Laser Spectroscopy of Exotic Helium Isotopes

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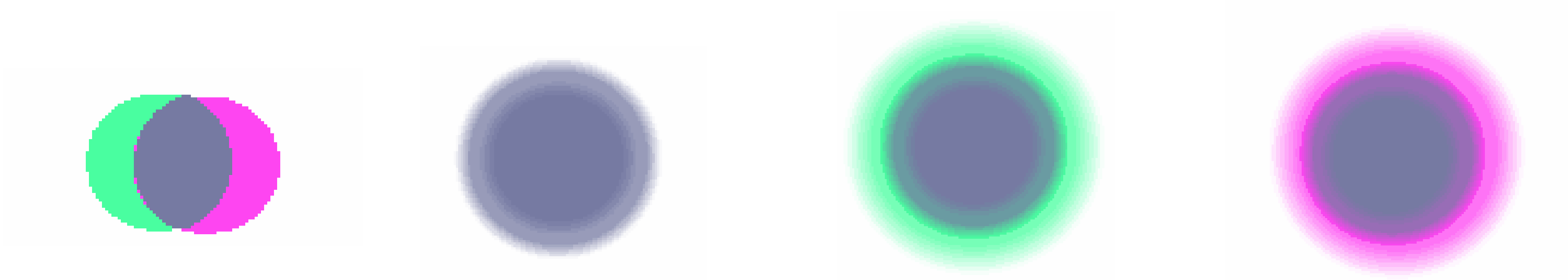
Neutron Halo

- Discovery of neutron halo change our common view of nuclear structure
- How is it discovered?

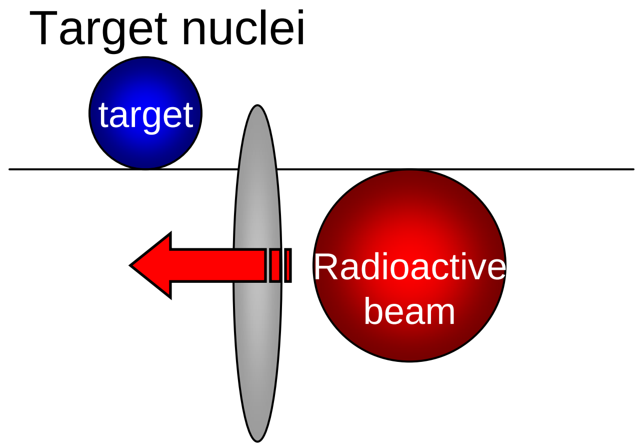


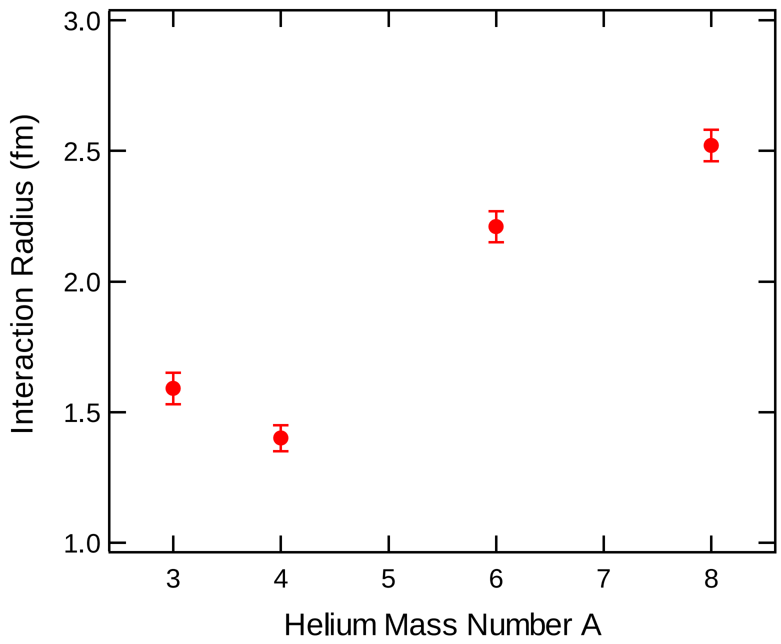
neutron proton | stable nucleus | neutron halo | proton halo

^{3,4}He, ^{6,7}Li, ^{40,48}Ca | ^{6,8}He, ^{11}Li, ^{14}Be | ^{8}B, ^{17}Ne(?)

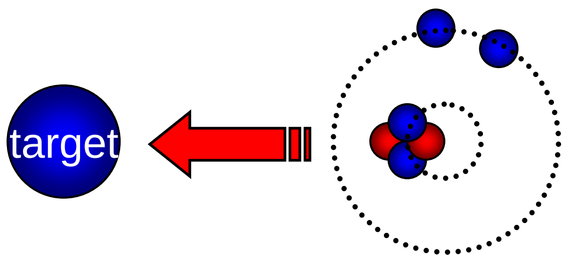
Nuclear Interaction Cross Section

- Interaction cross section
  $\sigma_I = \pi(R_{target} + R_{beam})^2$
- First observation of "halo nuclei" by Tanihata, 1985

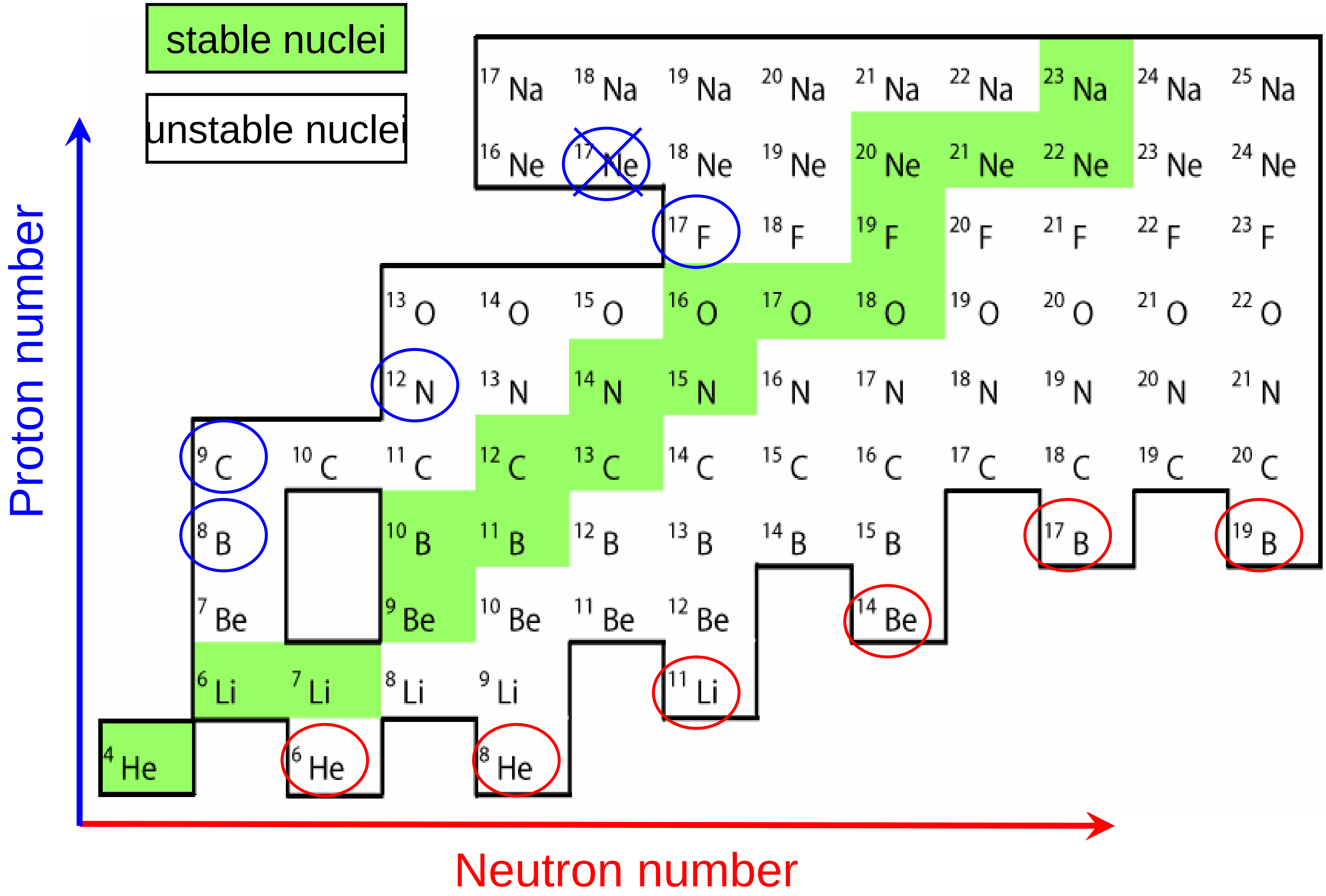




$\sigma_I(^6He) \sim \sigma_I(^4He) + \sigma_{-2n}(^6He)$

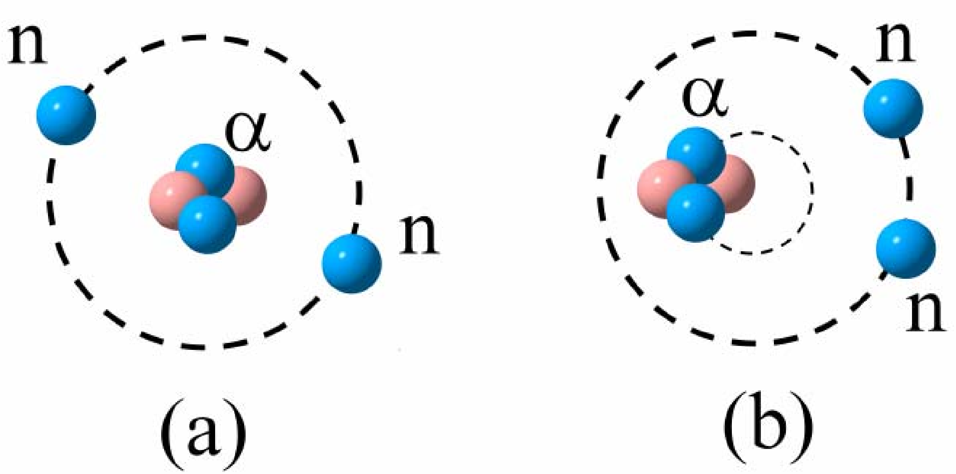


Nuclear Chart



Neutron-rich ^{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



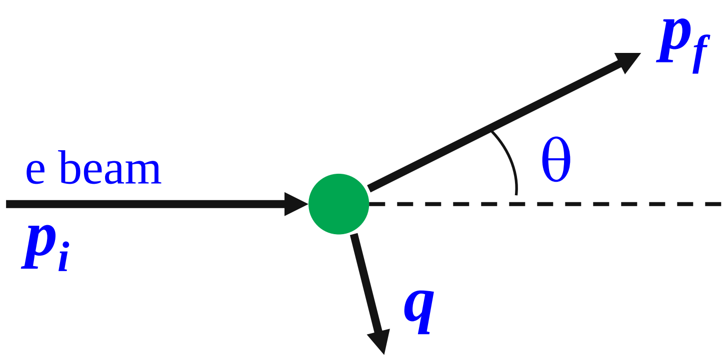
- Charge radius probes "valence neutron correlation"

Methods of Measuring Charge Radii

- Electron scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{Z^2\alpha^2(\hbar c)^2}{4E^2\sin^4\frac{\theta}{2}}$$

- Nuclei with finite size:



$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} * \cos^2\frac{\theta}{2} * \left|G_E(q^2)\right|^2$$

$$< r^2 >_{charge} = -6\hbar^2 \frac{dG_E(q^2)}{dq^2}\Big|_{q^2=0}$$

- R=1.21×A$^{1/3}$ fm for non-deformed nuclei
- Can NOT apply to unstable (short-lived) nuclei

Neutron-rich ^{6}He and ^{8}He

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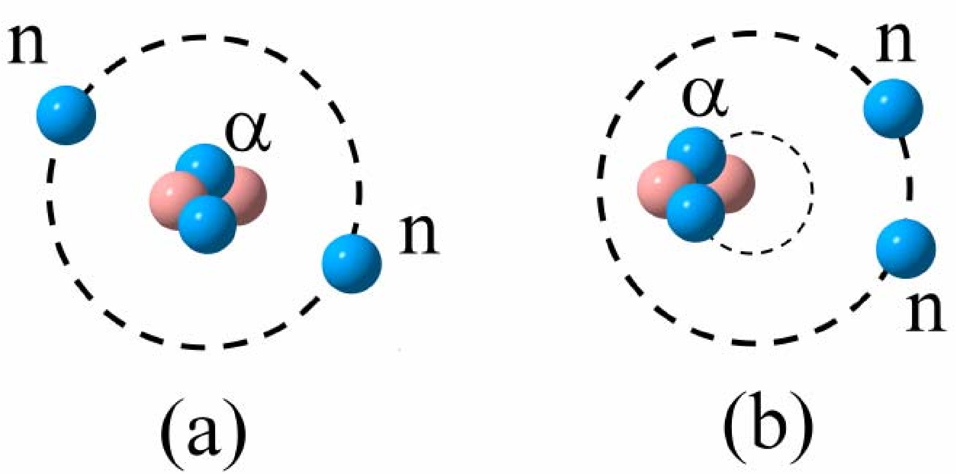
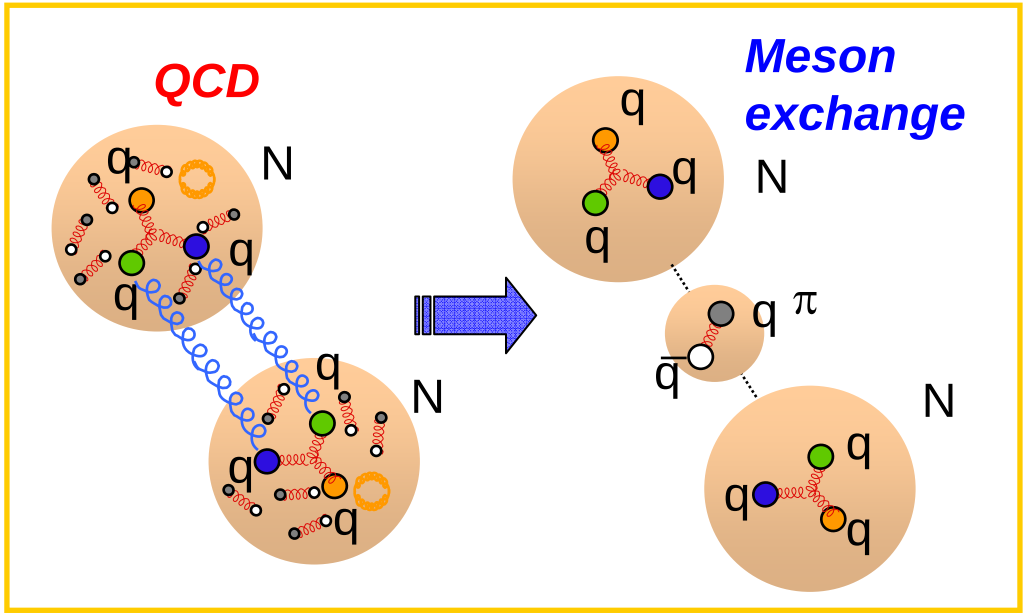


- Charge radius probes "valence neutron correlation"

Nuclear Force

- Fundamental theory QCD not calculable in low-energy regime
- Modern nuclear models use "effective potential"



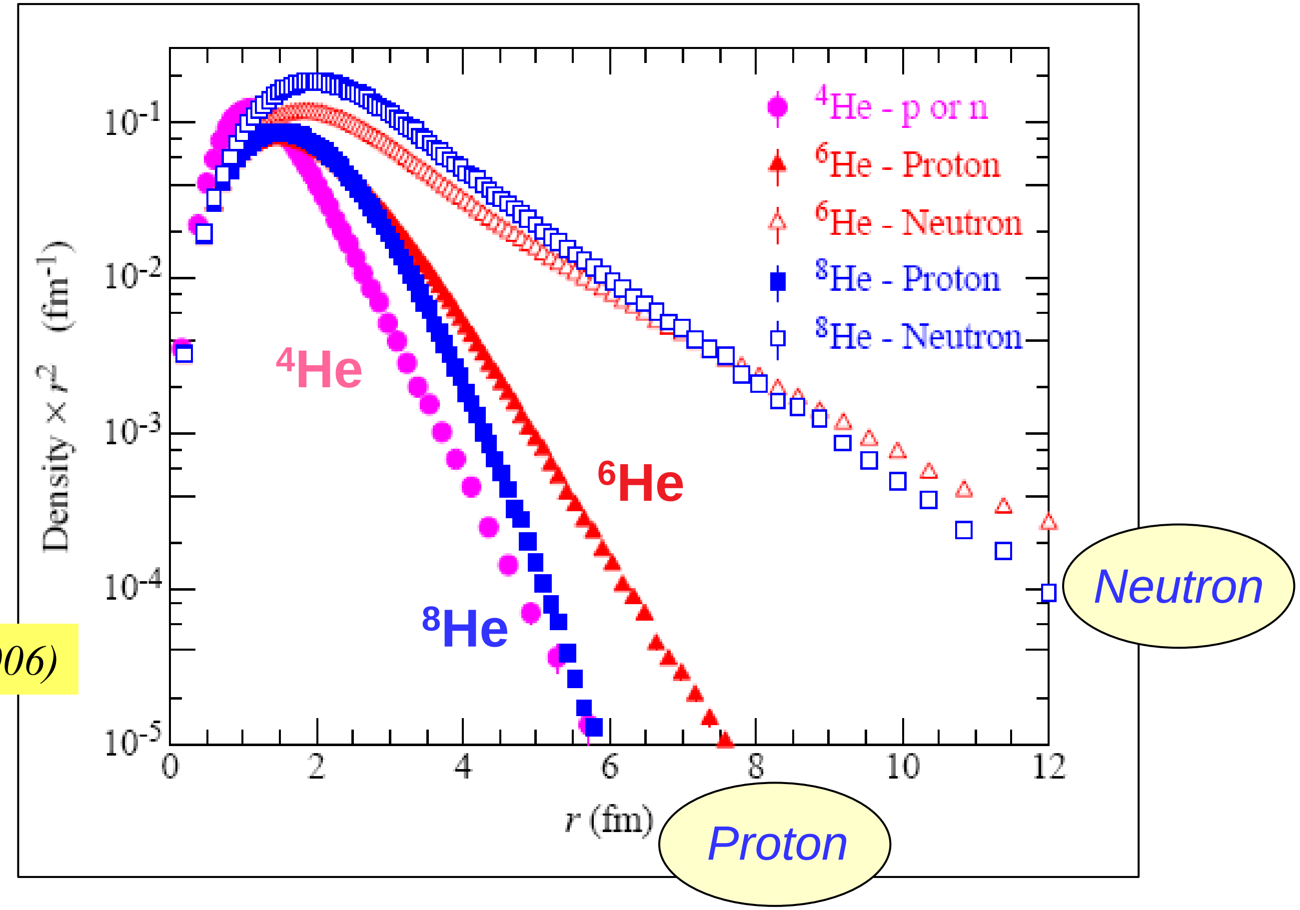
- Long range (~2 fm) attraction: one-pion exchange
- Intermediate range (~1 fm) attraction: two-pion exchange
- Short range repulsion: hard-core effect, quarks are fermions

Neutron Halo Nuclei 6He and 8He

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

Quantum Monte Carlo calculation

Pieper & Wiringa (2006)



Charge Radius of Helium Isotopes

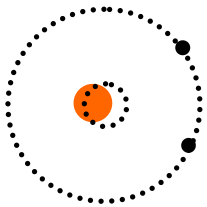
- Charge radii ^{4}He < ^{6}He ~ ^{8}He
- Electron scattering, not possible for ^{6}He, ^{8}He
- Elastic proton scattering involves strong interaction, cannot separate proton and neutron
- No "Poisson equation" for QCD to relate strong force to nucleon distribution
- Atomic isotope shift, measure the difference

	^{3}He	^{4}He	^{6}He	^{8}He
Theory	1.954(5)	1.662(5)	2.05(1)	1.99(1)
Electron scattering	1.96(3)	1.676(8)		
Proton scattering		1.79(4)	2.09(9) 1.95(8)	1.80(7) 1.56(6)
Atomic Isotope shift	1.964(1)	1.673(1)	?	?

Atomic Isotope Shift

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

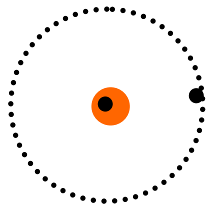
Mass shift: due to nucleus recoil



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

Nuclear mass precisely known

Field shift: due to nuclear size

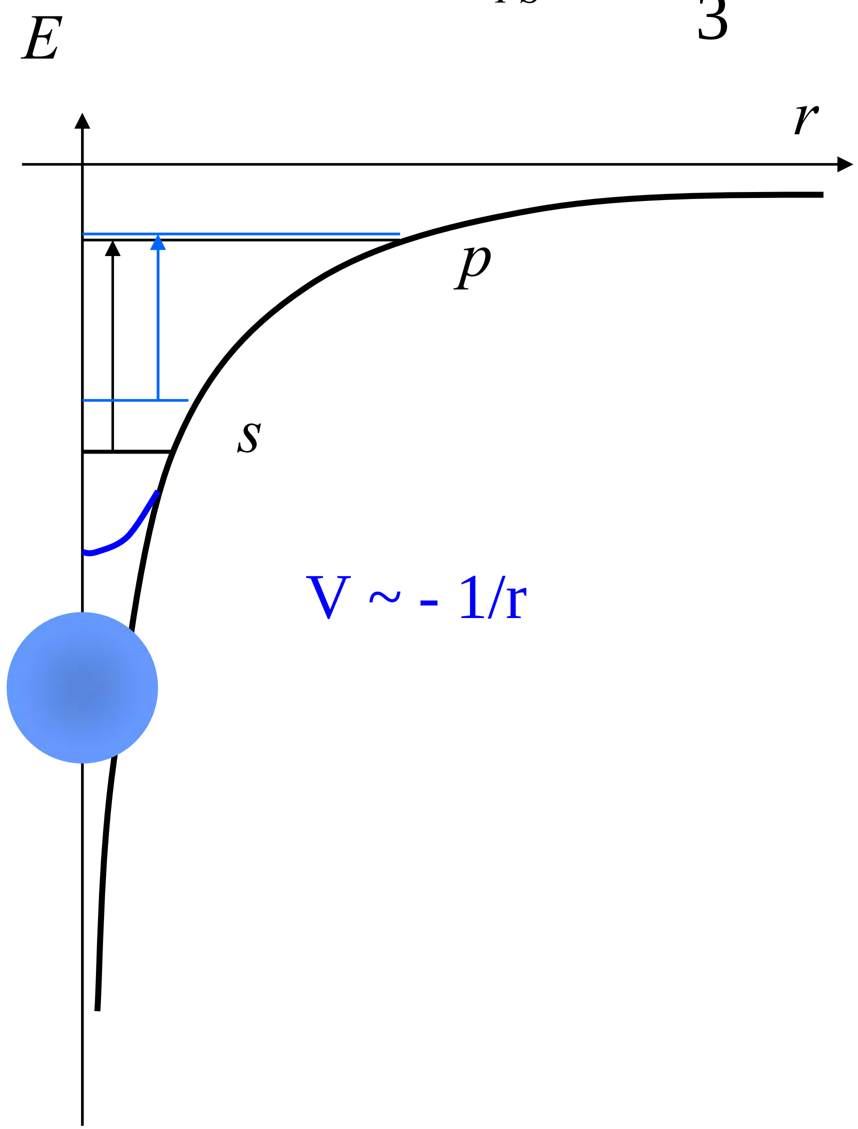


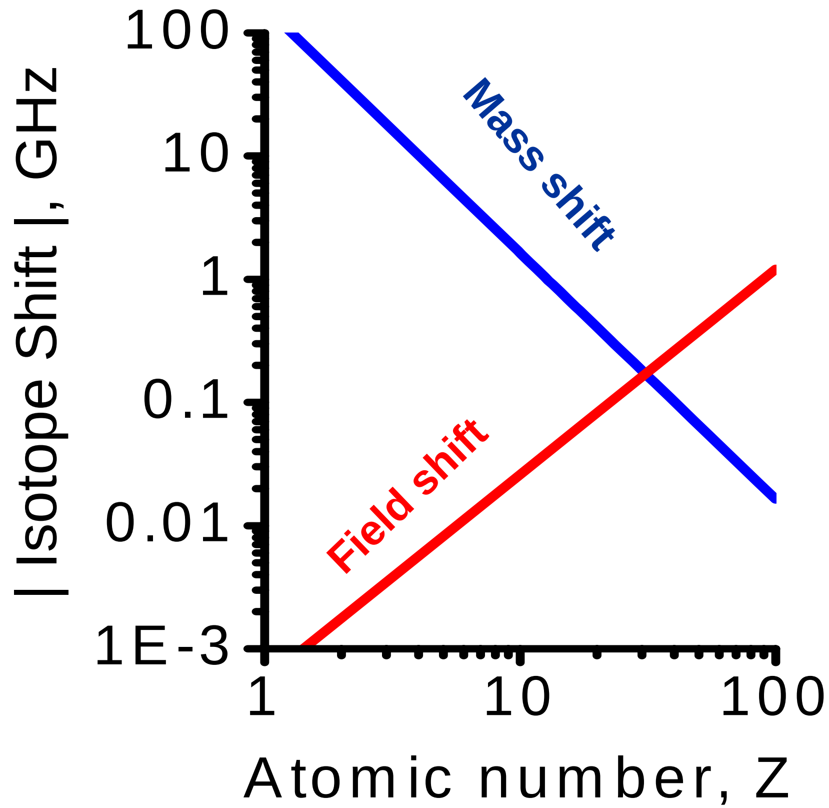
$$\delta\nu_{FS} \propto [\Psi(0)]^2 \times \delta\langle r_c^2 \rangle$$

Atomic structure $\Psi(0)$ calculable,
H, He, Li.

Field (Volume) Shift

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

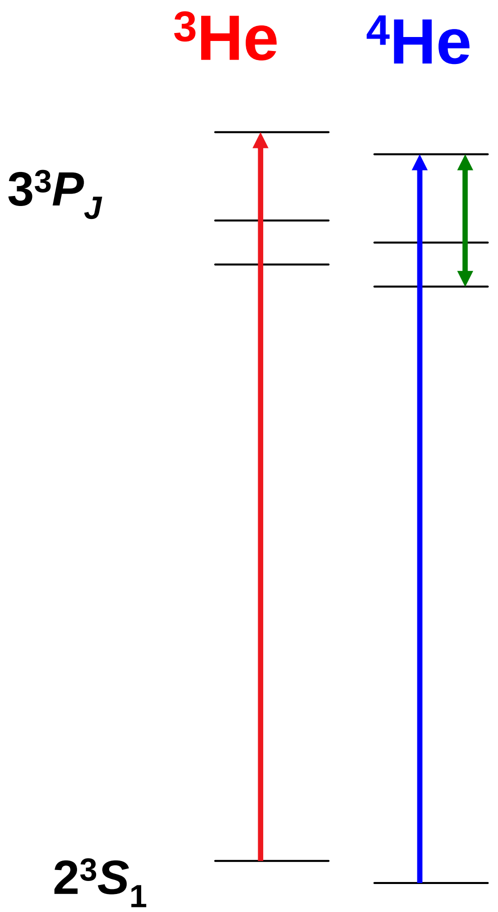




Atomic Theory of Helium

*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



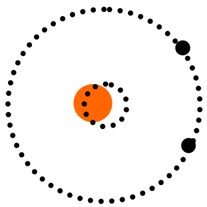
Experimental confirmation

- Total transition frequency
- ^{4}He Fine structure splitting
- ^{3}He-^{4}He Isotope shift + HFS

Atomic Isotope Shift

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

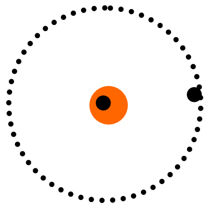
Mass shift: due to nucleus recoil



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

Nuclear mass precisely known

Field shift: due to nuclear size



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

Atomic structure $\Psi(0)$ calculable, H, He, Li.

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

^{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

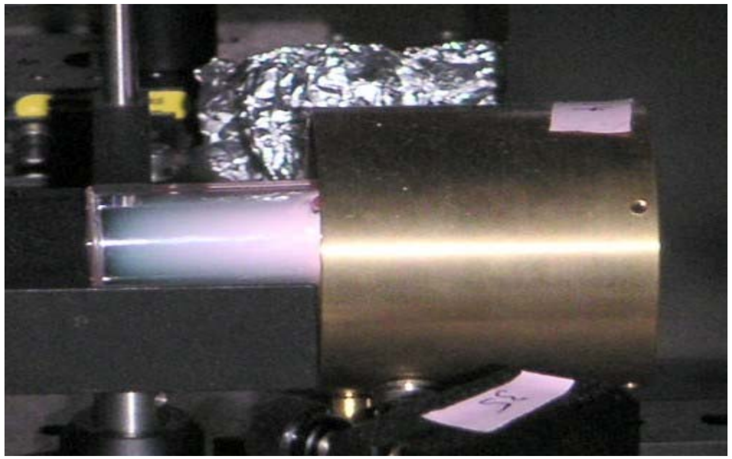
^{8}He - ^{4}He : $\delta\nu_{8,4}$ = 64702.410(70) MHz + 1.008 ($\langle r^2\rangle_{He4}$ - $\langle r^2\rangle_{He8}$) MHz/fm^2

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

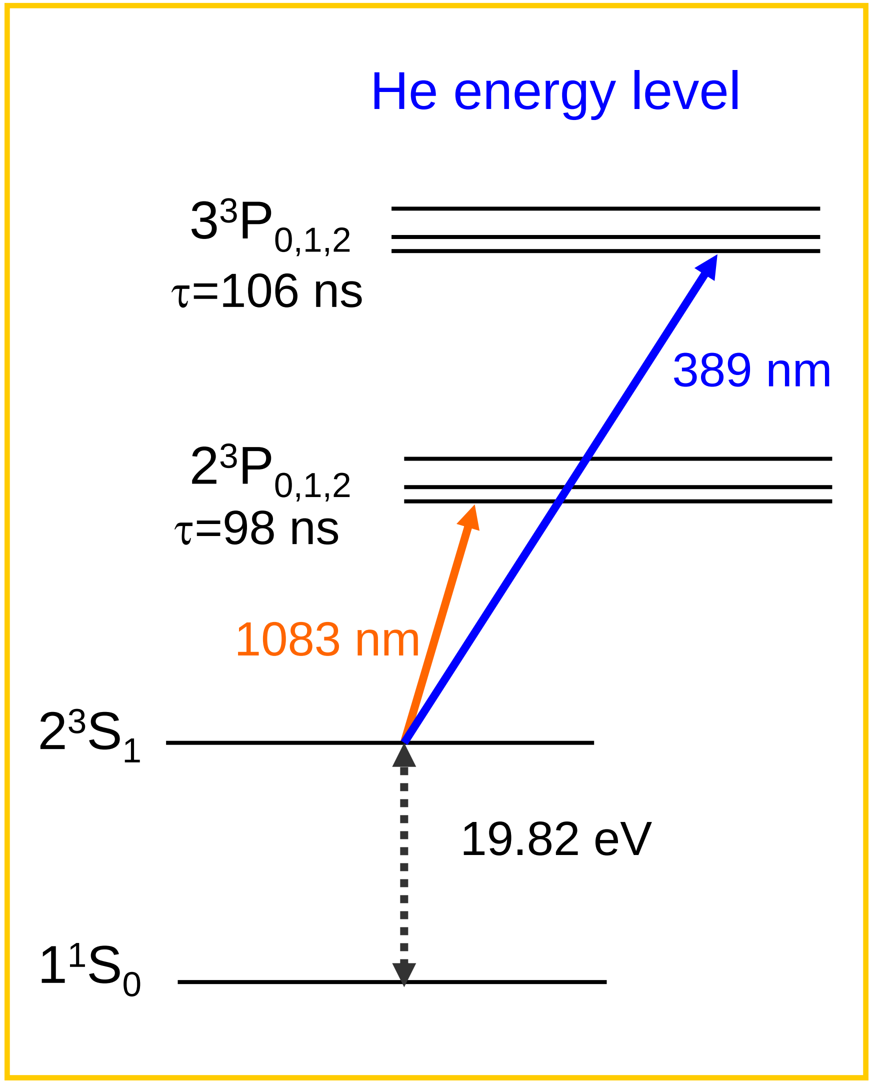
100 kHz error in IS ←→ ~ 1% error in radius

Helium Energy Level

- For noble gas atom, first excited state too high for laser excitation, (VUV)
- Exp. on metastable state
- RF discharge by electron collision



A glow discharge He gas cell



Spectroscopy of ^{6}He

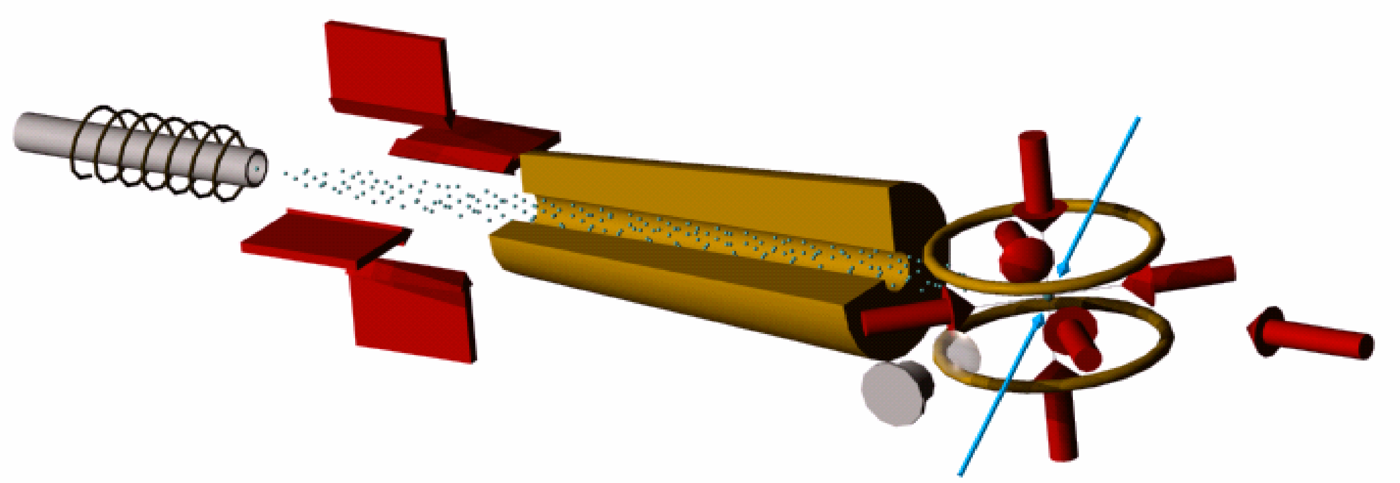
Technical challenges:

- ✗ Short lifetime, small samples (~ 10^6 atom/s available)
- ✗ Difficult spectroscopy (Metastable efficiency ~ 10^{-5})
- ✗ Precision requirement (100kHz = Doppler shift @ 0.04 m/s)

Solution:

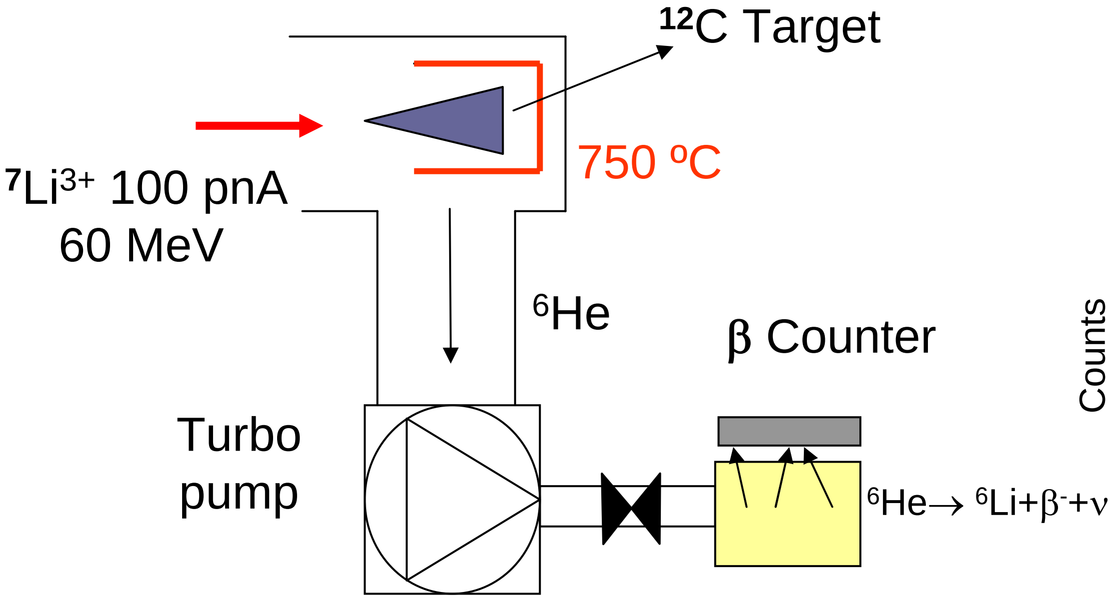
Spectroscopy with cooled atoms in a magneto-optical trap

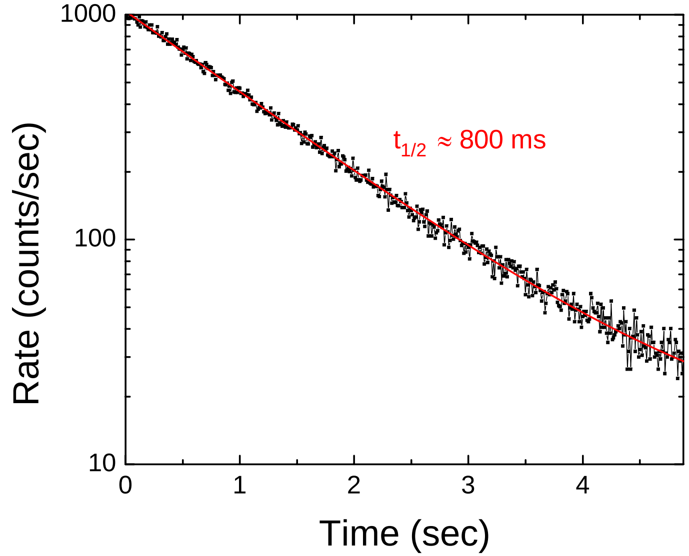
- ✓ High resolution: cold atoms, Doppler width largely reduced
- ✓ High sensitivity: capable of detecting a single atom

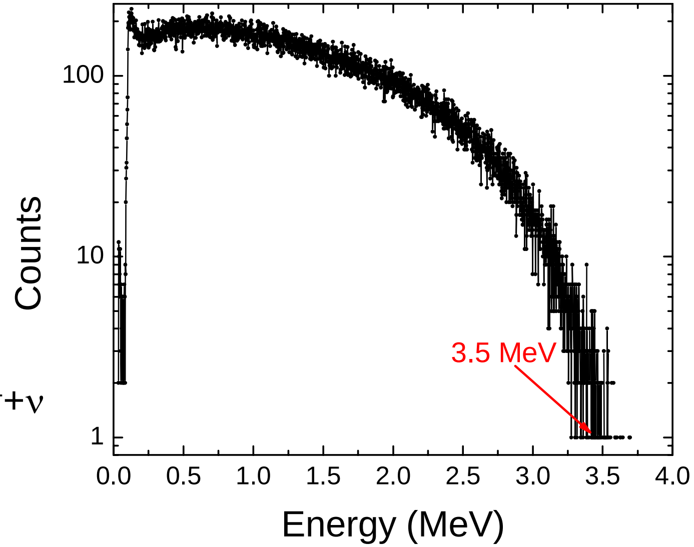


^{6}He Production

- Stripping reaction at ATLAS: $^{12}C(^{7}Li,^{6}He)^{13}N$
- ^{6}He extraction rate ~ 3×10^{6} /s

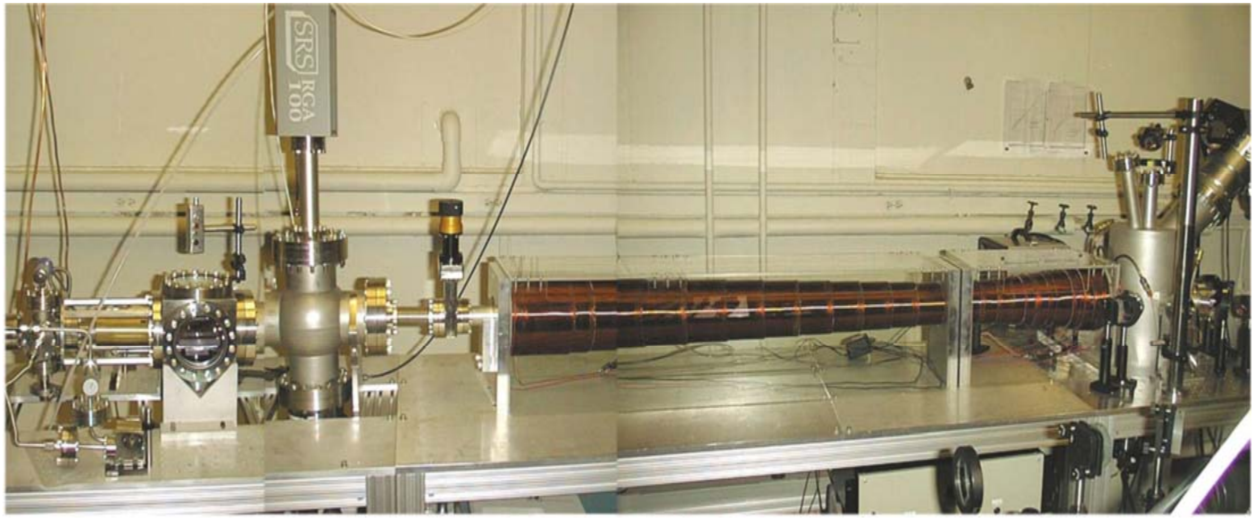




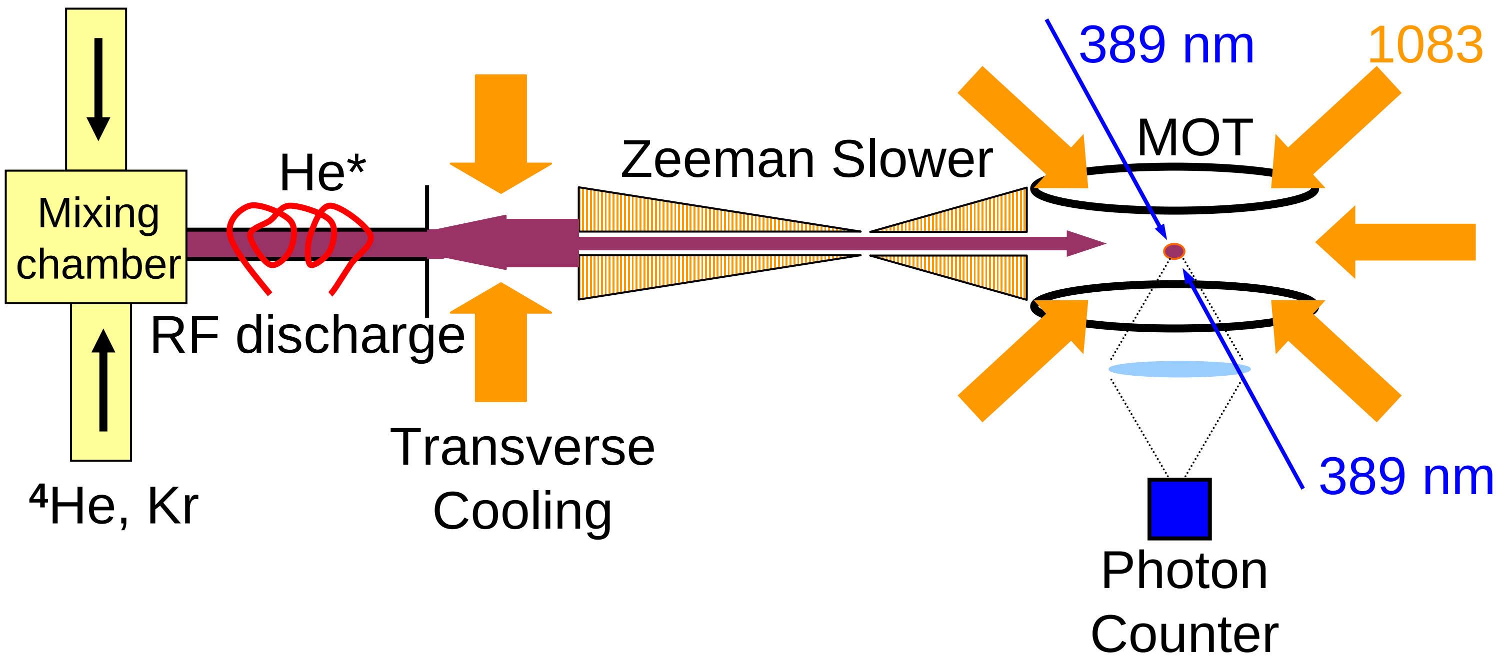


Experimental Setup

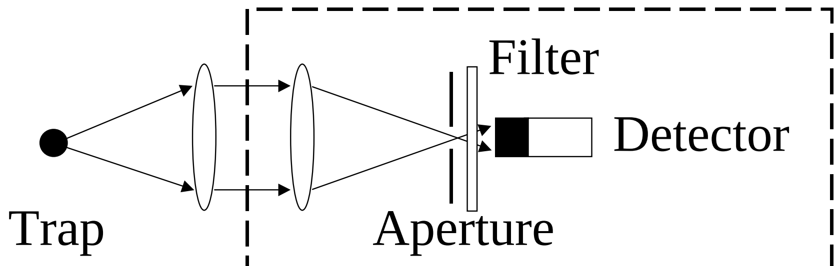
^{6}He from ATLAS
Transport time ~ 1 sec

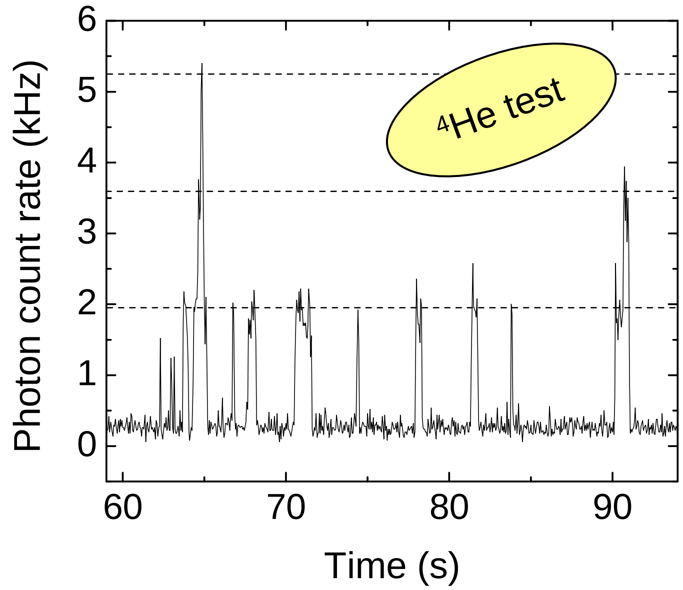


^{6}He

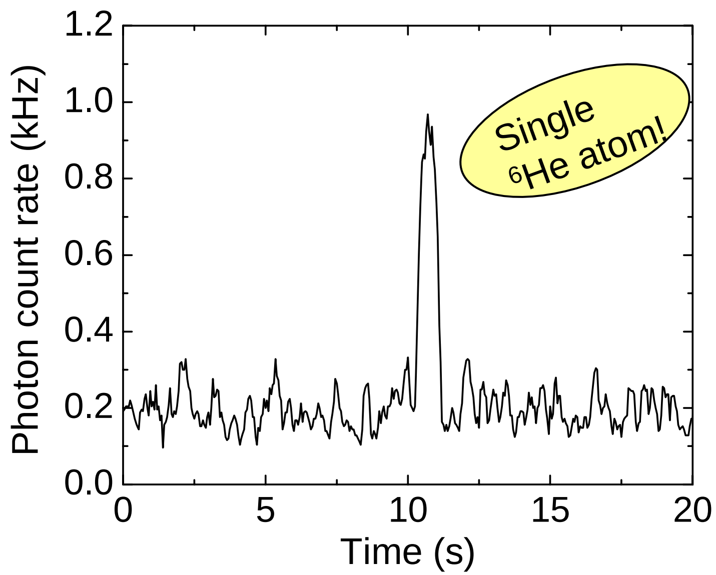


Single ^{6}He Atom Detection





- Capture efficiency ~ 2×10^{-8}
  single atom detection necessary!
- Imaging system and reducing background
- ^{6}He capture rate ~ 150 per hour

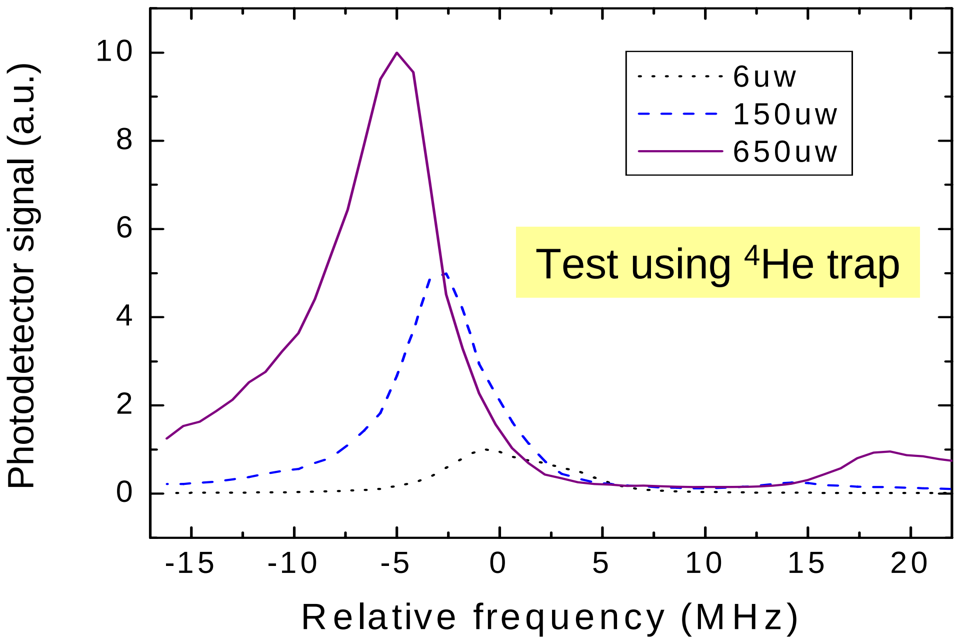


Spectroscopy of Trapped Atoms

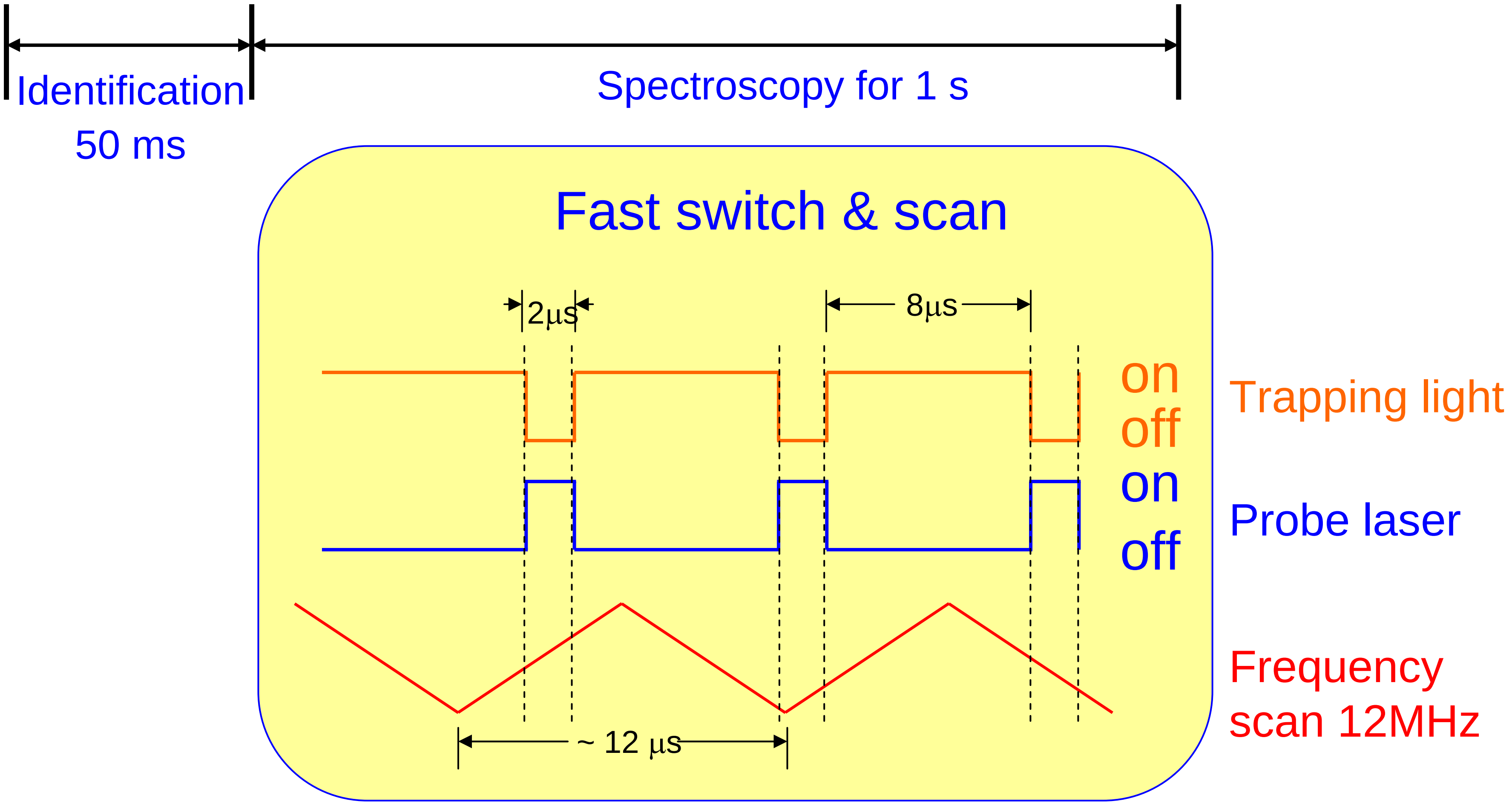
- Light shift and Zeeman shift
- Heating and cooling effect: asymmetric line shape

  → single γ recoil: 440 kHz for ^{6}He, 330 kHz for ^{8}He
- Probing laser power must be very low!

M. Zhu, C. Oates, J. Hall, Opt. Lett., **18**,1186 (1993)



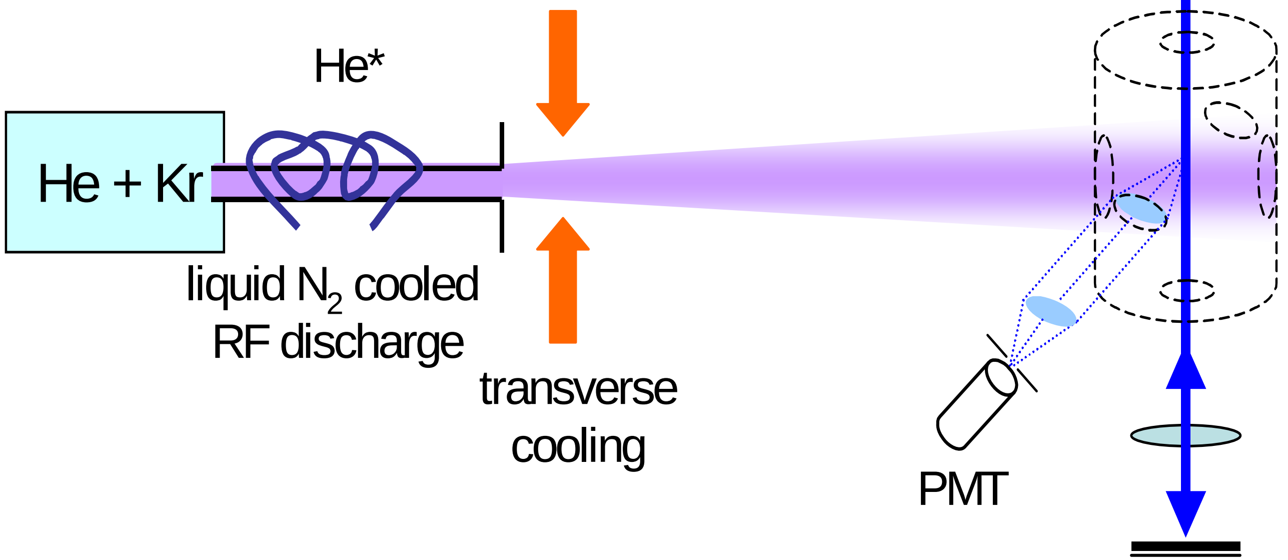
Frequency Scanning Strategy

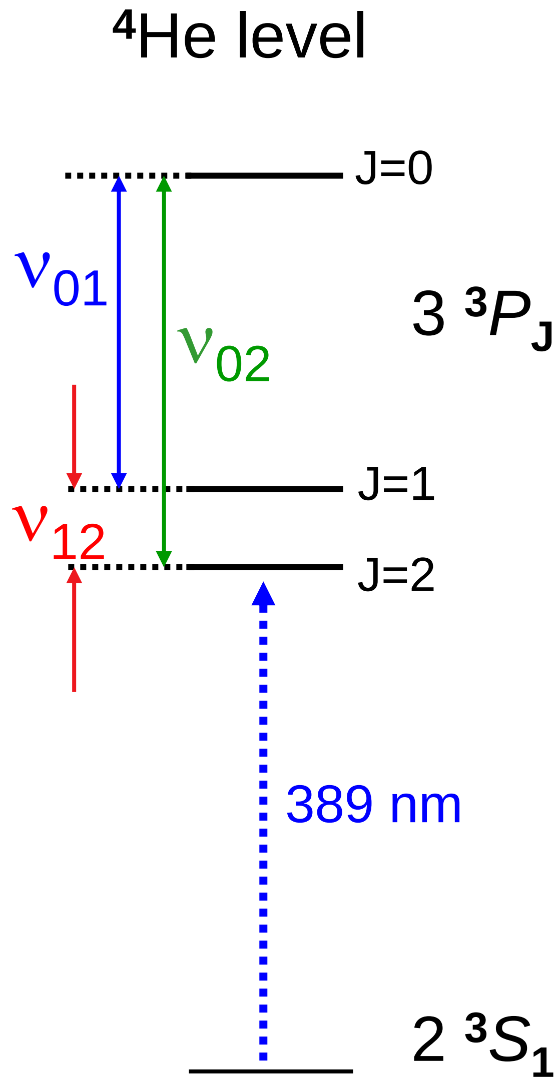


- Two frequency-detuning trap (hot and cold)
- Balance between the two probe beams

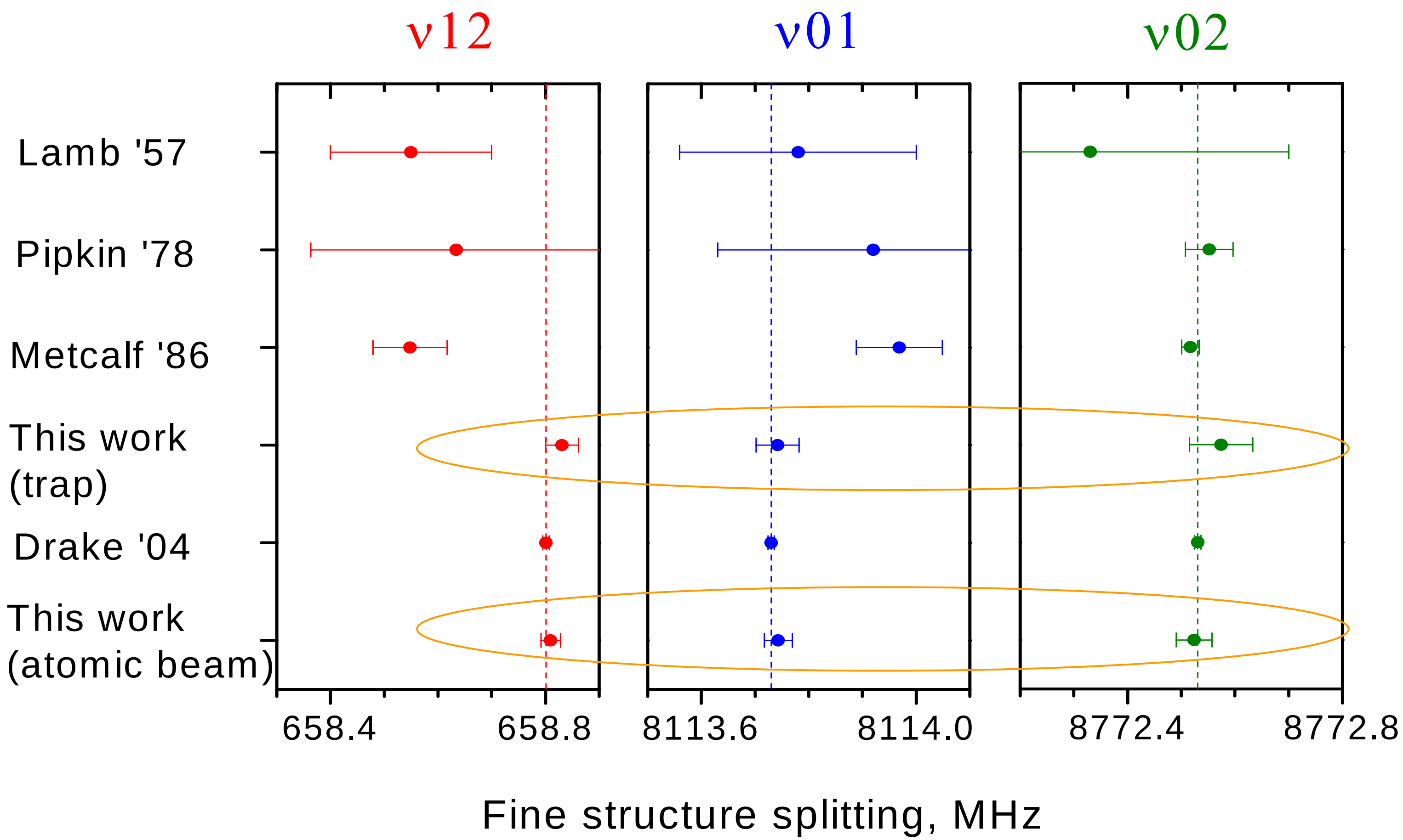
Systematic Effect Study

- ^{4}He fine structure splitting as a test
- Atomic Beam Experiment
- Very different systematic effect





^{4}He Fine Structure



References

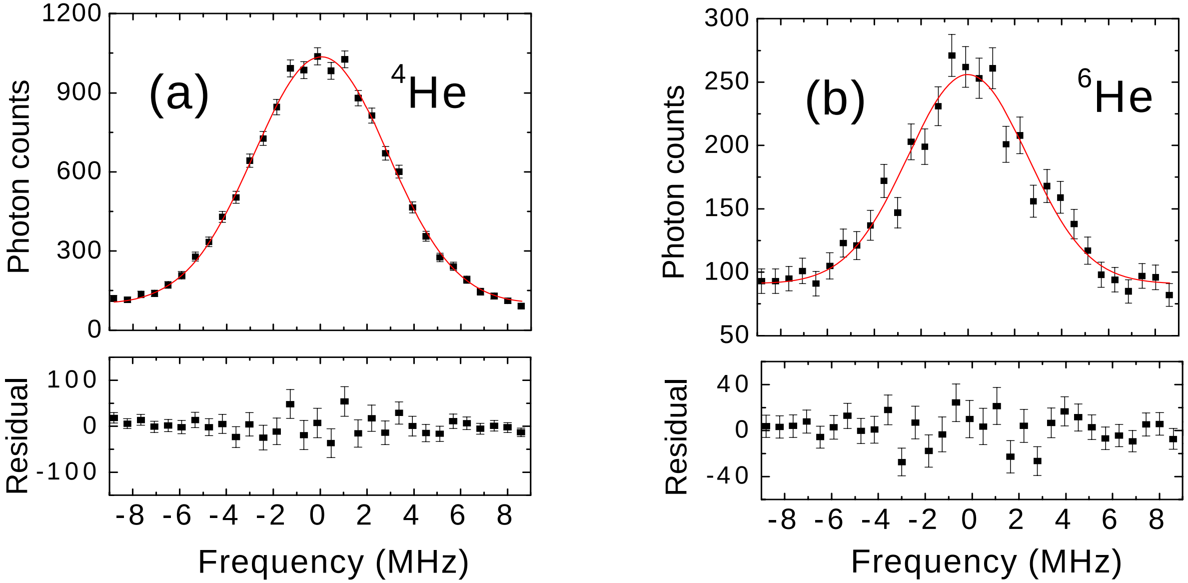
Lamb ‘57: *I. Wieder and W.E. Lamb, Jr., Phys. Rev. 107, 125 (1957)*

Pipkin ‘78: *P. Kramer and F. Pipkin, Phys. Rev. A18, 212 (1978)*

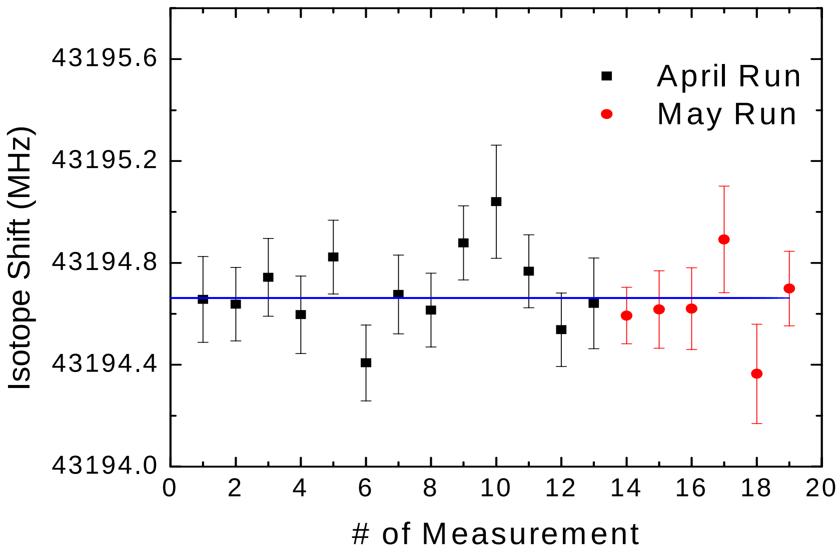
Metcalf ‘86: *D.-H. Yang, P. McNicholl, and H. Metcalf, Phys. Rev. A33, 1725 (1986)*

This work: *P. Mueller, L.-B. Wang, G.W.F. Drake, K. Bailey, R.J. Holt, Z.-T. Lu, and T.P. O’Connor, Phys. Rev. Lett. 94, 133001(2005)*

^{6}He Single-Atom Spectroscopy



~150 ^{6}He atoms in one hour



IS = 43 194.772(56) MHz

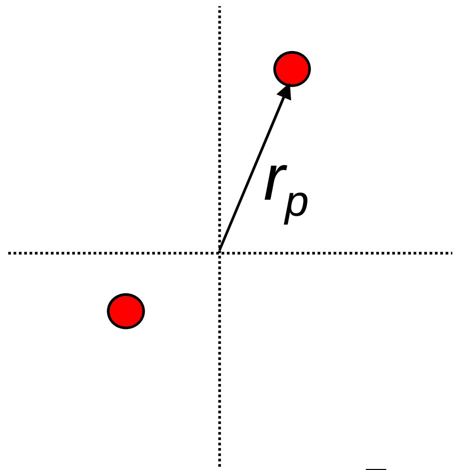
$<r_c^2>^{1/2}$ = 2.054(14) fm (0.7%)

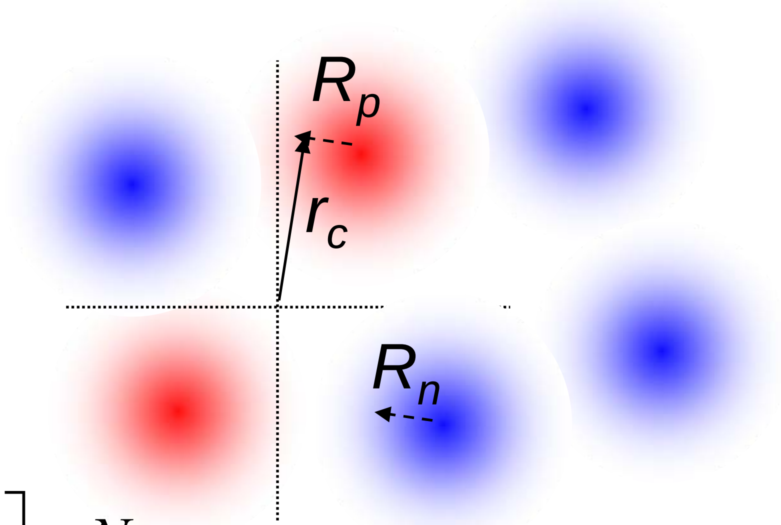
Phys. Rev. Lett. **93**, 142501 (2004)

Point Proton Radius

Theory:
ms point-proton radius $\langle r_p^2 \rangle$

Experiment:
ms charge radius $\langle r_c^2 \rangle$





$$\langle r_c^2 \rangle = \langle r_p^2 \rangle + \left[\langle R_p^2 \rangle + \frac{3}{4}\frac{1}{M_p^2} \right] + \frac{N}{Z} \langle R_n^2 \rangle$$

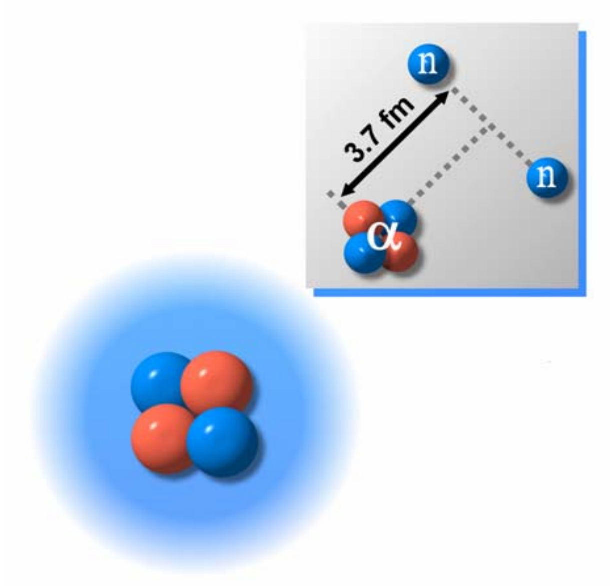
Experimental mean square charge radii:

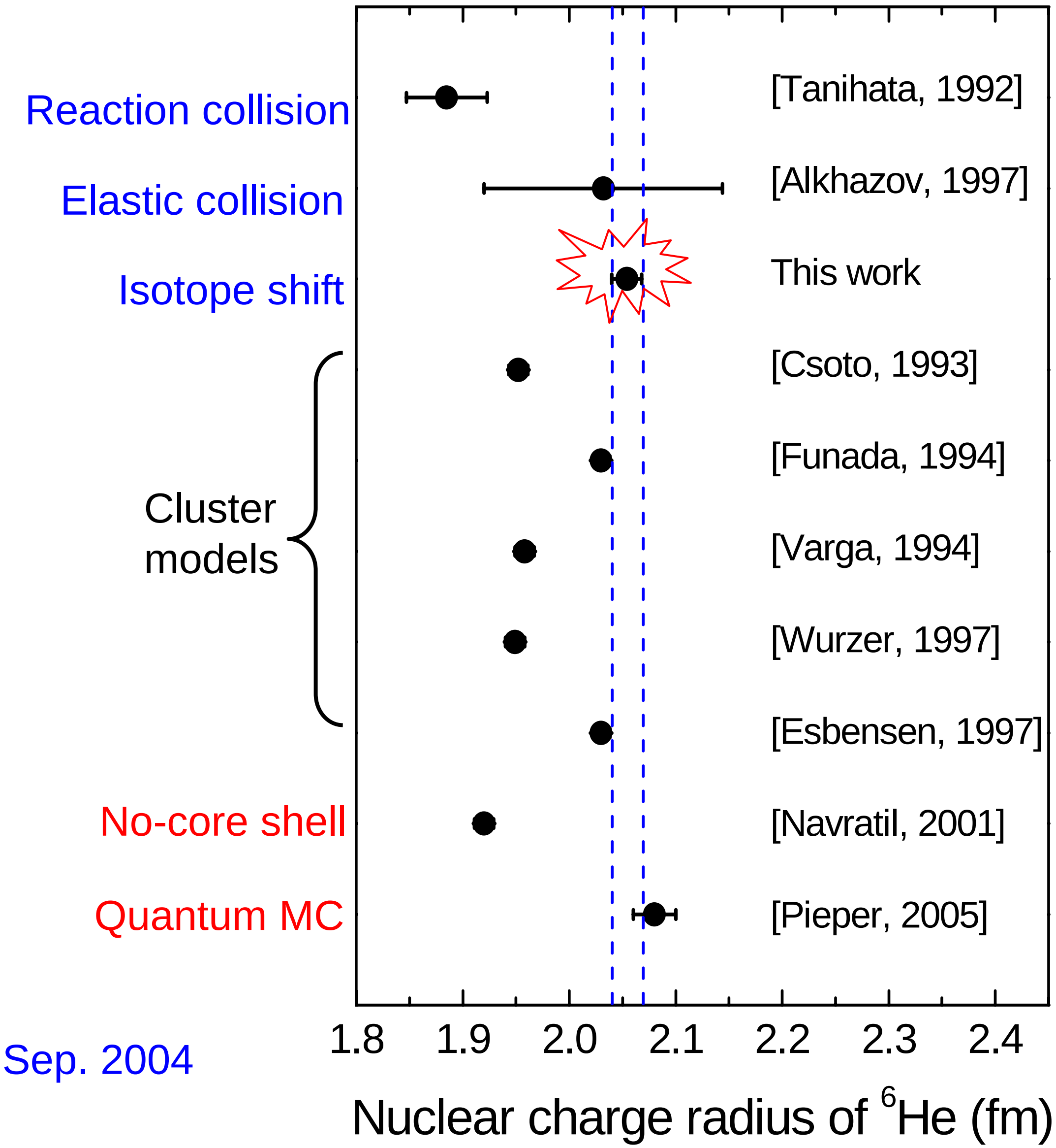
Proton $\langle R_p^2 \rangle^{1/2}$ = 0.895(18) fm, [Sick, 2003]

Neutron $\langle R_n^2 \rangle$ = –0.120(5) fm^2, [Kopecky, 1997]

Comparison with Theories

- Neutron-halo structure confirmed
- Underestimate in cluster models
- Disagree with nuclear collision





AIP Physics News Update, # 702-3, Sep. 2004

Where to find ^{8}He?

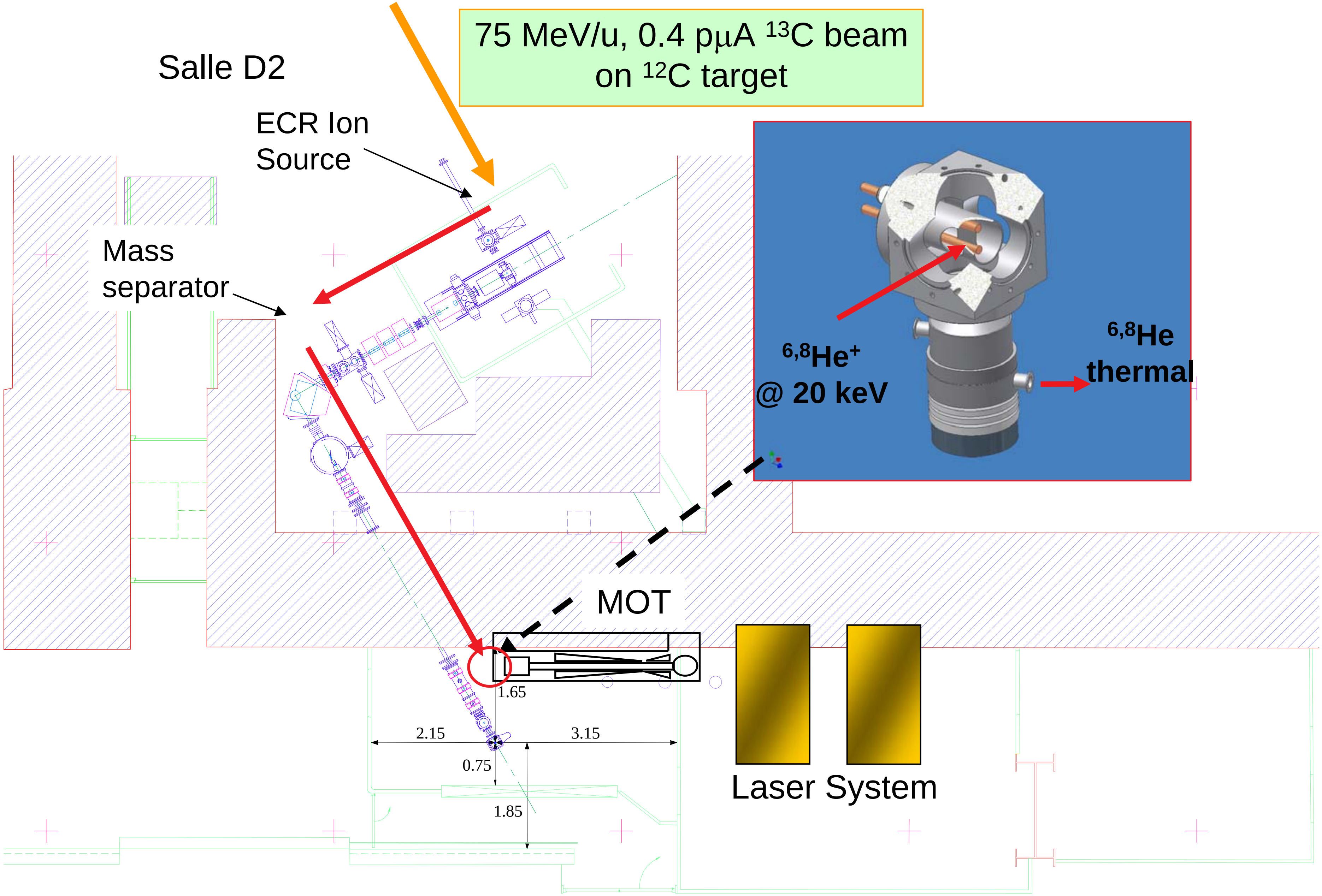
GANIL

Caen, France

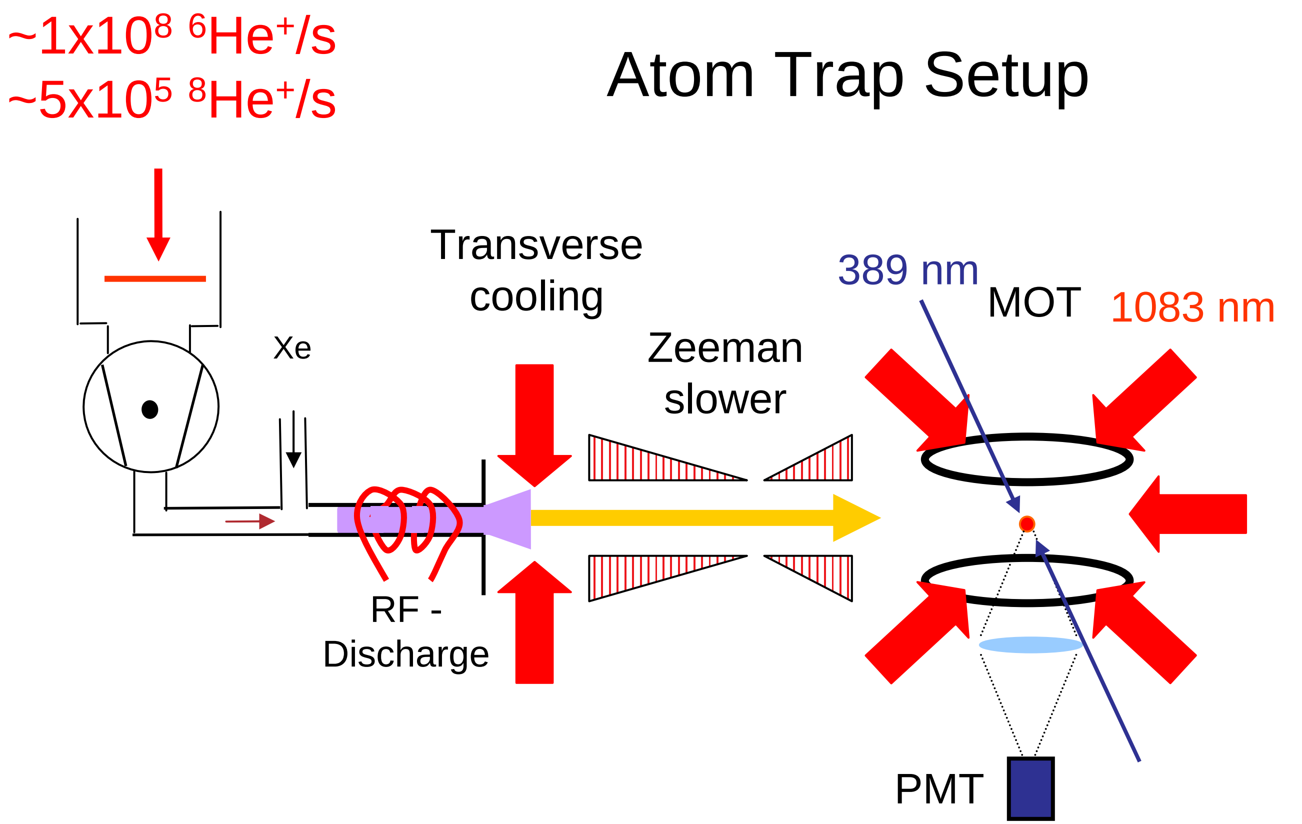
Other possible sites:

TRIUMF in Canada
ISOLDE @ CERN
NSCL @ MSU

^{8}He @ GANIL


75 MeV/u, 0.4 pμA ¹³C beam
on ¹²C target
Salle D2
ECR Ion
Source
Mass
separator
6,8He+
@ 20 keV
6,8He
thermal
MOT
1.65
2.15
3.15
0.75
1.85
Laser System

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

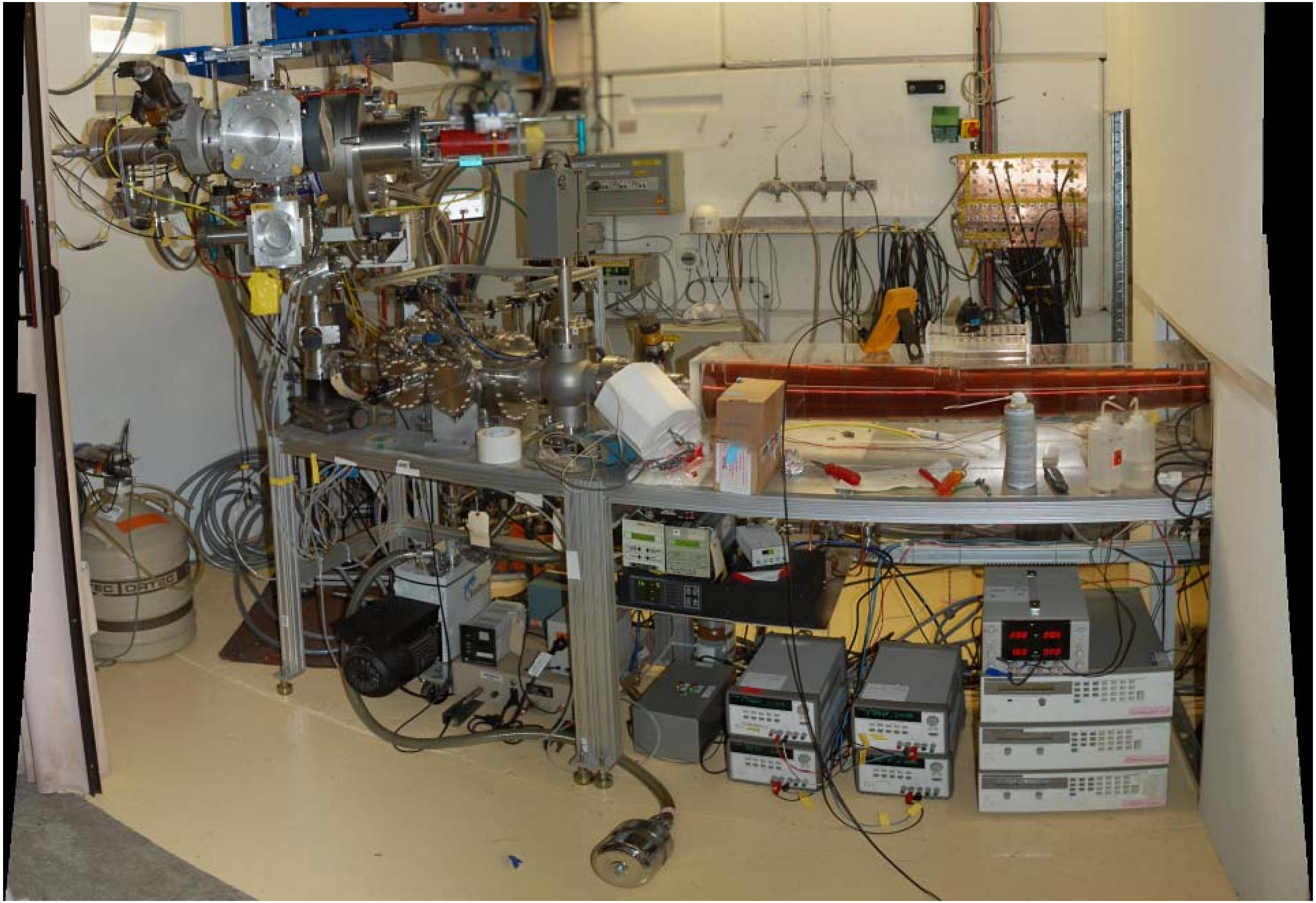


Source
~5x10^{7} He-6/s,
~1x10^{5} He-8/s

Capture efficiency
1x10^{-7}

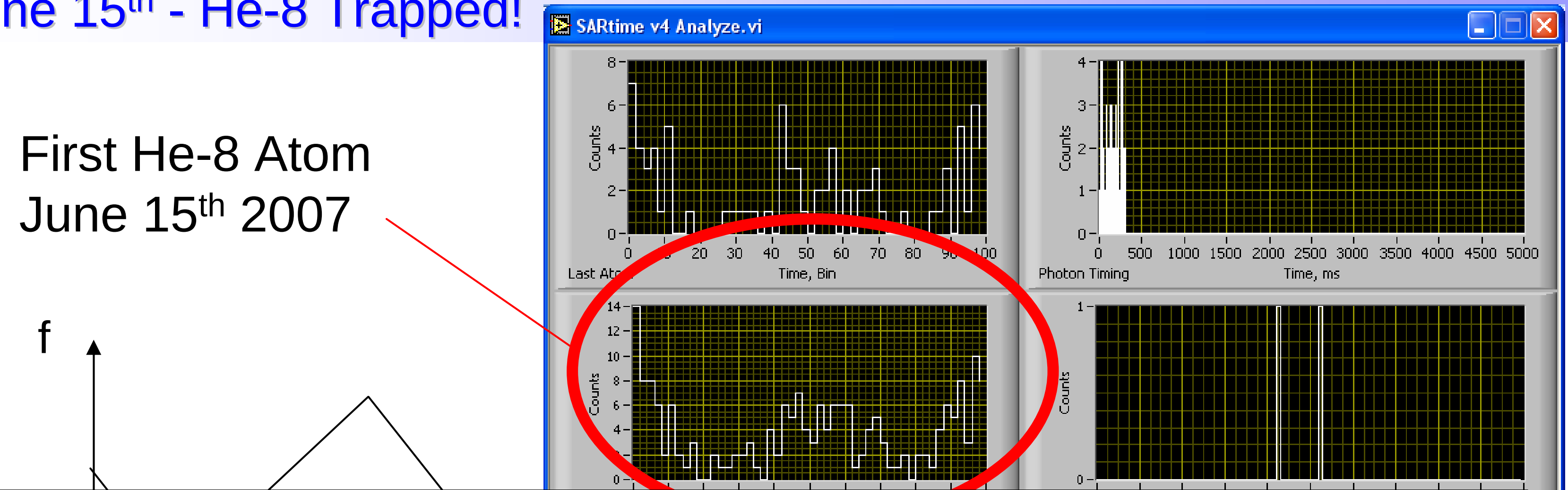
Trap
~5 He-6/s,
~30 He-8/hr

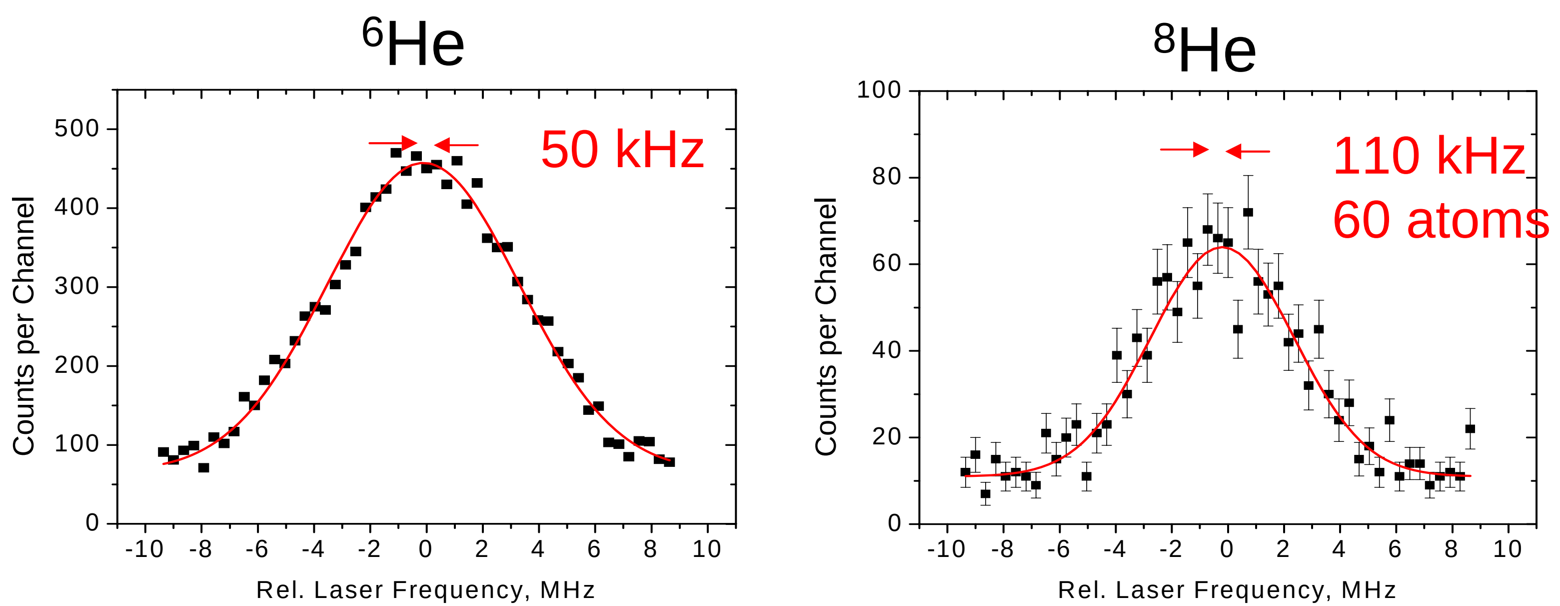

Jan. 26th 2007


ORTEC

June 15th - He-8 Trapped!

First He-8 Atom
June 15th 2007

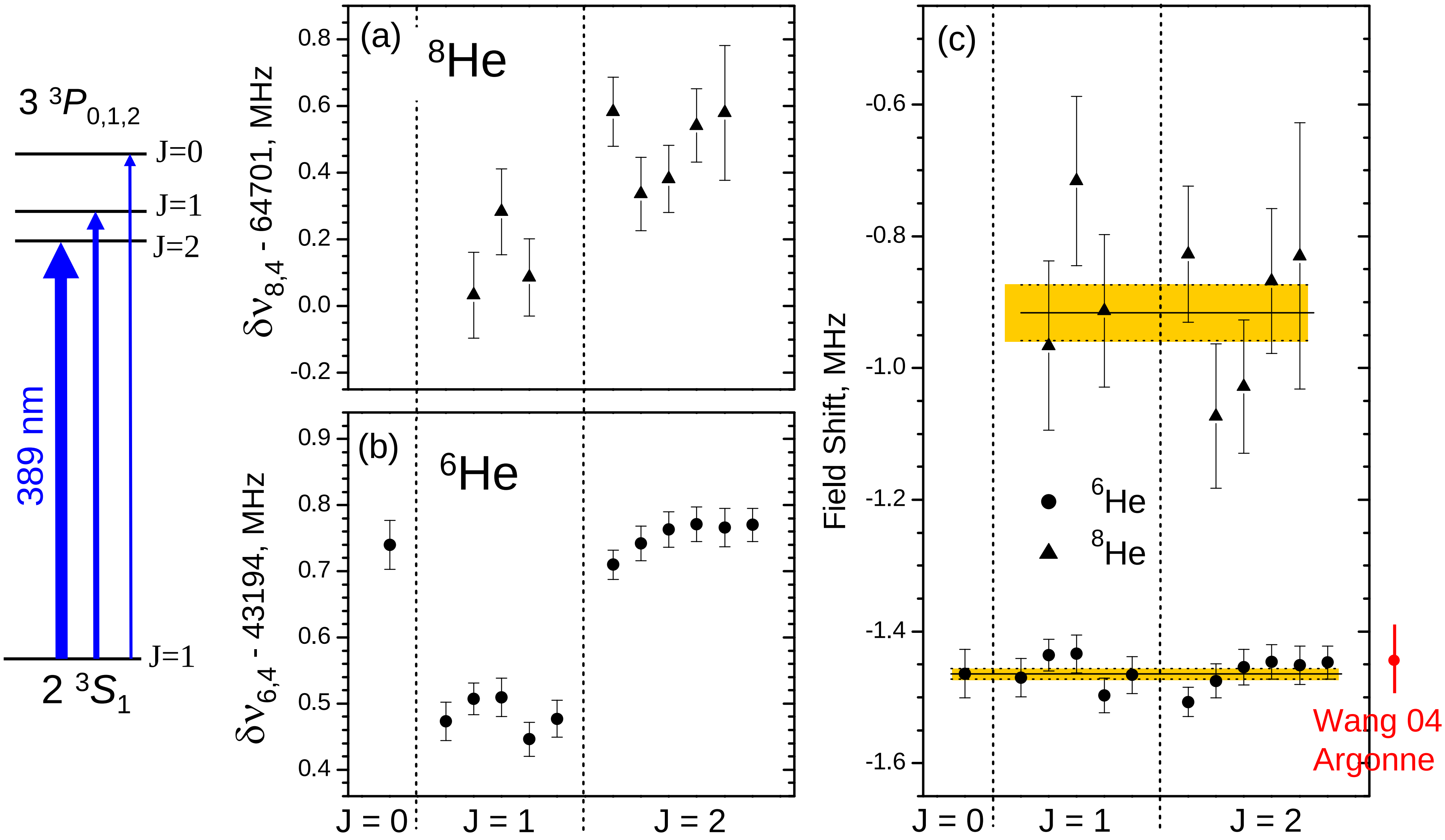




~ 5 ^{6}He atoms/s

~ 30 ^{8}He atoms/hr

Isotope Shift and Field Shift : J - Dependence?



Experimental Uncertainties and Corrections

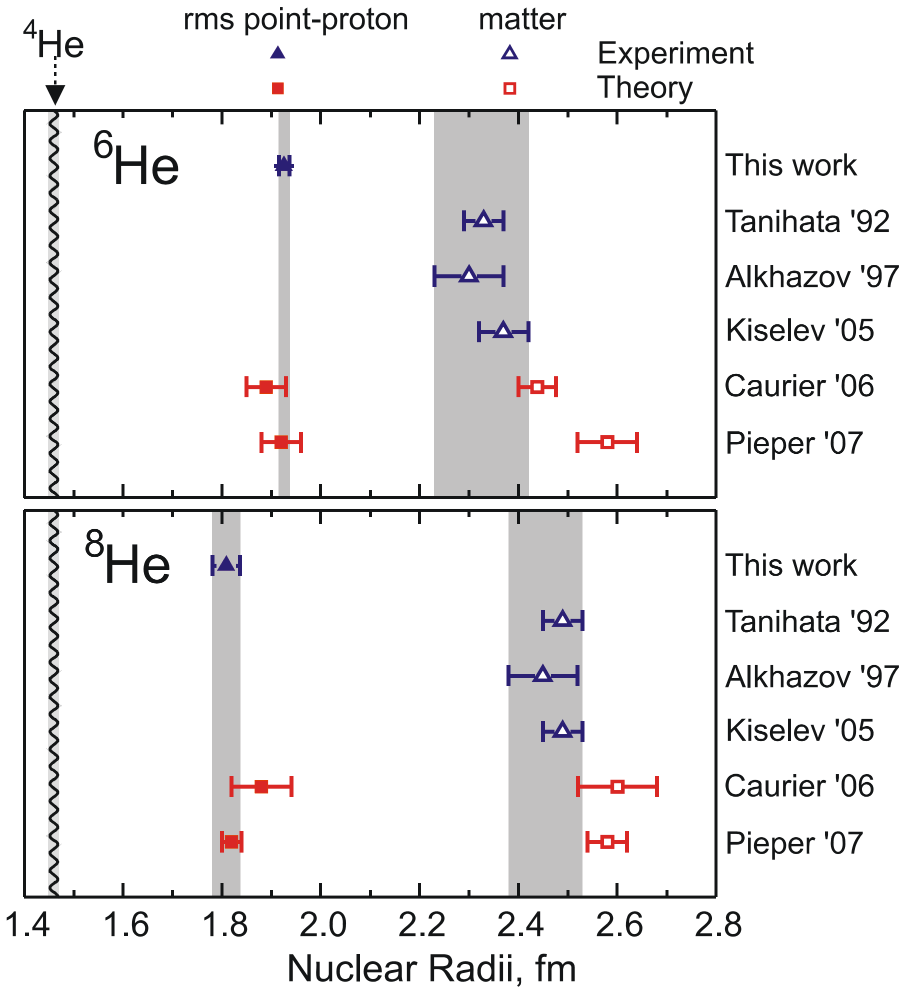
		^6He	^8He
Statistical	Photon Counting	8 kHz	32 kHz
	Laser Alignment Drift	2 kHz	12 kHz
	Reference Laser Drift	2 kHz	24 kHz
Systematic	Probing Power Shift	0 kHz	15 kHz
	Zeeman Shift	**30 kHz**	45 kHz
	Nuclear Mass	15 kHz	**74 kHz**
	TOTAL	**35 kHz**	**97 kHz**

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

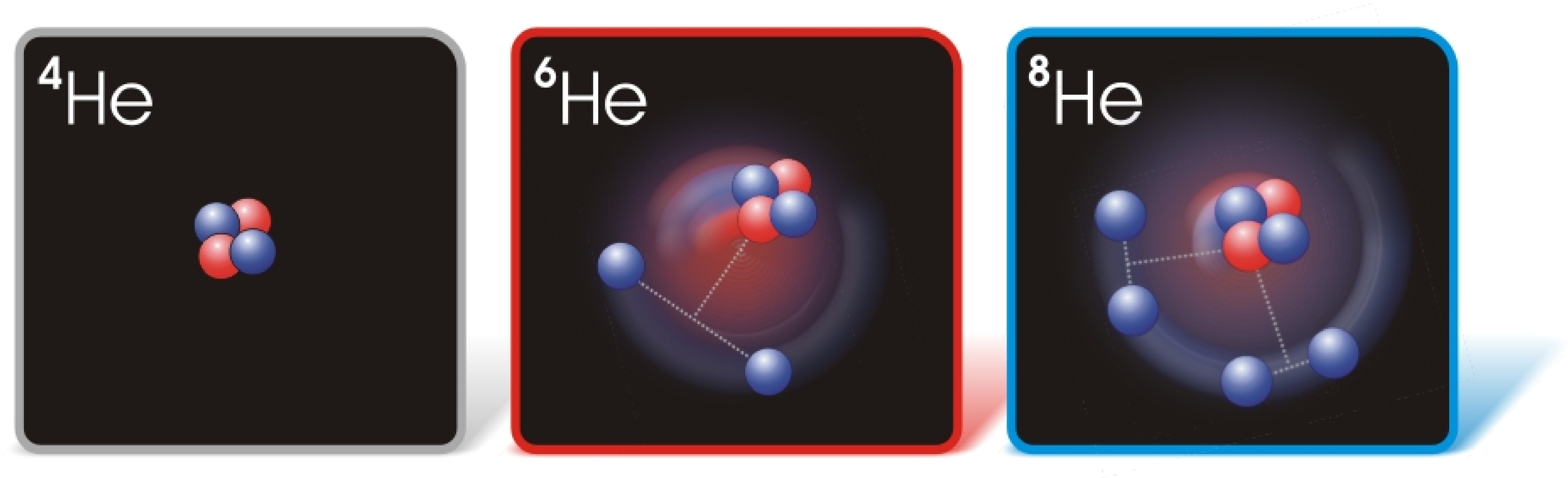
^{6}He & ^{8}He RMS Point Proton Radii

	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-0.916(95)
RMS R_{pp}, fm	**1.926(11)**	**1.809(28)**
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: 1.460(8) fm	0.3 %	0.4 %

PRL ***99***, *252501 (2007)*



^6He & ^8He Charge Radii



AIP Physics News Update, # 851-2, Dec. 2007

Conclusion

- Hypothesis of neutron-halo structure confirmed model-independently
- Demonstrated trap spectroscopy with single atom sensitivity

Outlook

- To further improve the precision and compare with theories:
  Nuclear polarizability and MEC (meson exchange current) correction necessary at this level of precision
- Need more precise value of proton radius
- Need more precise value of helium-4 radius
- See also recent laser spectroscopy work on Li-11 at GSI/TRIUMF
- New He-8 mass measurement in Penning trap @ TRIUMF in Dec. ‘07

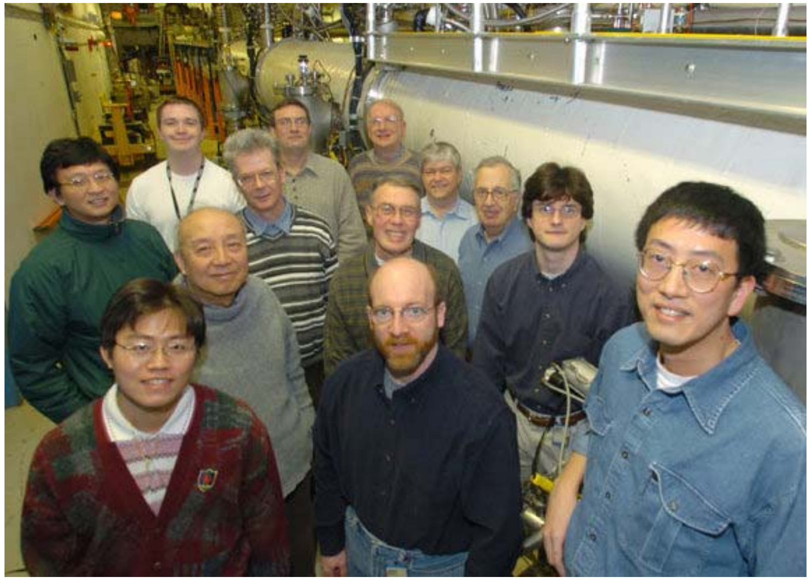
Collaboration

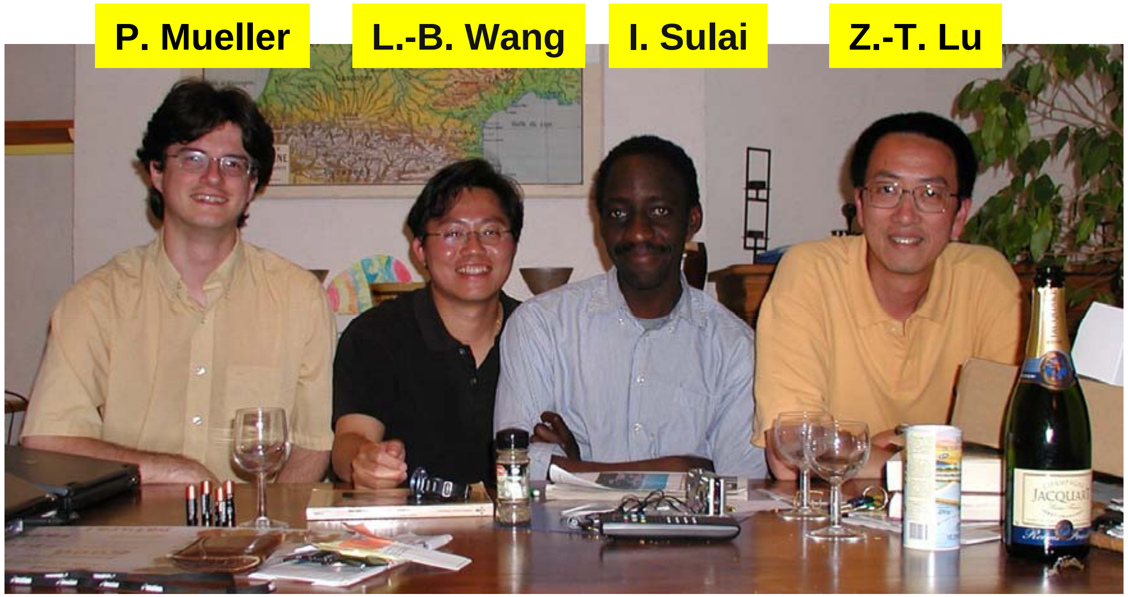
K. Bailey, J.P. Greene, D. Henderson, R.J. Holt, R. Janssens, C.L. Jiang, Z.-T. Lu, P. Mueller, T. O'Conner, R.C. Pardo, K.E. Rehm, J.P. Schiffer, I. Sulai, X.D. Tang
Argonne National Laboratory, USA

M.-G. Saint Laurent, *J.-Ch. Thomas, A.C.C. Villari et al.-* *GANIL, Caen, France*

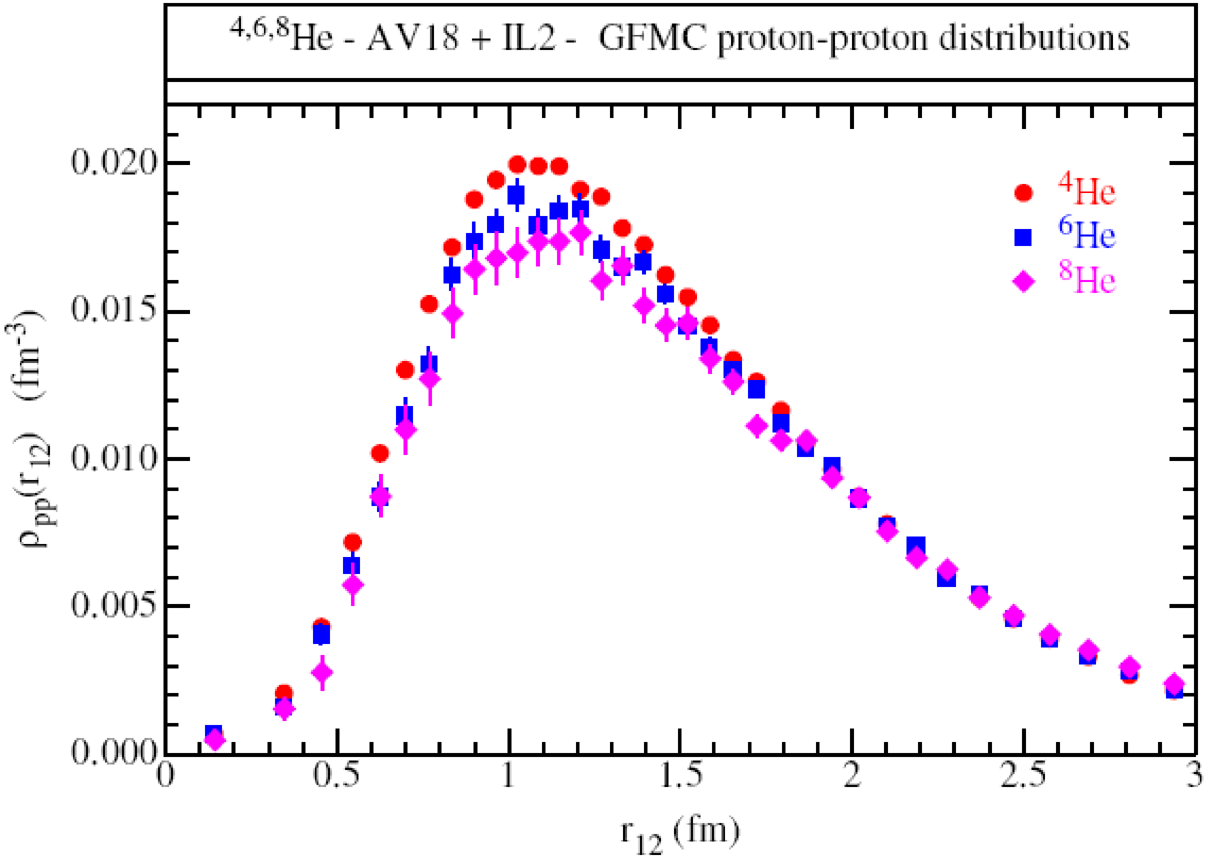
G. W. F. Drake - *University of Windsor, Canada*

L.-B. Wang - *Los Alamos National Laboratory, USA*





GFMC – What happens to the Core?



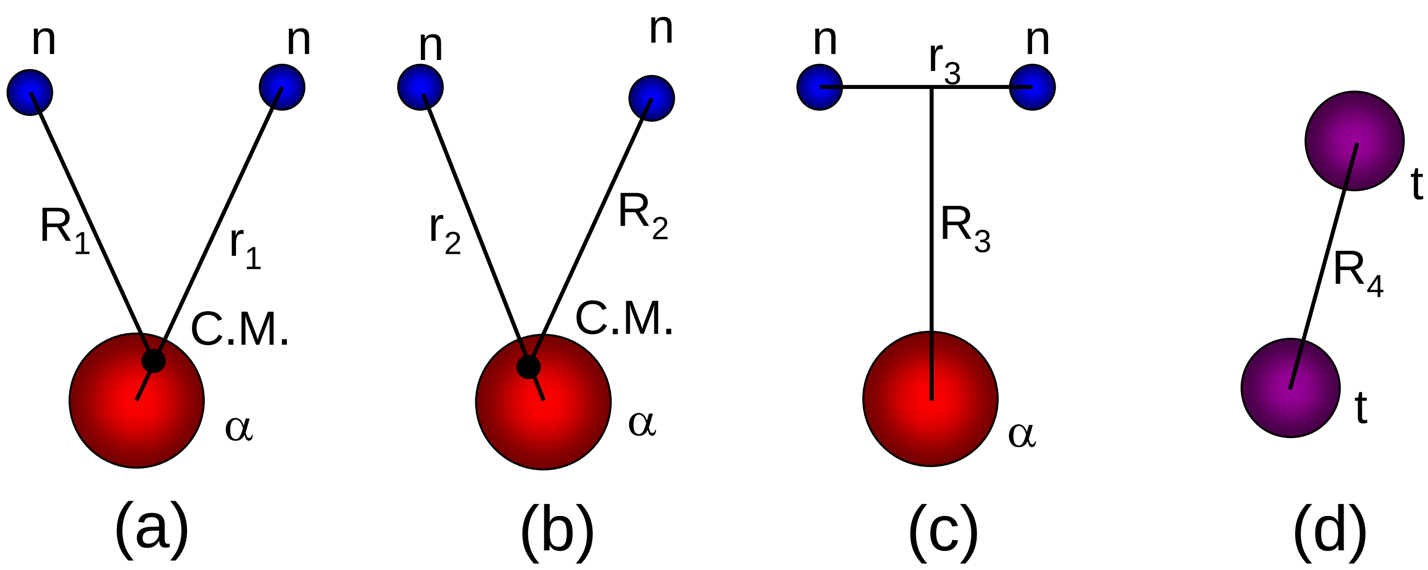
Meson-Exchange Current Correction

- Mesons mediating strong force carry electric charge
- Expected to be different among ^{4}He, ^{6}He and ^{8}He
- In H–D isotope shift, MEC correction ~0.2% of deuteron charge radius
- Small but NOT negligible at this precision
- $\Rightarrow$ further theoretical investigation necessary

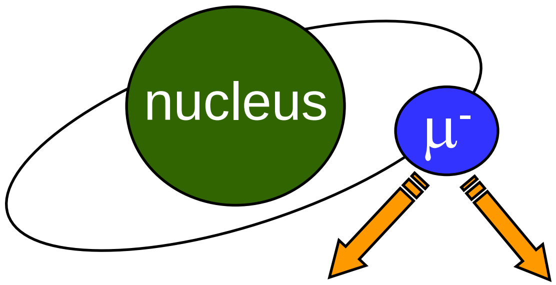
$$< r_c^{\ 2} > = < r_p^{\ 2} > + \left[< R_p^{\ 2} > + \frac{3}{4} \frac{1}{M_p^{\ 2}} \right] + \frac{N}{Z} < R_n^{\ 2} > + < r^2 >_{MEC}$$

Cluster Models for ^{6}He

- Assume α core not affected much by the two neutrons
- Empirical form of n-n, n-α potential, parameterized by scattering phase shift
- Cluster models
- Triton + triton channel used

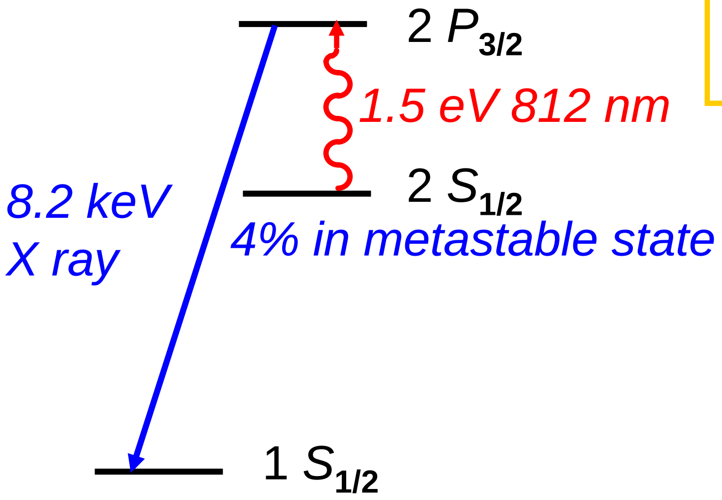


Muonic Atom X-ray Spectroscopy



muon decay $\mu^- \to e^- \nu \bar{\nu}$

Muonic $^4He^+$ Energy Level



- $m_\mu / m_e \sim 200$
- Bohr radius $a_0 \sim \frac{1}{m_e}$
- Energy level $E_n \sim -\frac{m_e}{n^2}$
- Wave function $\Psi(r) \sim a_0^{-3/2} e^{-r/a_0}$
- Energy shift due to nuclear size
- $\Delta \sim |\Psi(0)|^2 \delta \langle r^2 \rangle$
- Sensitivity ~ $(m_\mu / m_e)^3$

- $\delta\nu(2S_{1/2}\text{-}2P_{3/2}) = 1.813 - 0.102\langle r^2 \rangle$ eV
- 811.68(15)nm $\Rightarrow \langle r^2 \rangle^{1/2}(^4He) = 1.673(1)$ fm
- Carboni *et al*., Nucl. Phys. **A**278, (1977)
- Muonic hydrogen in PSI $\Rightarrow$ proton radius

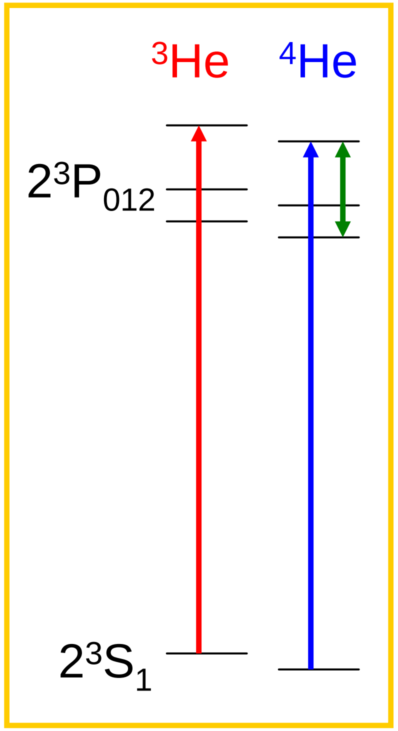
Atomic Theory of Helium

- Solve 3-body Schrödinger Equation

Error <10 kHz (Nonrelativistic energy through Finite mass correction (NMS))

Error ~10 MHz → QED correction (Lamb shift)

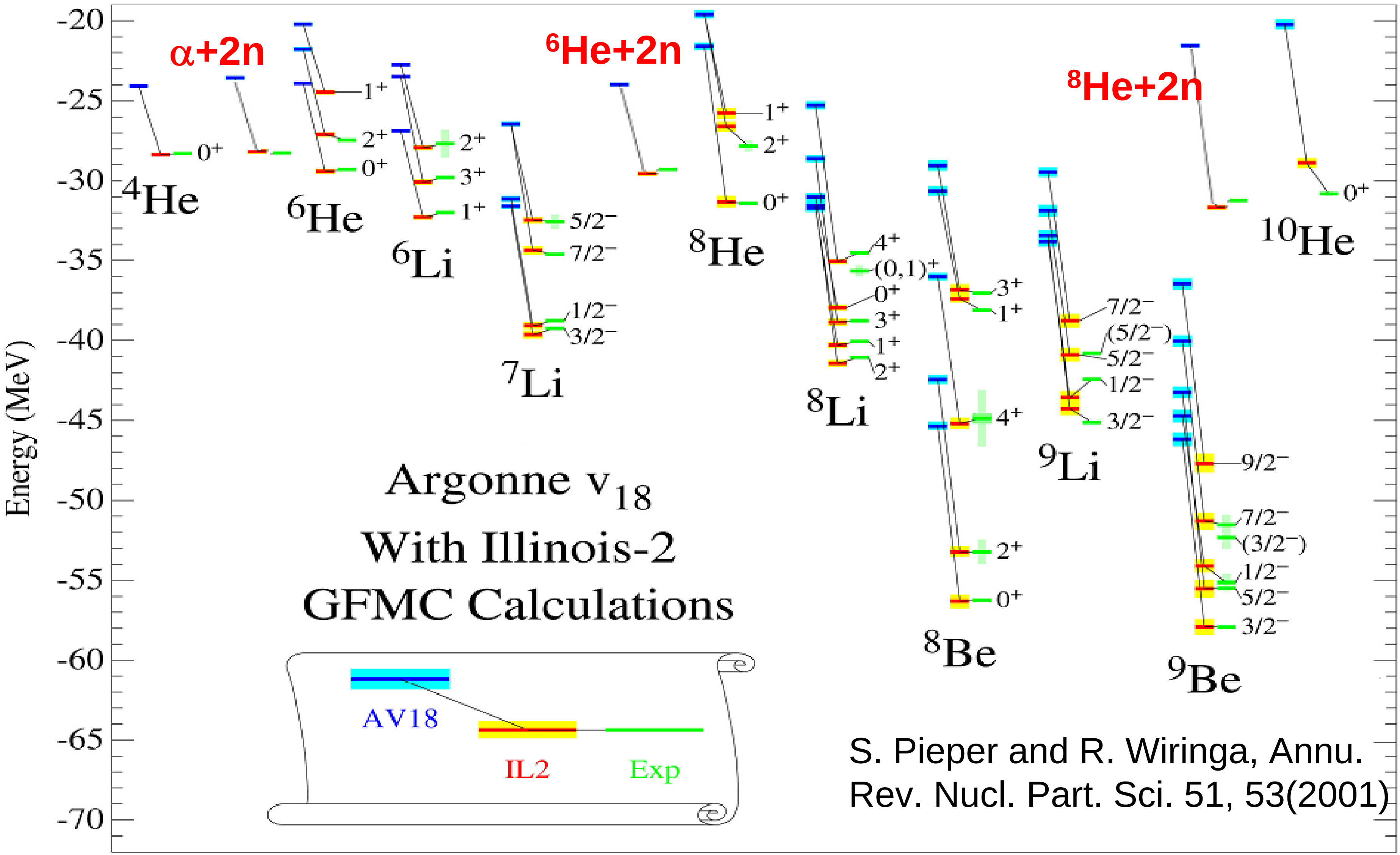
Contribution	Magnitude	
Nonrelativistic energy	Z^2	4
Relativistic correction	$Z^4\alpha^2$	9×10^{-4}
Anomalous magnetic moment	$Z^4\,\alpha^3$	7×10^{-4}
Mass polarization (SMS)	$Z^2\mu/M$	5×10^{-4}
Second-order mass polarization	$Z^2(\mu/M)^2$	8×10^{-8}
Finite mass correction (NMS)	$Z^4\,\alpha^2\,\mu/M$	1×10^{-7}
QED correction (Lamb shift)	$Z^4\,\alpha^3 \ln\,\alpha$	6×10^{-3}
Finite Nuclear Size	$Z^4\,(R_N/a_o)^2$	2×10^{-9}



- Total transition frequency → Lamb Shift
- Isotope shift → Nuclear radius
- Fine structure splitting → Fine structure constant

  1kHz → accuracy 1 part in 10^8

Binding Energy of Light Nuclei



S. Pieper and R. Wiringa, Annu. Rev. Nucl. Part. Sci. 51, 53(2001)

Monte Carlo Calculation

❖ Argonne *v18* two-body potential:

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

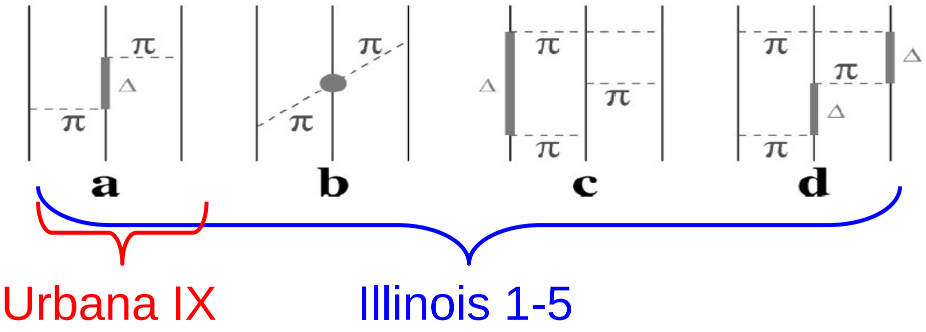
EM OPE TPE+HC

S. Pieper and R. Wiringa, Annu. Rev. Nucl. Part. Sci. 51, 53(2001)

- Coupling strength to fit NN scattering data
- Problem: binding energy of most light nuclei too small

❖ Illinois 3-body potential:

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



- In nuclei A>3, excitation of the excited state of nucleons
- Parameters to fit ^{3}H, ^{3}He binding energy
- Isospin dependant, Neutron-rich light nuclei, e.g. ^{6}He

Nuclear-Medium Correction

- Electron does NOT see the bare nucleus ⇒ Nuclear polarizability
- The energy shift in the helium $2^3S_1–3^3P_2$ transition:

$$\delta\nu = 7.08\ kHz \times \frac{\alpha_E(^6He) - \alpha_E(^4He)}{\alpha_E(^2H)}$$

G.W.F. Drake, private communication

$$\alpha_E = \frac{2\alpha}{3}\sum_{N\neq 0}\frac{\left|\langle N|\vec{D}|0\rangle\right|^2}{E_N - E_0}$$

$$\alpha_E + \beta_M = \frac{1}{2\pi^2}\int_0^\infty \frac{\sigma_\gamma(\omega)}{\omega^2}d\omega$$

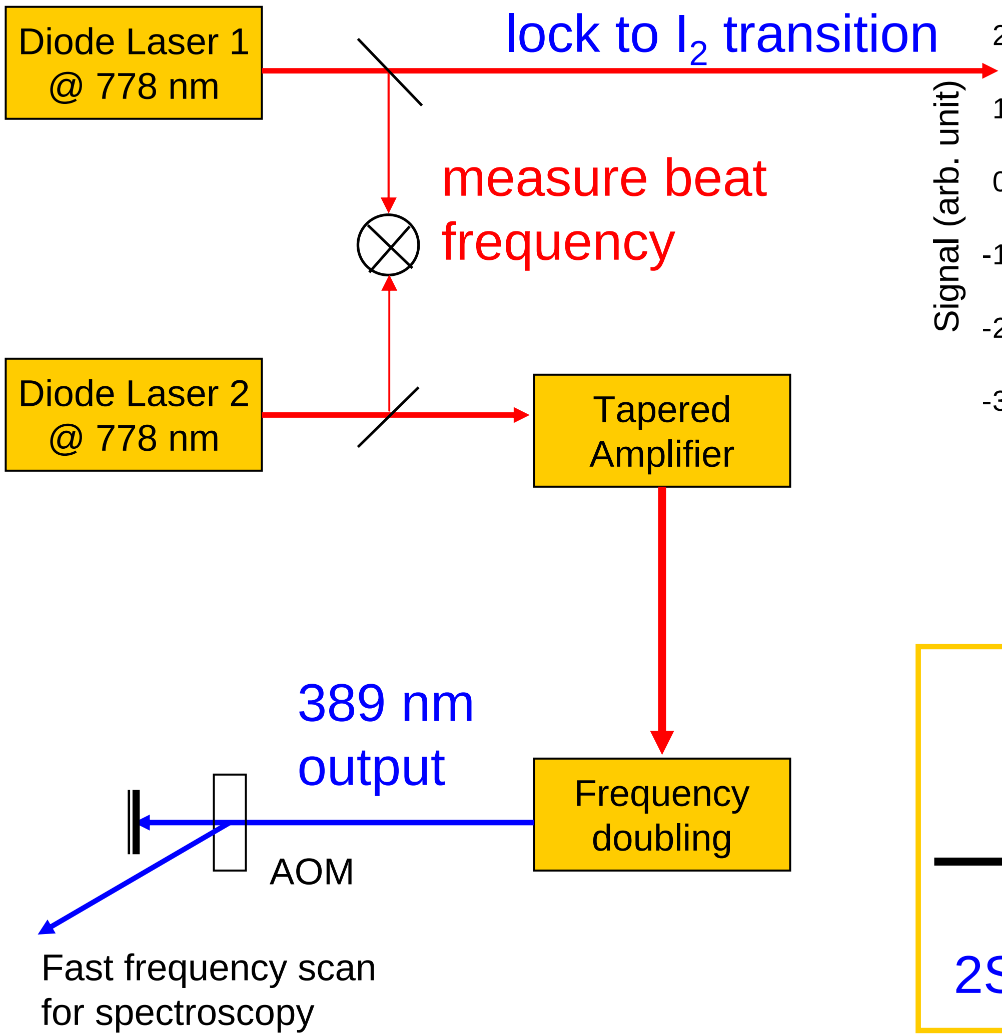
Baldin-Lapidus sum rule

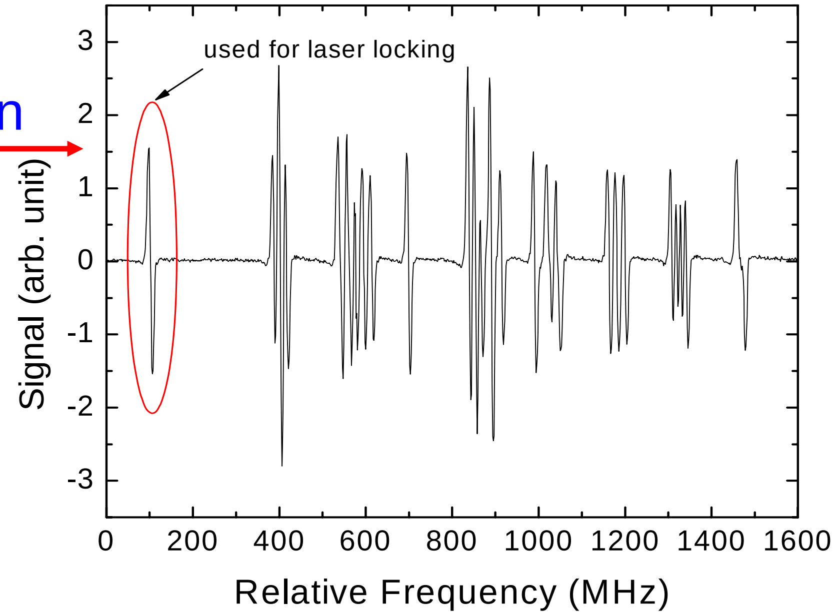
- $\alpha_E(^6He) = 0.68 – 0.74\ fm^3$ by Esbensen
- $\alpha_E(^6He) \sim 0.8\ fm^3$ by Bacca
- $\alpha_E(^2H) = 0.63\ fm^3$ by Friar

⇒

- 10 kHz shift expected
- Increase ^6He $\langle r_c^2\rangle^{1/2}$ by 0.1%

389 nm Spectroscopy Laser Setup





I_2 spectrum near 777.946 nm