

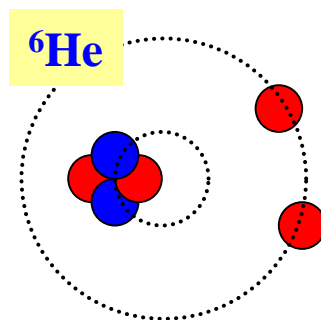


Laser Spectroscopic Determination of the Nuclear Charge Radius of ${}^6\text{He}$



Zheng-Tian Lu

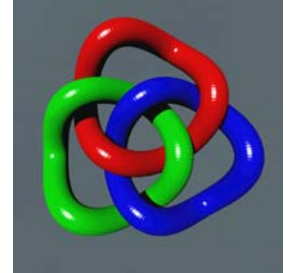
Physics Division, Argonne National Laboratory



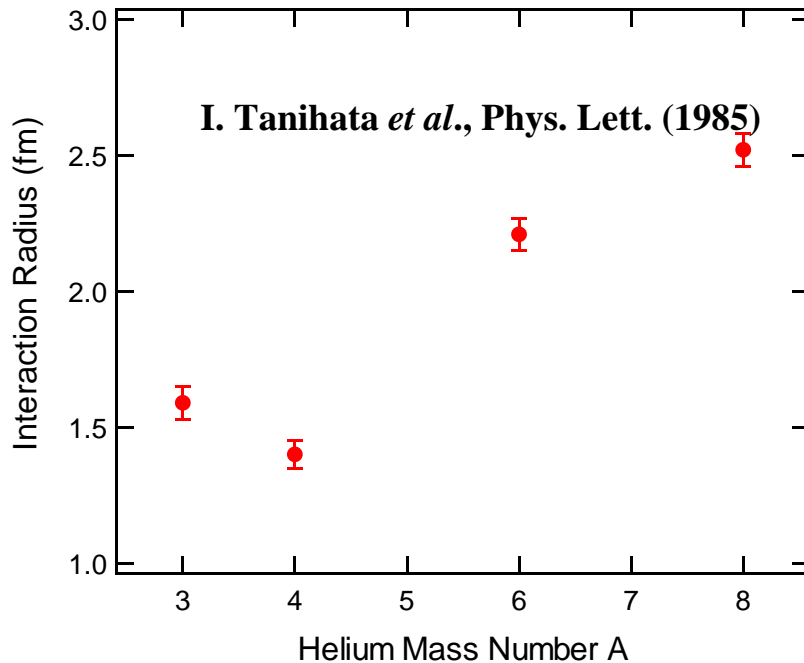
This work is supported by U.S. DOE, Office of Nuclear Physics

Halo Nuclei ${}^6\text{He}$ and ${}^8\text{He}$

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



Borromean



Core-Halo Structure

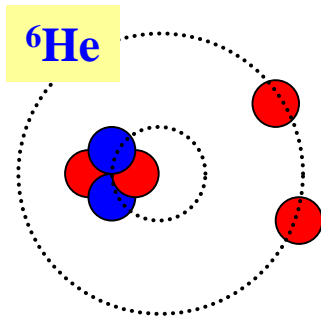
$$\sigma_I({}^6\text{He}) - \sigma_I({}^4\text{He}) = \sigma_{-2n}({}^6\text{He})$$

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

Charge Radii Measurements

Methods of measuring nuclear radii (interaction radii, matter radii, charge radii)

- ❖ Nuclear scattering – model dependent
- ❖ Electron scattering – stable isotope only
- ❖ Muonic atom spectroscopy – stable isotope only
- ❖ Atomic isotope shift



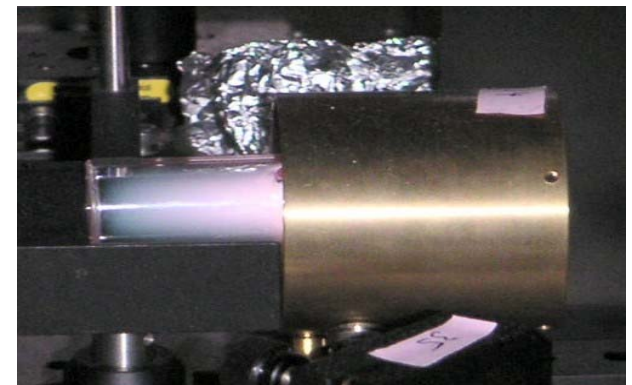
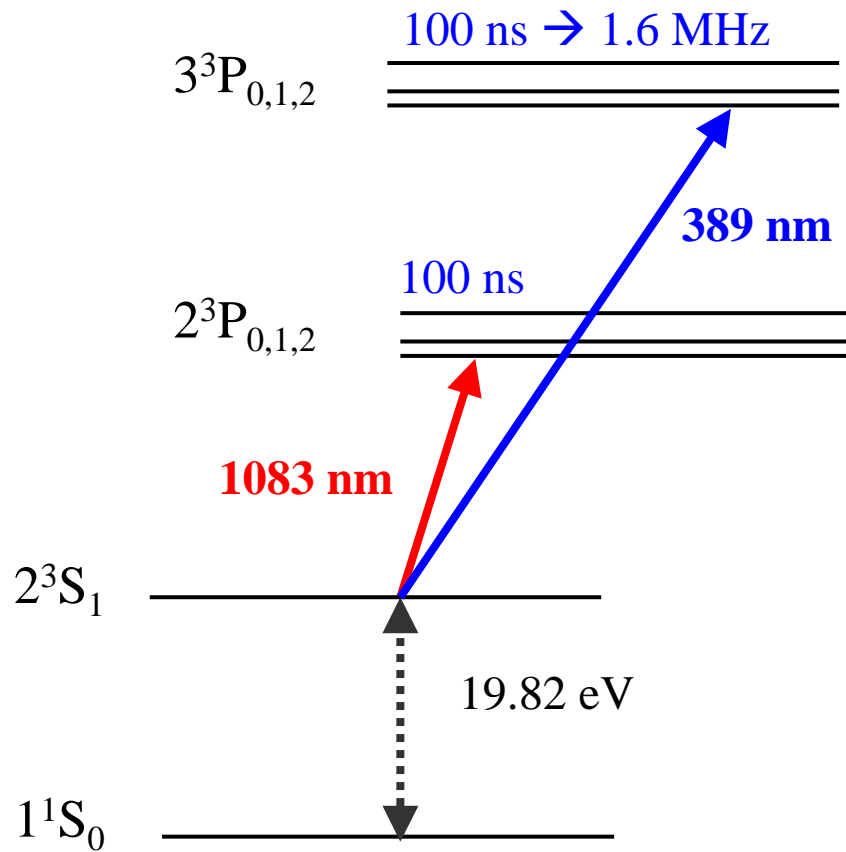
RMS point proton radii (fm) from theory and experiment

	He-3	He-4	He-6	He-8
QMC Theory	1.74(1)	1.45(1)	1.89(1)	1.86(1)
μ-He Lamb Shift		1.474(7)		
Atomic Isotope Shift	1.766(6)		?	?
p-He Scattering			1.95(10) GG 1.81(09) GO	1.68(7) GG 1.42(7) GO

G.D. Alkhazov et al., Phys. Rev. Lett. **78**, 2313 (1997);
D. Shiner et al., Phys. Rev. Lett. **74**, 3553 (1995).

Atomic Energy Levels of Helium

He energy level diagram



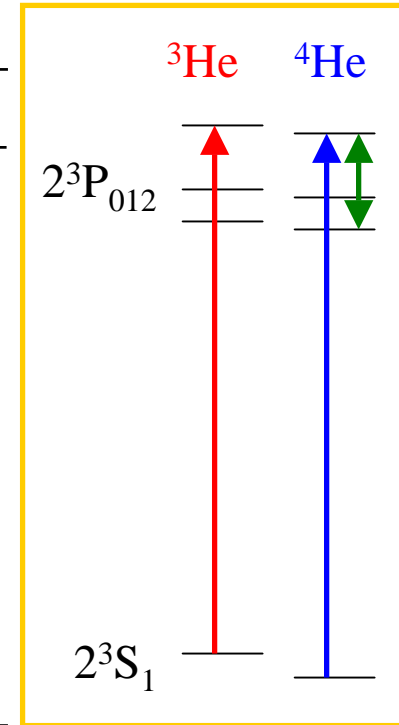
A helium glow discharge

Theory of Helium Atom

Drake, *High precision theory of atomic helium*, *Phys. Scripta T83*: 83 (1999)

Solve 3-body Schroedinger Equation

	Contribution	Magnitude
Error < 10 kHz	Nonrelativistic energy	Z^2 1
	Relativistic correction	$Z^4\alpha^2$ 10^{-3}
	Anomalous magnetic moment	$Z^4\alpha^3$ 10^{-5}
	Mass polarization (SMS)	$Z^2\mu/M$ 10^{-4}
	Second-order mass polarization	$Z^2(\mu/M)^2$ 10^{-8}
	Relativistic recoil (NMS)	$Z^4\alpha^2\mu/M$ 10^{-7}
Error ~ 10 MHz	QED correction (Lamb shift)	$Z^4\alpha^3\ln\alpha$ 10^{-5}
	Finite Nuclear Size	$Z^4(R_N/a_0)^2$ 10^{-9}



- ❖ Total transition frequency → **Lamb Shift**
- ❖ Fine structure splitting (err ~ 1 kHz) → **Fine structure constant** (err ~ 10^{-8})
- ❖ Isotope shift (err ~ 100 kHz) → **Nuclear radius** (err ~ 1%)

Atomic Isotope Shift

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

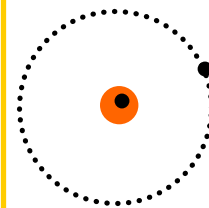
Mass shift:

due to nucleus recoil


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

Field shift:

due to nucleus size


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

$$\text{IS}(2^3\text{S}_1 - 2^3\text{P}_2) = 34473.625(20) + 1.210(\langle r^2 \rangle_{\text{He4}} - \langle r^2 \rangle_{\text{He6}}) \text{ MHz}$$

$$\text{IS}(2^3\text{S}_1 - 3^3\text{P}_2) = 43196.202(20) + 1.008(\langle r^2 \rangle_{\text{He4}} - \langle r^2 \rangle_{\text{He6}}) \text{ MHz}$$

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

100 kHz error in frequency \leftrightarrow 1% error in radius

Approach & Collaboration

Production



Trap and Detection



Precision Spectroscopy



Calc. Charge Radius with
Atomic Theory



Compare Results with
Nuclear Theory

Collaboration list

ATTA: L.-B. Wang*, P. Mueller, K. Bailey,
R.J. Holt, **Z.-T. Lu**, T.P. O'Conner

*Physics Division, Argonne National Laboratory
University of Illinois at Urbana-Champaign

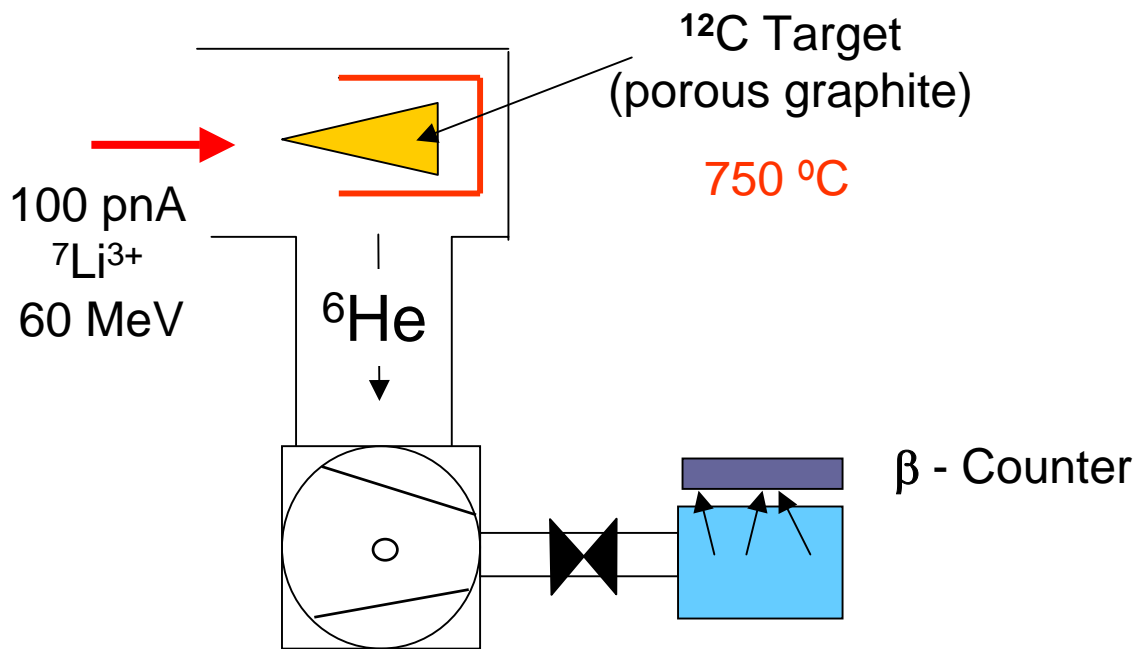
Heavy Ion Group: J.P. Greene, D. Henderson,
R.V.F. Janssens, C.L. Jiang, R.C. Pardo, **K.E.
Rehm**, J.P. Schiffer, X.D. Tang

Physics Division, Argonne National Laboratory

Atomic Theory: G.W.F. Drake
University of Windsor, Canada

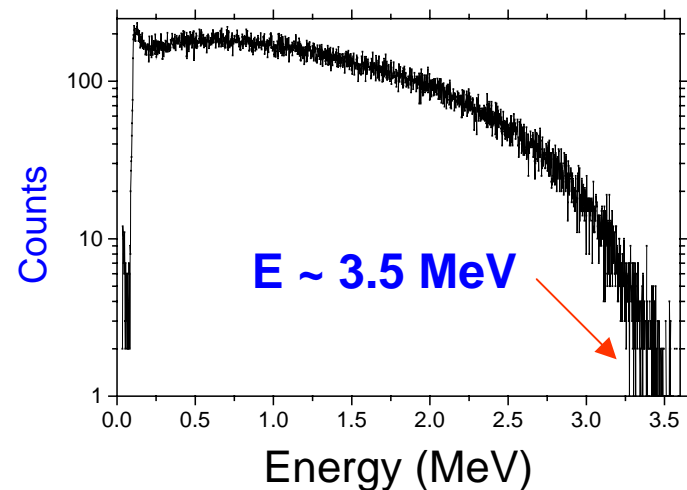
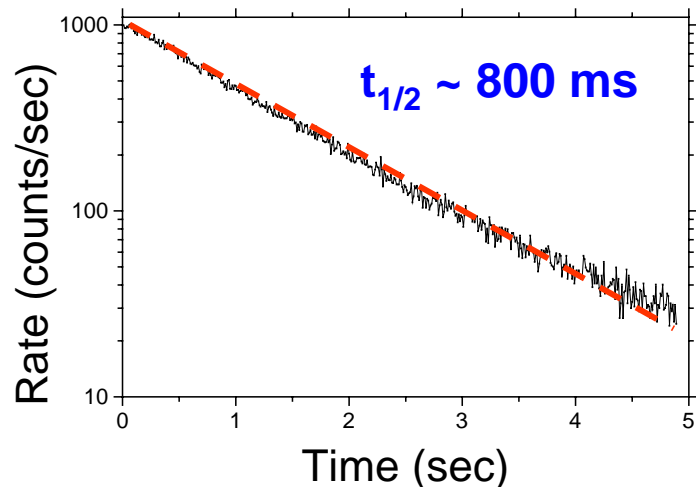
${}^6\text{He}$ - Production at ATLAS

${}^{12}\text{C}({}^7\text{Li}, {}^6\text{He}){}^{13}\text{N}$ - Reaction



 ${}^6\text{He}$ atoms extracted: $\sim 1 \times 10^6/\text{s}$

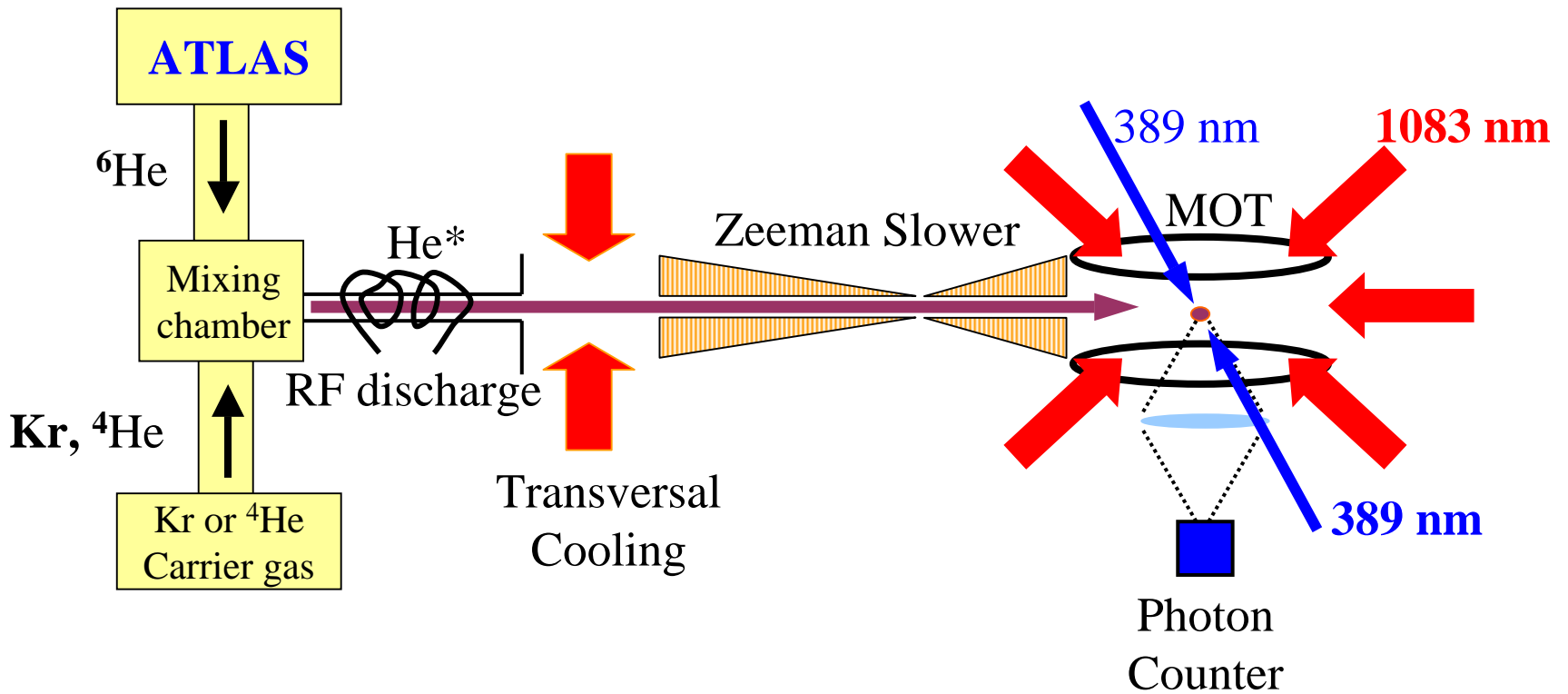
Identification of ${}^6\text{He}$



Experimental Setup - Schematic

${}^6\text{He}$ production: $1 \times 10^6 \text{ s}^{-1}$

Transport time $\sim 1 \text{ sec}$



Laser Trapping and Cooling of Neutral Atoms

<http://www.nobel.se/physics/laureates/index.html>

Atom Trappers / Nobel Laureates



Cohen-Tannoudji



Chu



Phillips



Cornell



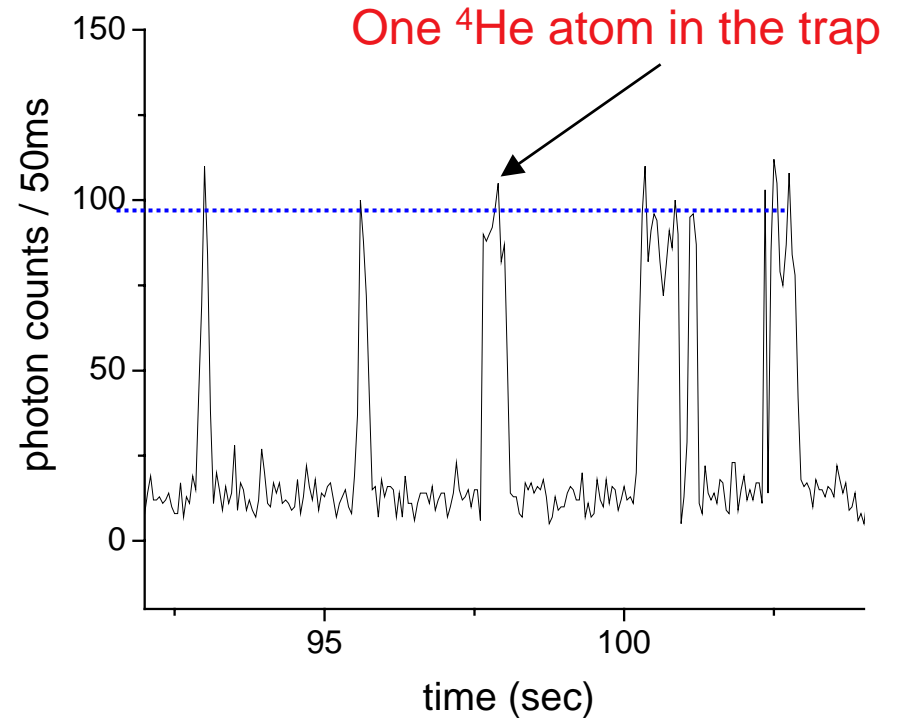
Ketterle



Wieman

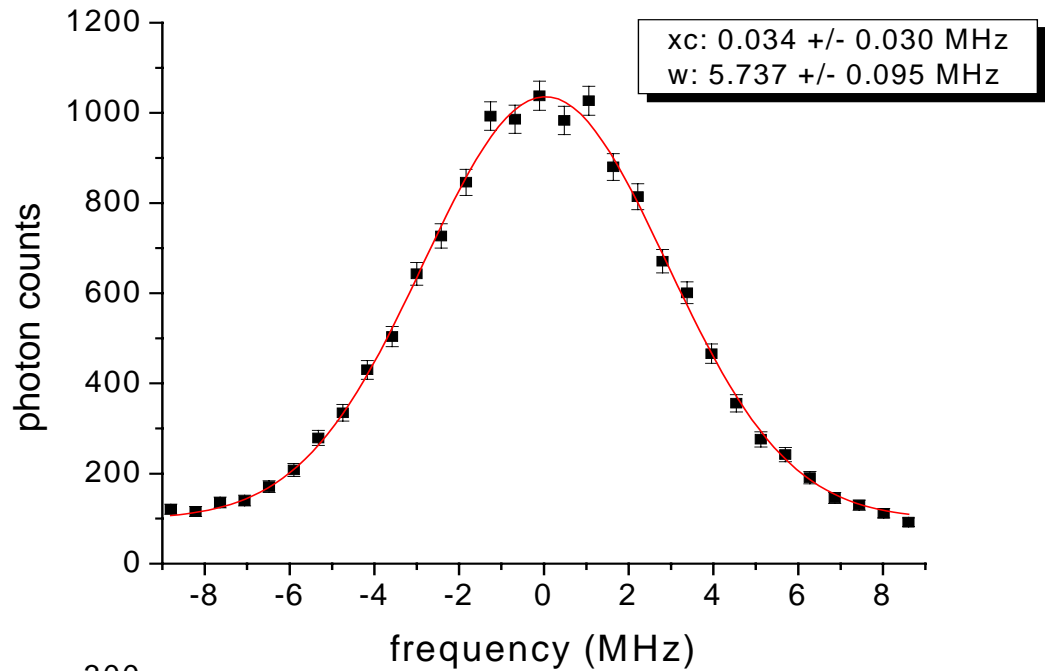
Single Atom Detection

- ❖ Capture efficiency $\sim 10^{-8}$
Single atom detection necessary!
- ❖ Single-atom signal ~ 1.5 kHz
- ❖ Single-atom S/N ~ 10 in 100 ms
- ❖ ${}^6\text{He}$ capture rate ~ 100 per hour



Single Atom Spectroscopy

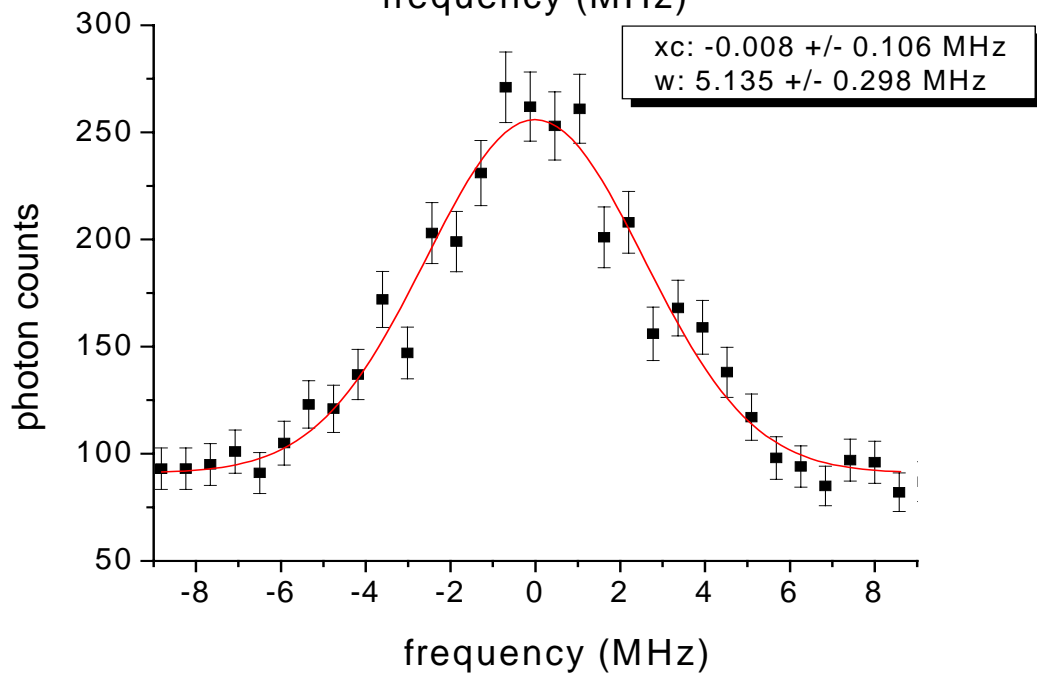
^4He



^6He

~ 150 ^6He atoms in one hour

April 6, 2004



Results

Errors Budget

Source	Correction (kHz)	Error (kHz)
Statistical		33
Trap effects		40
Uneven background		20
Frequency counter		9
Recoil effect	+ 110	< 1
Total	+ 110	56

Recoil Correction

$$E_{\gamma} = E_{\text{int}} + \frac{P_{\gamma}^2}{2M_{\text{atom}}}$$

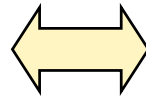
$$\text{IS}(2^3\text{S}_1 - 3^3\text{P}_2, {}^6\text{He} - {}^4\text{He}) = 43,194.772 (56) \text{ MHz}$$

$$\text{RMS Charge Radius of } {}^6\text{He} = 2.054 (14) \text{ fm}$$

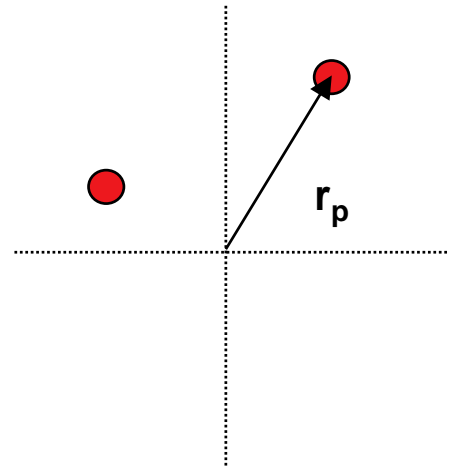
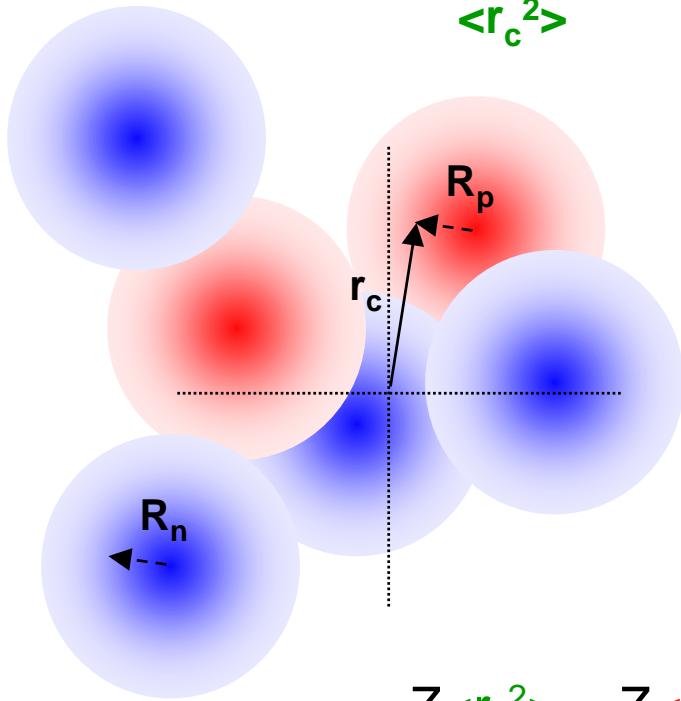
$$\text{Point-Proton Radius of } {}^6\text{He} = 1.912 (18) \text{ fm}$$

Charge Radius vs. Point-Proton Radius

Experiment:
mean square
charge radius
 $\langle r_c^2 \rangle$



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



$$Z\langle r_c^2 \rangle = Z\langle r_p^2 \rangle + Z\langle R_p^2 \rangle + N\langle R_n^2 \rangle$$

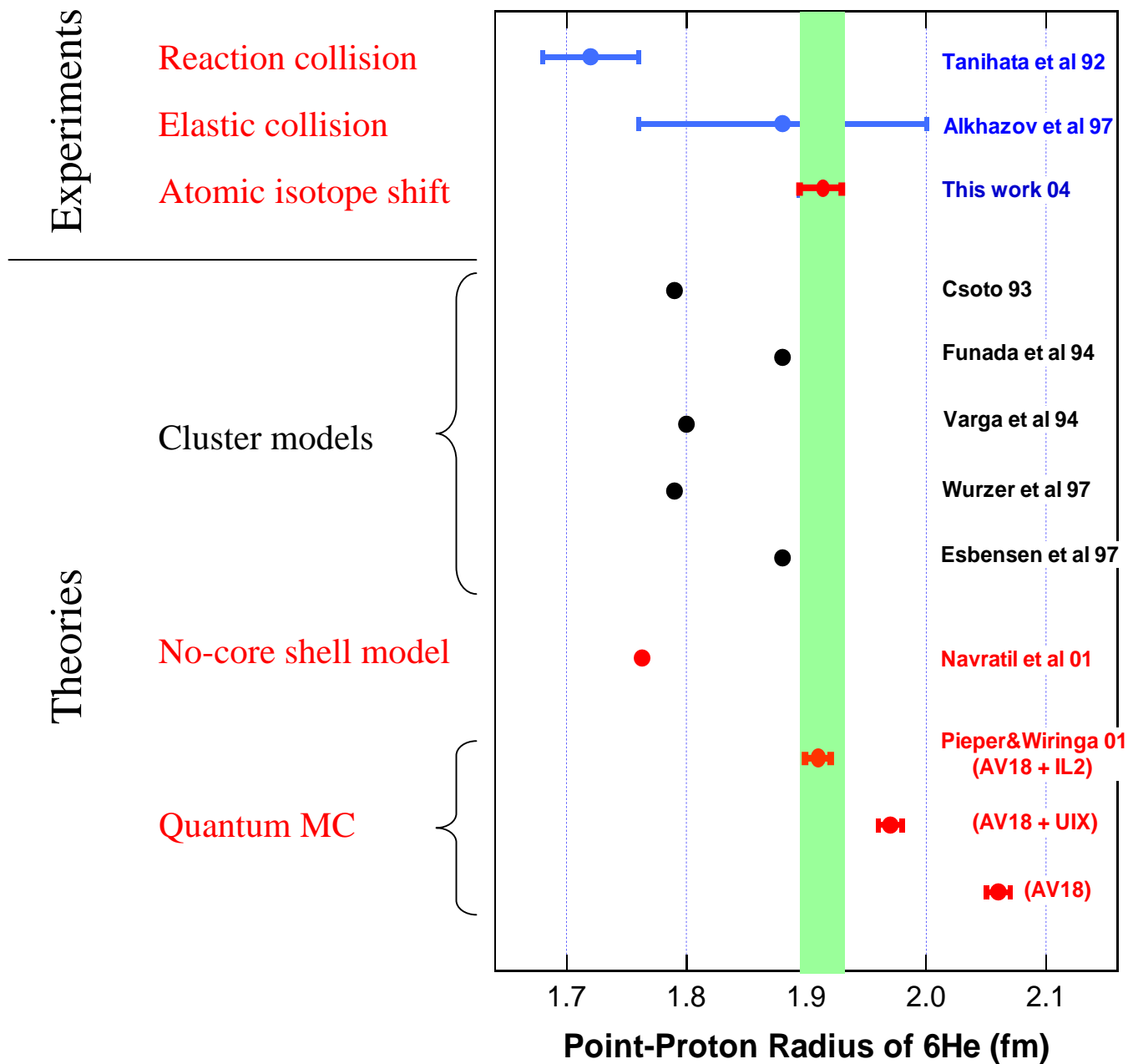
Experimental mean square charge radii:

Proton $\langle R_p^2 \rangle = 0.801(32) \text{ fm}^2$

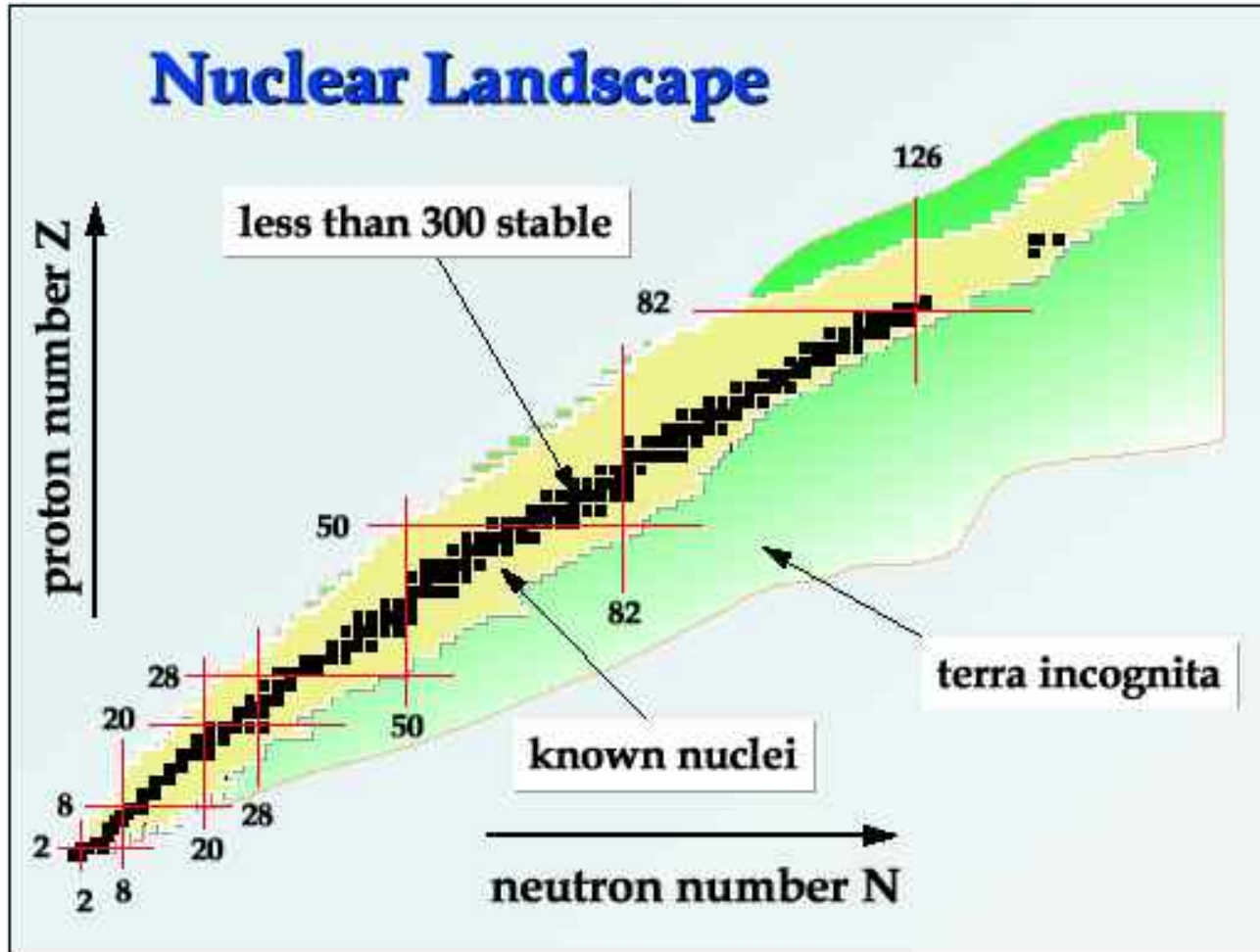
Neutron $\langle R_n^2 \rangle = -0.120(5) \text{ fm}^2$

A Proving Ground for Nuclear Structure Theories

L.-B. Wang et al., nucl-ex/0408008



Spectroscopy of Exotic Atoms at RIA



- **Light nuclei:** precision measurements (${}^6\text{He}$, ${}^8\text{He}$, ${}^{11}\text{Li}$...);
- **Intermediate-mass:** Evolution of structure along isotope chains (Kr...);
- **Super-heavy ?**