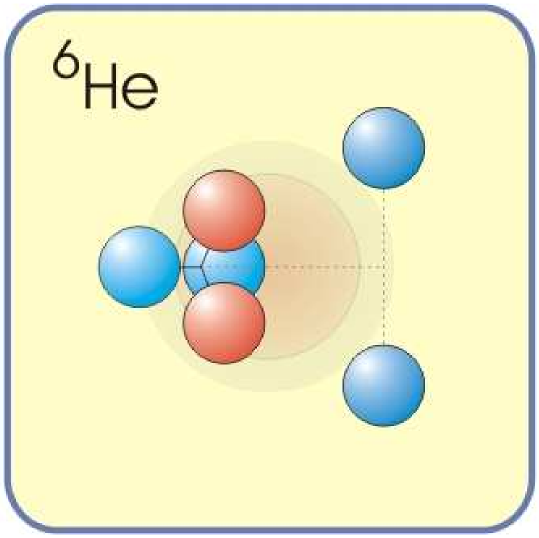
2011: ^{6}He & ^{8}He masses @ TRIUMF, M. Brodeur, *et al.* PRL **108**, 052504 (2012)

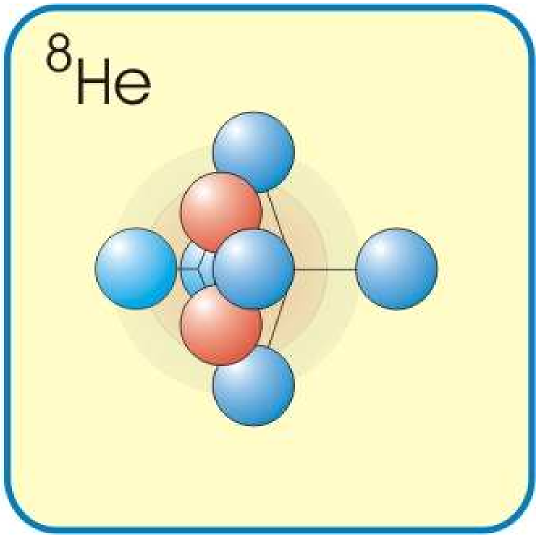
^{6}He: 2.060(8) fm	^{4}He: 1.681(4) fm, I. Sick PRC **77**, *041302(R) (2008)*
^{8}He: 1.959(16) fm	masses from TITAN Penning trap

^{6}He-^{4}He IS 2004 *vs.* 2007 in MHz			**MS**	**FS**
2004: J=	1-> 2	43194.772(47)(30) MHz	43196.157(1)	-1.385(47)
2007: J=	1-> 2	43194.751(10)(30) MHz	"	-1.419(10)
	1-> 1	43194.483(12)(30) MHz	43195.897(1)	-1.414(12)
	1-> 0	43194.740(37)(30) MHz	43196.171(1)	-1.417(37)

RMS Charge Radii : ^{4}He - ^{6}He - ^{8}He







1.681(4) fm | 2.060(8) fm | 1.959(16) fm

Charge Radius Contributions

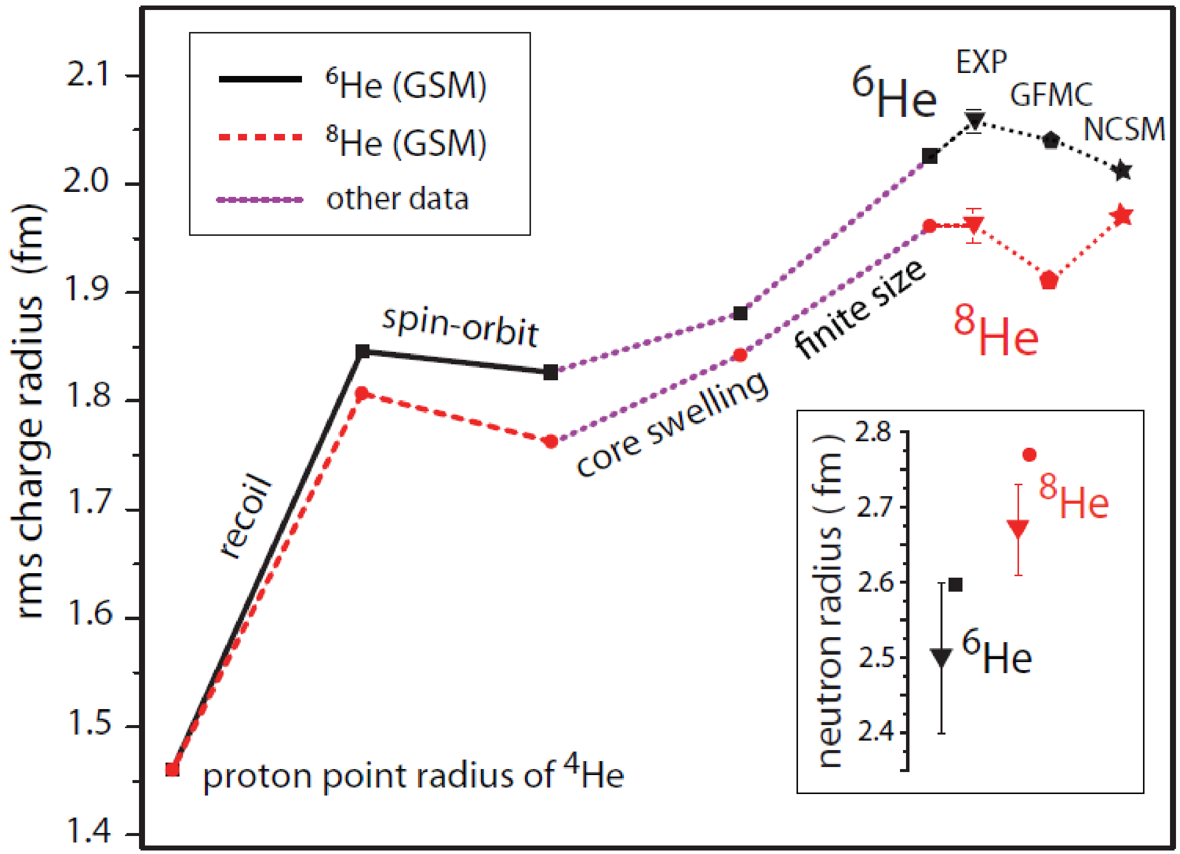
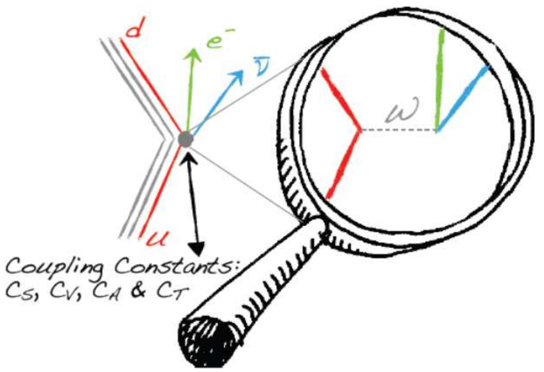
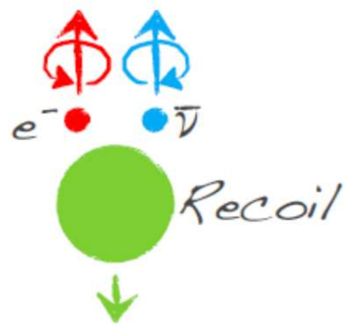


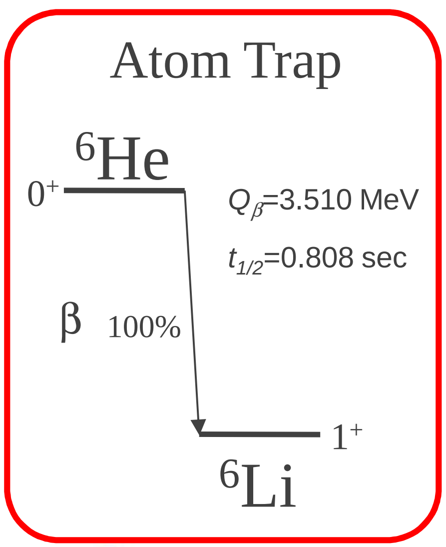
Fig. 4 from G. Papadimitriou, *et al.* PRC **84**, 051304(R) (2011)
(core swelling from GFMC)

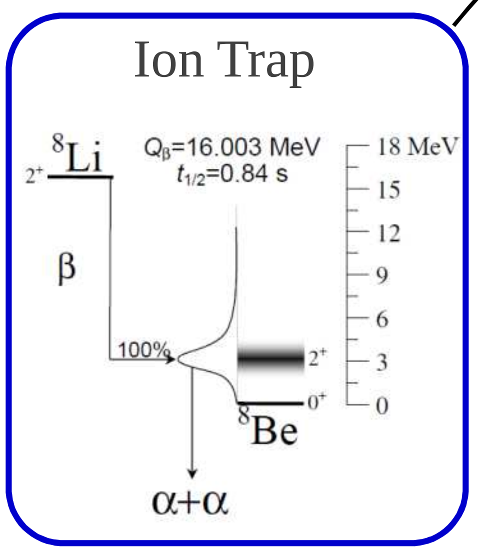
Weak Interaction Studies: *β–ν Angular Correlations*

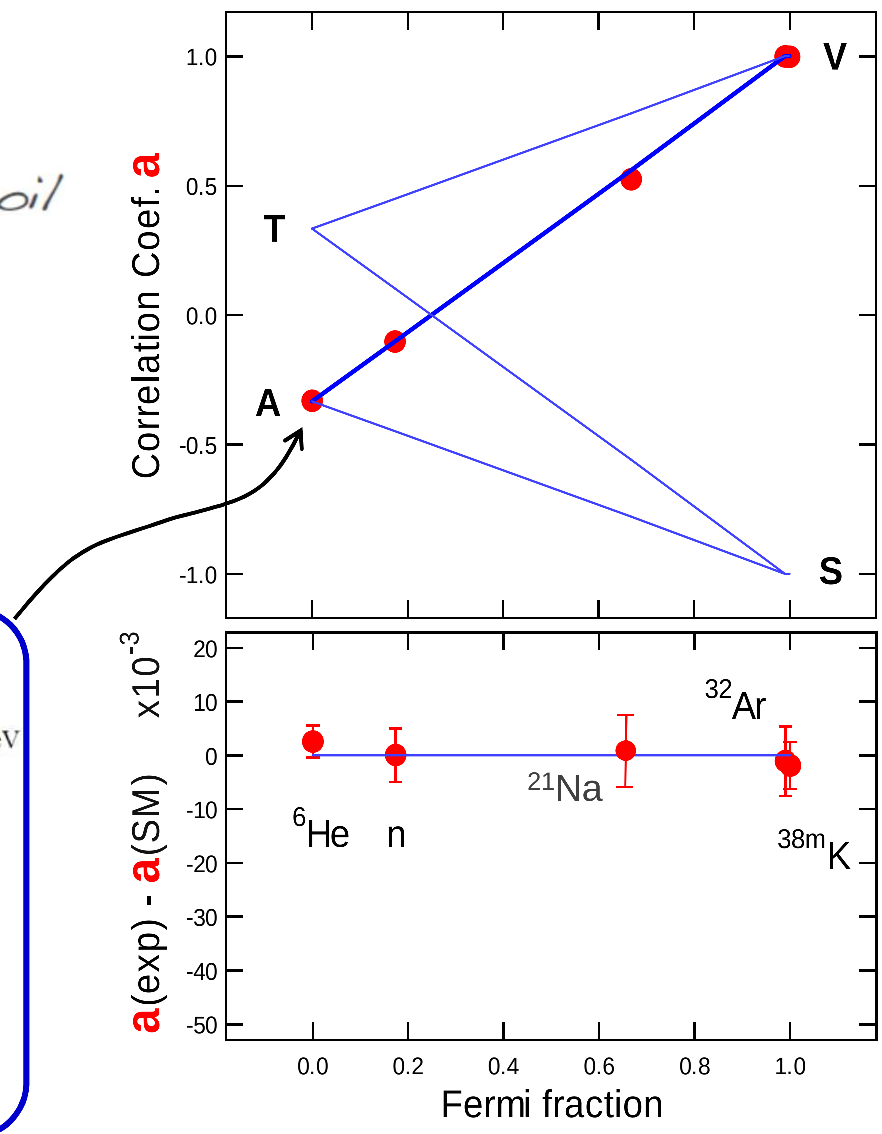




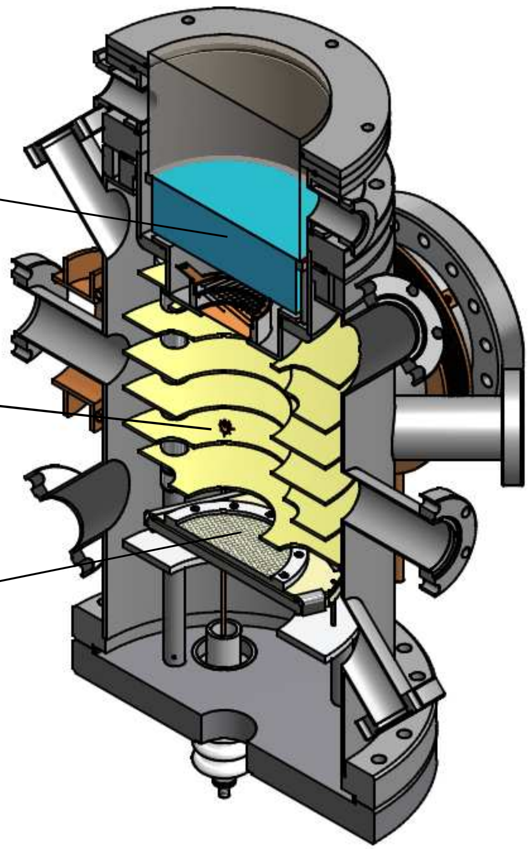
$$N(E_\beta,\theta_{\beta\nu}) \propto 1 + a\frac{p_\beta}{E_\beta}\cos(\theta_{\beta\nu}) + b\frac{m}{E_\beta}$$



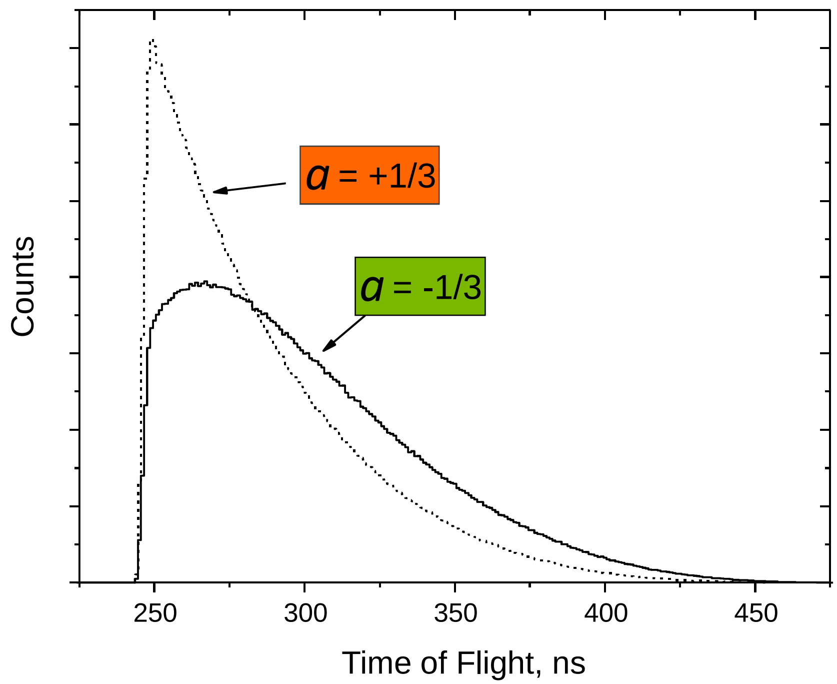




Beta-Decay Study with Laser Trapped ^{6}He



Recoil time-of-flight spectrum
(MC simulation)



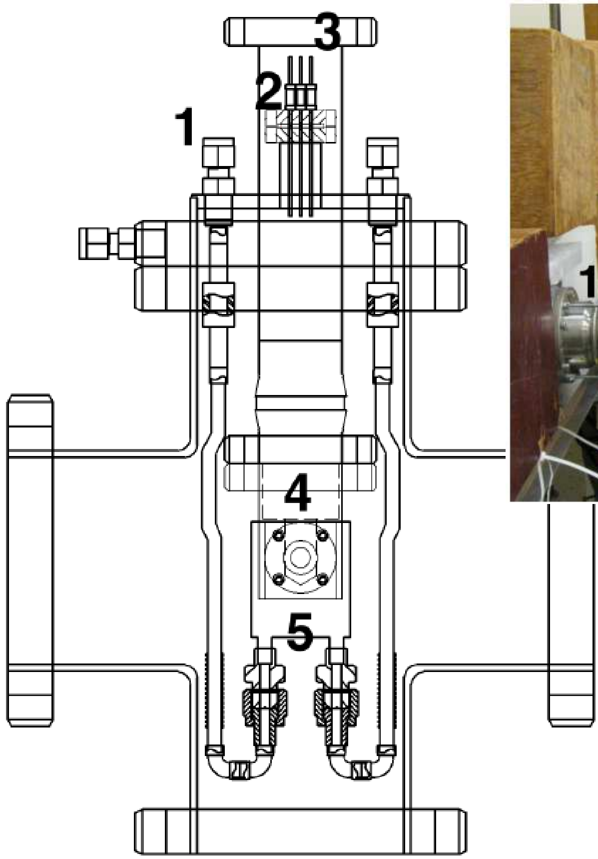
Atom trap properties

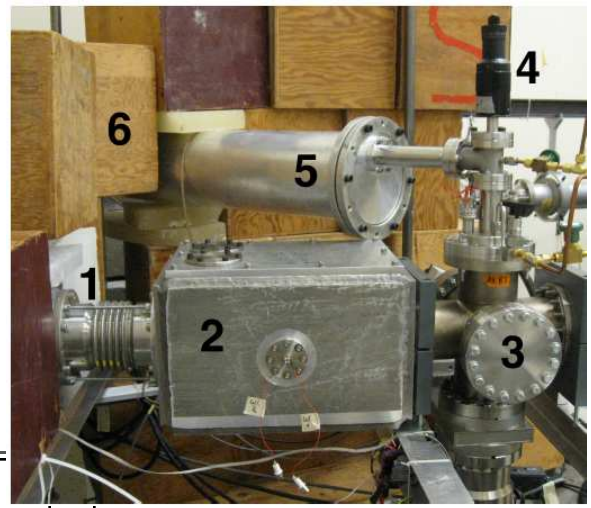
- Highly selective capture
- No RF fields or space charge
- Low temperature sample (mK)
- Tight spatial confinement (< 100μm)

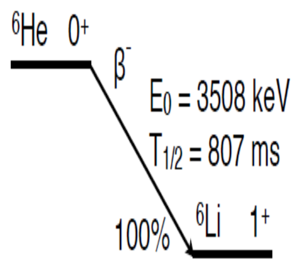
- ~1x10^{9} ^{6}He/s production yield
- trapping rate ~2x10^{3} ^{6}He/s
- ~0.1% statistics in ~4 weeks beam time

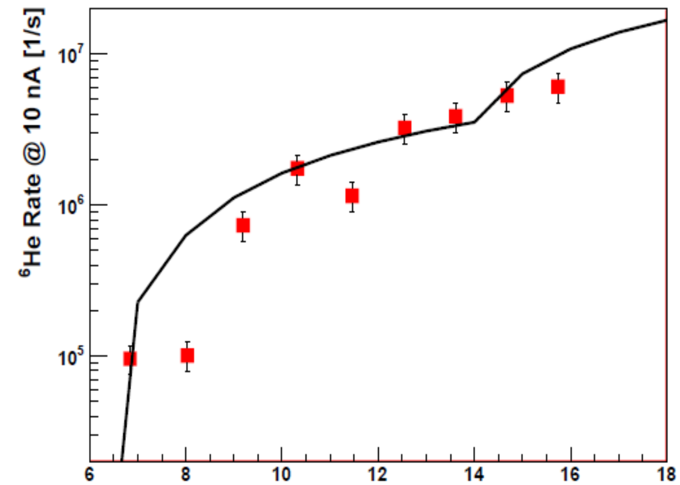
^{6}He Production

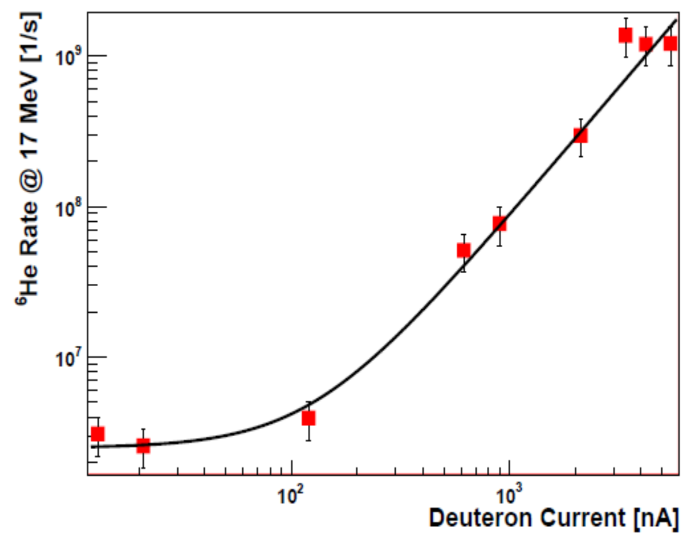
- at CENPA, UWash Seattle, tandem accelerator
- via $^{7}Li(d,^{3}He)^{6}He$ with liquid Li target





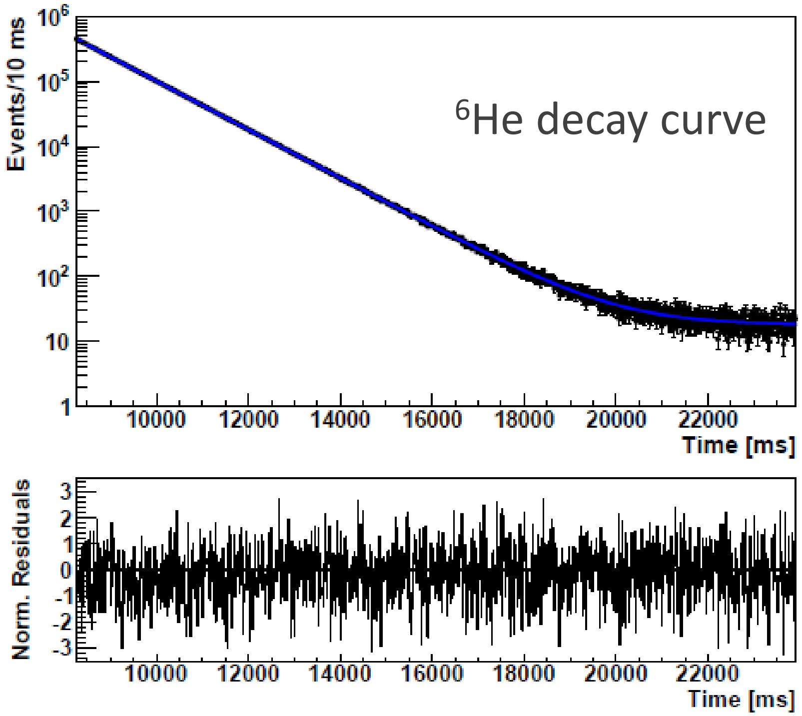




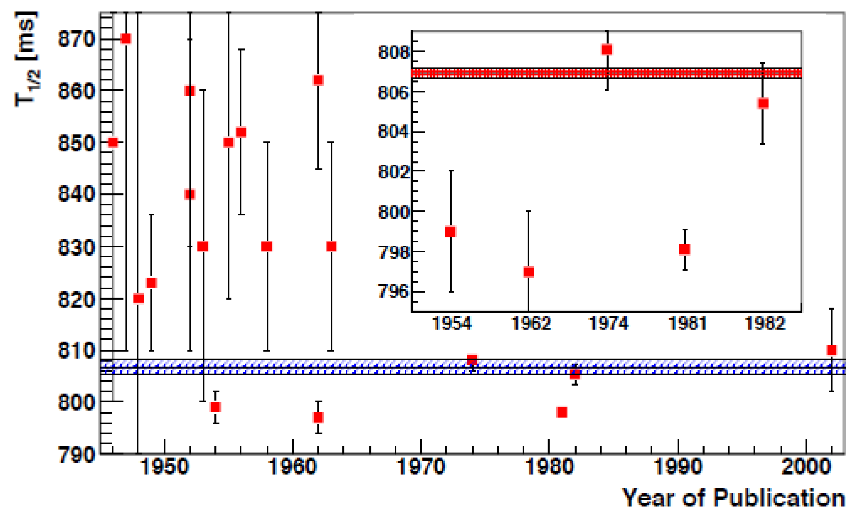


A. Knecht *et al.*, NIM A **660**, 43 (2011)

Measure ^{6}He Lifetime



Source	Shift [ms]	Uncertainty [ms]
Deadtime correction	-	0.037
^{6}He Diffusion	0	$< {}^{+0.12/0.22}_{-0}$
Gain shift	-0.19	0.19
^{8}Li contamination	0	$< {}^{+0}_{-0.007}$
Background	0.046	0.004
Data correction	0	< 0.01
Deadtime drift	0	0.009
Afterpulsing	0	< 0.003
Clock accuracy	0.006	0.011
Total	-0.14	${}^{+0.23}_{-0.19}$ / ${}^{+0.29}_{-0.19}$



^{6}He half-life

$$806.89 \pm 0.11_{\rm stat} \;{}^{+0.23}_{-0.19}\;{\rm syst}$$

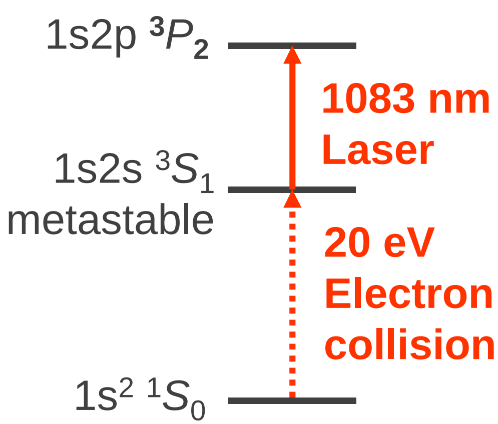
ft-value

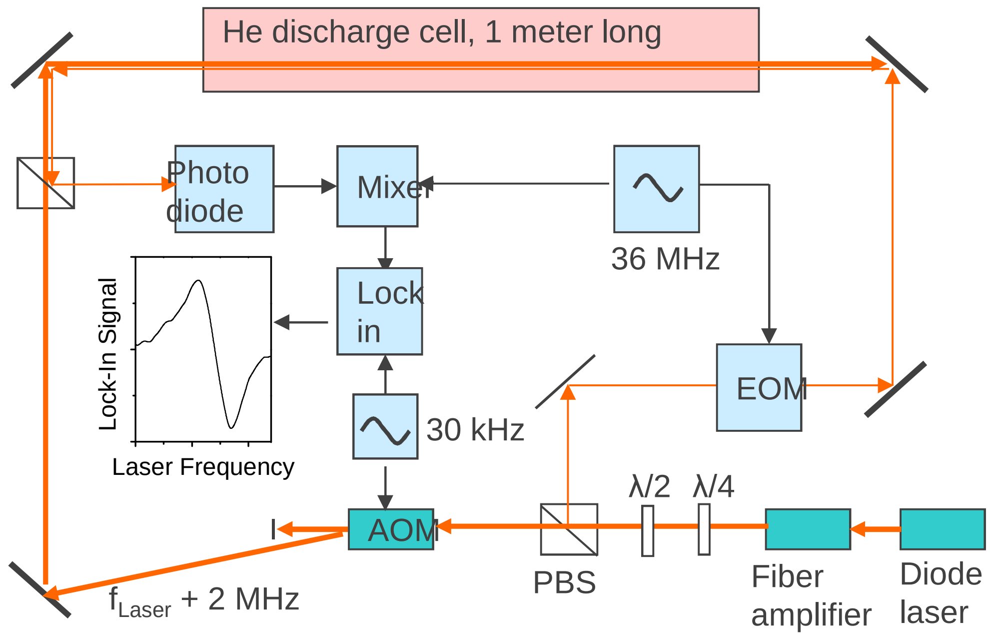
$$804.65(57)\ {\rm s}$$

Compare with *ab-initio* calculations of $|M_{GT}|$ to obtain g_A in nuclear medium

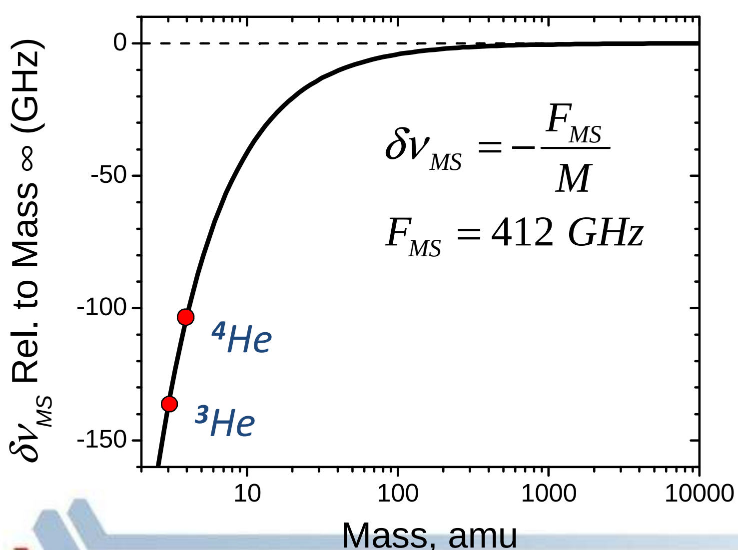
A. Knecht *et al.*, PRL **108**, 122502 (2012)
A. Knecht *et al.*, PRC **86**, 035506 (2012)

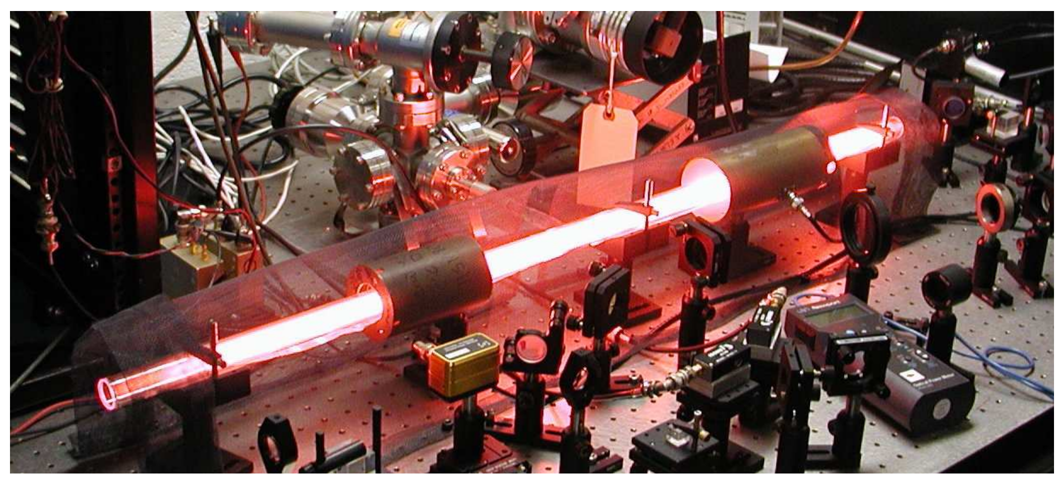
New IS Measurement via FM Saturation Spectroscopy?





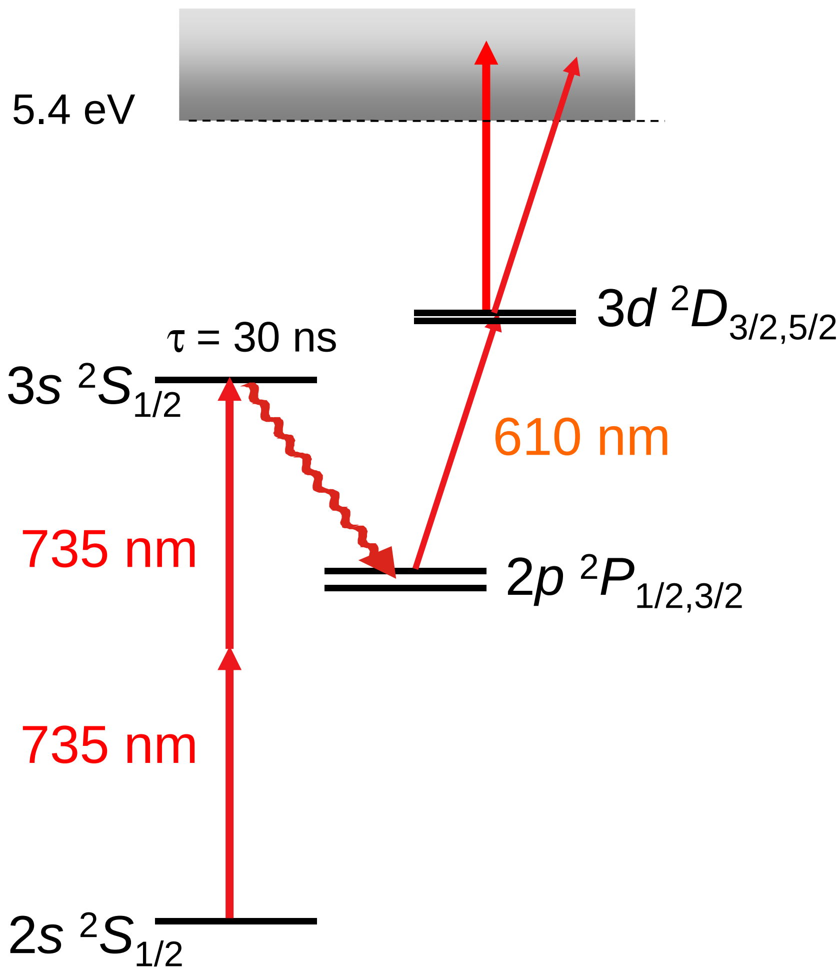
Isotope Shift vs. Mass



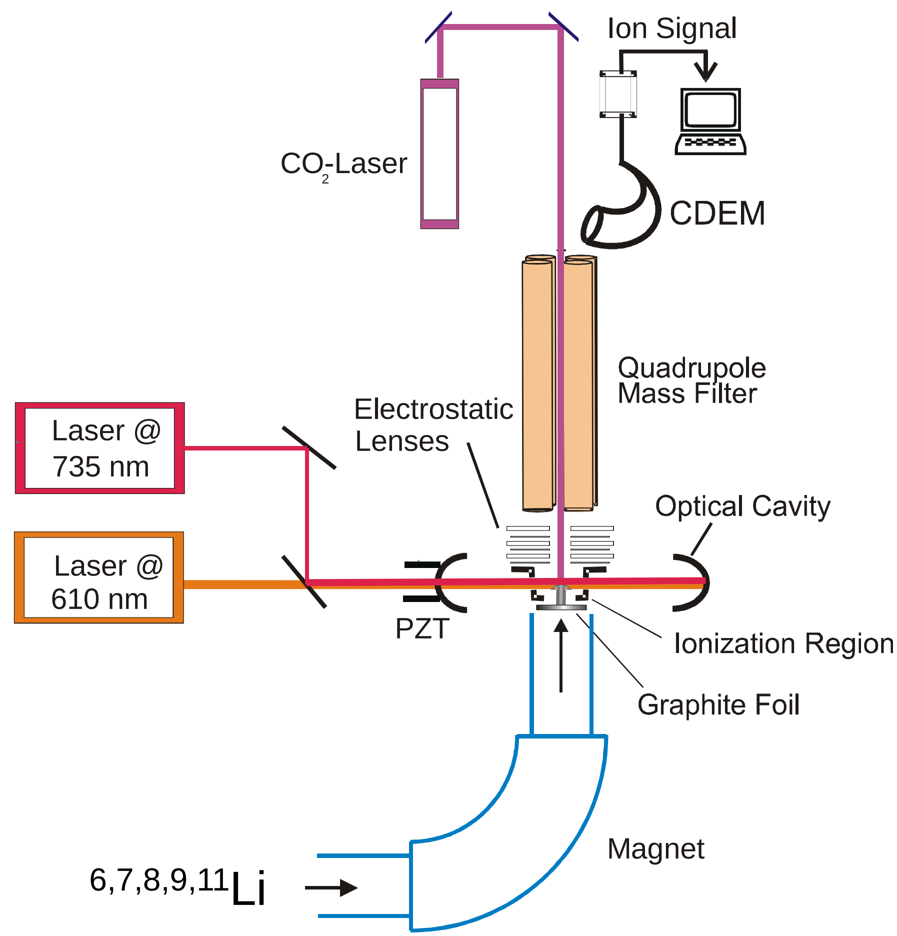


Resonance Ionization of Lithium

Lithium atomic levels



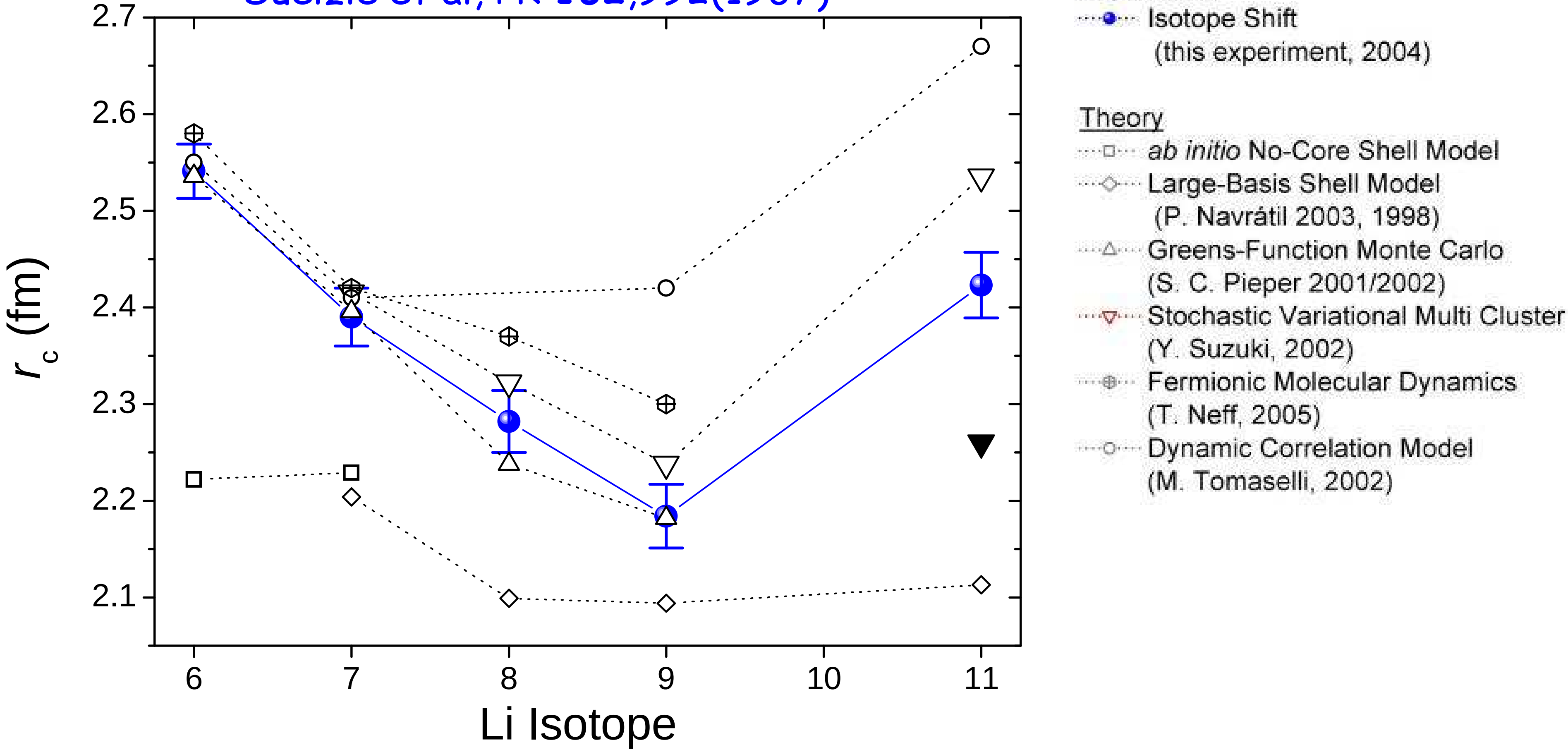
Experimental setup



Courtesy of W. Noertershaeuser, Mainz University

Nuclear Charge Radii – Comparison with Theory

$r_c(^7Li)$ = 2.39(3) fm
Suelzle et al, PR **162**,992(1967)

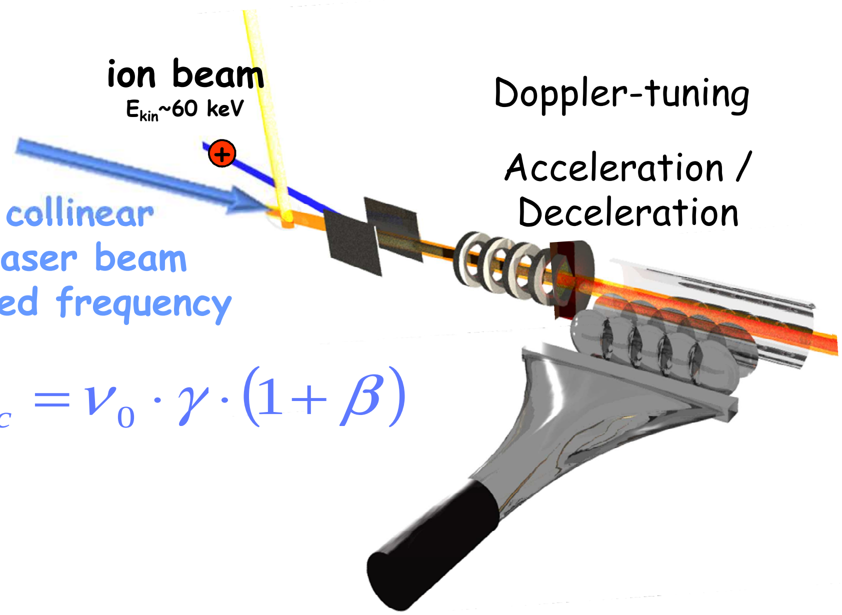


R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)
M. Puchalski *et al.*, PRL 97, 133001 (2006)

$$\sqrt{[R_{\mathrm{C-CM}}]^2 + [r_c(^9\mathrm{Li})]^2} = 2.40(6)\ \mathrm{fm}$$

Collinear Spectroscopy

„CONVENTIONAL SETUP"



$$\nu_c = \nu_0 \cdot \gamma \cdot (1+\beta)$$

$\gamma = \gamma(U,m)$, $\beta = \beta(U,m)$,

$\Delta U/U \approx 10^{-4}$

$\Rightarrow \delta\nu_{IS}$ (^{9}Be,^{11}Be) = 14 MHz

Impossible for Light Elements (Z<10) !!

NEW APPROACH

$$\nu_c = \nu_0 \cdot \gamma \cdot (1+\beta)$$

$$\nu_a = \nu_0 \cdot \gamma \cdot (1-\beta)$$

$$\nu_a \cdot \nu_c = \nu_0^2 \cdot \gamma^2 \cdot (1-\beta^2) = \nu_0^2$$

anticollinear laser beam fixed frequency

Completely independent of U !

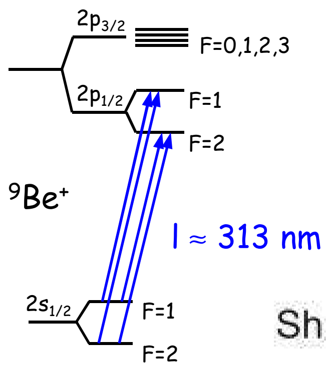
Requirements:

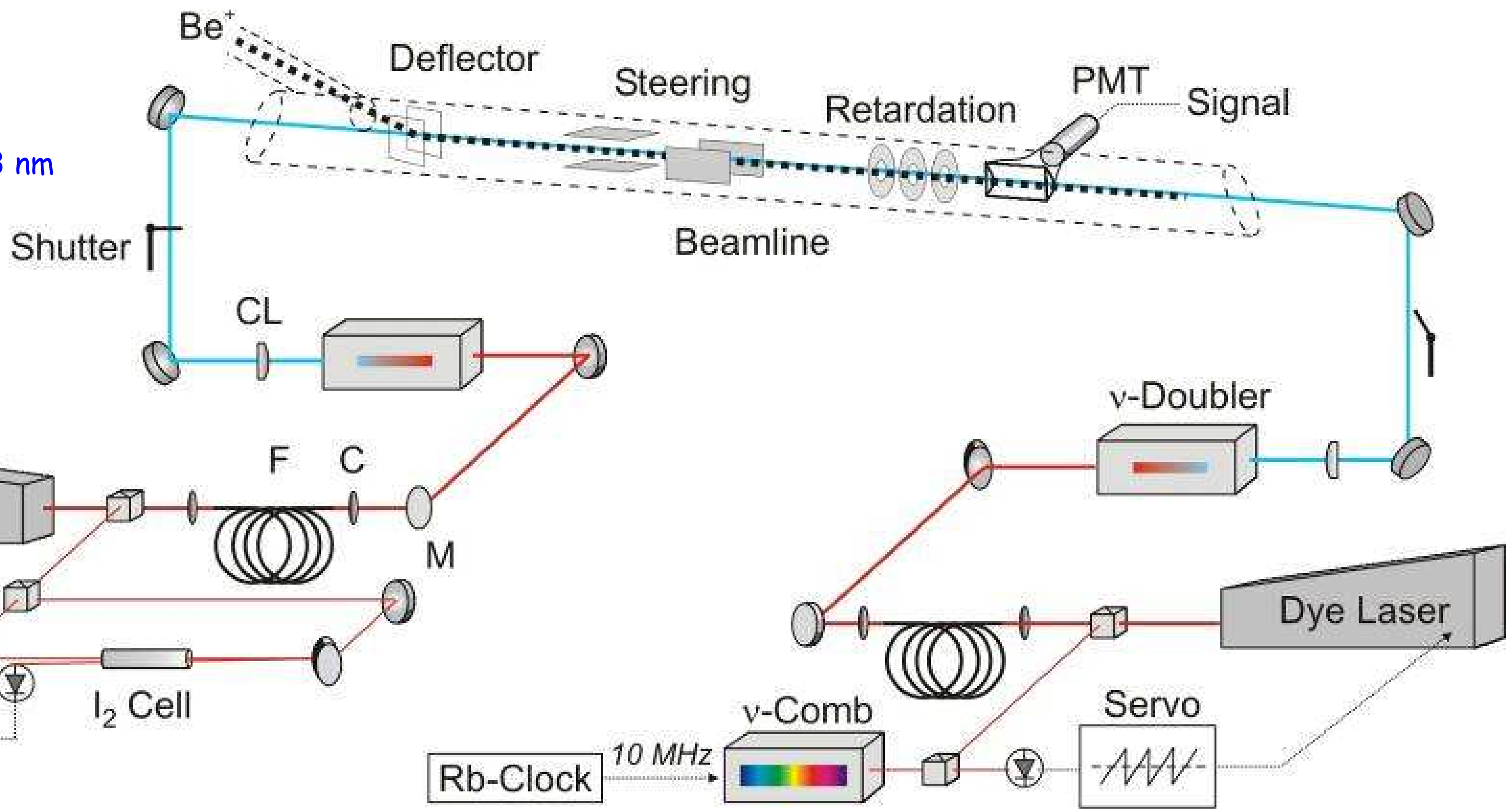
Measure absolute frequencies

Accuracy: $\Delta\nu/\nu < 10^{-9}$

Dedicated Laser System for absolute Frequency Measurements

Experimental Setup



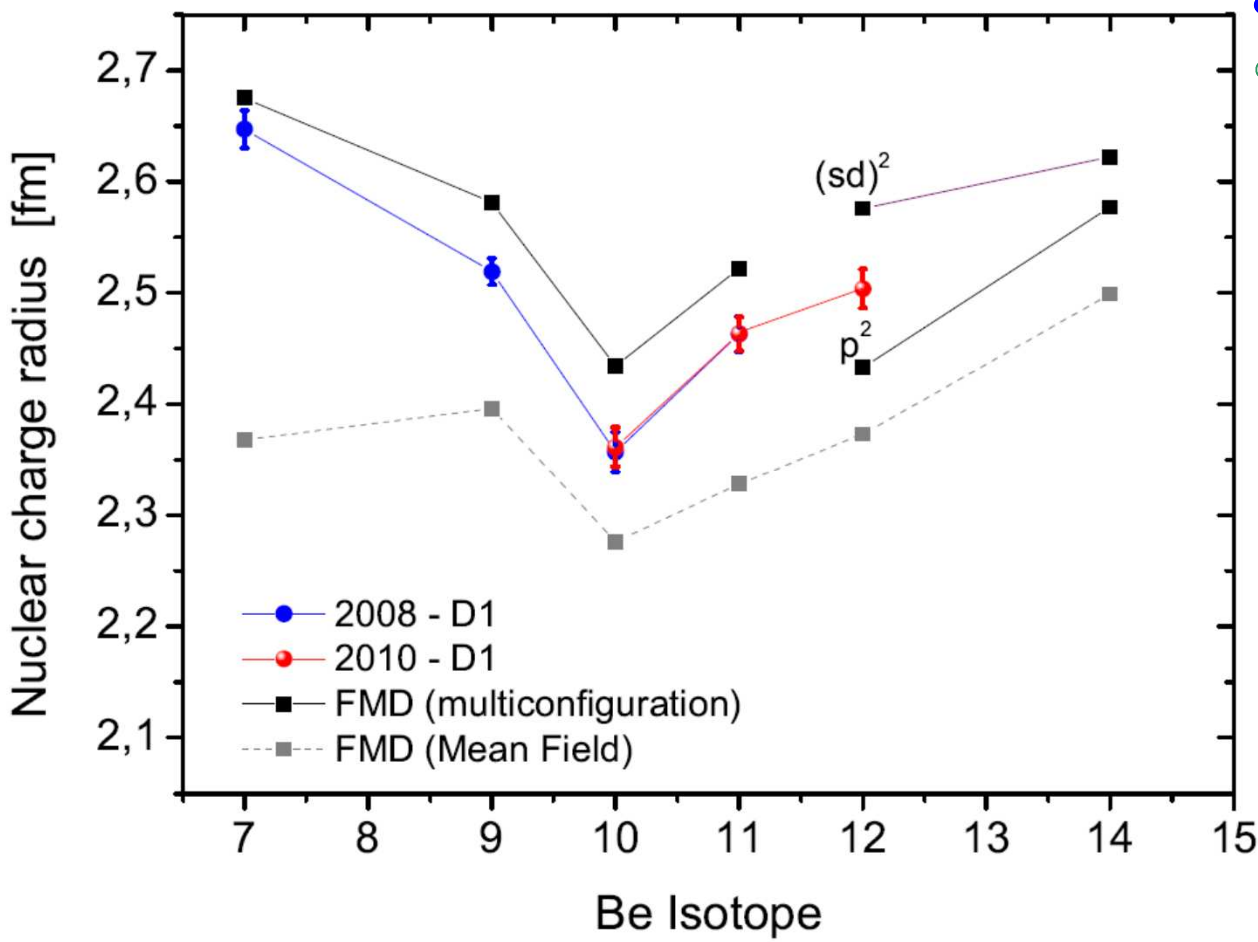


Collinear

Anticollinear

Beryllium: Nuclear Charge Radii

Electron Scattering: $r_c(^9Be)$ = 2.519(12) fm, J.A. Jansen et al., Nucl.Phys.A **188**, 337 (1972).
Muonic Atoms: $r_c(^9Be)$ = 2.39(17) fm, L.A. Schaller, Nucl.Phys.A **343**, 333 (1980).



● Experiment
○ Interaction cross section (Tanihata)
\+ Greens-Funct. Monte-Carlo Calcul.
Δ Fermonic Molecular Dynamics
□ No-Core Shell Model

References:

NCSM2005: No Core Shell Model
P. Navratil, PRC 73, 065801 (2006) (^{7}Be)
C. Forssen, Phys. Rev. C71 (2005) (^{9,11}Be)
P. Navratil, priv. comm. (2008) (^{10}Be)

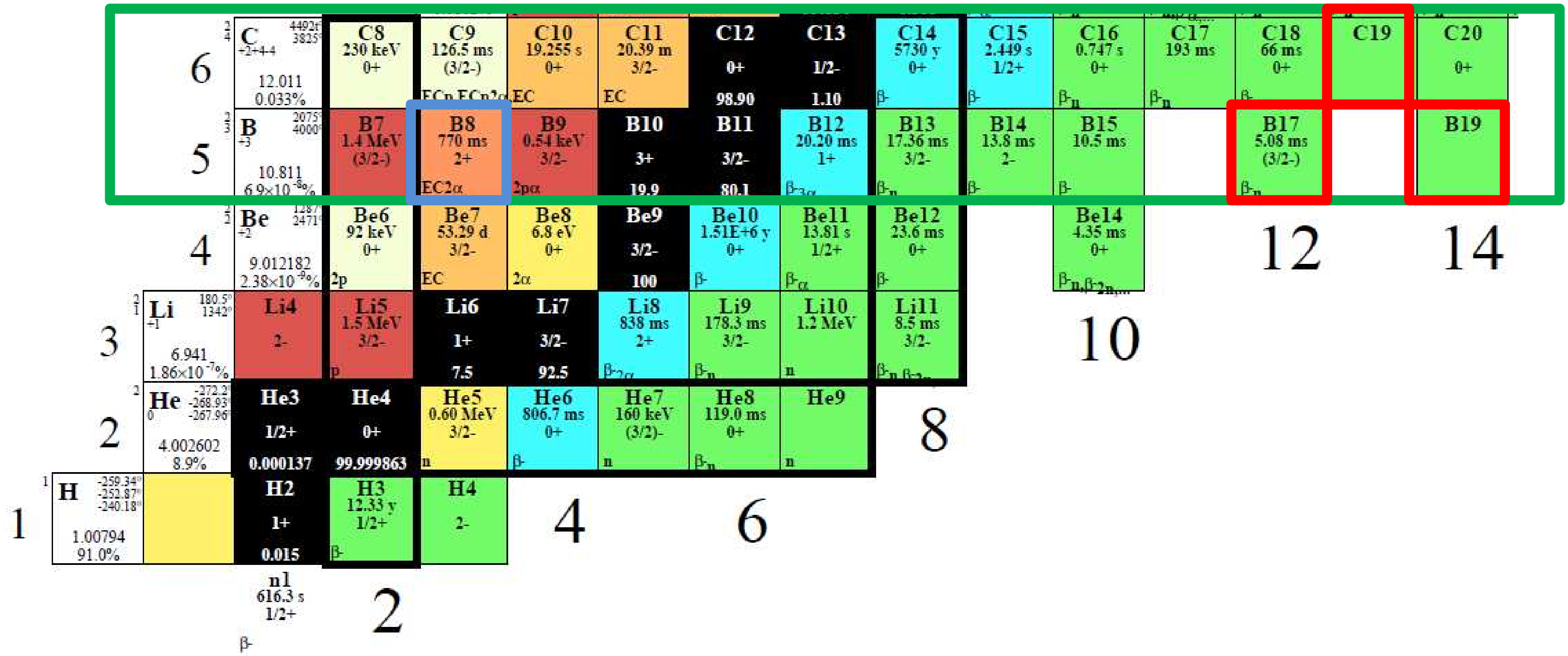
Tanihata: Interaction Cross Sections with Glauber model
I. Tanihata, Phys. Lett B 206,592 (1988)

GFMC: Greens Function Monte Carlo AV18/IL2
S. Pieper, Annu.Rev.Nucl.Part.Sci. 51, 53 (2001)
S. Pieper, PRC 66, 044310 (2002)

FMD: Fermionic Molecular Dynamic
R. Torabi, GSI, priv. comm. (2008)

^{7}Be - ^{12}Be: W. Nörtershäuser *et al.*, PRL **102**, 062503 (2009)
A. Krieger *et al.*, PRL **108**, 142501 (2012)

Beyond Be: Boron, Carbon, …



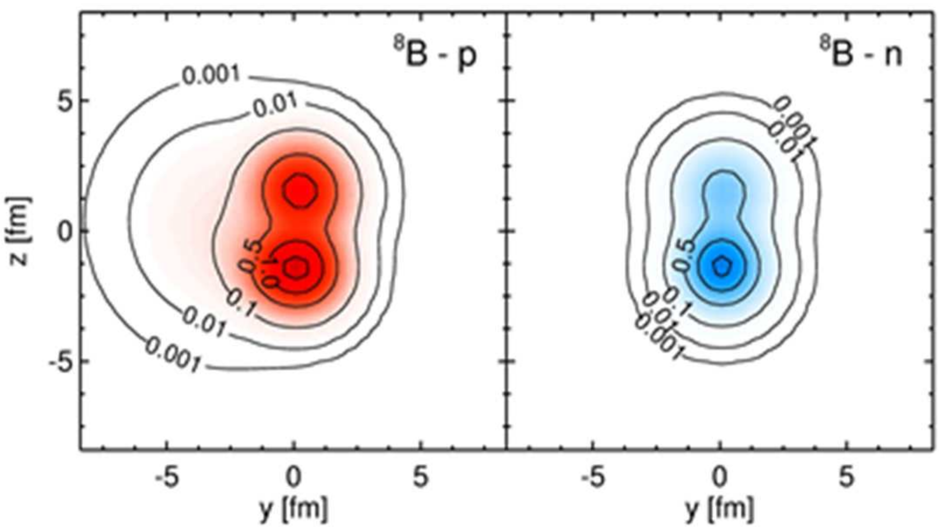
- Proton and neutron halo isotopes
- Charge radius directly sensitive to ^{8}B proton halo, but …

- Boron difficult to get out of target
- Laser spectroscopy of boron very challenging

^{8}B Nuclear Structure

- Very low proton-separation energy: ~140 keV

- Evidence of large spatial extend of valence proton (“proton halo”)
  - large quadrupole moment (+65 mb) measured via β-NMR
    T. Minamisono et al., PRL 69, 2058 (1992), T. Sumikama et al. PRC 74 024327 (2006)
  - large reaction cross section near Coulomb barrier
    E.F. Aguilera et al., PRC 79,021601(R) (2009)



Intrinsic p and n densities of ^{8}B calculated from Fermionic Molecular Dynamics model
T. Neff, priv. comm. (2012)

Charge radius measurement

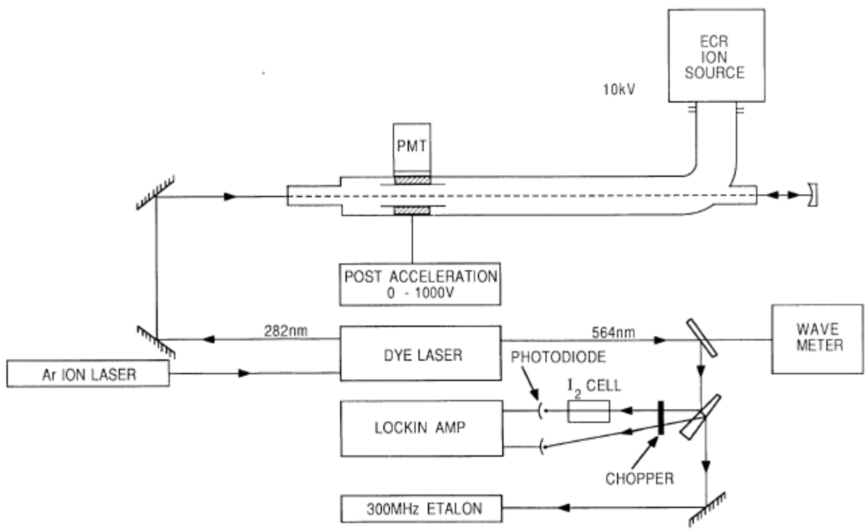
- directly sensitive to proton distribution
- Probe ^{8}B cluster structure
  p-^{7}Be p-^{3}He-^{4}He
- Test *ab-initio* calculations of proton-rich light nuclei

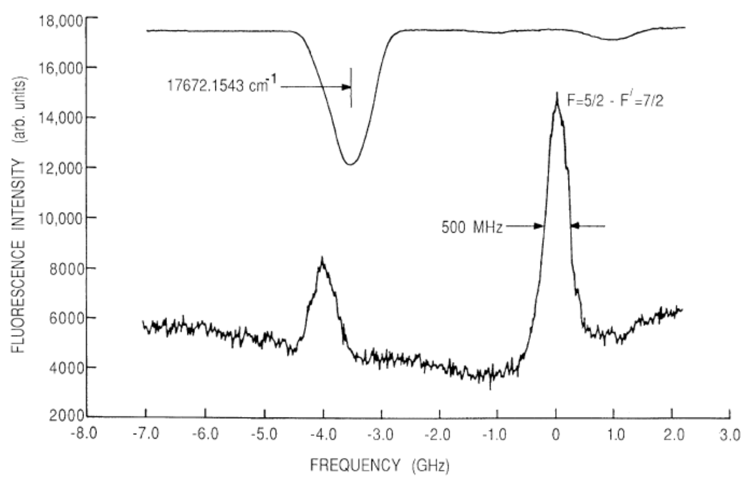
Boron Laser Spectroscopy

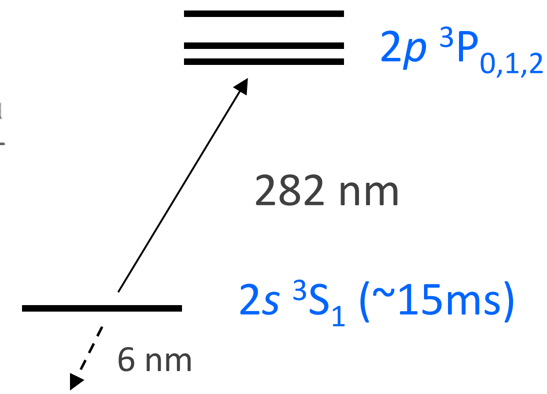
VOLUME 66, NUMBER 22 PHYSICAL REVIEW LETTERS 3 JUNE 1991

Precision Measurements of Relativistic and QED Effects in Heliumlike Boron

T. P. Dinneen,[a] N. Berrah-Mansour, H. G. Berry, L. Young, and R. C. Pardo
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 31 August 1990)







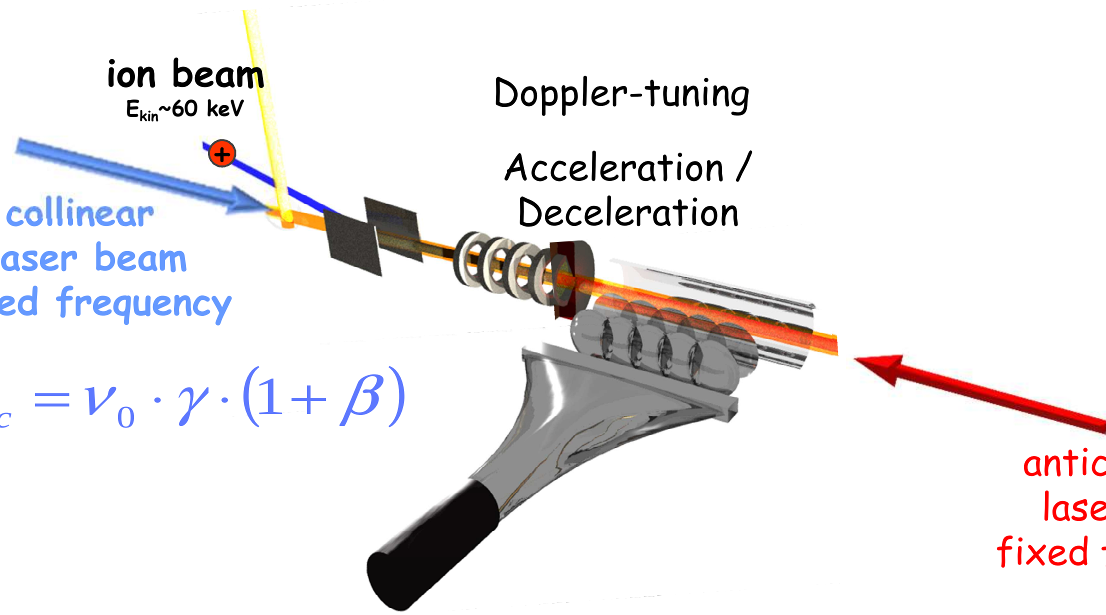
Collinear laser spectroscopy of metastable, helium-like B^{3+} from ECR

For ^8B need:

- Atomic theory ☑
- Nuclear theory (GFMC for A=8)
- In-flight production
- Stop, low energy B^+ -> source
  … gas catcher
- Charge breeding
  … to B^{3+} or B^{4+}
- Populate metastable state
  … in source or charge-ex.
- High-resolution laser spec
  … collinear laser spectroscopy

Laser Spectroscopy

Collinear/Anti-collinear approach (see Be^+)



$$\nu_c = \nu_0 \cdot \gamma \cdot (1+\beta)$$

$$\nu_c = \nu_0 \cdot \gamma \cdot (1+\beta)$$

$$\nu_a = \nu_0 \cdot \gamma \cdot (1-\beta)$$

$$\nu_a \cdot \nu_c = \nu_0^2 \cdot \gamma^2 \cdot (1-\beta^2) = \nu_0^2$$

Completely independent of U !

$\gamma = \gamma(U,m)$, $\beta = \beta(U,m)$,

$\Delta U/U \approx 10^{-4}$

$\Rightarrow \delta\nu_{IS}$ (^{9}Be,^{11}Be) = 14 MHz

<u>Requirements:</u>

Measure absolute frequencies

Accuracy: $\Delta\nu/\nu < 10^{-9}$

Dedicated Laser System for absolute Frequency Measurements

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Thank you!

^{6}He Collaboration

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