Argonne NATIONAL LABORATORY

... for a brighter future

Precision Laser Spectroscopy of Exotic Helium Isotopes

Peter Müller

U.S. Department of Energy

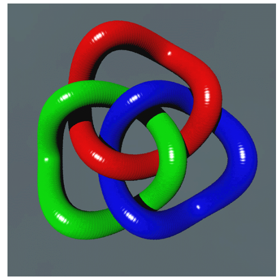
UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

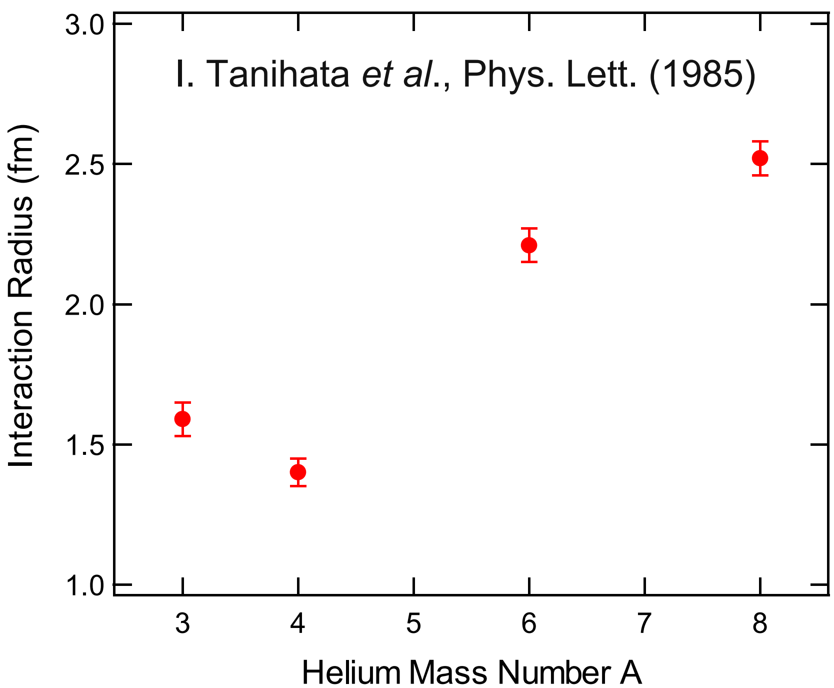
A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Neutron Halo Nuclei ^{6}He and ^{8}He

Isotope	Half-life	Spin	Isospin	Core + Valence
He-6	807 ms	0^+	1	α + 2n
He-8	119 ms	0^+	2	α + 4n



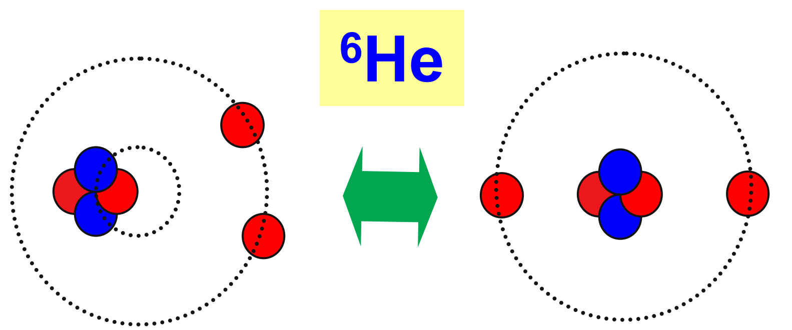
Borromean



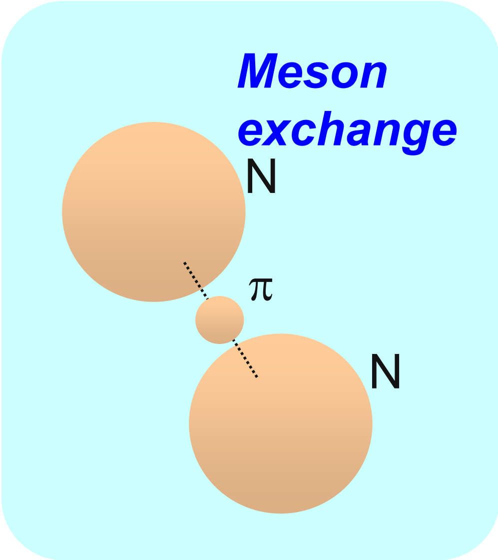
Core-Halo Structure

$$\sigma_I(^6He) - \sigma_I(^4He) = \sigma_{-2n}(^6He)$$

I. Tanihata *et al*., Phys. Lett. (1992)



Effective Model of Nuclear Interaction



Two-body potential: *Argonne V18*

$$H = \sum_i K_i + \sum_{i<j} v_{ij}^{\gamma} + v_{ij}^{\pi} + v_{ij}^{R}$$

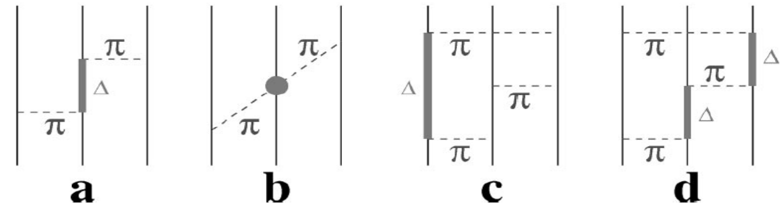
EM 1-π short-range

Coupling parameters fit to NN scattering data

Problem: binding energy of most light nuclei too small

Three-body potential: *Illinois-2*

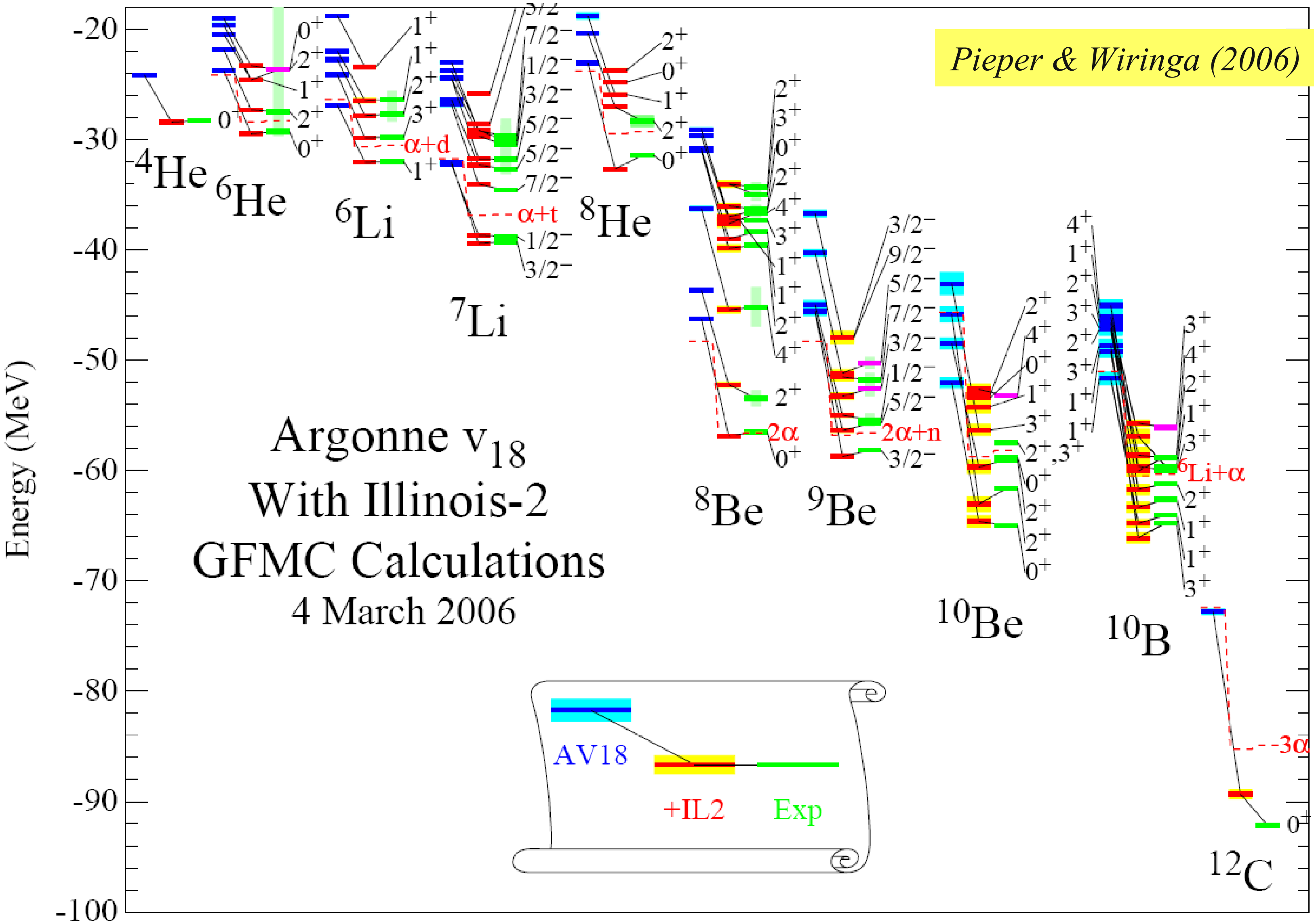
$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{3\pi} + V_{ijk}^{R}$$



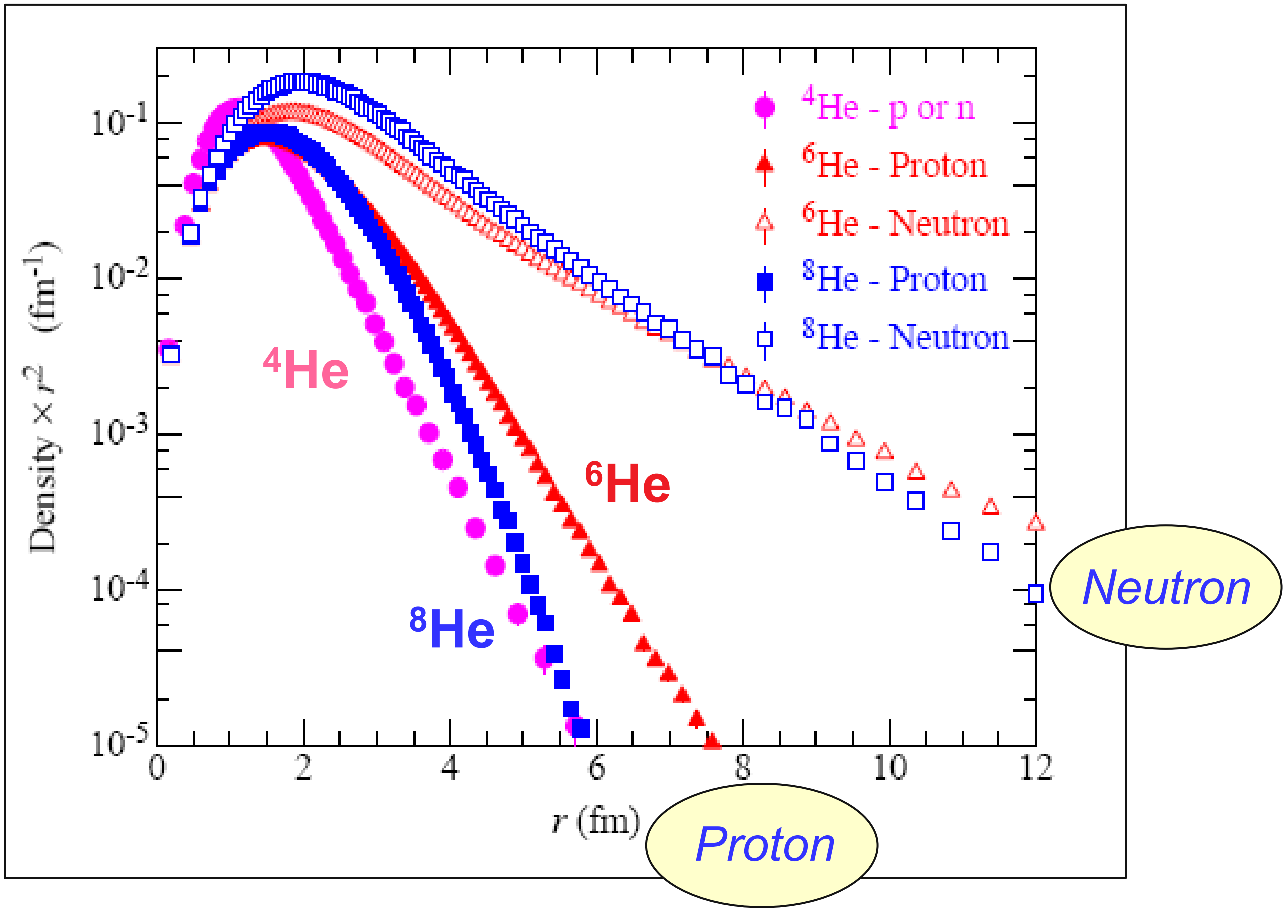
Coupling parameters fit to energy levels of light nuclei

Pieper & Wiringa. Ann. Rev. Nucl. Part. Sci. (2001)

Green's Function Monte Carlo Calculations

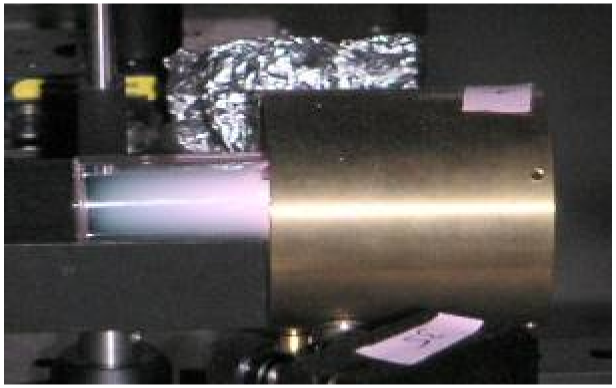


GFMC – Neutron and Proton Densities in Helium-4,6,8

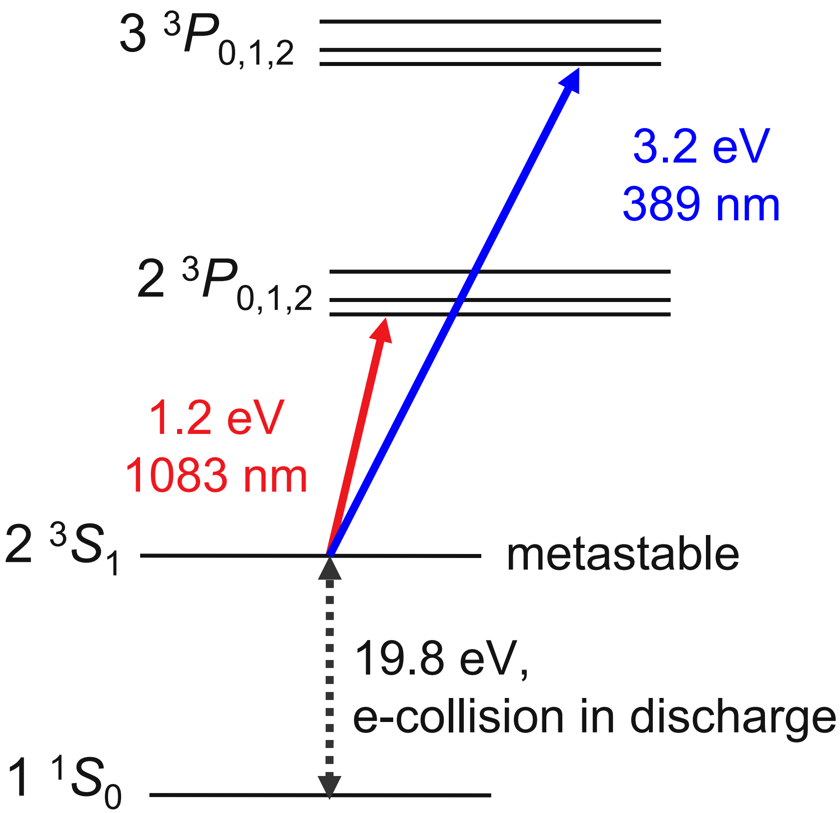


Atomic Energy Levels of Helium

He discharge



He energy level diagram

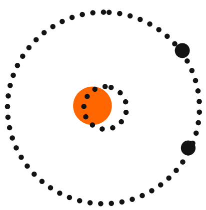


Atomic Isotope Shift

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

Mass shift:

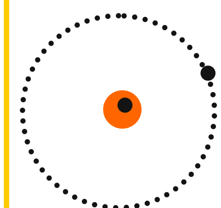
due to nucleus recoil



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

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:

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

^{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(1) MHz + 1.008 ($\langle r^2\rangle_{He4}$ - $\langle r^2\rangle_{He8}$) MHz/fm^2

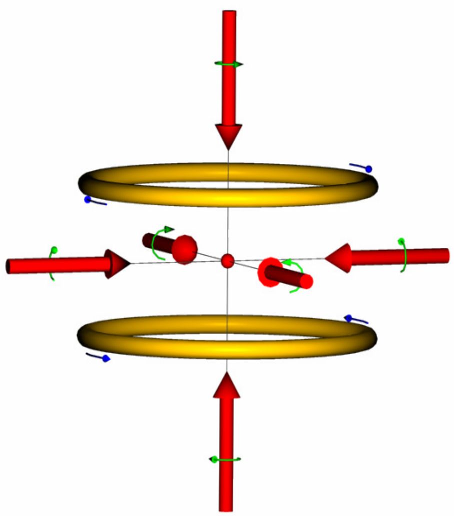
G.W.F. Drake, Univ. of Windsor, *Nucl. Phys. A737c, 25 (2004)*

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

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 isotobic / isobaric interference

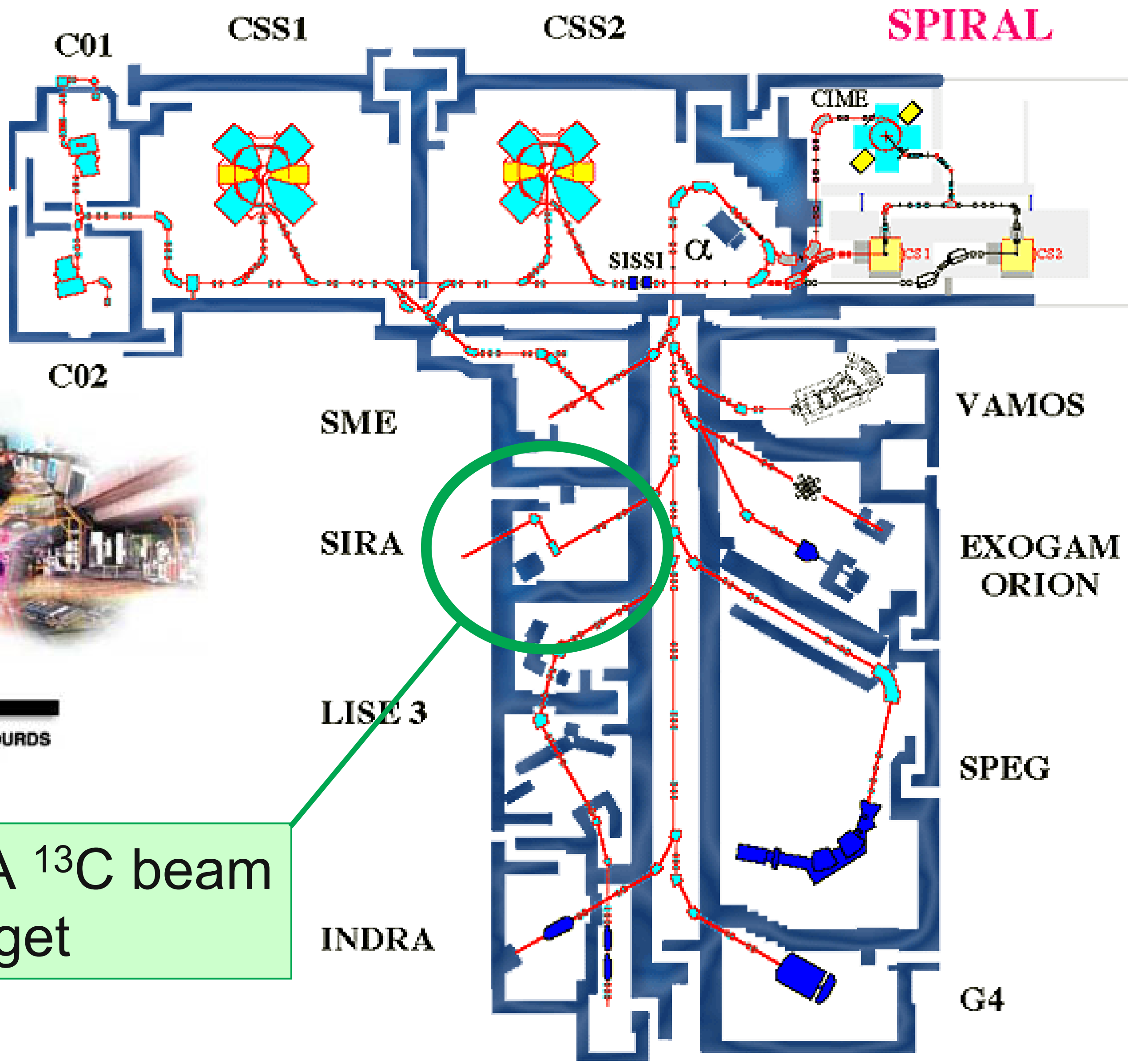
Where to find ^{8}He?

GANIL

Caen, France

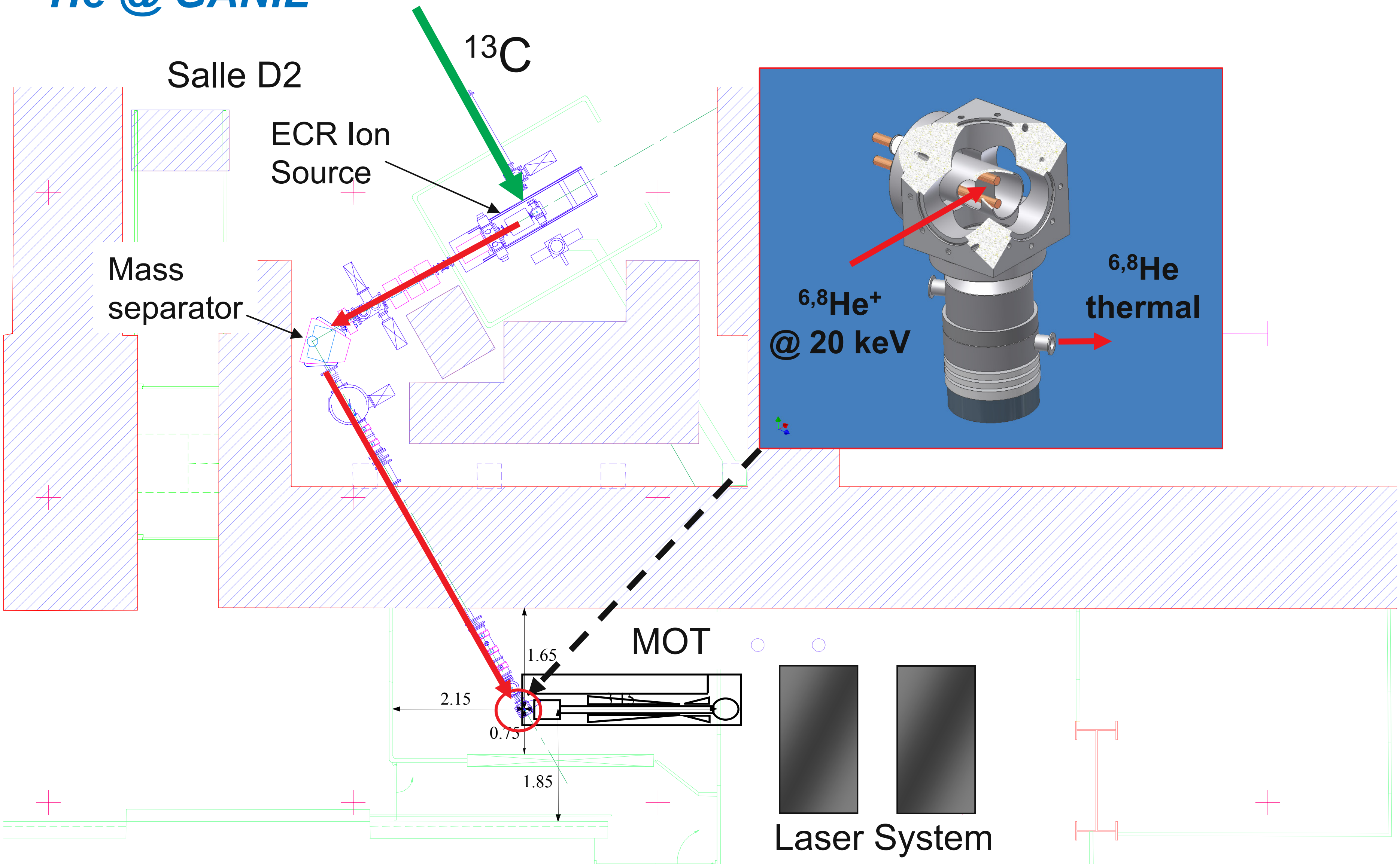
He-8 @ GANIL

GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS
LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS



75 MeV/u, 0.4 pμA ^{13}C beam on ^{12}C target

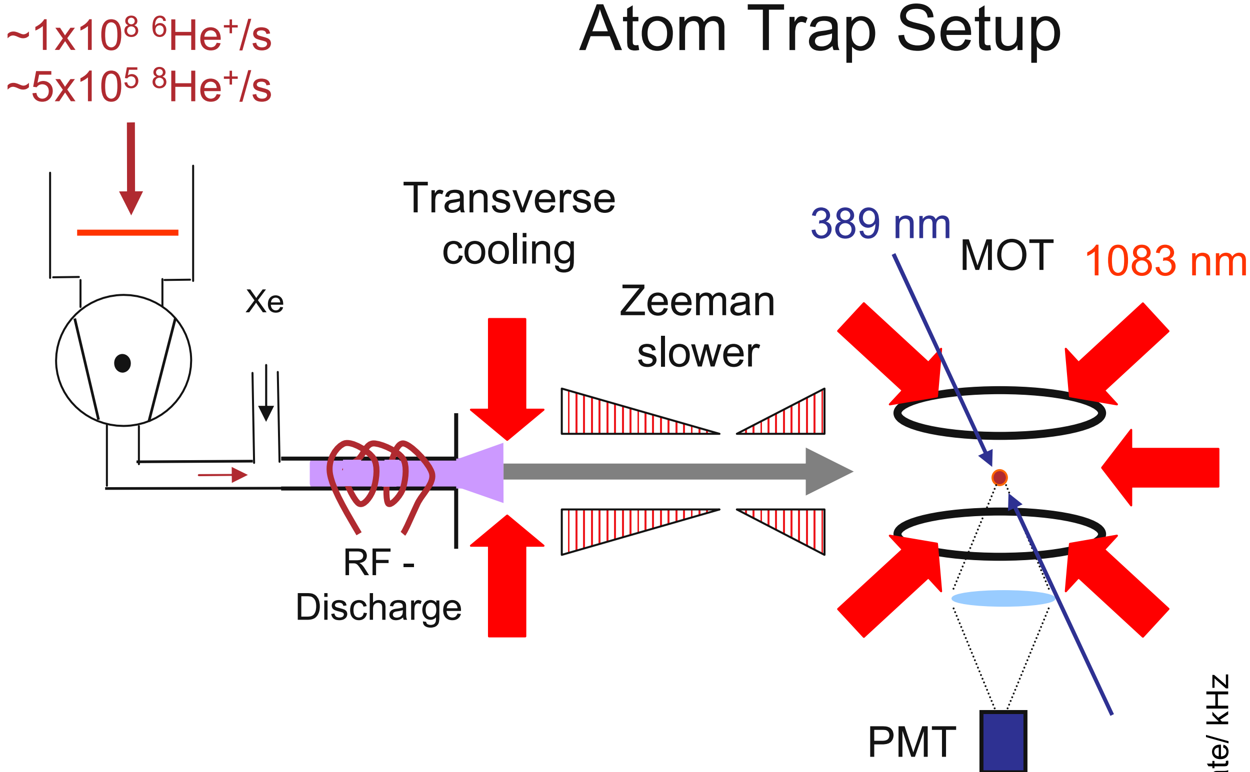
^{8}He @ GANIL

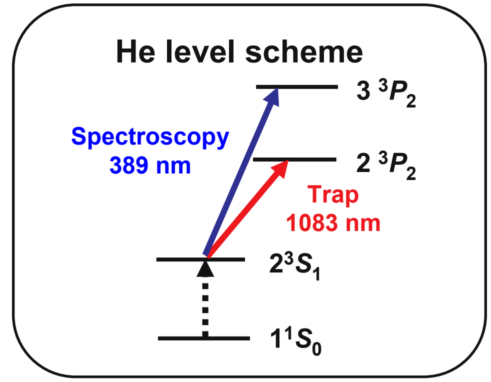


13C
Salle D2
ECR Ion Source
Mass separator
6,8He+ @ 20 keV
6,8He thermal
MOT
1.65
2.15
0.75
1.85
Laser System

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

Atom Trap Setup



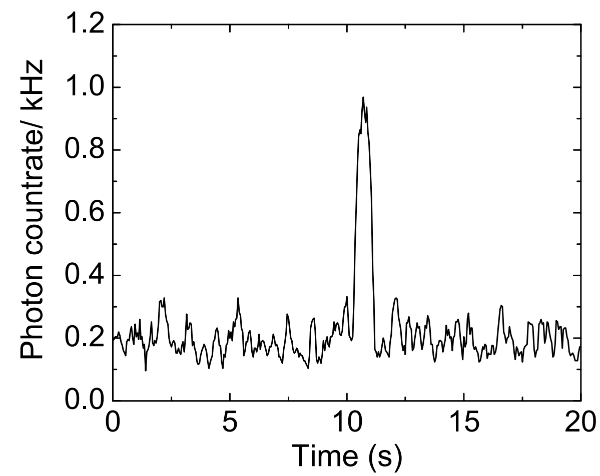


Source
~5x10^{7} He-6/s,
~1x10^{5} He-8/s

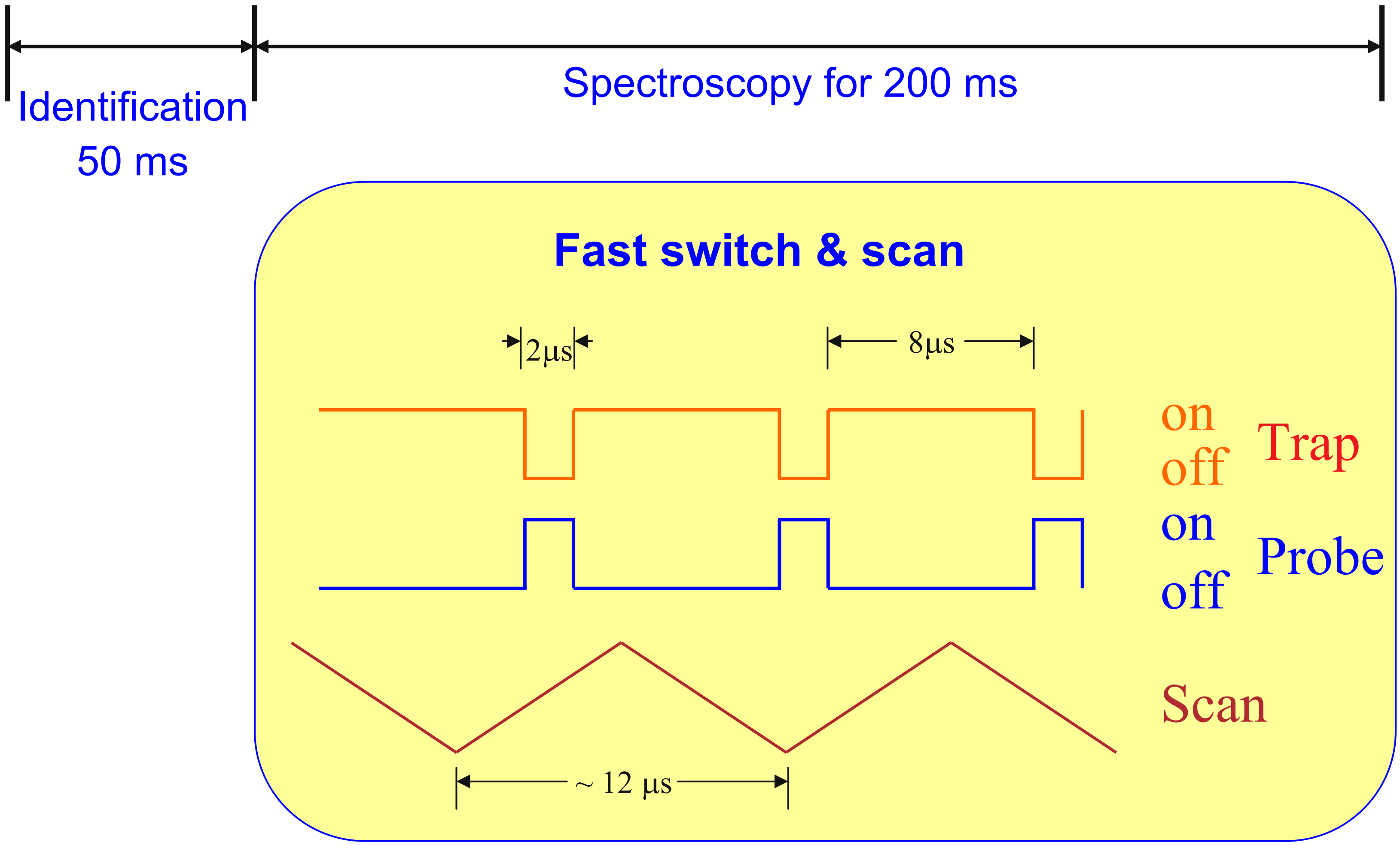
Capture efficiency
1x10^{-7}

Trap
~5 He-6/s,
~30 He-8/hr

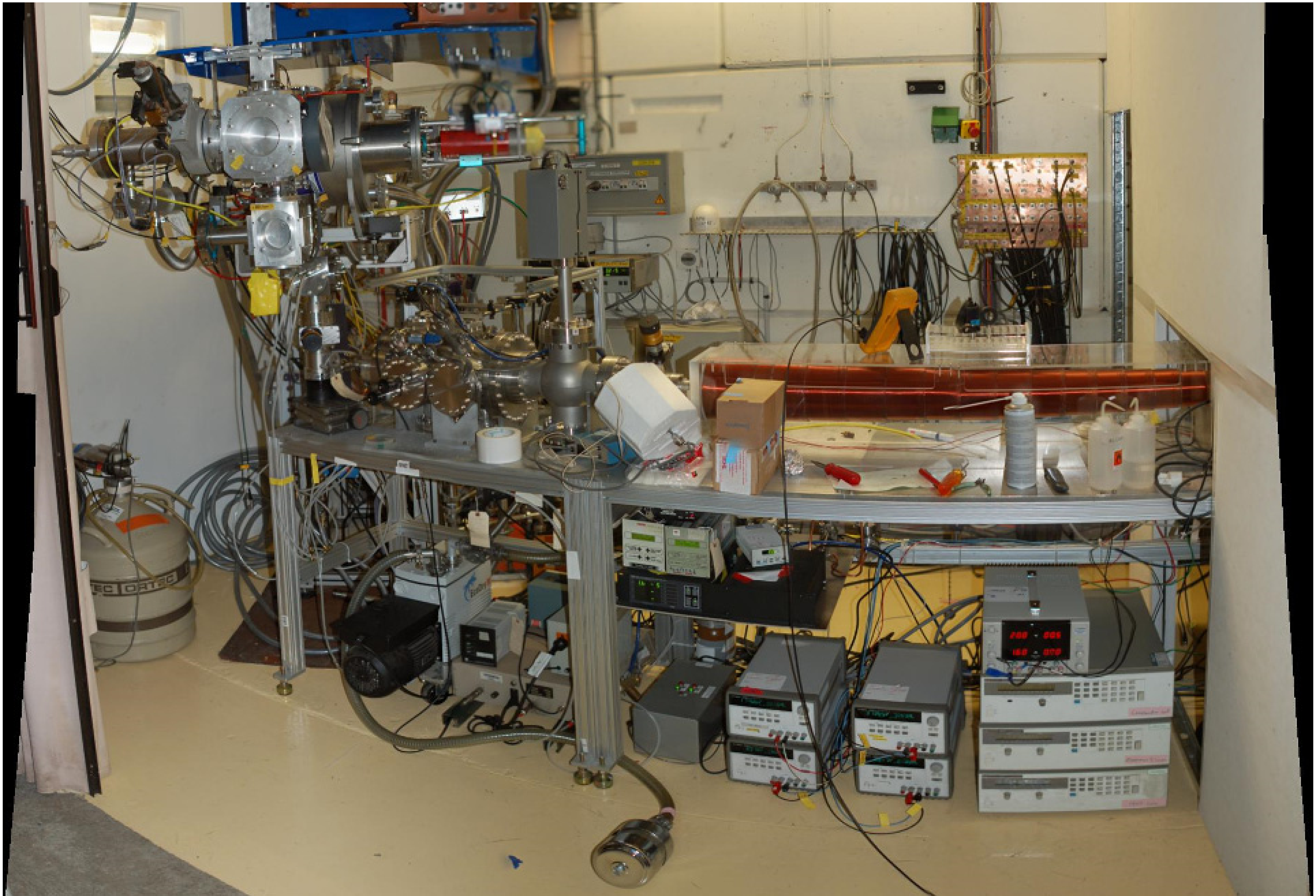
One trapped ^{6}He atom

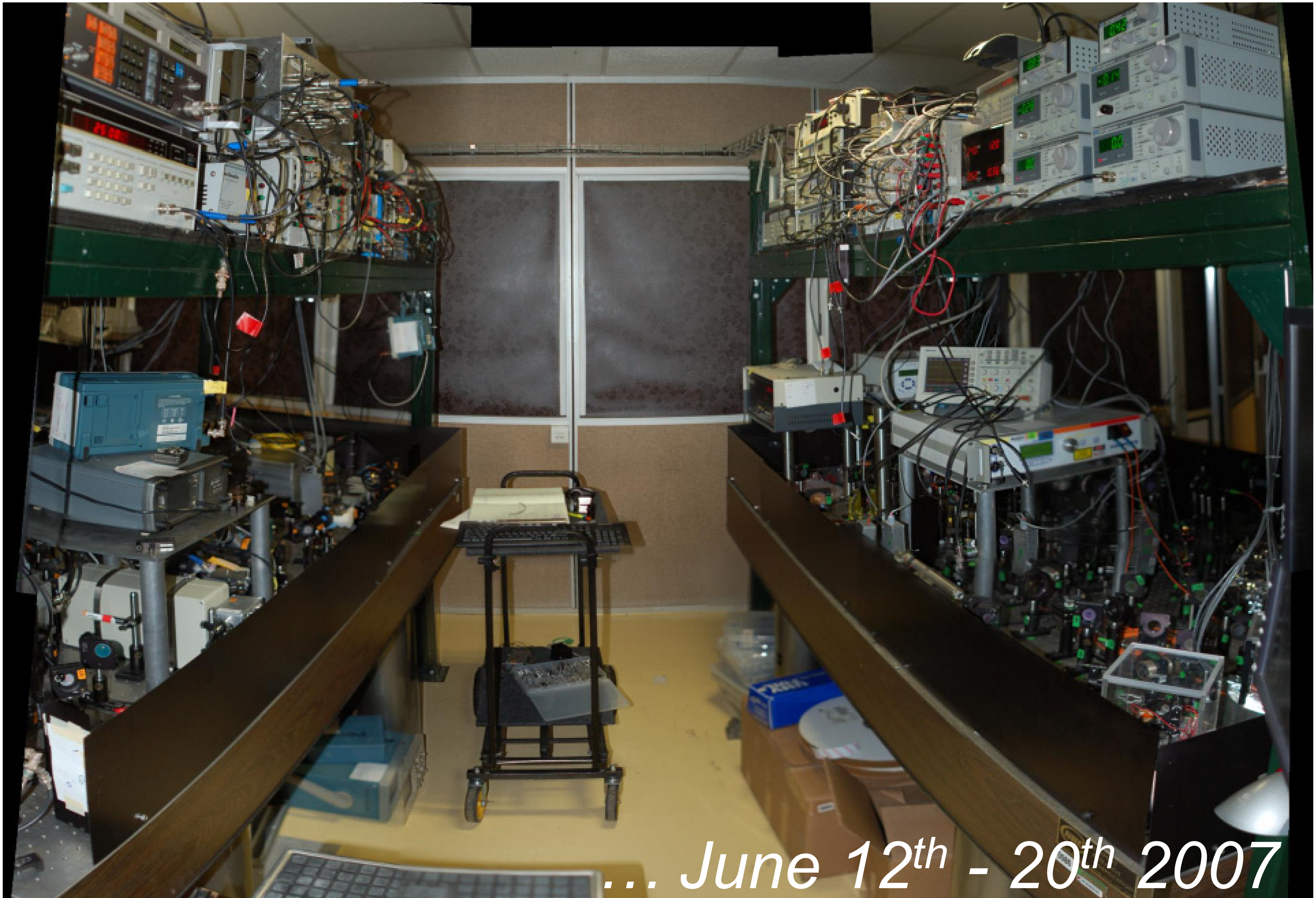


Switch & Scan


Identification
50 ms
Spectroscopy for 200 ms
Fast switch & scan
2μs
8μs
on
off
Trap
on
off
Probe
Scan
~ 12 μs

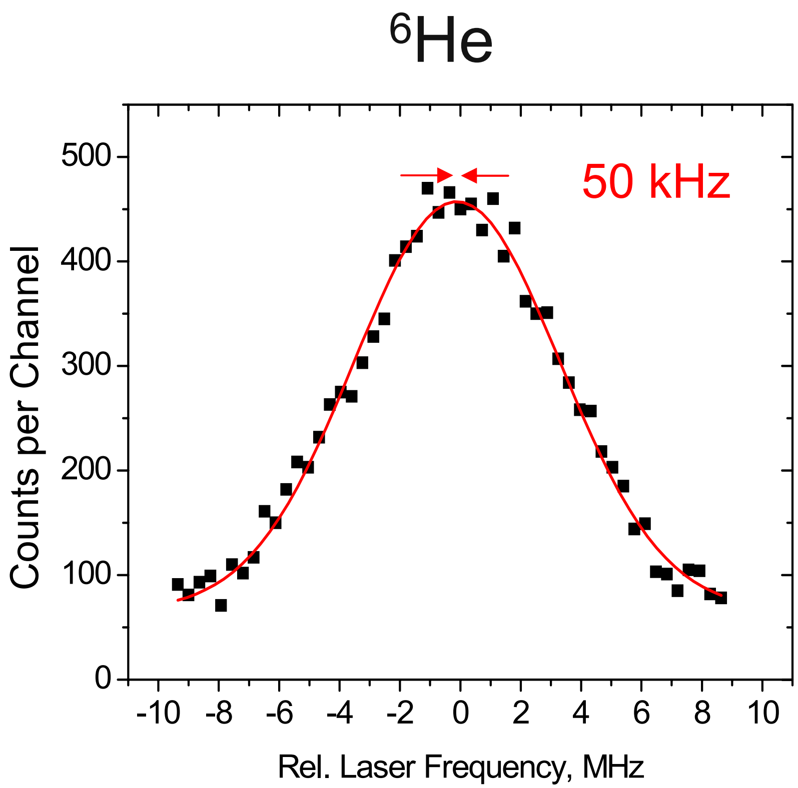

Jan. 26th 2007


ORTEC

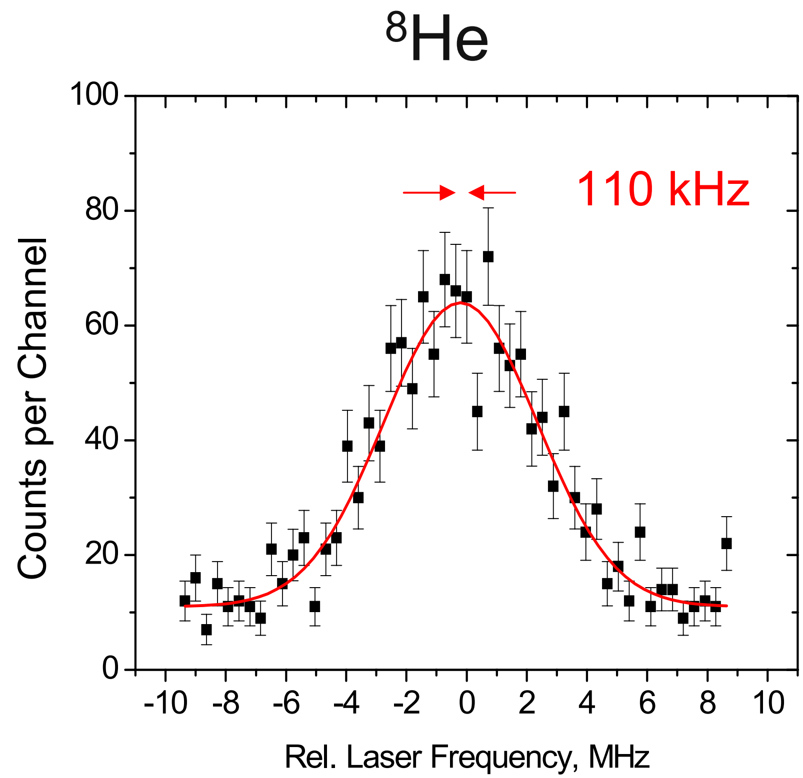


… June 12th - 20th 2007

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

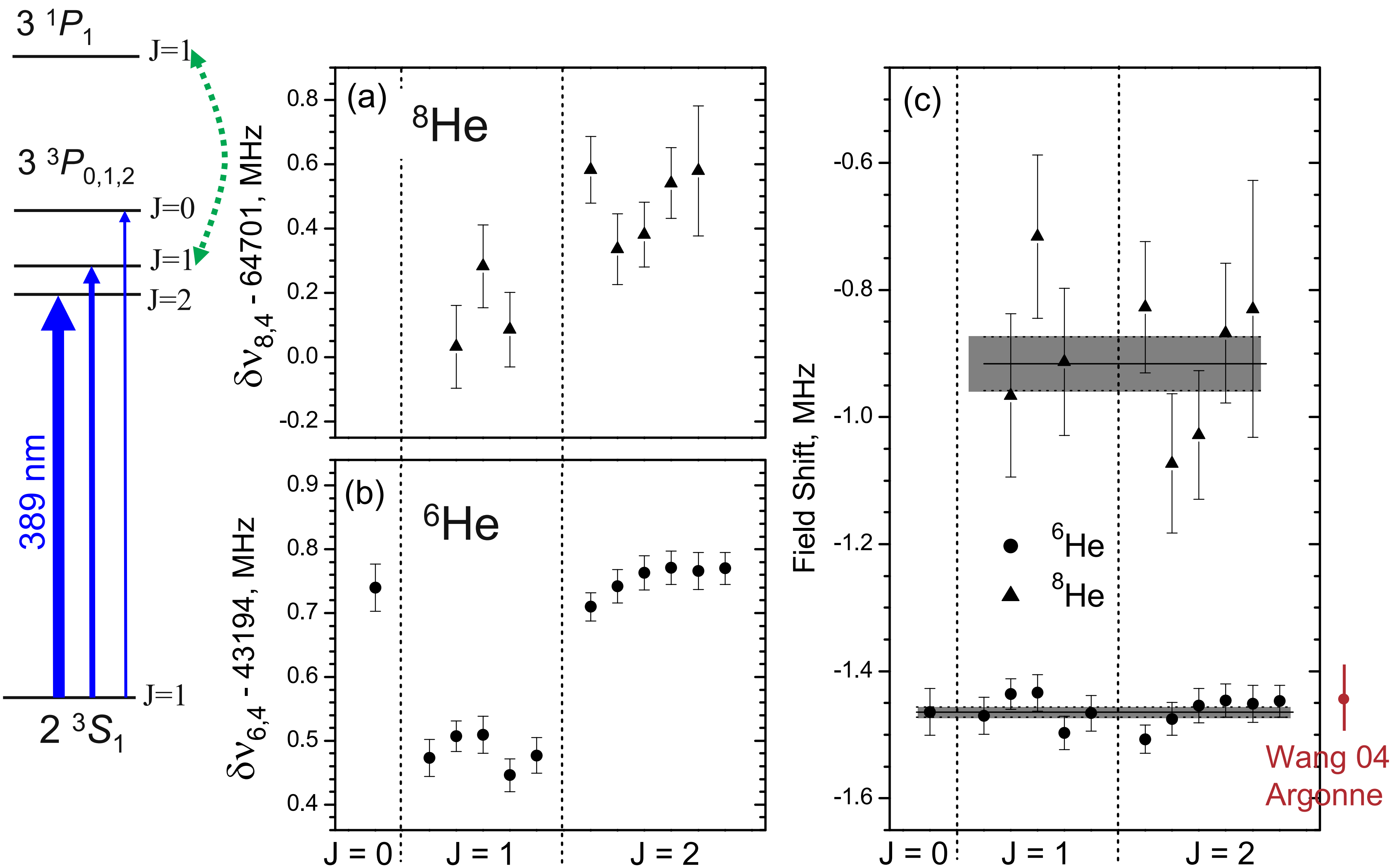


~ 5 ^{6}He atoms/s
2 minutes



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

Isotope Shift and Field Shift : J - Dependence?



Experimental Uncertainties and Corrections

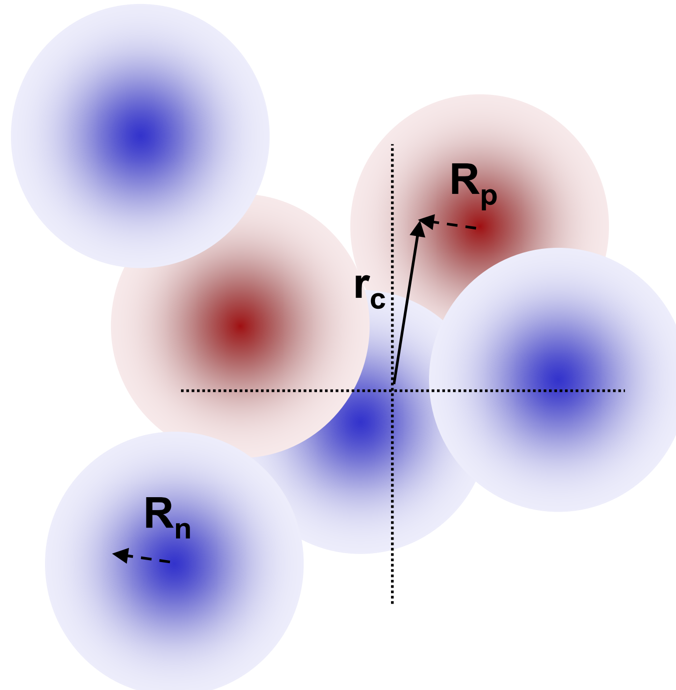
		^{6}*He*	^{8}*He*
Statistical	Photon Counting	8 kHz	32 kHz
	Laser Alignment	2 kHz	12 kHz
	Reference Laser	2 kHz	24 kHz
Systematic	Probing Power Shift	0 kHz	15 kHz
	Zeeman Shift	**30 kHz**	45 kHz
	Nuclear Mass	15 kHz	**1 kHz**
	TOTAL	**35 kHz**	**63 kHz**

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

TITAN Penning Trap @ TRIUMF, V. L. Ryjkov *et al.*, PRL **101**, 012501 (2008)

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

	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-1.026(63)
RMS R_{CH}, fm	**2.072(9)**	**1.961(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 %*



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

$$- \delta_{SO} - MEC$$

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

\+ V. L. Ryjkov *et al.*, PRL **101**, *012501 (2008): He-8 mass*

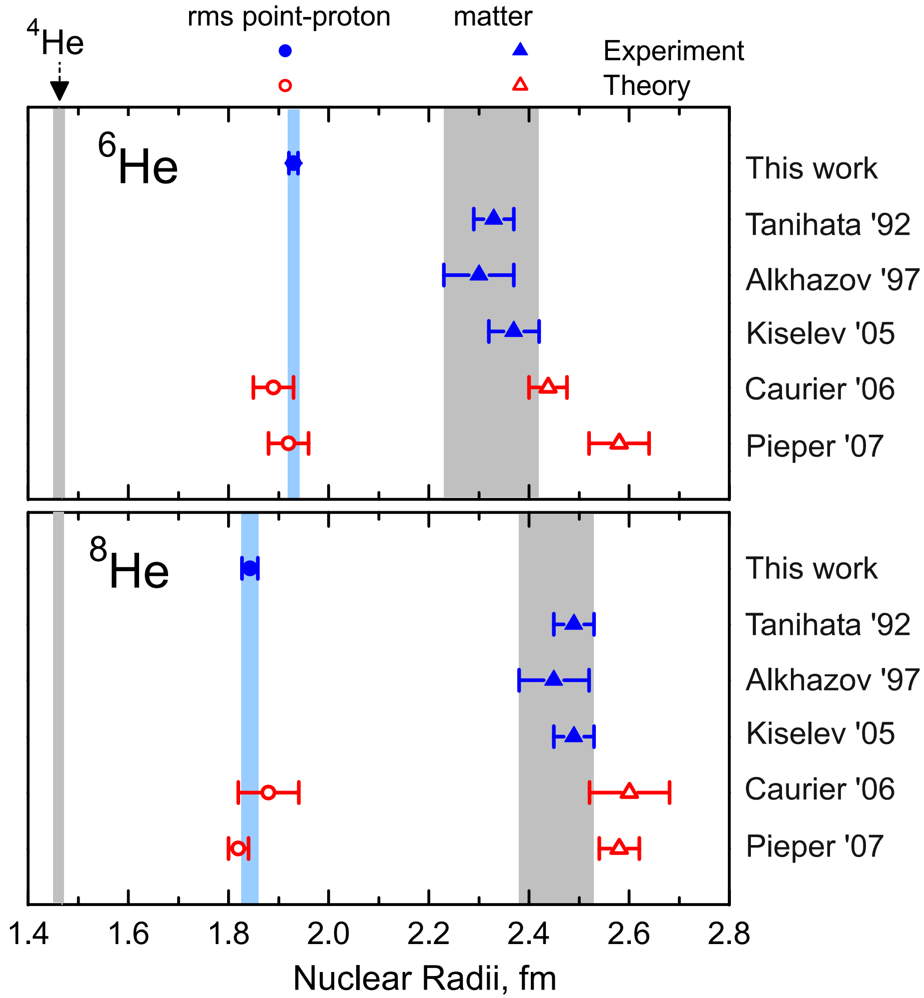
\+ I. Sick PRC **77**, *041302(R) (2008): He-4 Charge Radius*

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

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

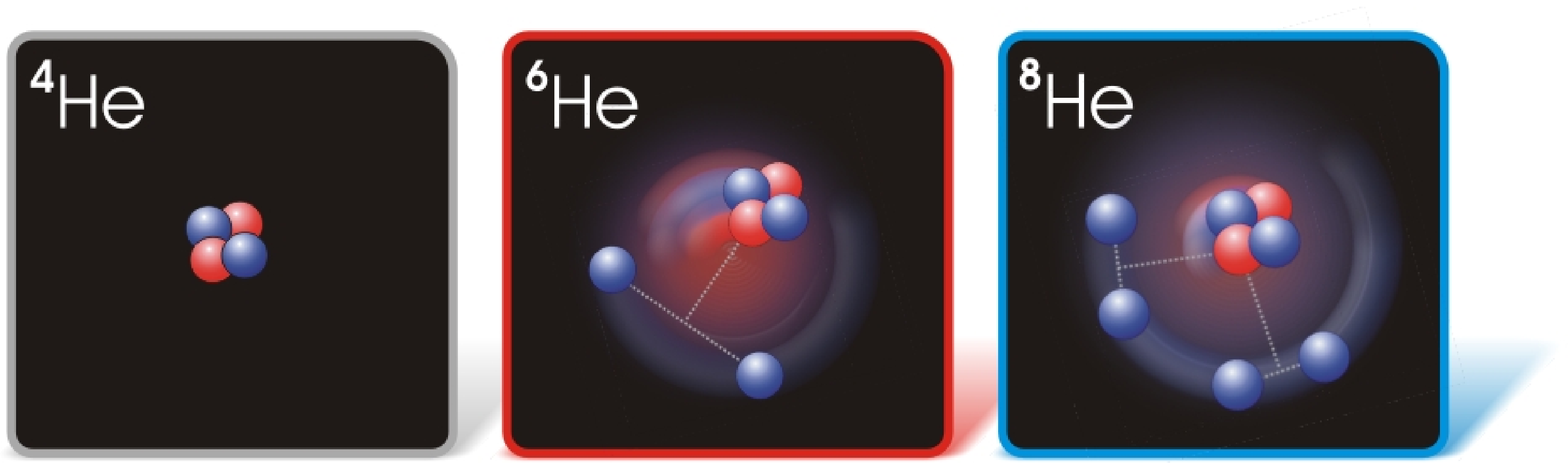
^{6}He & ^{8}He RMS Point Proton and Matter Radii

	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-1.026(63)
RMS R_{pp}, fm	**1.930(9)**	**1.843(16)**
Total Uncertainty	**0.4 %**	**0.9 %**
- Statistical	*0.1 %*	*0.6 %*
- Trap Systematics	*0.3 %*	*0.6 %*
- Mass Systematics	*0.2 %*	*0.0 %*
- He-4: 1.465(4) fm	*0.1 %*	*0.1 %*



No Spin-Orbit and *MEC* ...

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



1.681(4) fm   2.072(9) fm   1.961(16) fm

Thank You!

^{6}He Collaboration

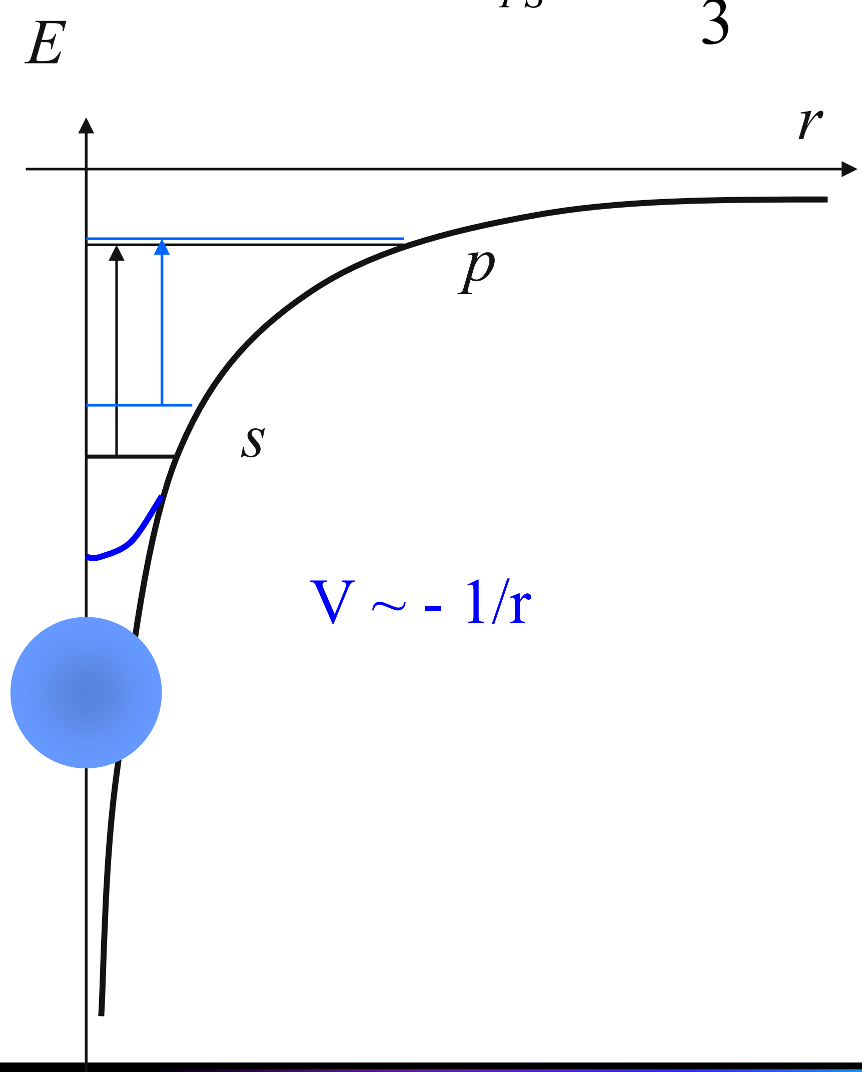
P. Mueller, L.-B. Wang, K. Bailey, J.P. Greene, D. Henderson, R.J. Holt, R. Janssens, C.L. Jiang, Z.-T. Lu, T. O'Conner, R.C. Pardo, K.E. Rehm, J.P. Schiffer, X.D. Tang - *Physics Division, Argonne National Laboratory, USA*
G. W. F. Drake - *University of Windsor, Windsor, Canada*

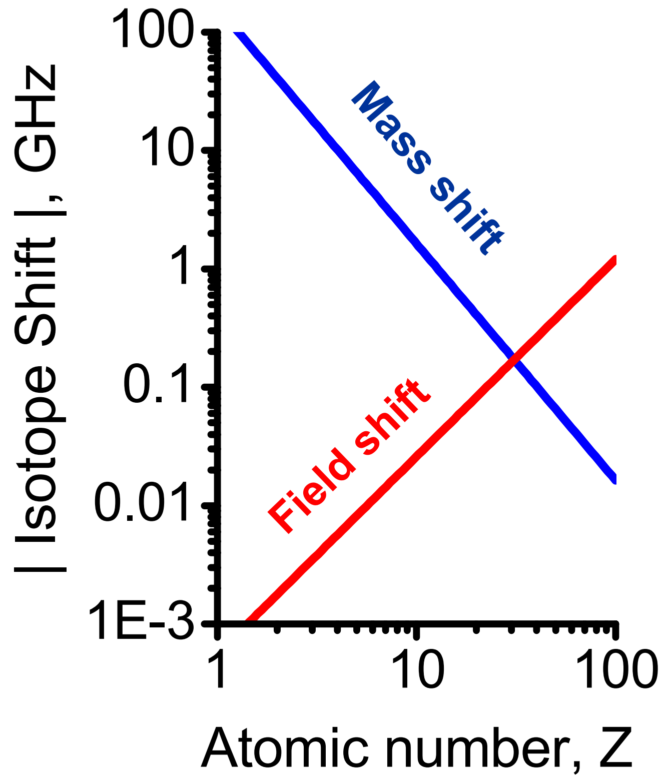
^{8}He Collaboration

P. Mueller, K. Bailey, R. J. Holt, R. V. F. Janssens, Z.-T. Lu, T. P. O'Connor, I. Sulai - *Physics Division, Argonne National Laboratory, USA;* **M.-G. Saint Laurent, *J.-Ch. Thomas, A.C.C. Villari et al.-*** *GANIL, Caen, France* **G. W. F. Drake -** *University of Windsor, Windsor, Canada* **L.-B. Wang –** *Los Alamos National Laboratory, USA*

Field (Volume) Shift

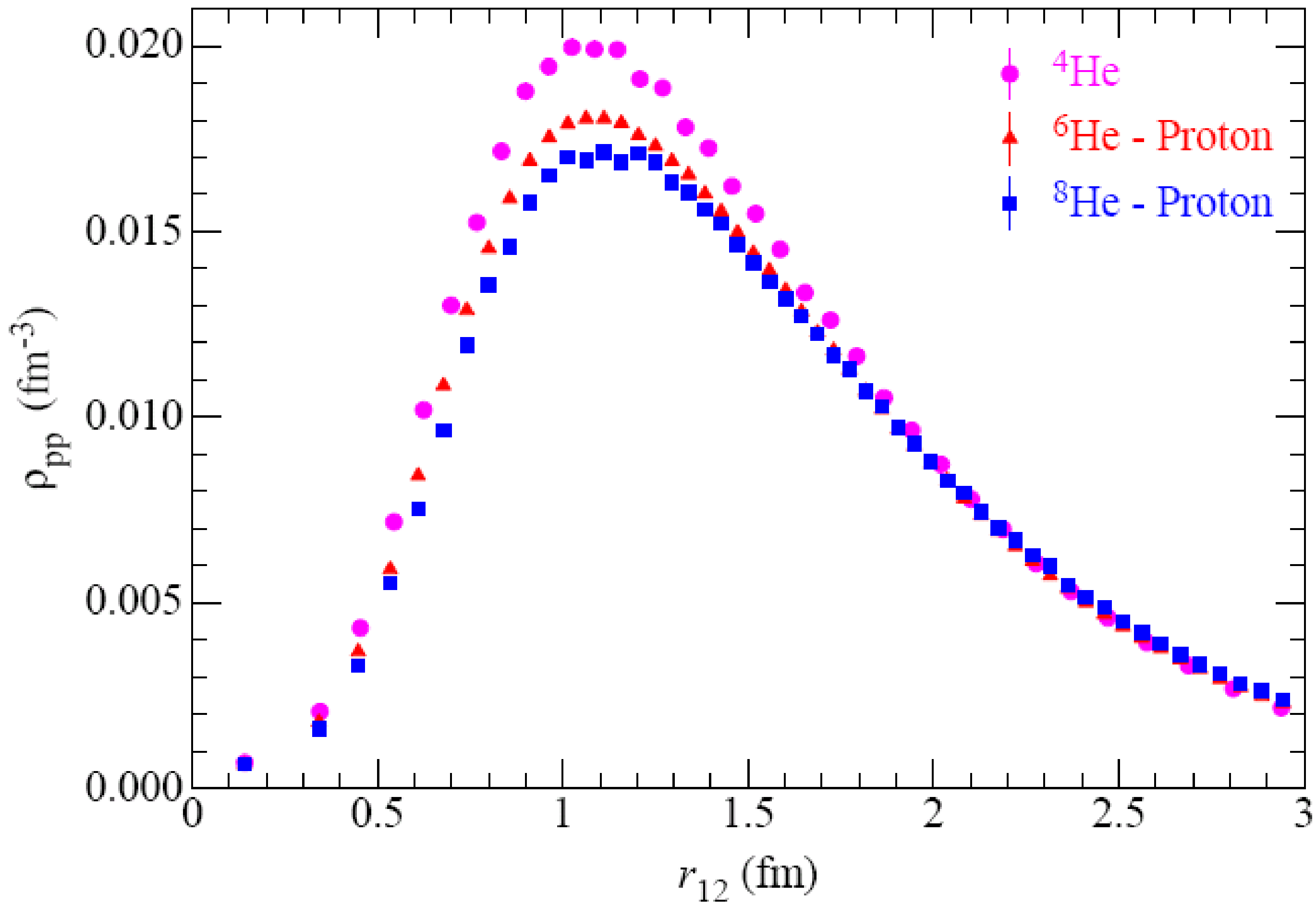
$$\delta\nu_{FS} = -\frac{2\pi}{3} Ze^2 \cdot \Delta\left|\Psi(0)\right|^2 \cdot \delta\left\langle r^2 \right\rangle^{AA'}$$



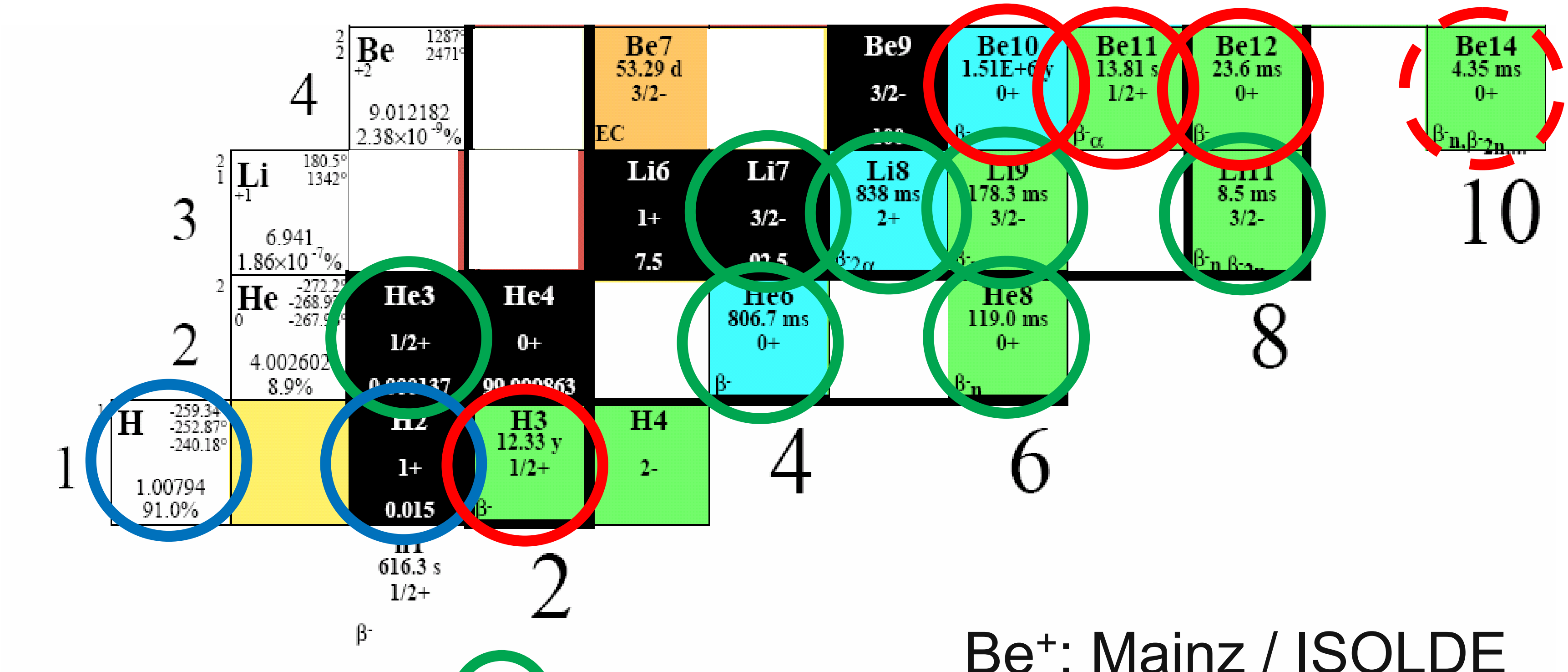


GFMC – What happens to the α-core?

AV18 + IL2 GFMC proton-proton distributions



Charge Radii of Light Isotopes by Laser Spectroscopy



Isotope Shift:

IS+absolute ν:

In prep.:

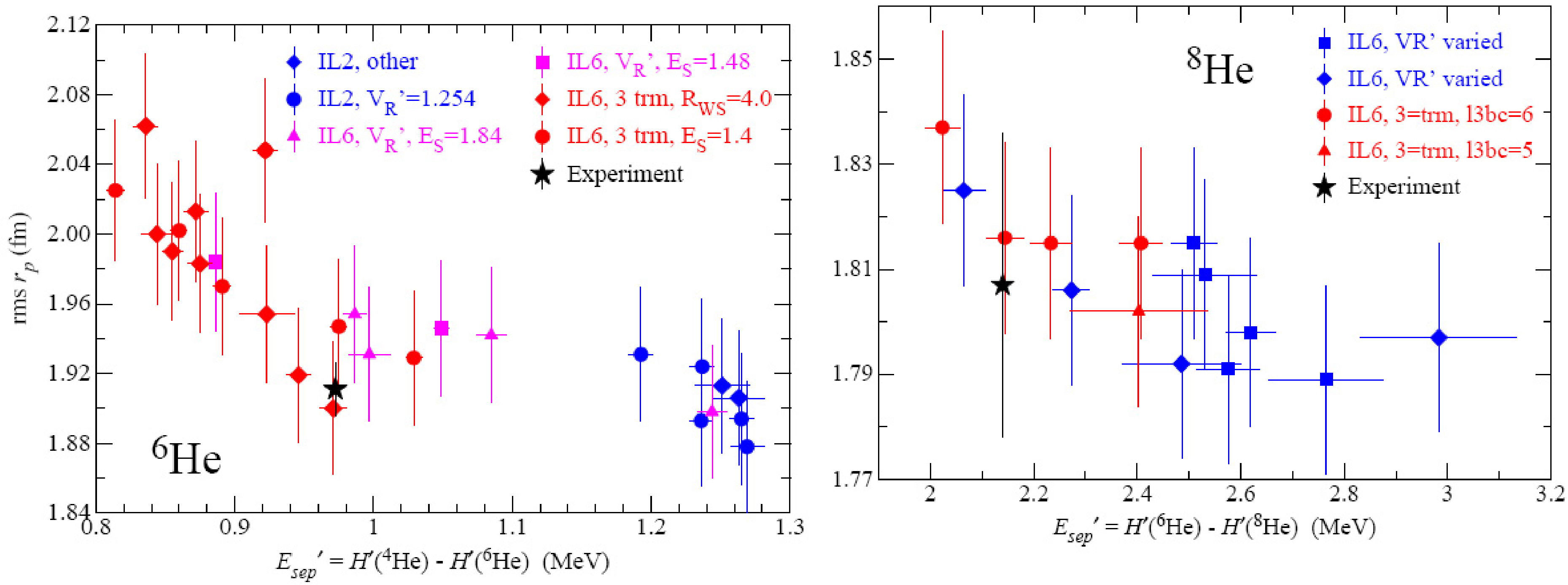
Be^{+}: Mainz / ISOLDE

Li: GSI / TRIUMF

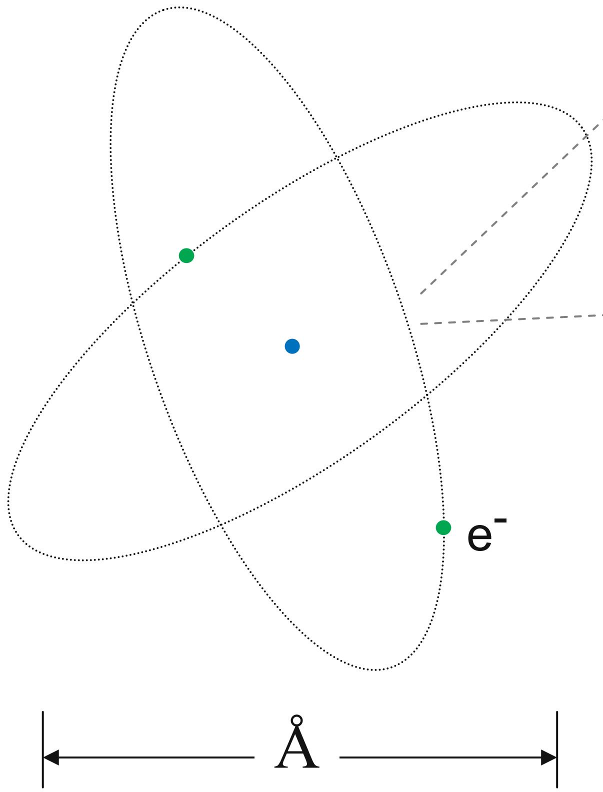
He: Argonne / GANIL

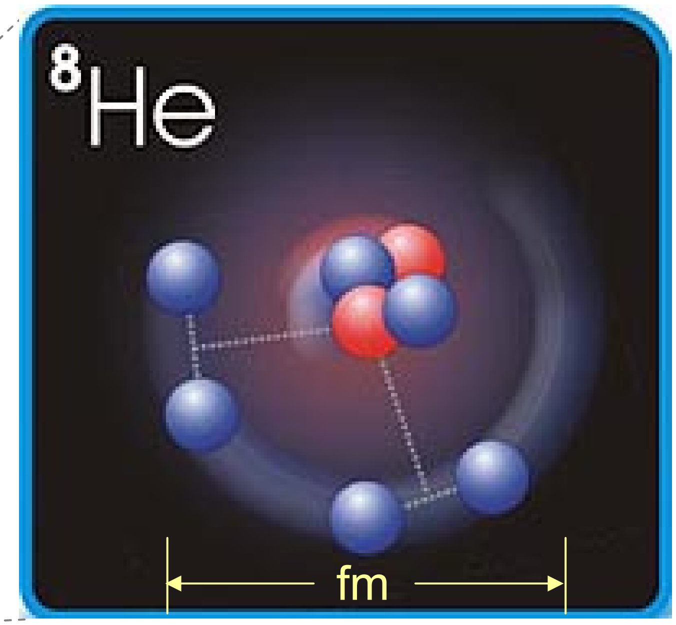
H: MPQ Munich

GFMC – Binding Energy vs. Charge Radius



Helium Atom





Ionization Energy of Helium Atom

Level 2 $^3S_1$

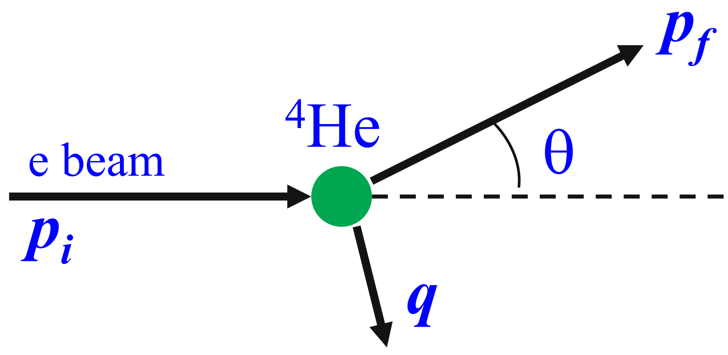
Calculation	1 152 842 741 ± 6	MHz
Experiment	1 152 842 743	MHz

Gordon Drake, Phys. Scripta (1999)

E&M Probe of Nuclear Charge Distribution

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left|F(q^2)\right|^2$$

$$F(q^2) = 1 - \frac{1}{6} q^2 < r^2 >_{charge} + \cdots$$



mean-square radius $< r^2 >= \int \rho(r) \cdot r^2 dv$

root-mean-square radius $\sqrt{< r^2 >}$

^{4}He rms charge radius = 1.681(4) fm [I. Sick *PRC 77, 041302(R) (2008)*]

Conclusions & Outlook

- Precision laser spectroscopy and atomic physics
  test precision nuclear structure calculations of light, neutron rich isotopes
  at the ~1% level

- The charge radii will improve with …
  – new He-6/8 mass measurement in Penning trap @ TRIUMF in Dec. '07
  – Improved value for He-4 (I. Sick, priv. comm.)

- Measurement at the 0.1% level (~ 10 kHz) for He are feasible …
  if warranted

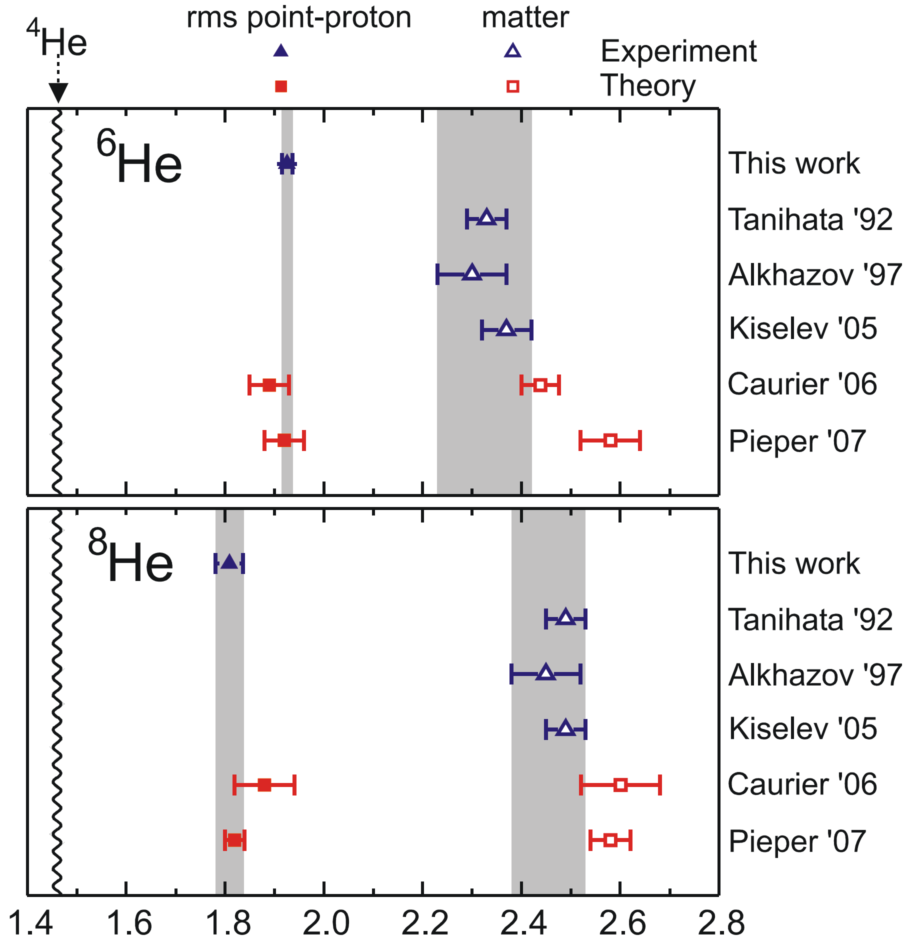
^{6}He & ^{8}He Charge Radii

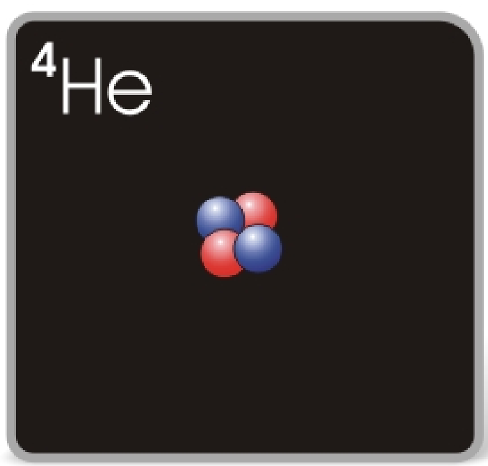
	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-0.916(95)
RMS R_{CH}, fm	**2.068(11)**	**1.929(26)**
Total Uncertainty	0.5 %	1.3 %
- Statistical	0.1 %	0.6 %
- Trap Systematics	0.3 %	0.6 %
- Mass Systematics	0.2 %	1.0 %
- He-4: 1.676(8) fm	0.3 %	0.4 %

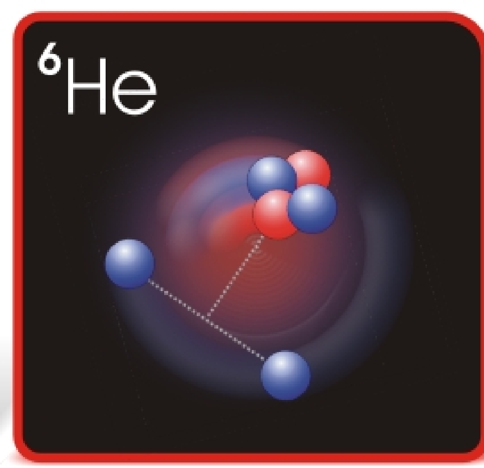
P. Mueller *et al.*, PRL ***99****, 252501 (2007)*

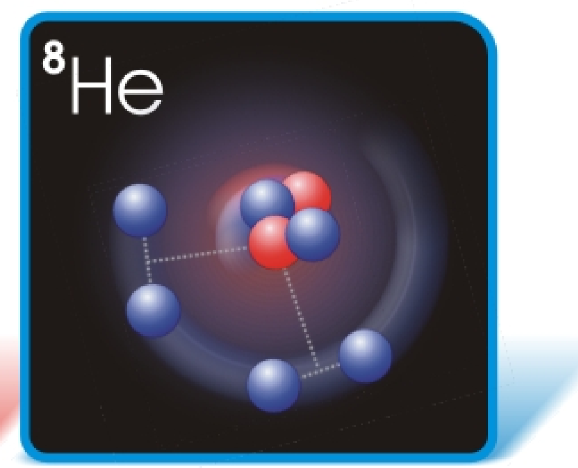
L.-B. Wang *et al., PRL 93, 142501 (2004): 2.054(14) fm for He-6*

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









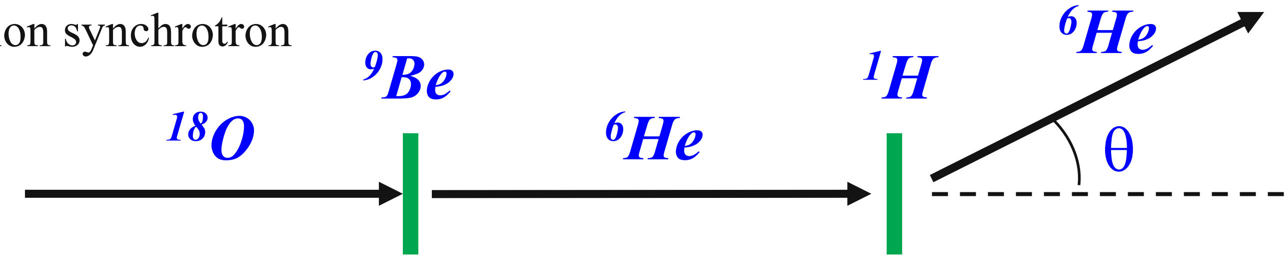
Argonne NATIONAL LABORATORY

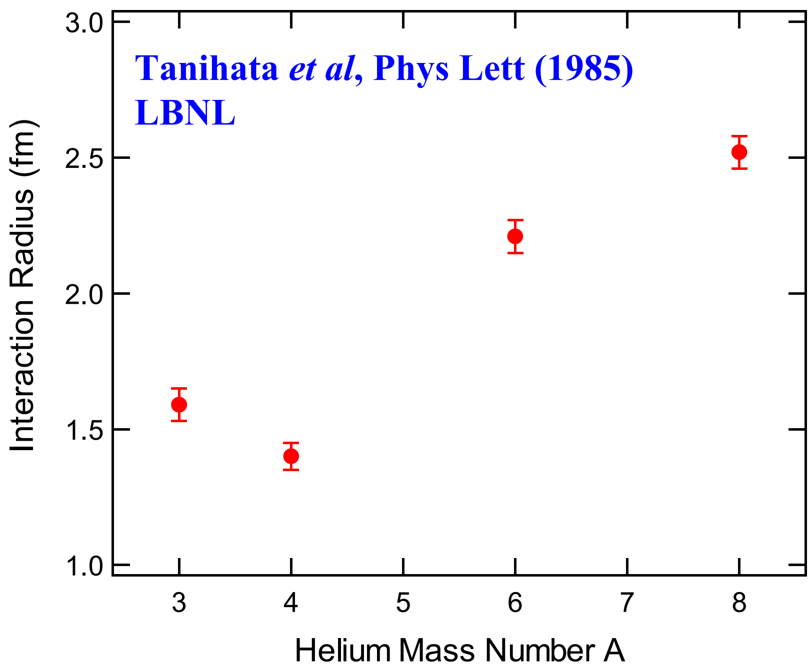
Outline

- Neutron Halo Isotopes $^{6,8}He$
- Charge Radii and Isotope Shift
- Atom Trapping of $^{6,8}He$ @ Argonne and GANIL
- ^{8}He Larger or Smaller than ^{6}He?

Hadronic Probe: Scattering of ^{6}He & ^{8}He Beams

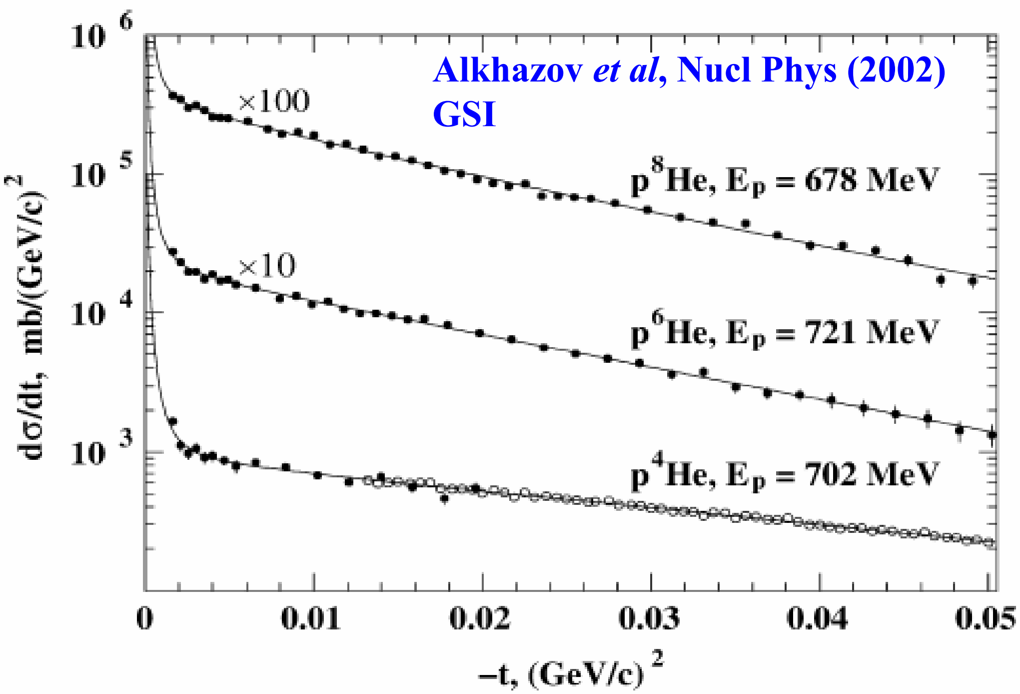
GSI heavy-ion synchrotron





Elastic and inelastic collision: He on C, B

$$\sigma_I(6He) - \sigma_I(4He) = \sigma_{-2n}(6He)$$



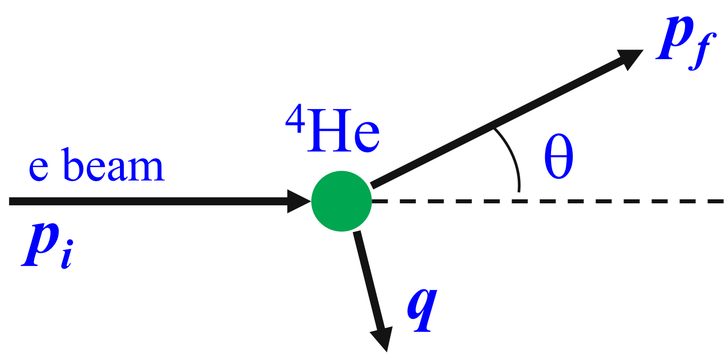
Elastic collision: He on proton, 700 MeV/u

Matter distribution, matter radii

E&M Probe of Nuclear Charge Distribution

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left|F(q^2)\right|^2$$

$$F(q^2) = 1 - \frac{1}{6} q^2 < r^2 >_{charge} + \cdots$$



mean-square radius $< r^2 > = \int \rho(r) \cdot r^2 dv$

root-mean-square radius $\sqrt{< r^2 >}$

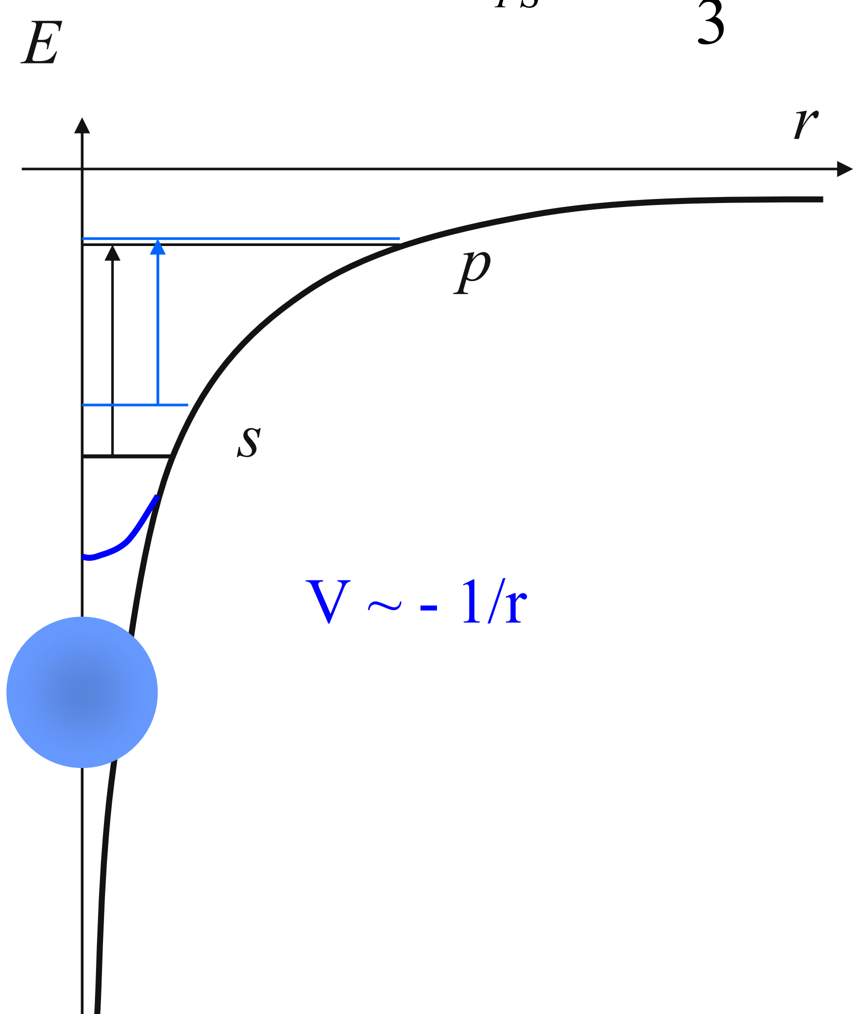
^{4}He rms charge radius = 1.676(8) fm [*I. Sick Phys Lett B (1982)*]

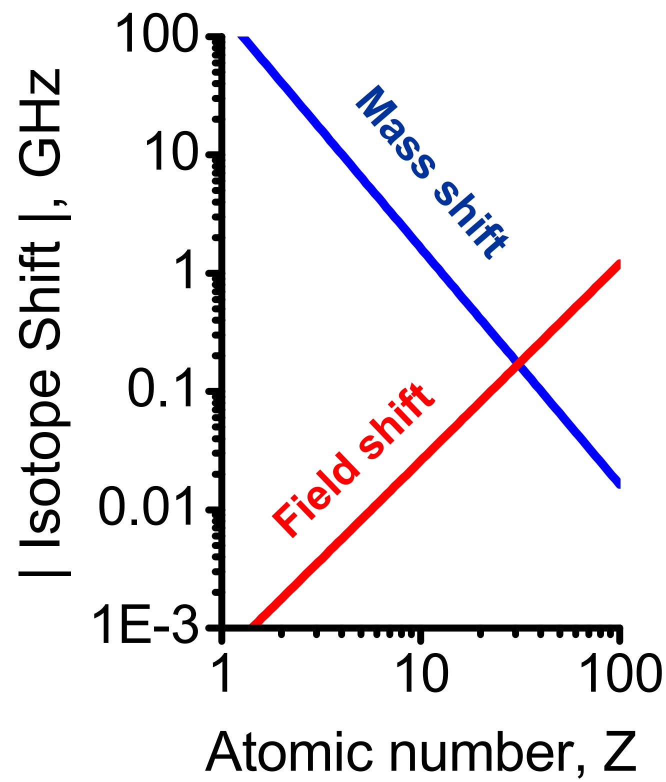
Proton rms charge radius = 0.895(18) fm [*I. Sick Phys Lett B (2003)*]

June 14th …. Trip to Brittany

Field (Volume) Shift

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

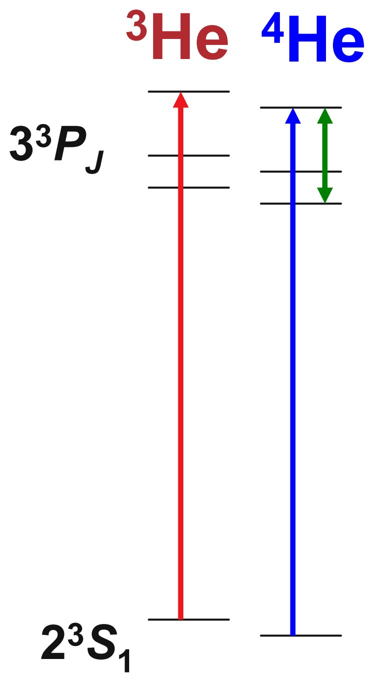




Atomic Theory of Helium

Gordon W.F. Drake (Can. J. Phys ***84****, 83 2006)*

- Non-relativistic wave functions from variational calculations
- Perturbation theory for relativistic corrections, QED, *finite nuclear mass* and *nuclear charge radius*
- QED terms “cancel” in isotope shift



Experimental confirmation

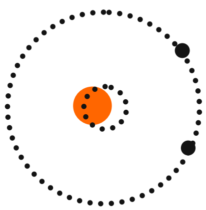
- Total transition frequency — F.S. Pavone *et al.*, PRL **73**, 42 (1994)
- ^{4}He Fine structure splitting — P. Mueller *et al.*, PRL **94**, 133001 (2005)
- ^{3}He-^{4}He Isotope shift + HFS — I. Sulai *et al., in preparation*

Atomic Isotope Shift

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

Mass shift:

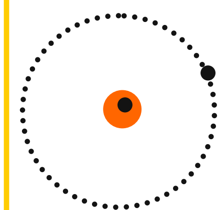
due to nuclear recoil



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

Field shift:

due to charge distribution



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