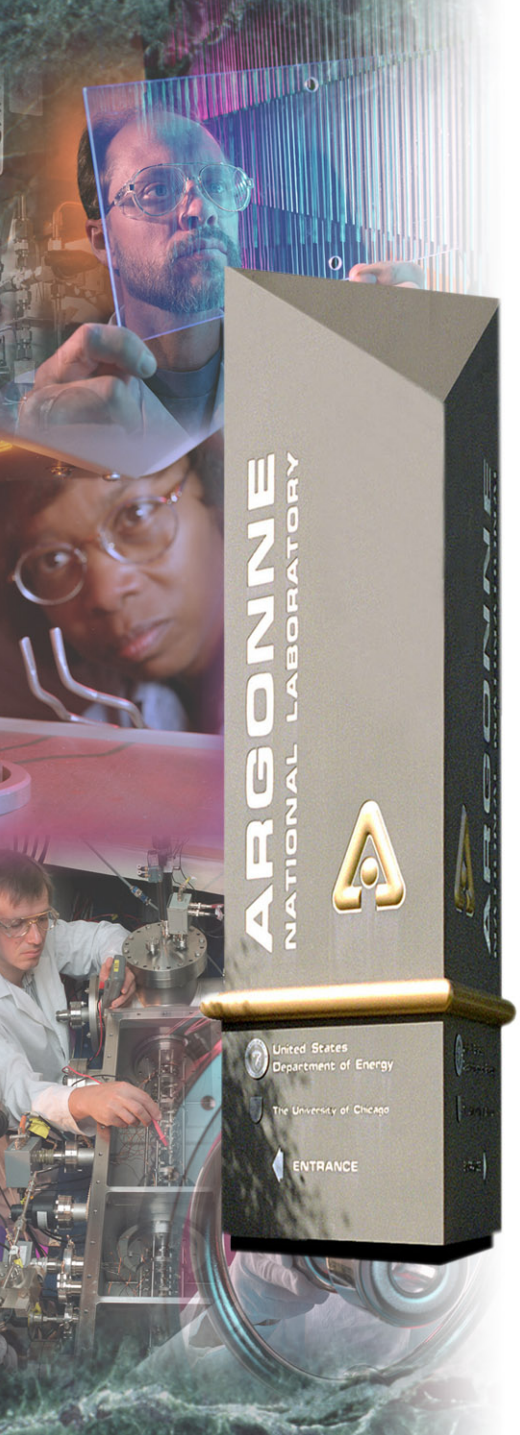


Charge Radius Measurement of ^{6}He in an Atom Trap

Peter Mueller

Argonne National Laboratory

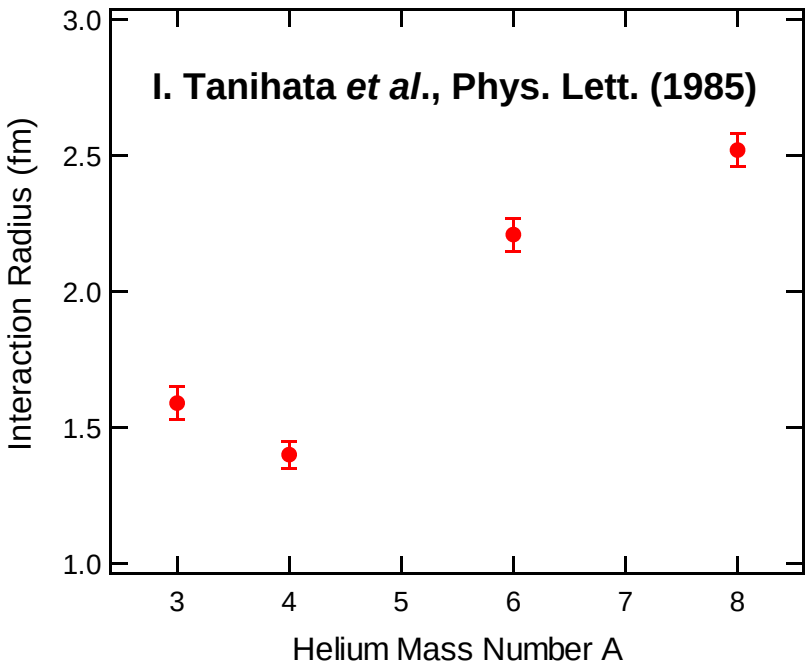
Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

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

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

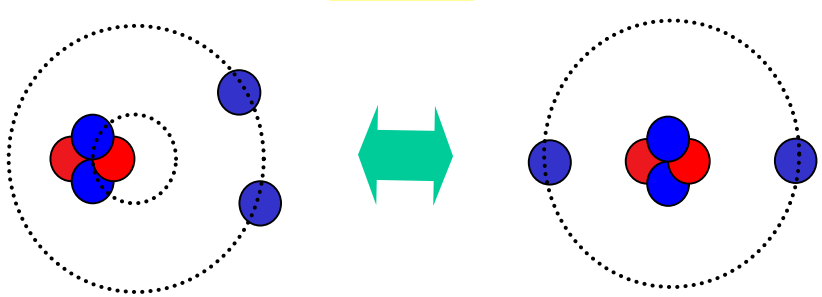
I. Tanihata *et al*., Phys. Lett. (1992)

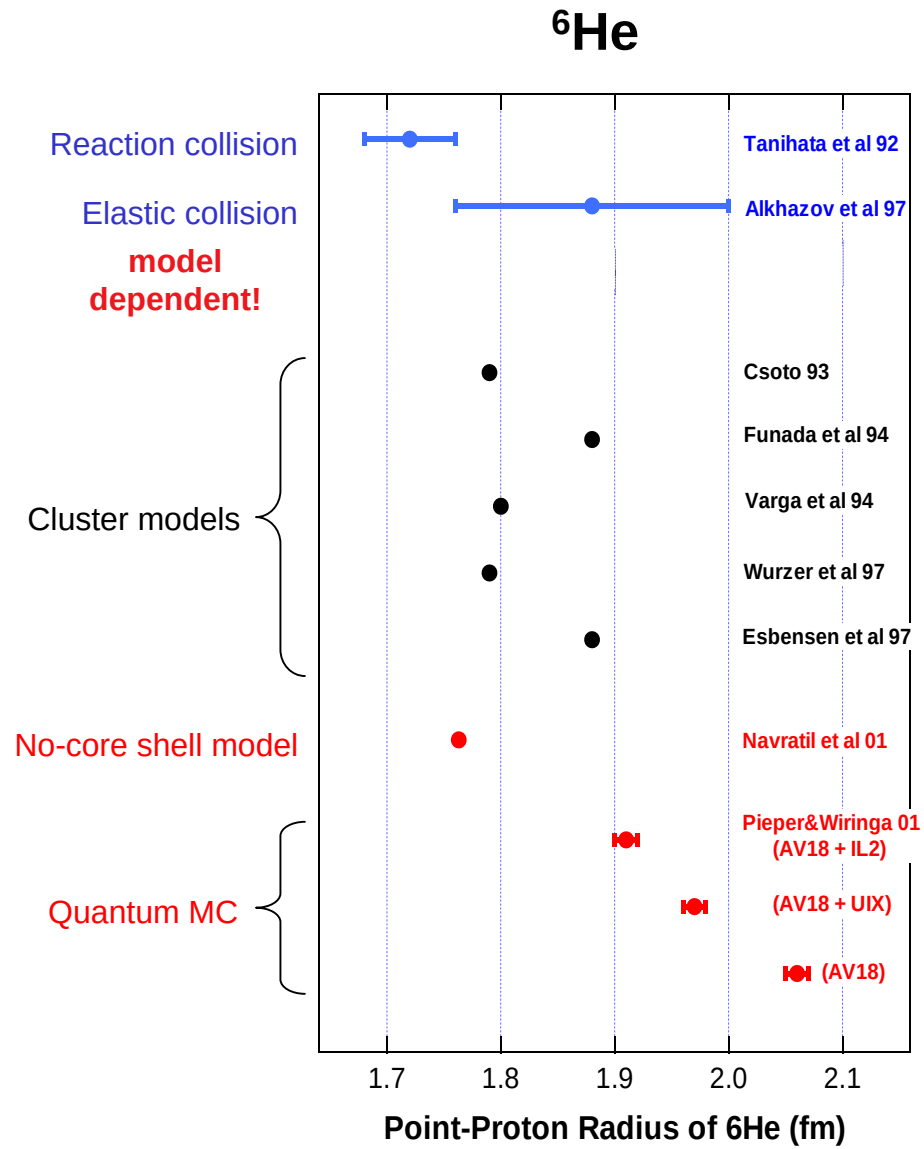
Charge Radii of He Isotopes

RMS point proton radii (fm):
theory and experiment

	He-3	He-4	He-6	He-8
QMC Theory	1.74(1)	1.45(1)	1.91(1)	1.88(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

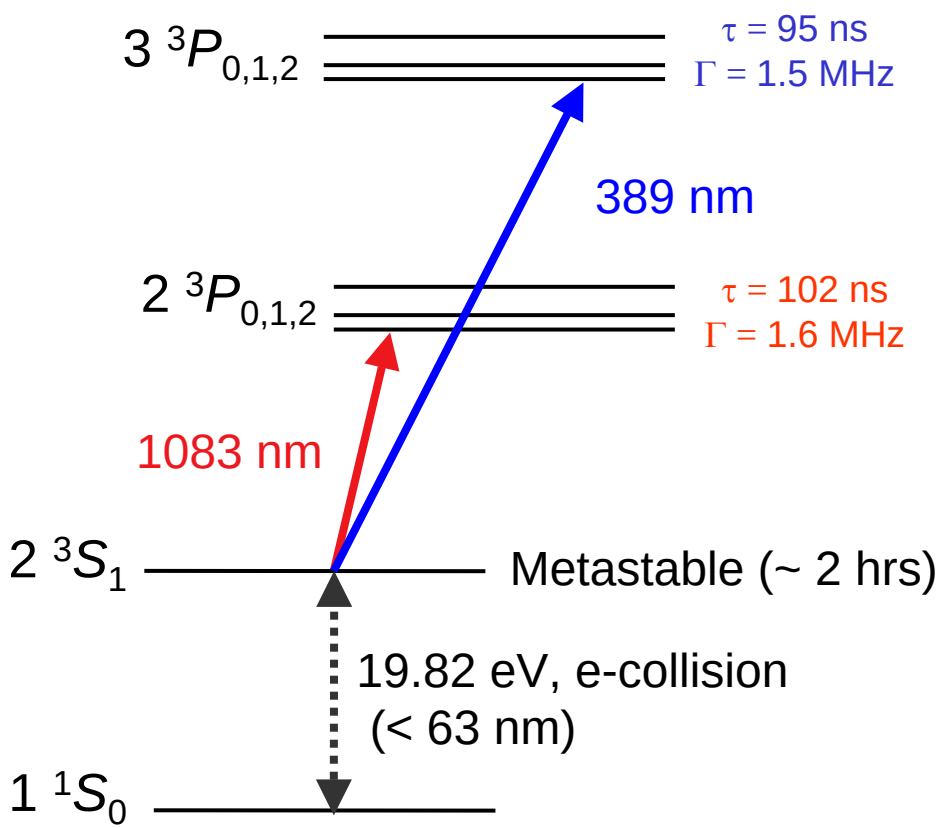
^{6}He



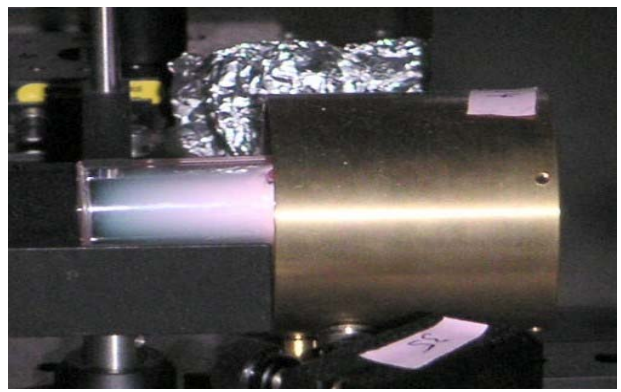


Atomic Energy Levels of Helium

He energy level diagram



He discharge

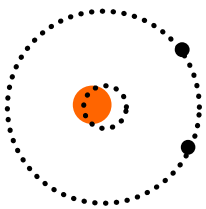


Atomic Isotope Shift

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

Mass shift:

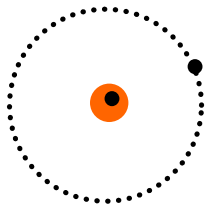
due to nucleus recoil



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

Field shift:

due to nucleus size



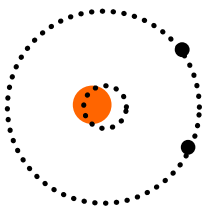
$$\delta\nu_{\mathbf{FS}} \propto Z \times \Delta[\Psi(0)]^2 \times \delta\langle r^2\rangle$$

Atomic Isotope Shift

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

Mass shift:

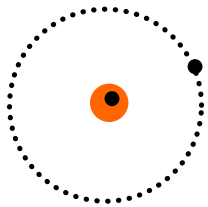
due to nucleus recoil



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

Field shift:

due to nucleus size



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

$IS(2^3S_1 - 3^3P_2) = 43196.202(16) + 1.008(\langle r^2\rangle_{He4} - \langle r^2\rangle_{He6})$ MHz

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

100 kHz error in frequency ←→ 1% error in radius

Spectroscopy of ^{6}He

Technical challenges:

- Short lifetime, small sample
- Metastable efficiency ~ 10^{-5}
- Precision requirement (IS ~ 40 GHz, Field shift ~1 MHz)

Solution:

Laser spectroscopy of individual trapped ^{6}He* atoms

✓ High resolution: cold atoms, Doppler width largely reduced

✓ High sensitivity: capable of detecting a single atom

Approach & Collaboration

Production

↓

Trap and Detection

↓

Precision Spectroscopy

↓

Subtract Mass Shift by Atomic Theory

↓

Compare Results with Nuclear Theory

Collaboration list

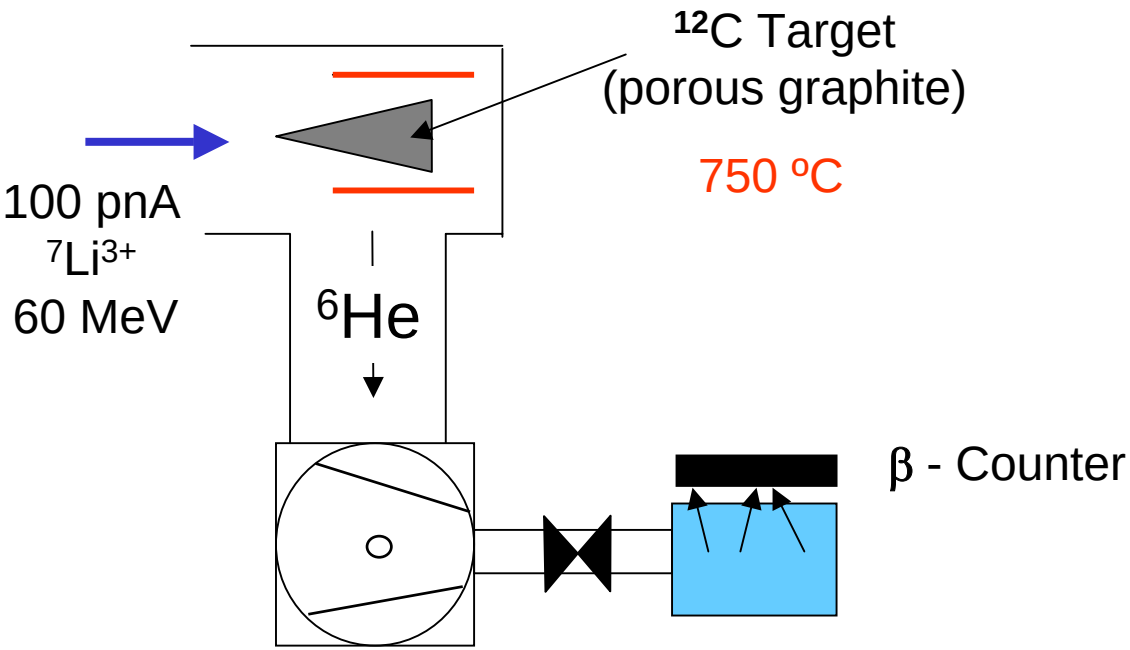
ATTA: P. Mueller, L.-B. Wang*, K. Bailey, R.J. Holt, Z.-T. Lu, T. O'Conner
Physics Division, Argonne National Laboratory
**University of Illinois at Urbana-Champaign*

Heavy Ion Group: J.P. Greene, D. Henderson, R. 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

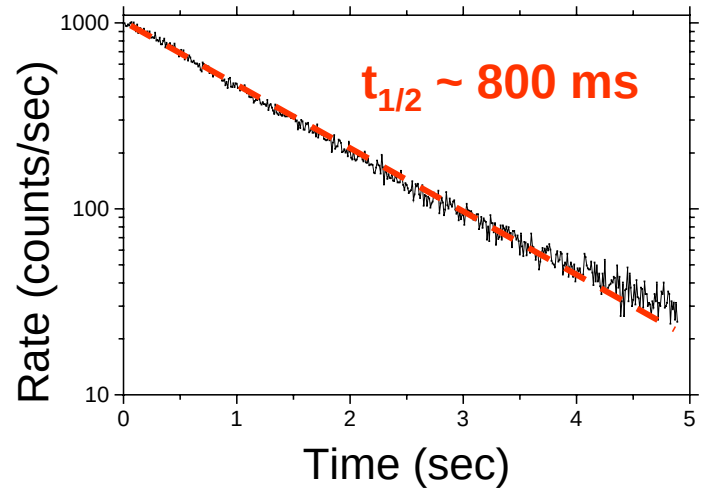
^{6}He - Production at ATLAS

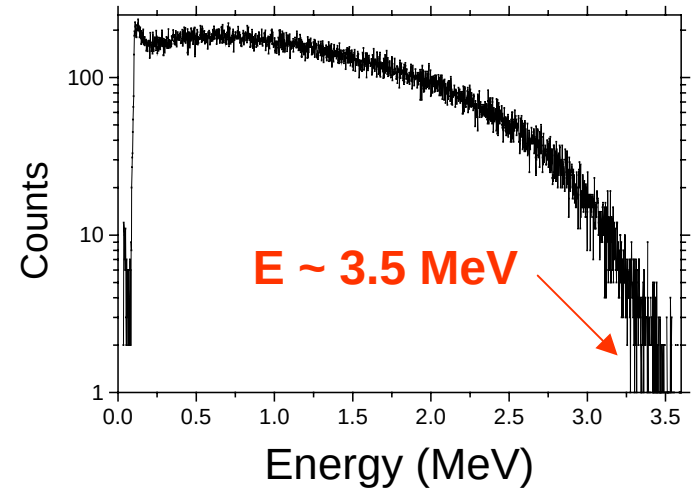
$^{12}C(^{7}Li,^{6}He)^{13}N$ - Reaction



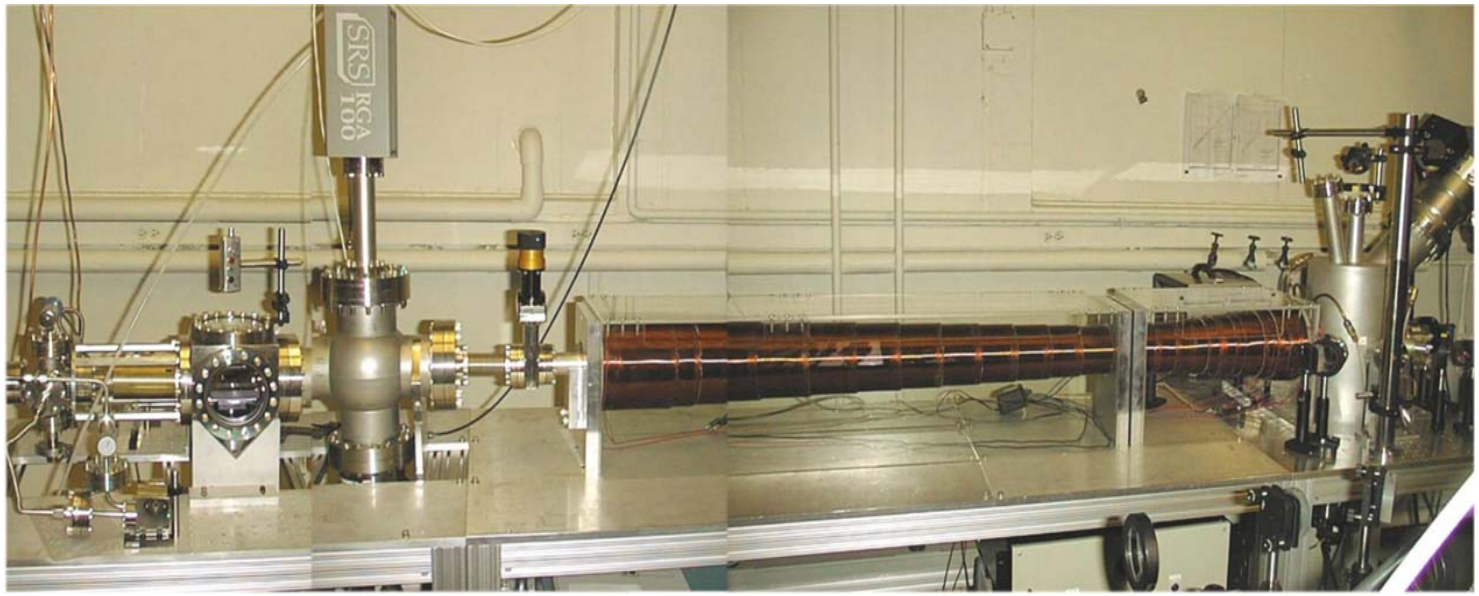
^{6}He atoms extracted: ~ 1×10^{6}/s

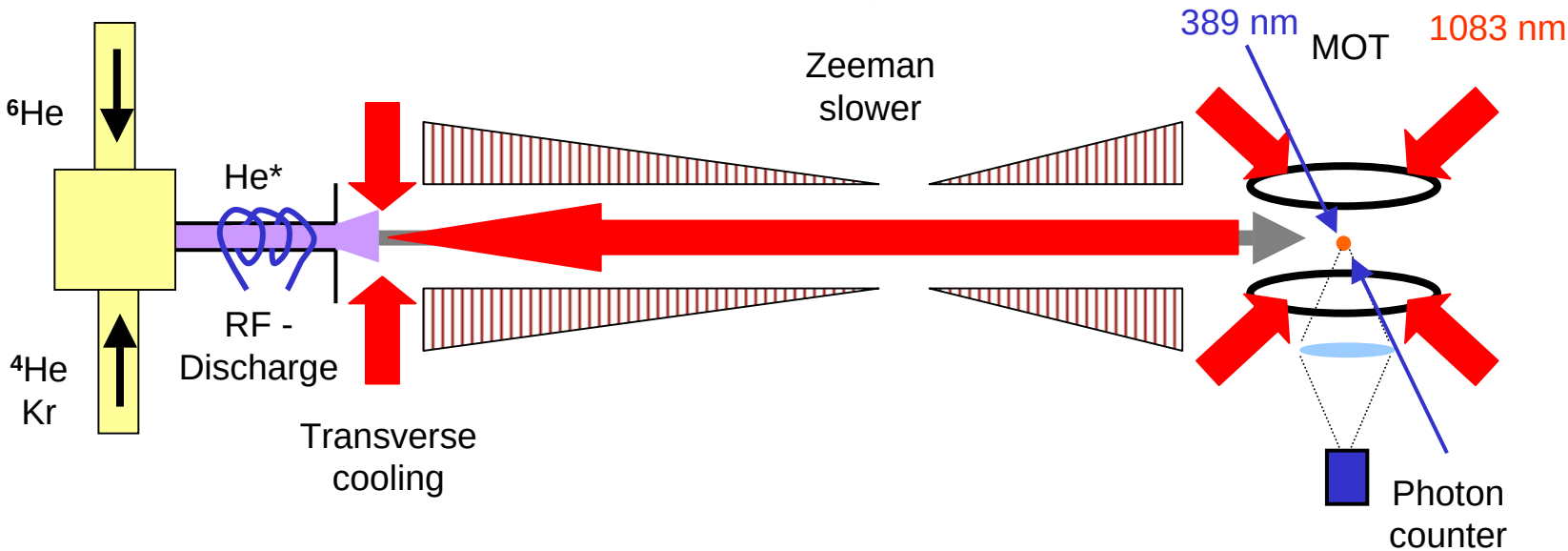
Identification of ^{6}He

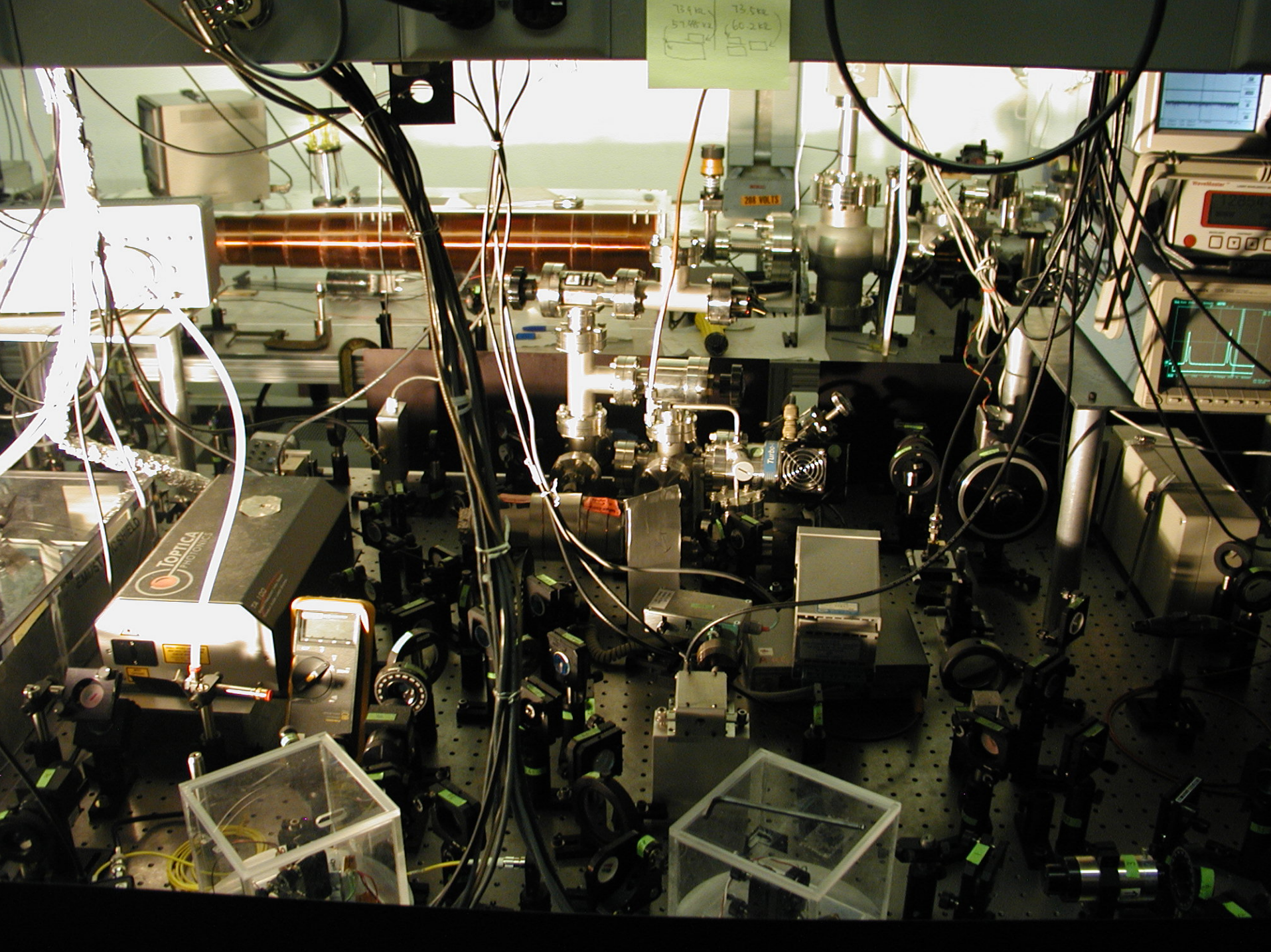




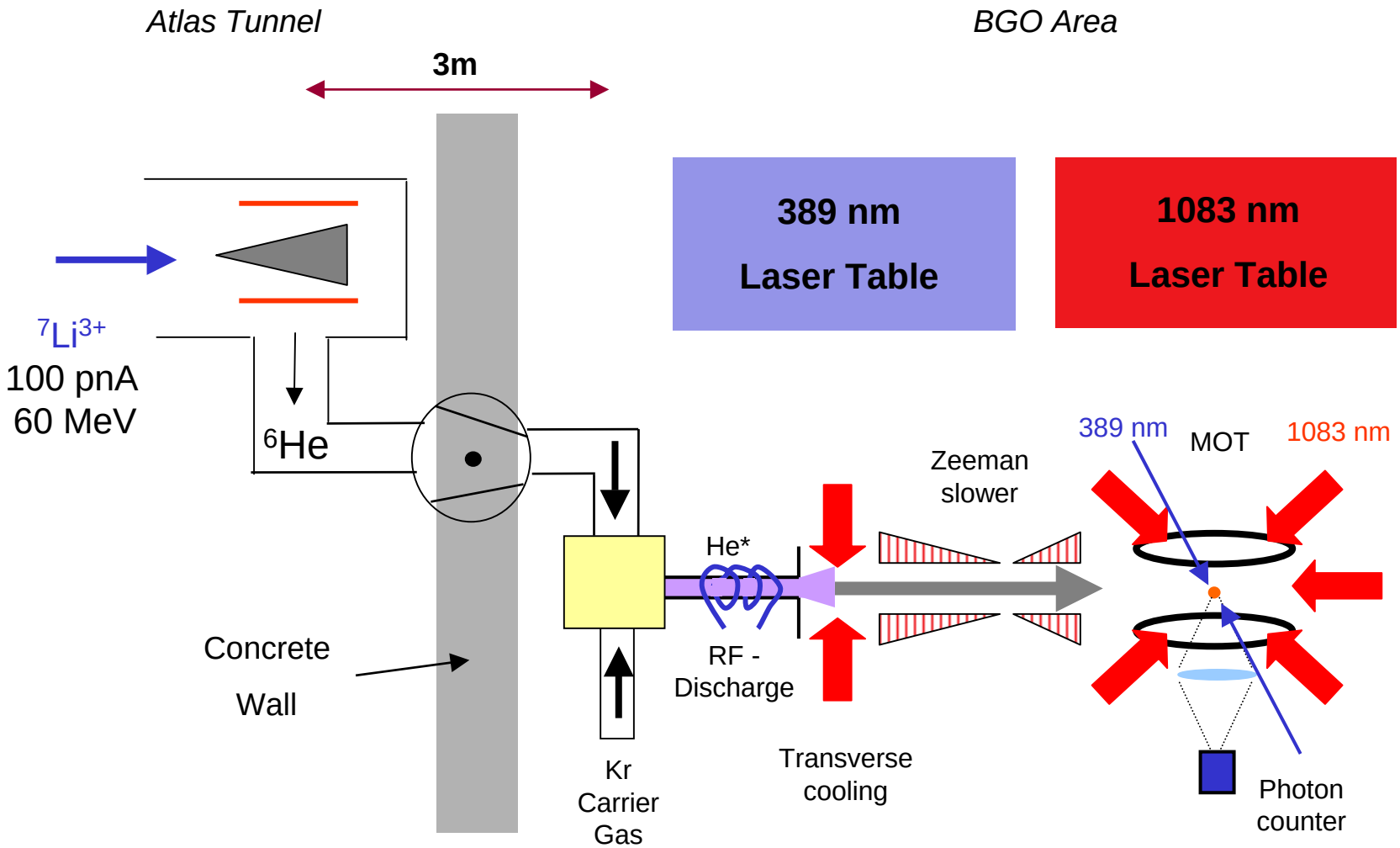
Atom Trapping of Helium






TOPTICA
PHOTONICS
Turbo

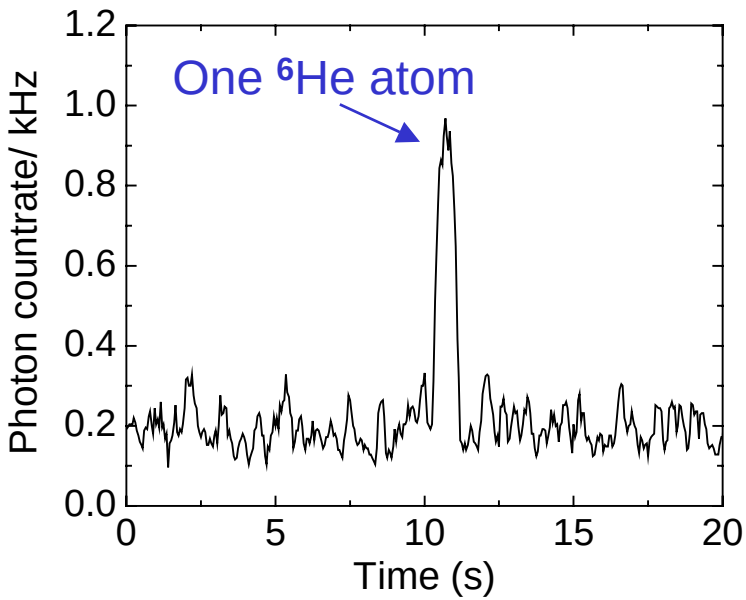
Atom Trapping of ^{6}He

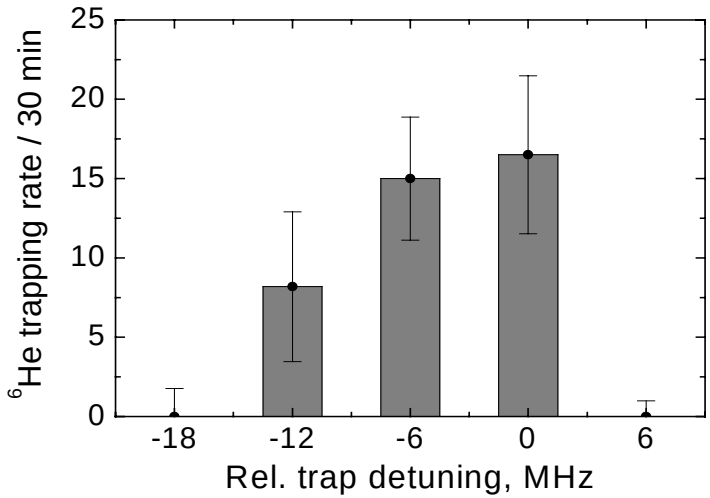


^{6}He - Single Atom Signal

- Capture efficiency ~ 10^{-8}

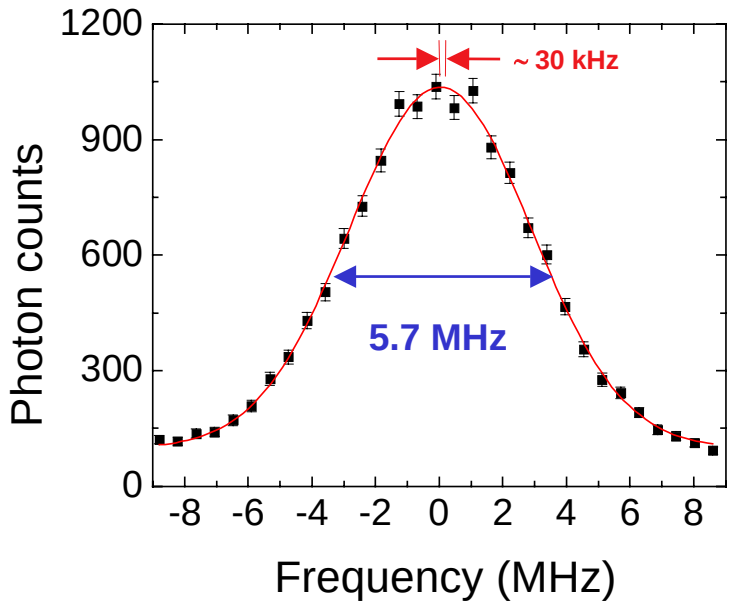
  Single atom detection necessary!
- Single-atom signal ~ 1.0 kHz
- Single-atom S/N ~ 10 in 100 ms
- ^{6}He capture rate ~ 150 per hour



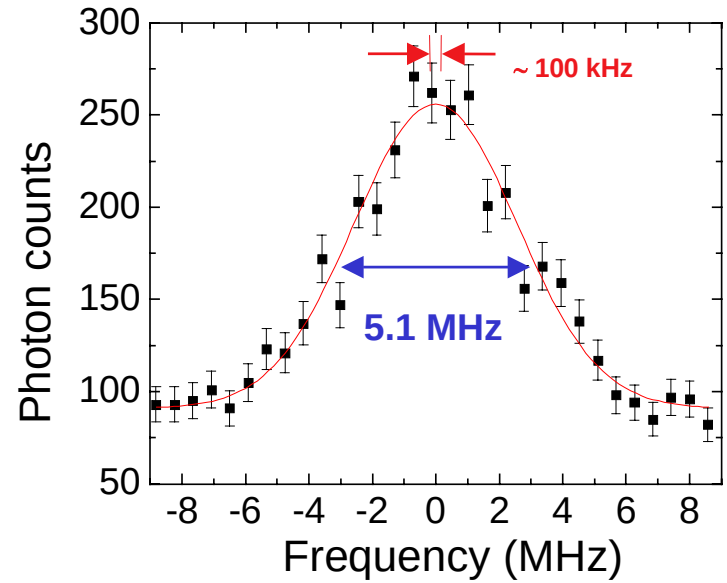


Single-Atom Spectroscopy

^{4}He



^{6}He



- 43195 GHz

~ 150 ^{6}He atoms in one hour

Isotope Shift Result

IS (2^3S_1 - 3^3P_2, ^{6}He – ^{4}He) = 43 194.772(56) MHz

RMS Charge Radius of ^{6}He $\langle r_c^2 \rangle^{1/2}$ = 2.054(14) fm (0.7%)

Error Budget

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

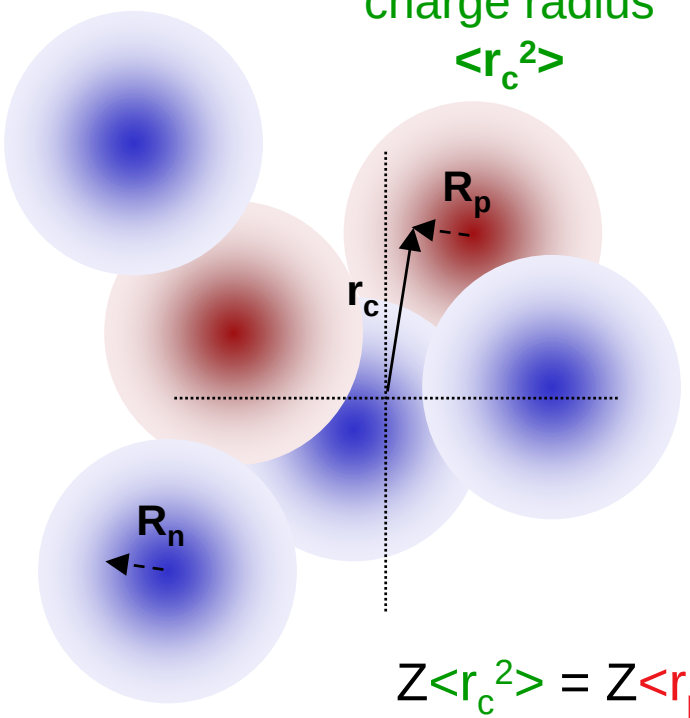
Recoil Correction

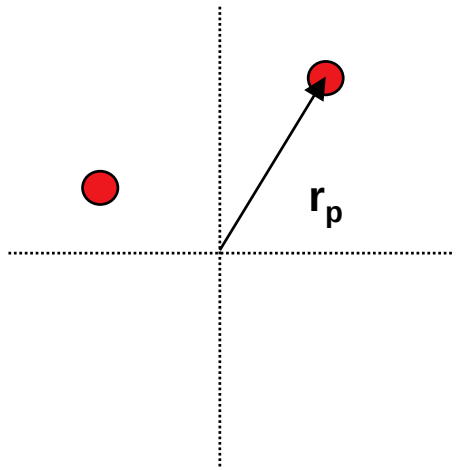
$$E_\gamma = E_{\text{int}} + \frac{P_\gamma^2}{2M_{atom}}$$

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

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

Conclusion and Outlook

^{6}He Point-Proton Radius

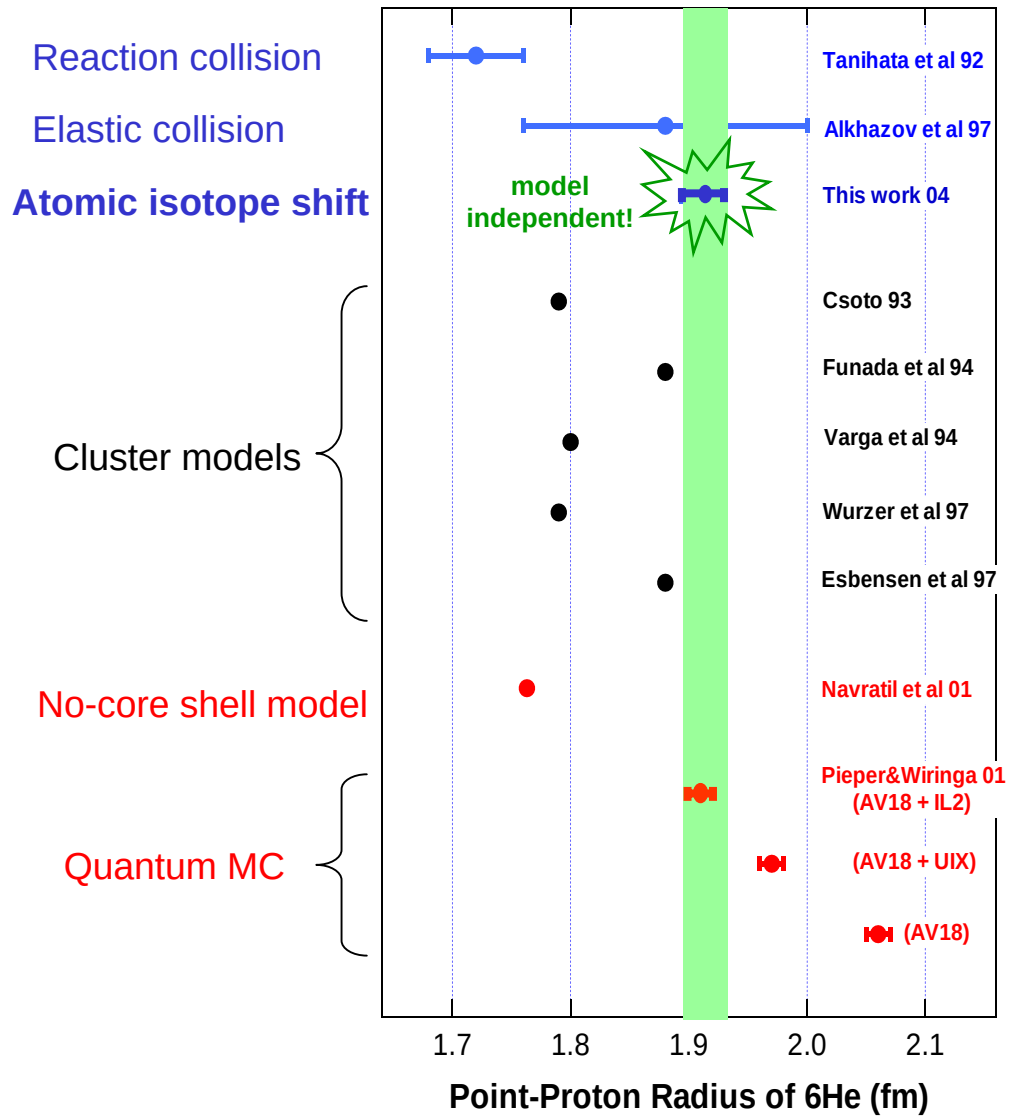
$\langle r_p^2 \rangle^{1/2} = 1.912(18)$ fm

Precision

- Spectroscopy ~ 60 kHz or 0.7%
- Proton-Neutron radii ~ 0.4%
- QMC theory ~ 0.5%

^{8}He Production Rate

- ATLAS ~ 10^4-10^5 s^{-1}
- ISOLDE >10^5 s^{-1}
- NSCL ~ 10^6 s^{-1}
- RIA ~ 10^9 s^{-1}



Thank You!

Co-Authors

L.-B. Wang, K. Bailey, J.P. Greene, D. Henderson, R.J. Holt, R.V.F. Janssens, C.L. Jiang, Z.-T. Lu, T.P. O'Connor, R.C. Pardo, K.E. Rehm, J.P. Schiffer, X.D. Tang

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G.W.F. Drake

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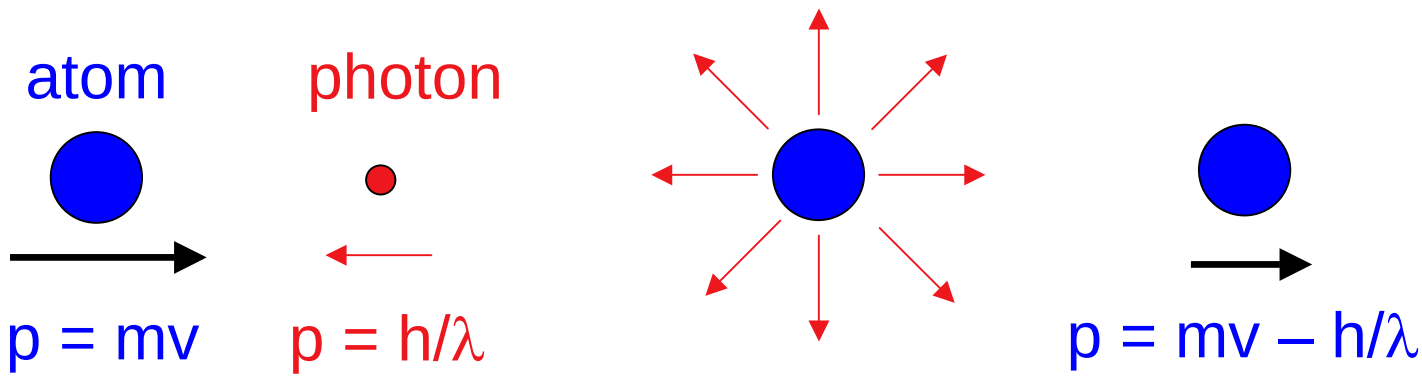
Other Collaborators

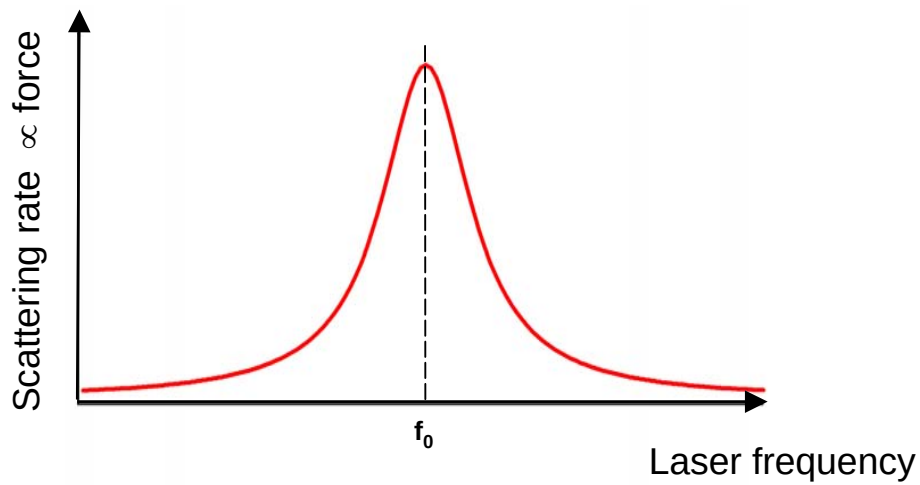
P. Collon, X. Du, A.M. Heinz, C. Law, I.D. Moore, M. Paul, T. Pennington

$$$

DOE, Office of Nuclear Physics

Manipulating Neutral Atoms with Light



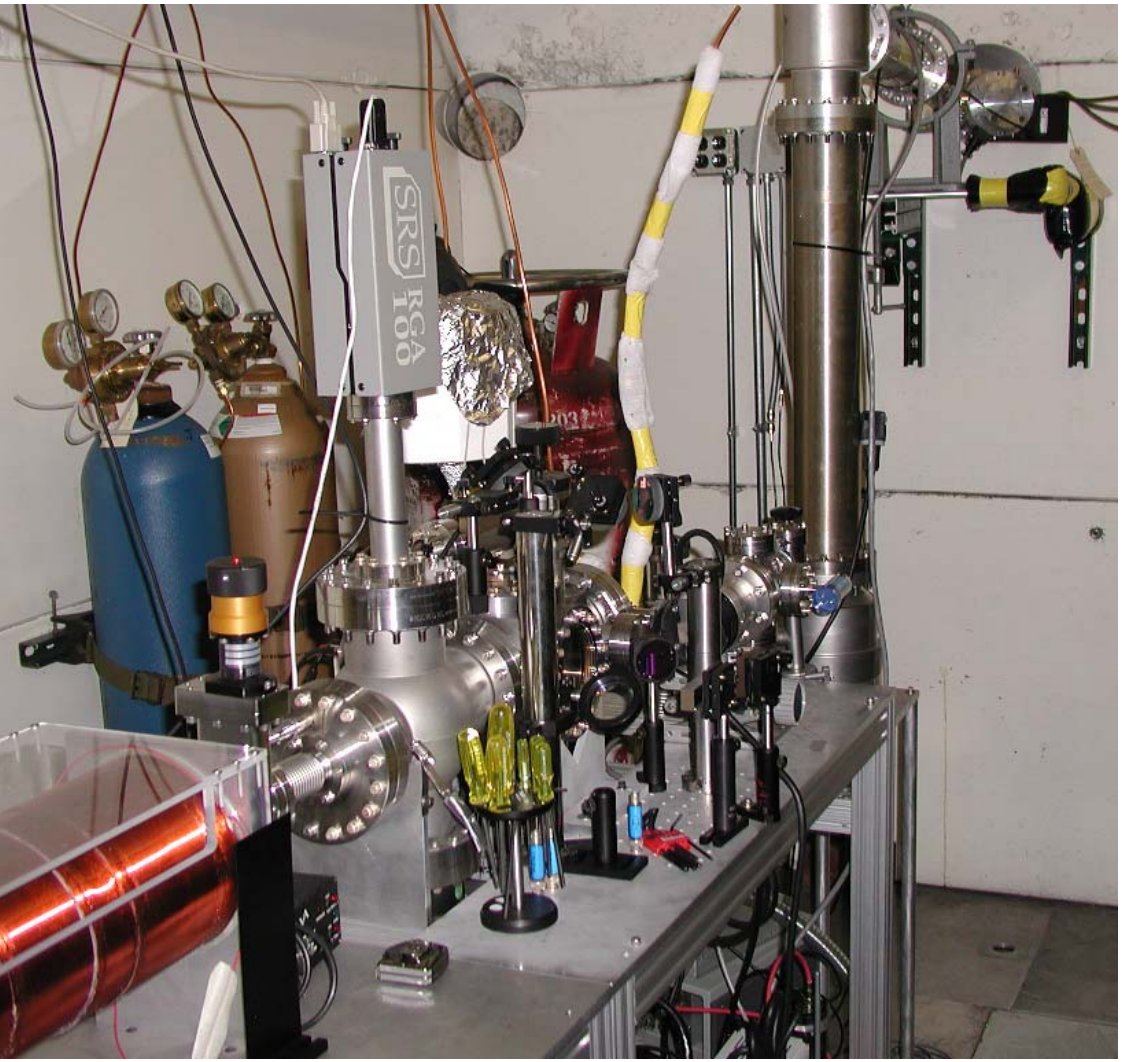


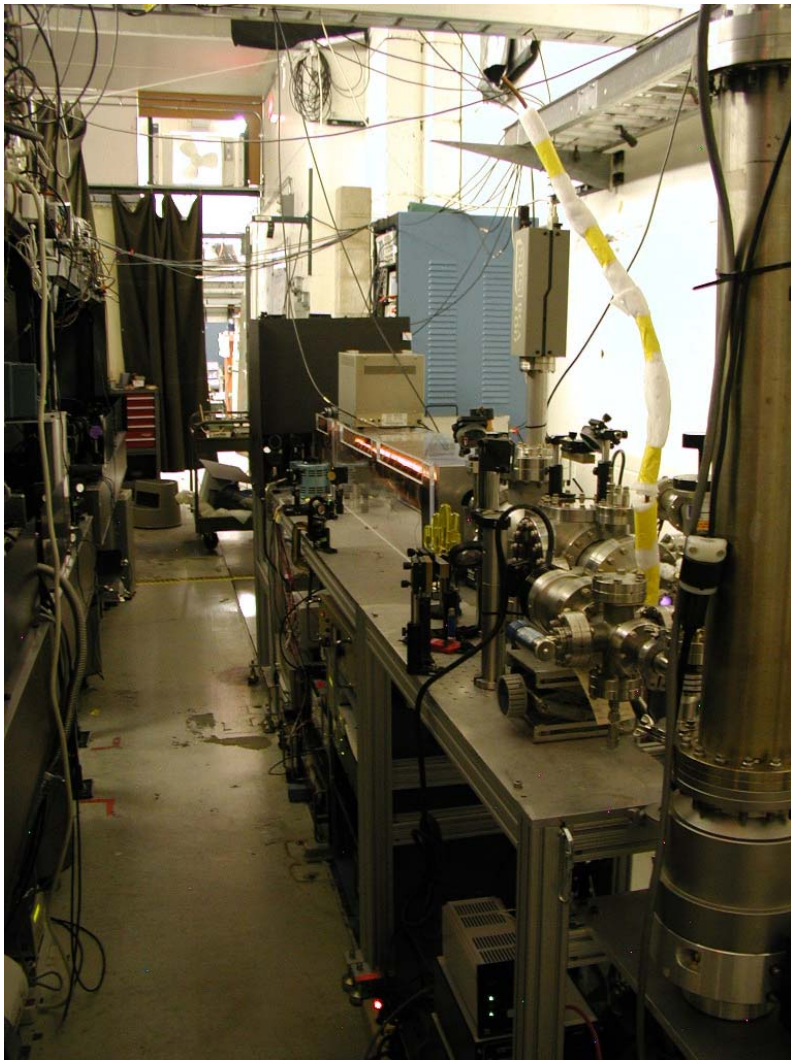
$\tau \sim 100$ ns

scattering rate ~ 5 MHz

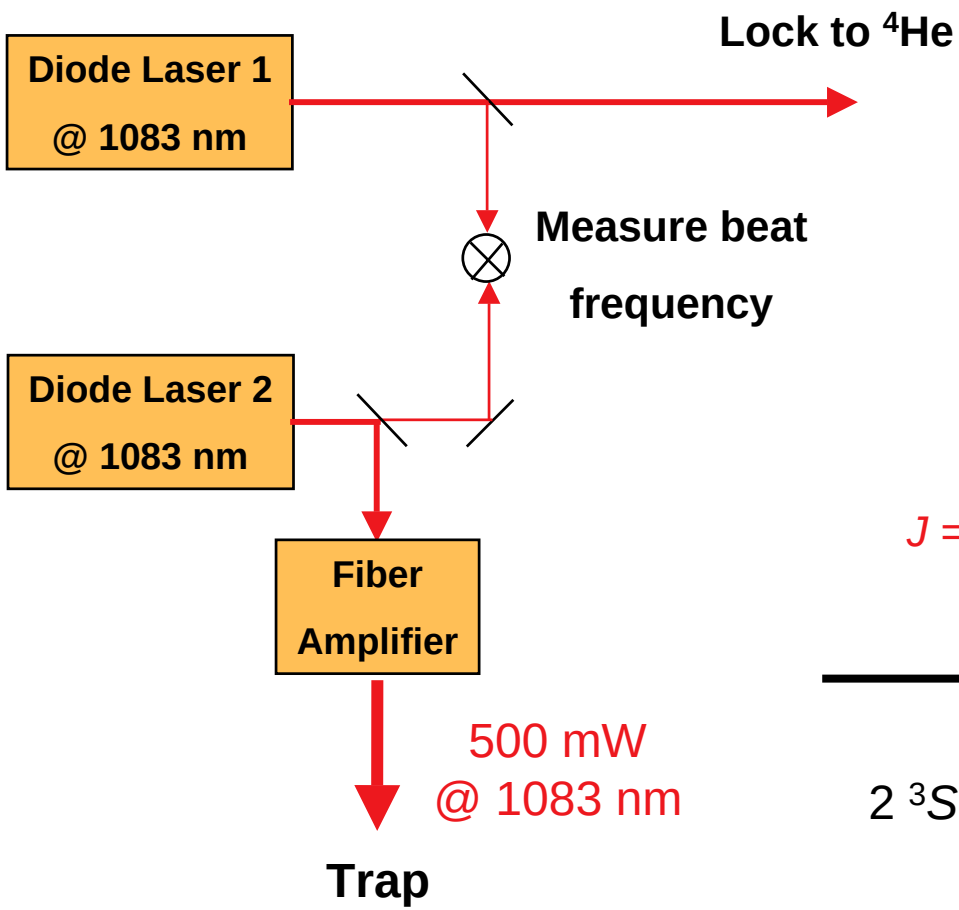
$a \sim 10^4$ m/s²

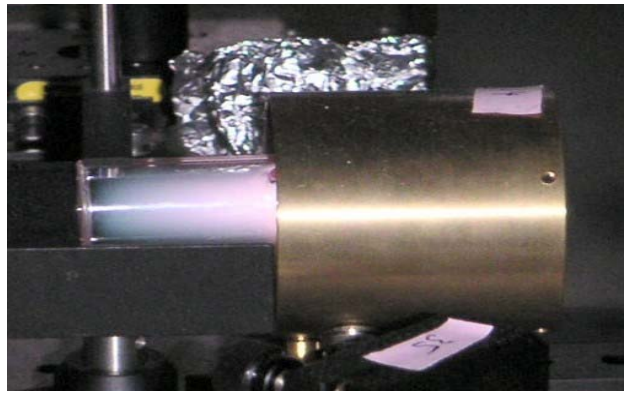
Trap On-Line at ATLAS

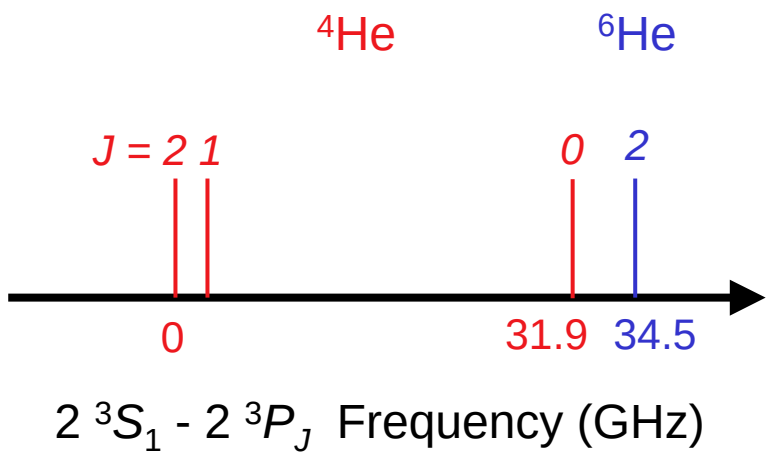




Laser Setup - 1083 nm



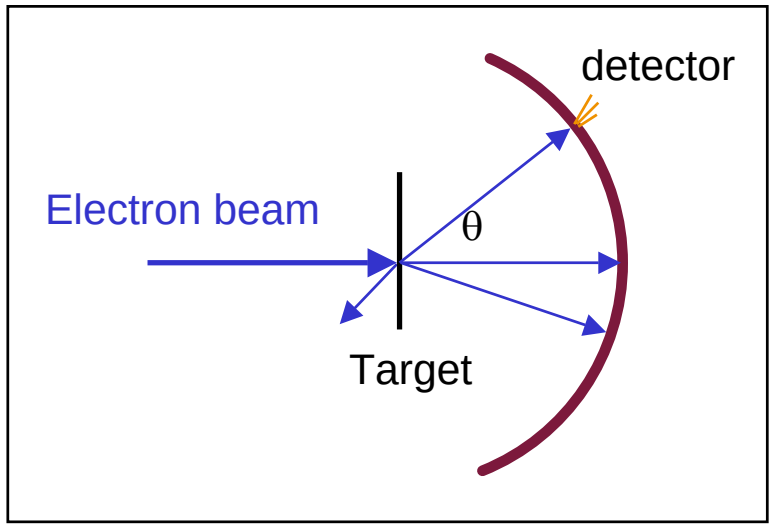




Electron Scattering

- Point-charge

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



- Nuclei with finite size

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

$$< r^2 >_{charge} = -6\hbar^2 \left.\frac{dF(q^2)}{dq^2}\right|_{q^2=0}$$

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

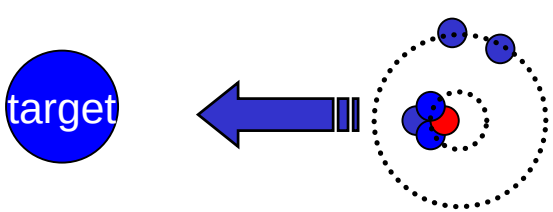
Inverse Kinematik Proton Scattering

- Interaction cross section
  $\sigma_I = \pi(R_{target}+R_{beam})^2$

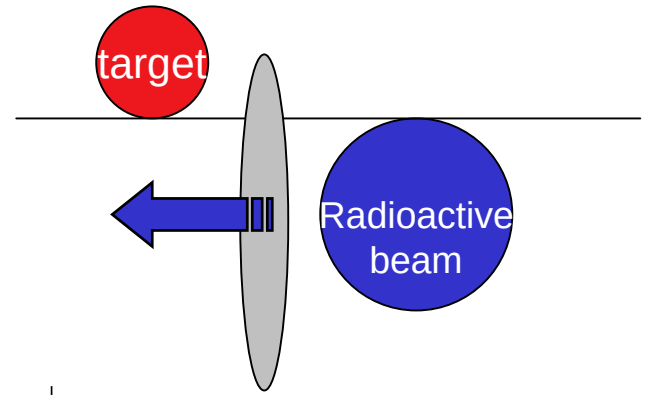
- Can not separate proton and neutron distribution model-independently

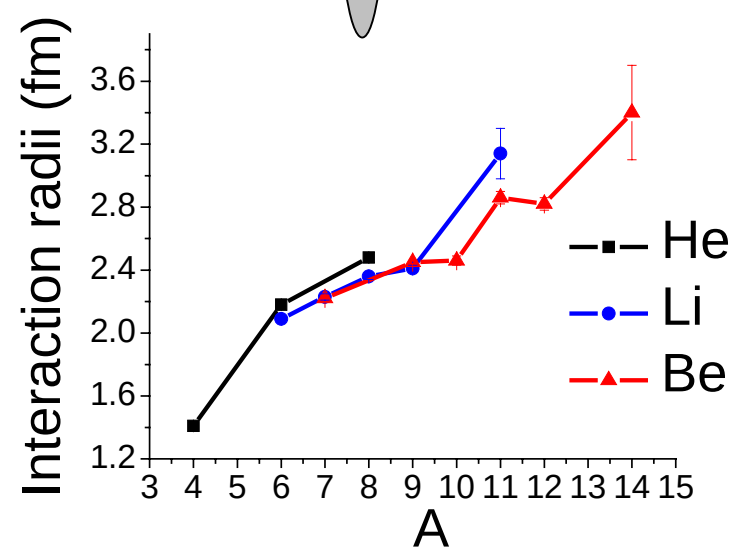
- First observation of "halo nuclei" by Tanihata, 1985

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



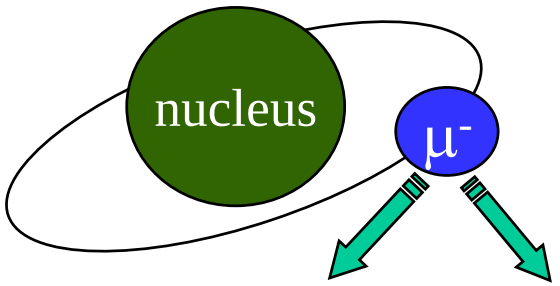
Proton (Hydrogen) target





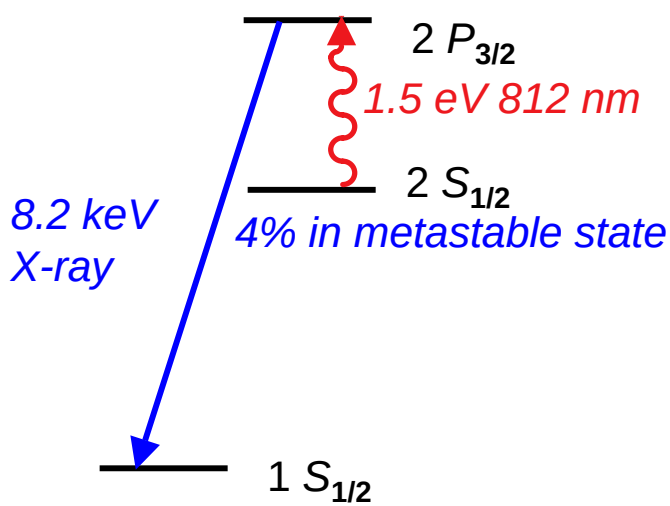
I. Tanihata, *et al.*, PRL **55**, 2676, (1985)

Muonic Atom X-Ray Spectroscopy



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

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~

$$\Delta |\Psi(0)|^2 \langle r^2 \rangle$$

- Sensitivity ~ $(m_\mu/m_e)^2$

- $\delta\nu(2S_{1/2}\text{-}2P_{3/2}) = 1.813 - 0.102\langle r^2\rangle$ eV
- $\langle r^2\rangle^{1/2}(^4He) = 1.673(1)$ fm,

Carboni et al., Nucl. Phys. A278, (1977)