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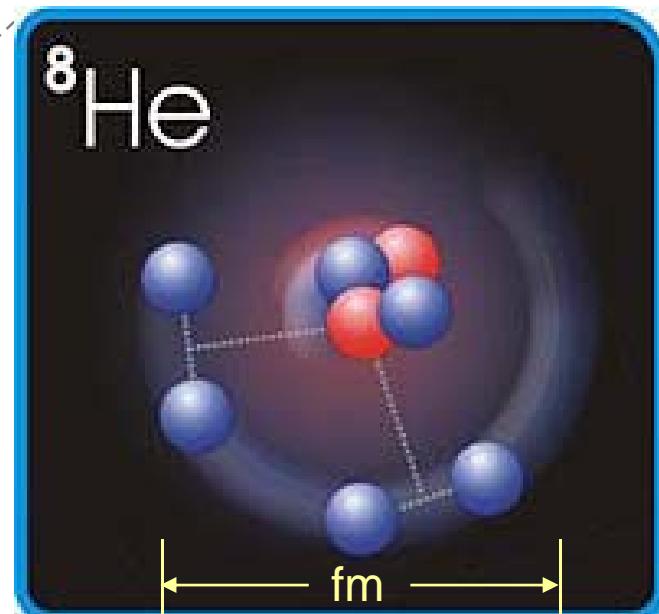
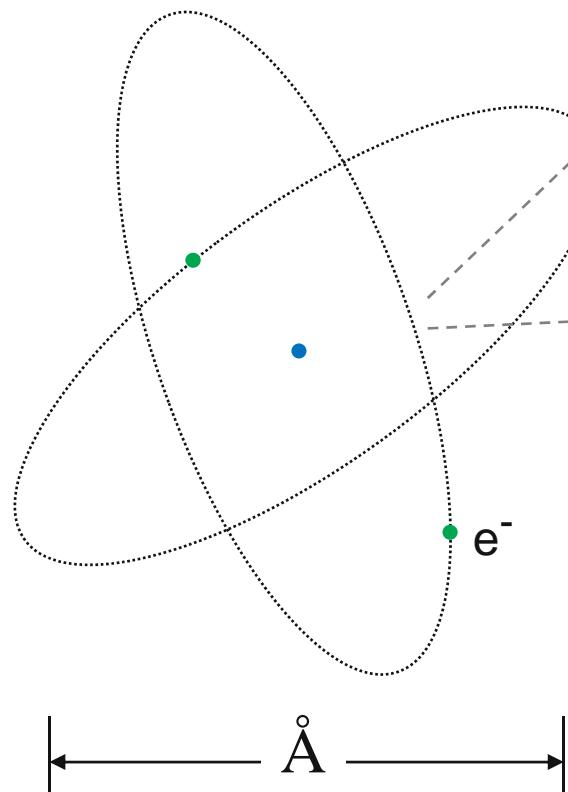
Simple Atom, Extreme Nucleus: Laser Trapping and Probing of He-8

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Argonne National Laboratory
University of Chicago

Funding: DOE, Office of Nuclear Physics

Helium Atom



Ionization Energy of Helium Atom

Level 2 3S_1

Calculation $1\ 152\ 842\ 741 \pm 6$ MHz

Experiment $1\ 152\ 842\ 743$ MHz

Gordon Drake, Phys. Scripta (1999)

Effective Model of Nuclear Interaction

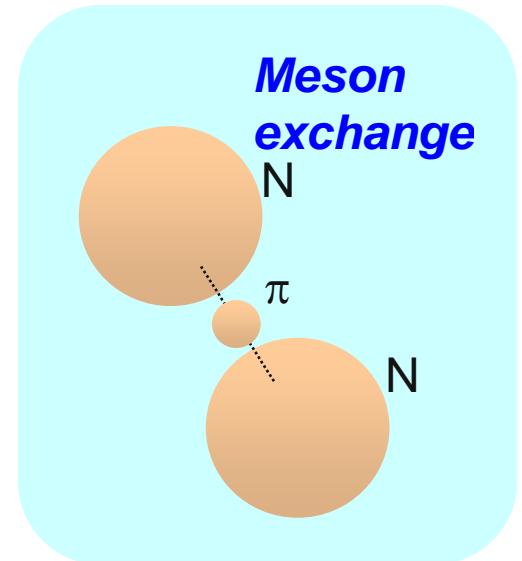
Two-body potential: *Argonne V18*

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

EM 1- π short-range

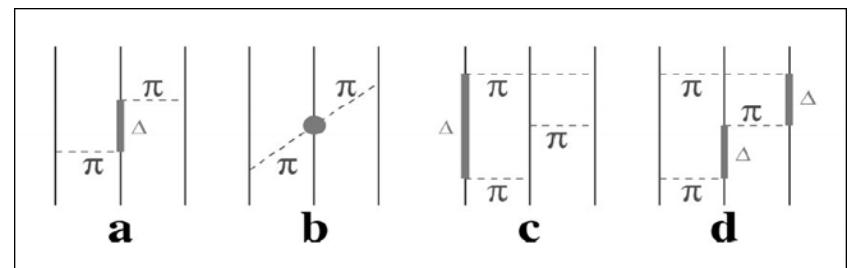
Coupling parameters fit to NN scattering data

Problem: binding energy of most light nuclei too small



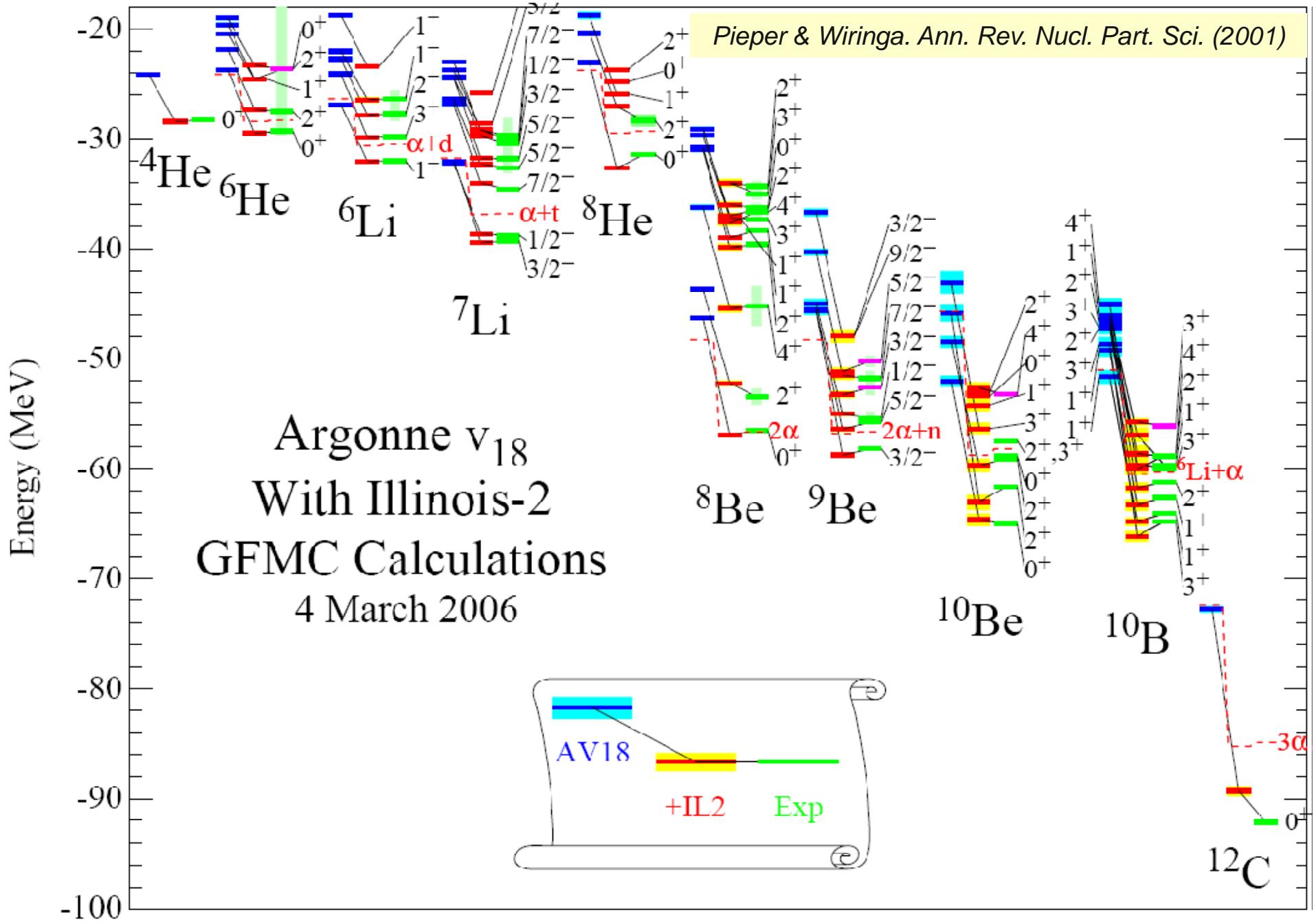
Three-body potential: *Illinois-2*

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



Coupling parameters fit to energy levels of light nuclei

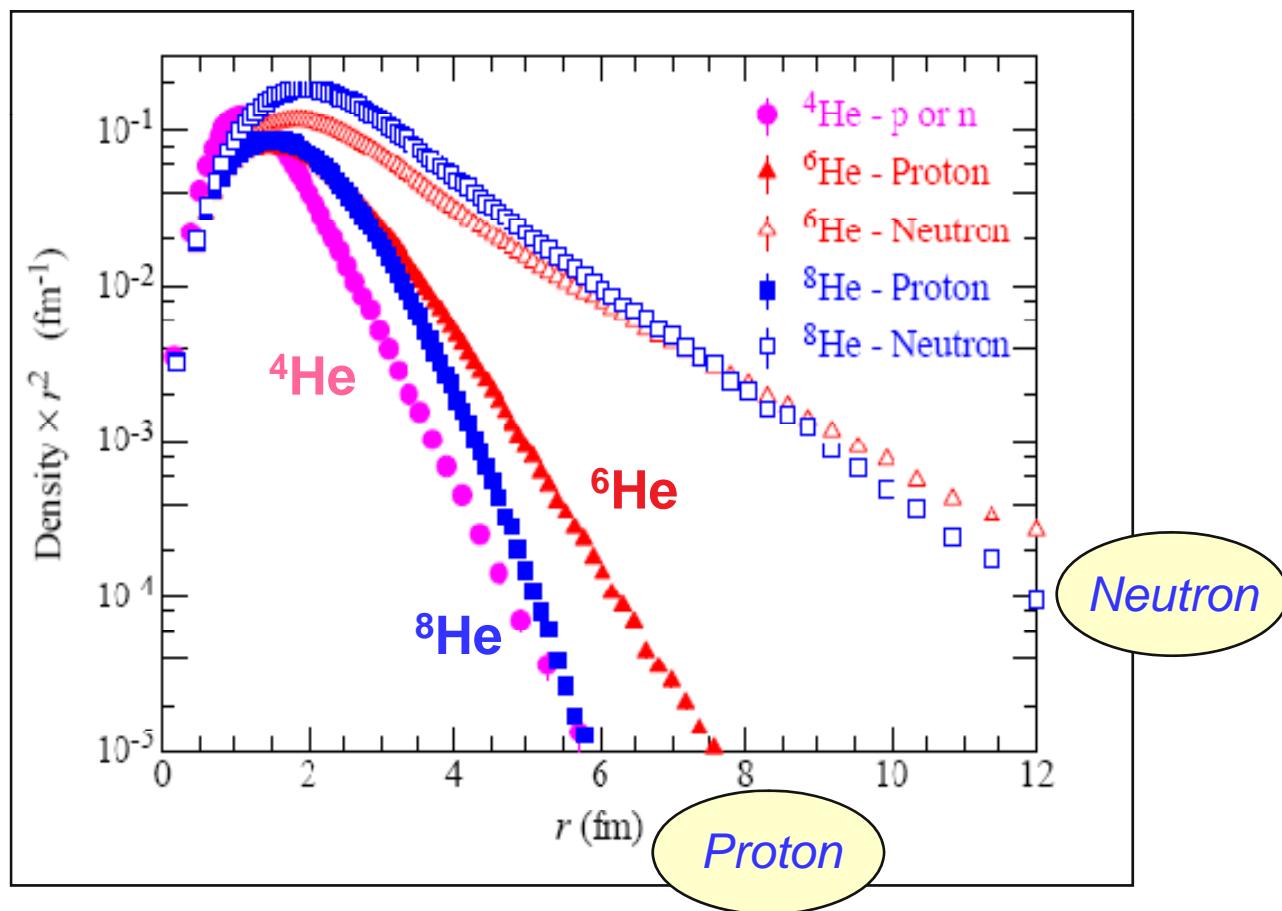
Quantum Monte Carlo Calculations of Light Nuclei



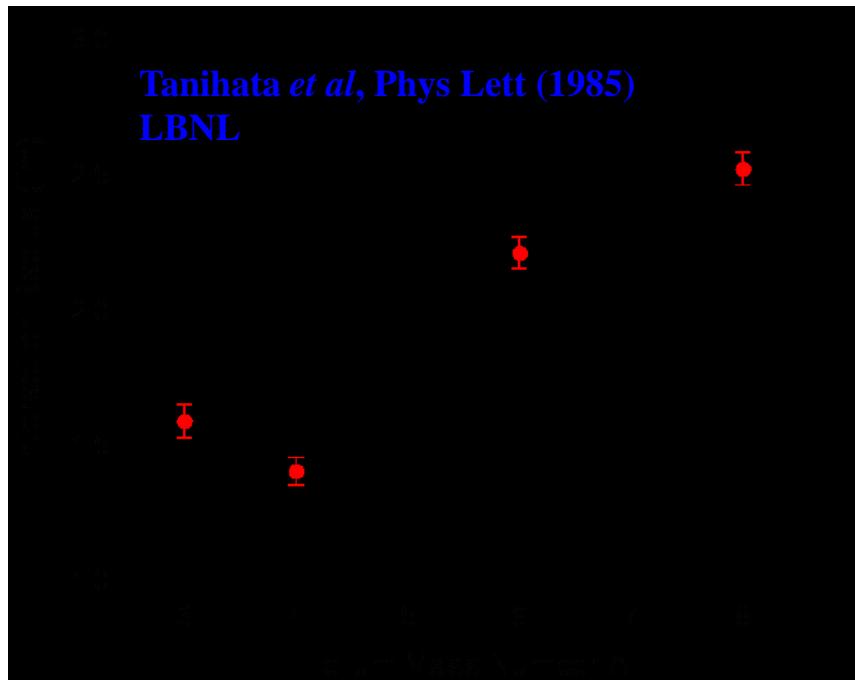
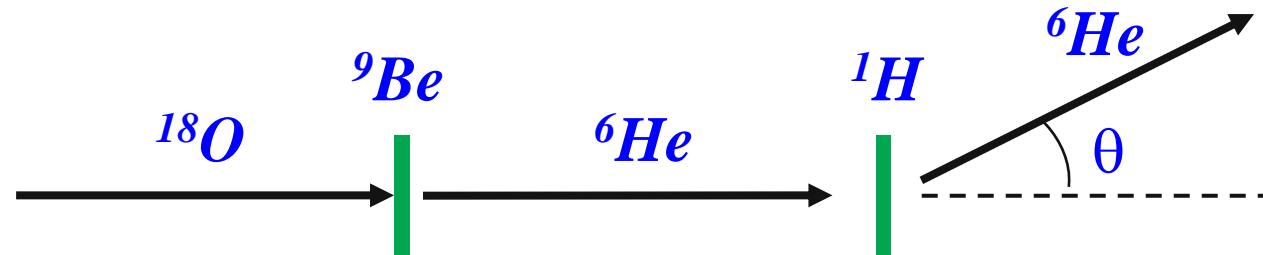
Halo Nuclei ${}^6\text{He}$ and ${}^8\text{He}$

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

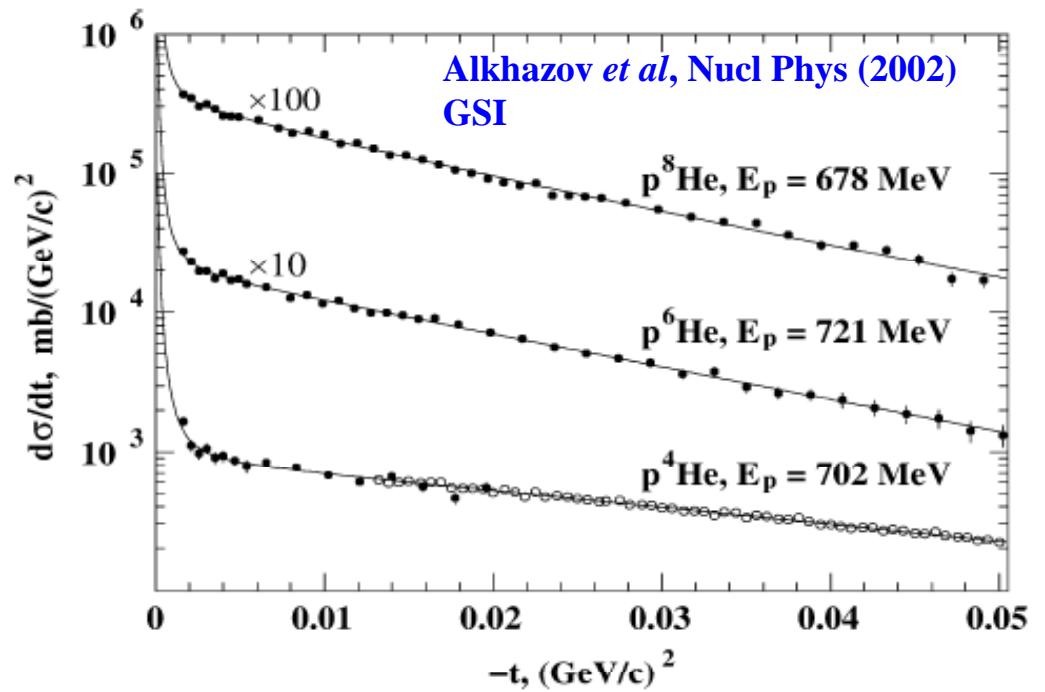
Quantum
Monte Carlo
calculation



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



Elastic and inelastic collision: He on C, B



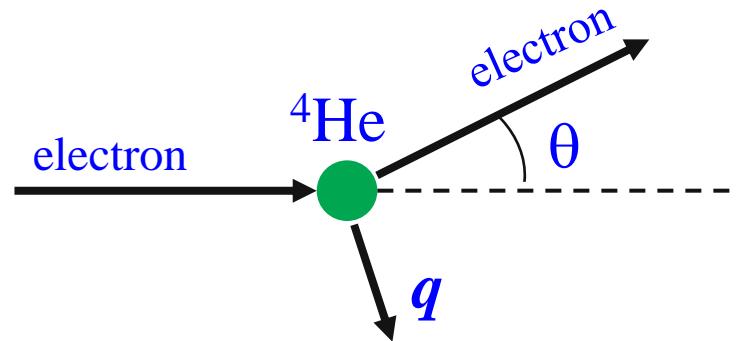
Elastic collision: He on H, 700 MeV/u

Matter distribution, matter radii

E&M Probe of Nuclear Charge Distribution

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

$$F(q^2) = 1 - \frac{1}{6} q^2 \langle r^2 \rangle_{\text{charge}} + \dots$$



mean-square radius $\langle r^2 \rangle = \int \rho(r) \cdot r^2 d\nu$

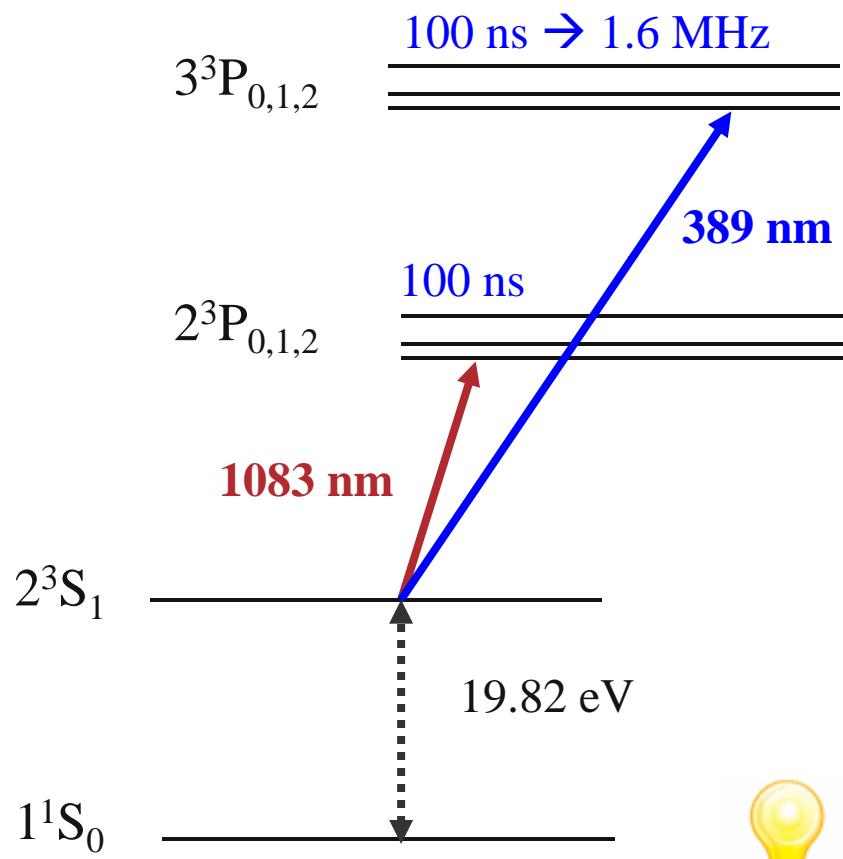
root-mean-square radius $\sqrt{\langle r^2 \rangle}$

${}^4\text{He}$ 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)]

Atomic Energy Levels of Helium

He energy level diagram



Cooling & Trapping at 1083 nm

- Single photon kick $\rightarrow 0.1 \text{ m/s}$
- Transition rate $\sim 4 \times 10^6 / \text{s}$
- Acceleration $\sim 4 \times 10^5 \text{ m/s}^2$

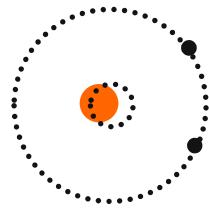
Spectroscopy at 389 nm

- Single photon kick $\rightarrow 0.3 \text{ m/s}$
- Doppler shift $\rightarrow 400 \text{ kHz}$

Atomic Isotope Shift

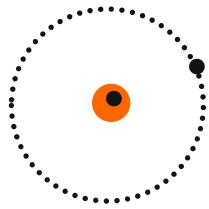
$$Isotope\ Shift \quad \delta\nu = \delta\nu_{MS} + \delta\nu_{FS}$$

Mass shift: due to nucleus recoil



$$\delta\nu_{MS} \propto \frac{m_e}{1 + \frac{m_e}{M_N}} \approx m_e \left(1 - \frac{m_e}{M_N} \right)$$

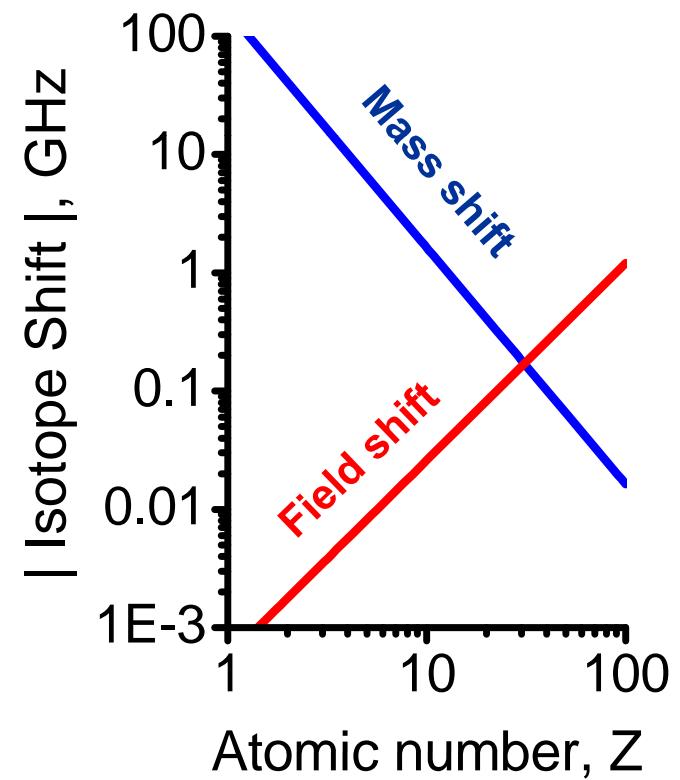
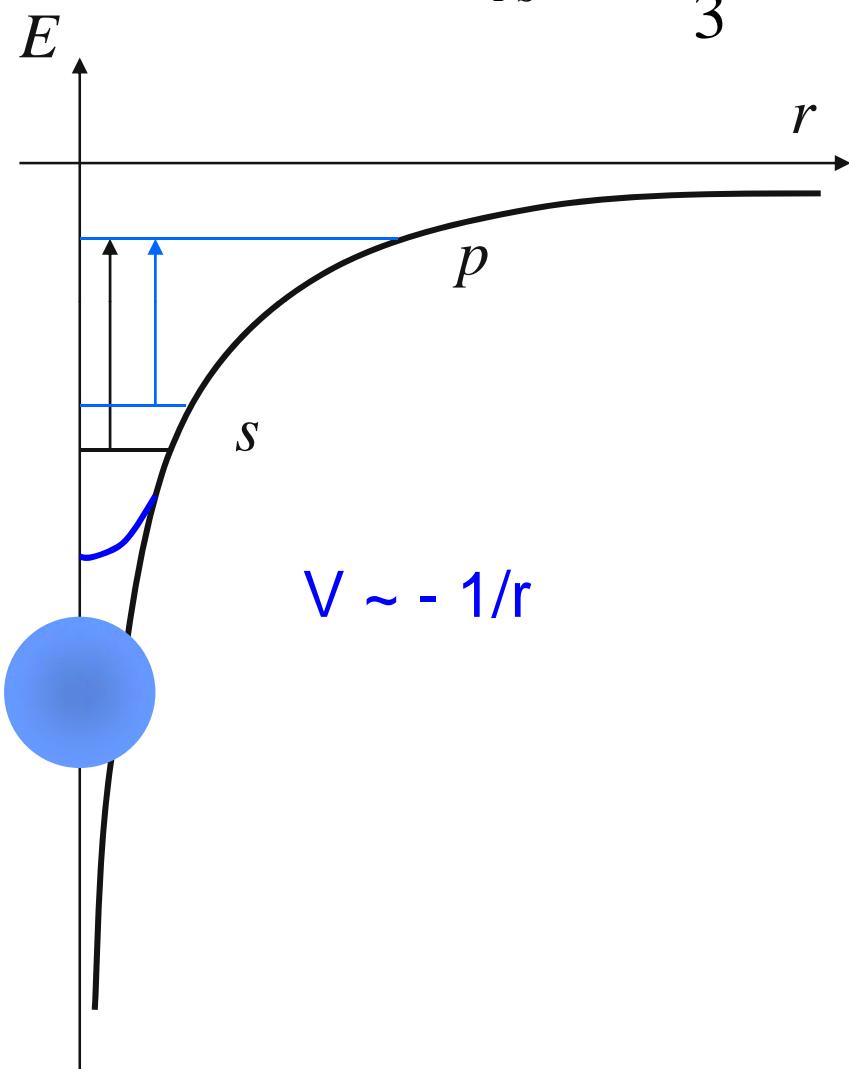
Field shift: due to nucleus size



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

Field (Volume) Shift

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

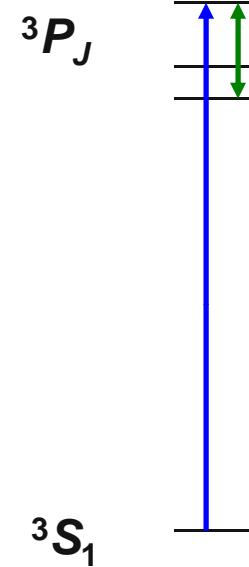


Atomic Theory of Helium

Drake, Can. J. Phys (2006);

Pachucki & Sapirstein, J Phys B (2002)

- ◆ 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



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

$${}^6\text{He} - {}^4\text{He} : \delta\nu_{6,4} = 43196.207(15) \text{ MHz} + 1.008 (\langle r^2 \rangle_{\text{He}4} - \langle r^2 \rangle_{\text{He}6}) \text{ MHz/fm}^2$$

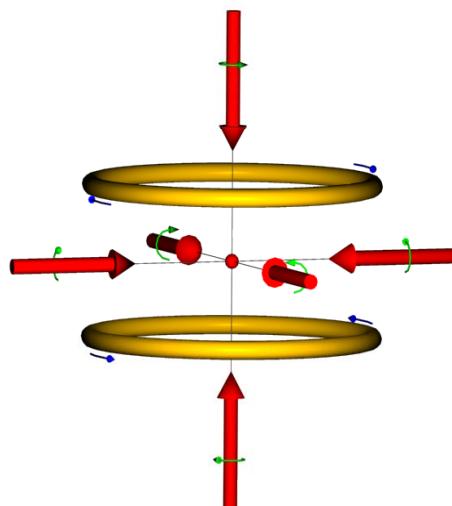
$${}^8\text{He} - {}^4\text{He} : \delta\nu_{8,4} = 64702.409(74) \text{ MHz} + 1.008 (\langle r^2 \rangle_{\text{He}4} - \langle r^2 \rangle_{\text{He}8}) \text{ MHz/fm}^2$$

100 kHz error in IS \leftrightarrow ~1% error in radius

Laser Cooling and Trapping

Technical challenges:

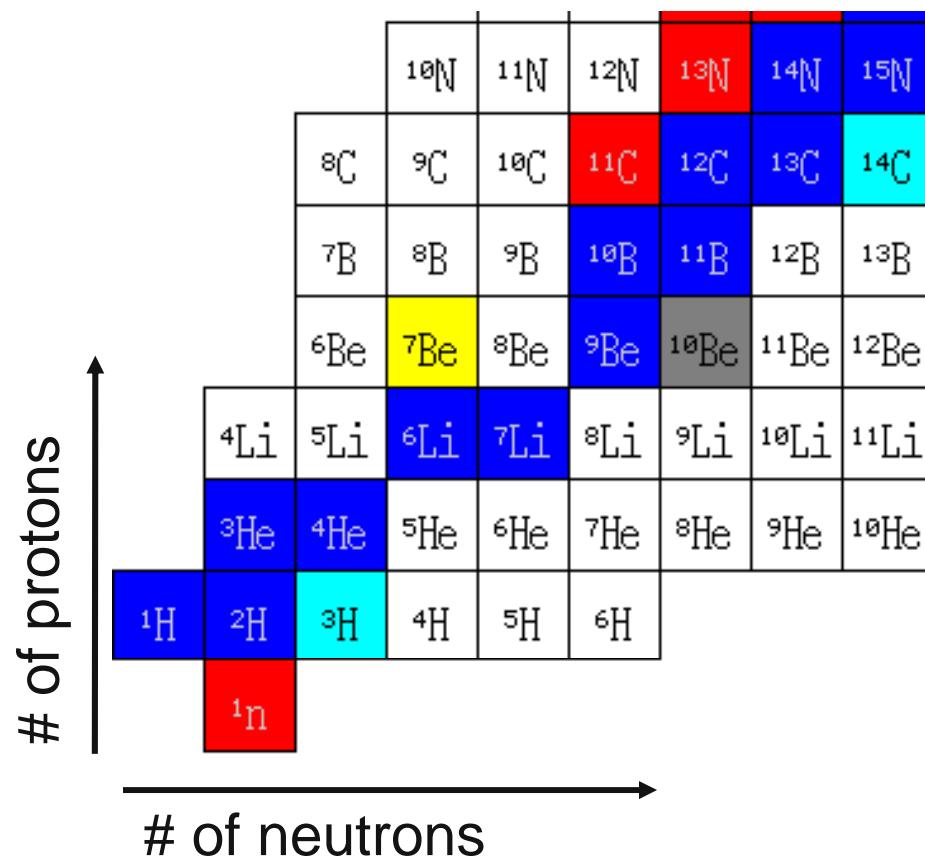
- Short lifetime, small samples ($< 10^6$ atoms/s available)
- Metastable efficiency $\sim 10^{-5}$
- Precision requirement (~ 100 kHz)

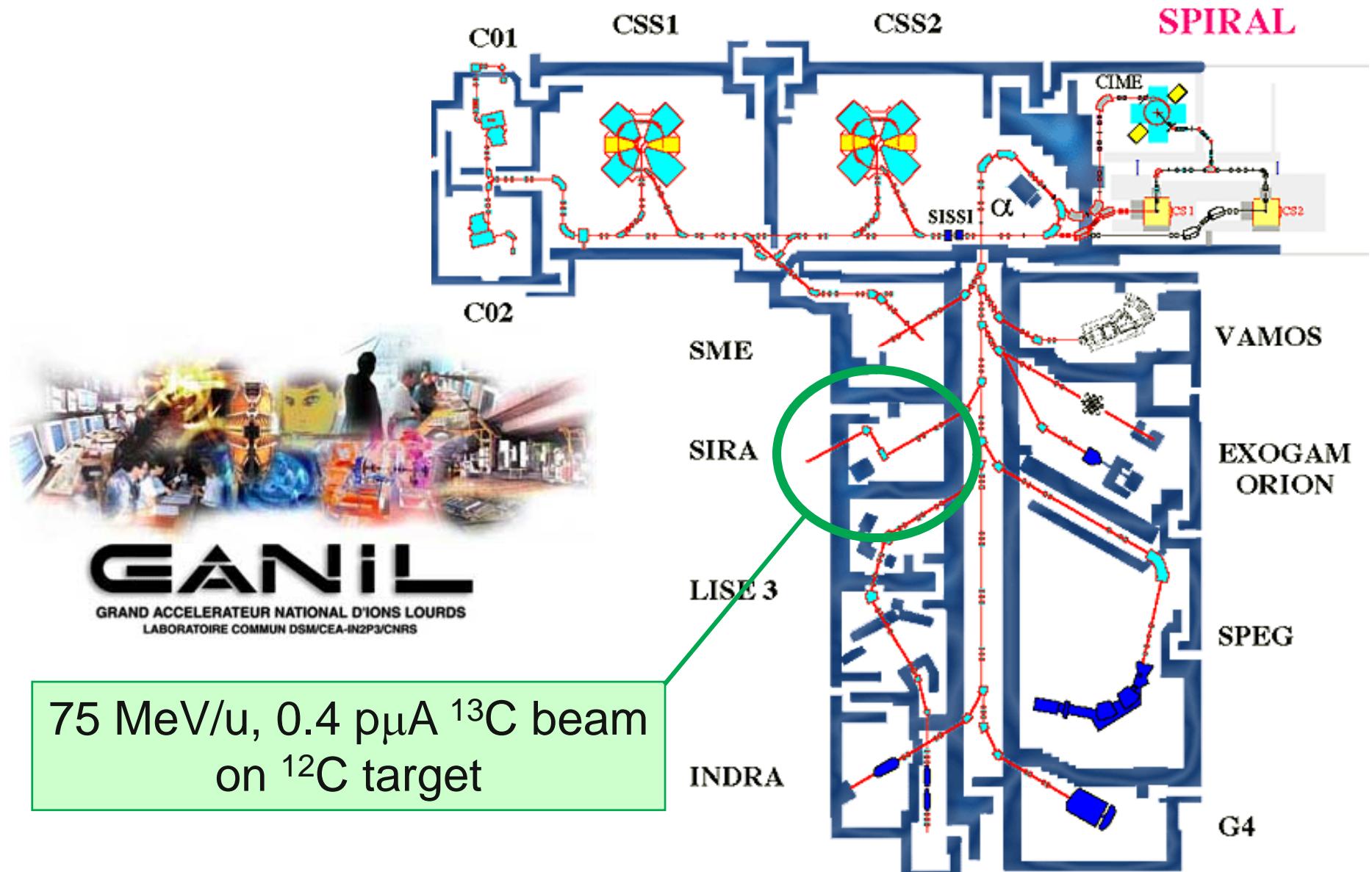


Magneto-Optical Trap (MOT)

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

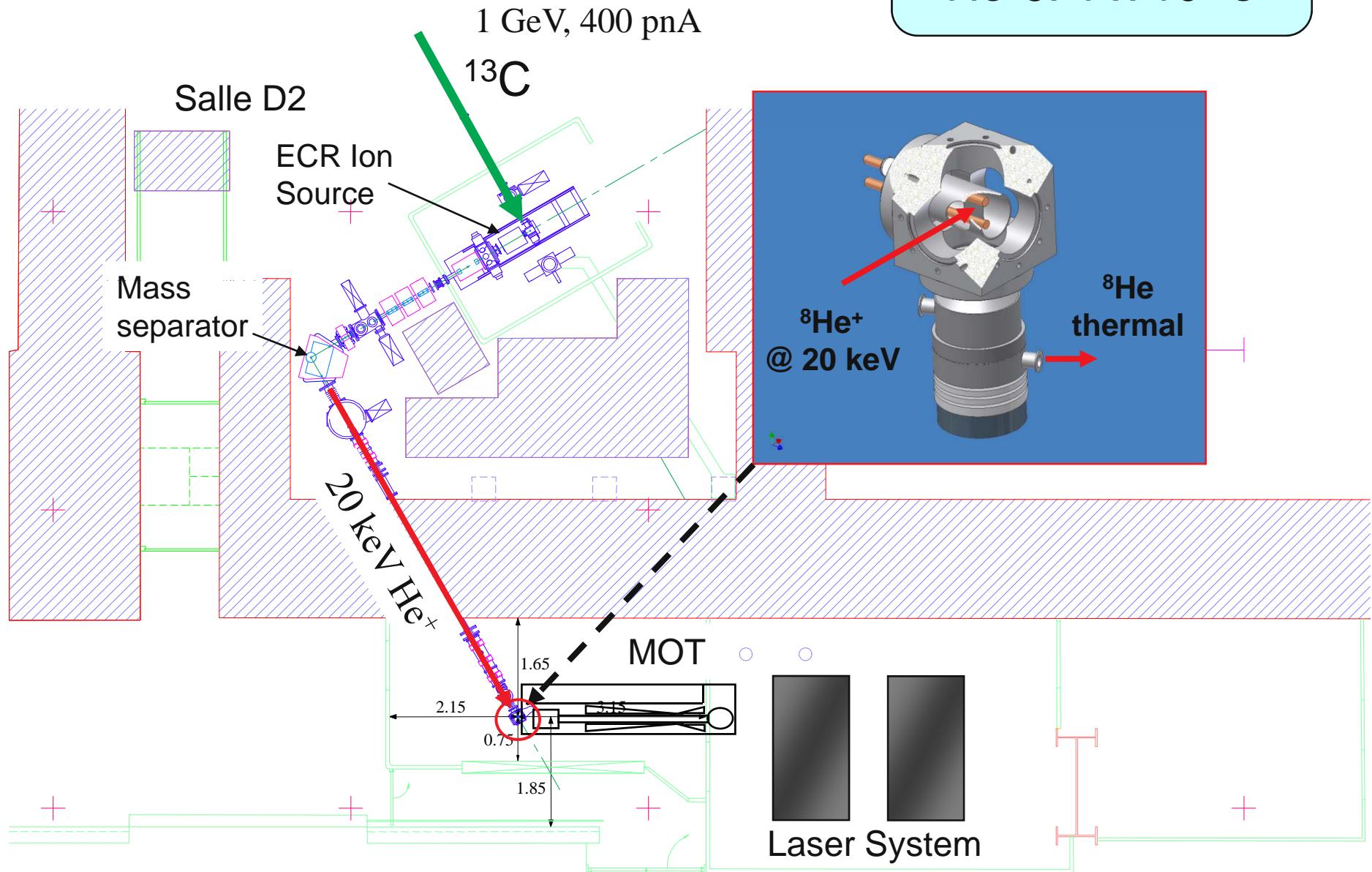
^8He : The Most Neutron-Rich Nucleus



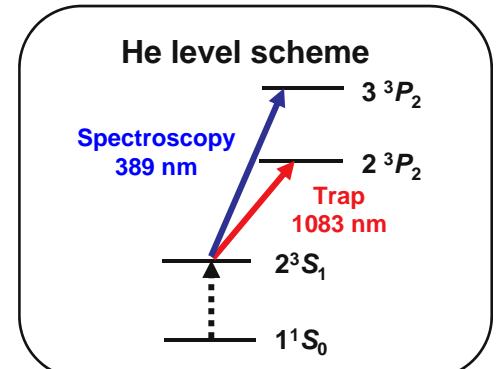
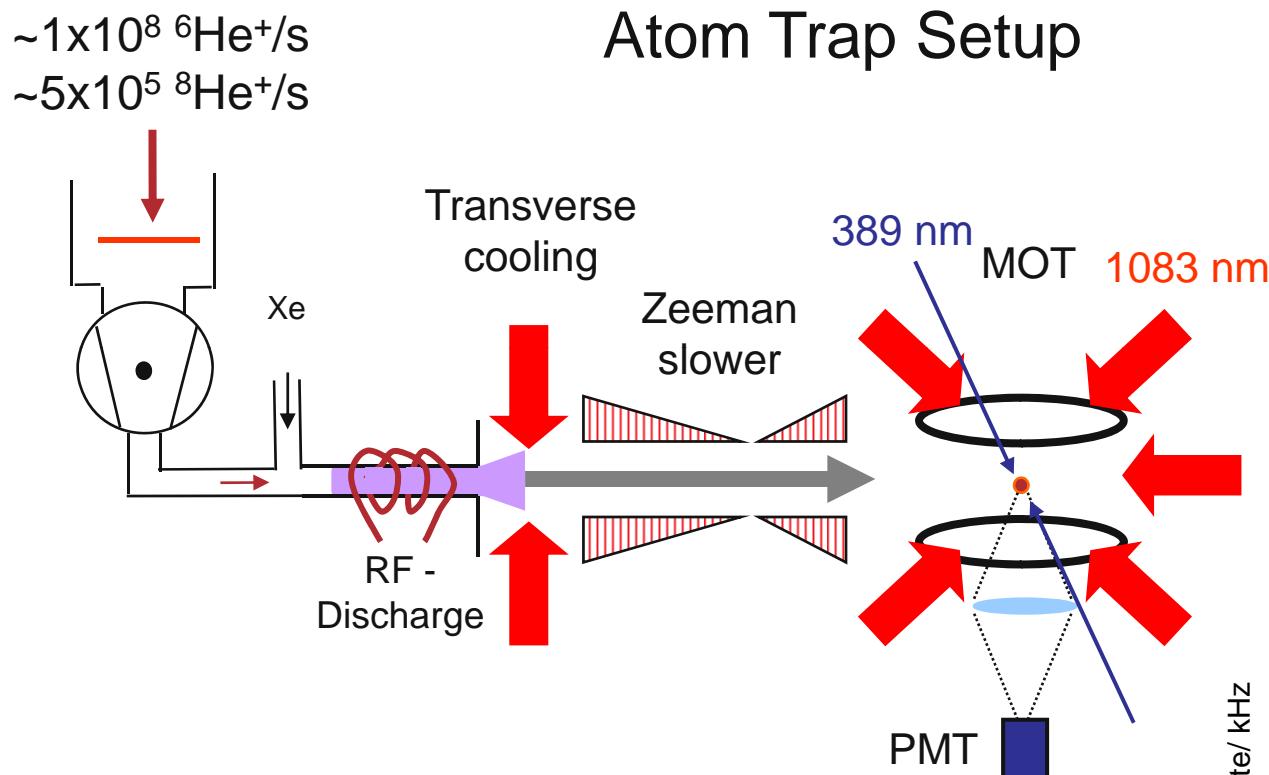


${}^8\text{He}$ @ GANIL by Antonio Villari *et al.*

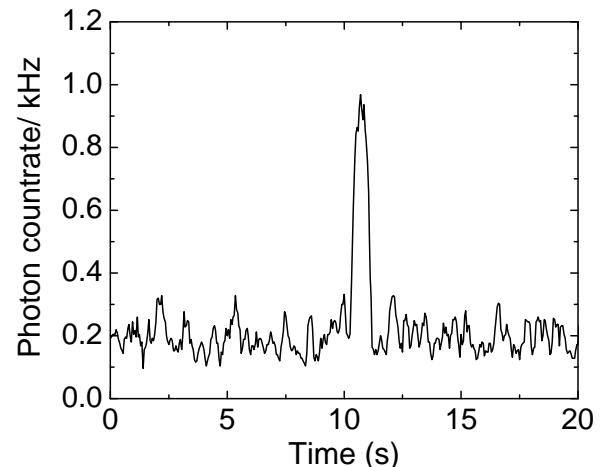
- He-8: $5 \times 10^5 \text{ s}^{-1}$
- He-6: $1 \times 10^8 \text{ s}^{-1}$



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

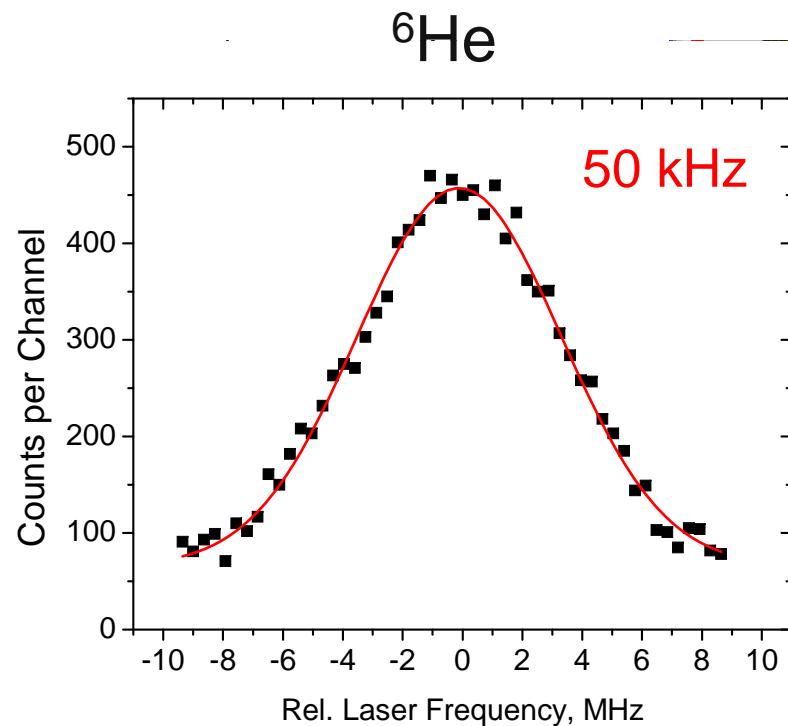
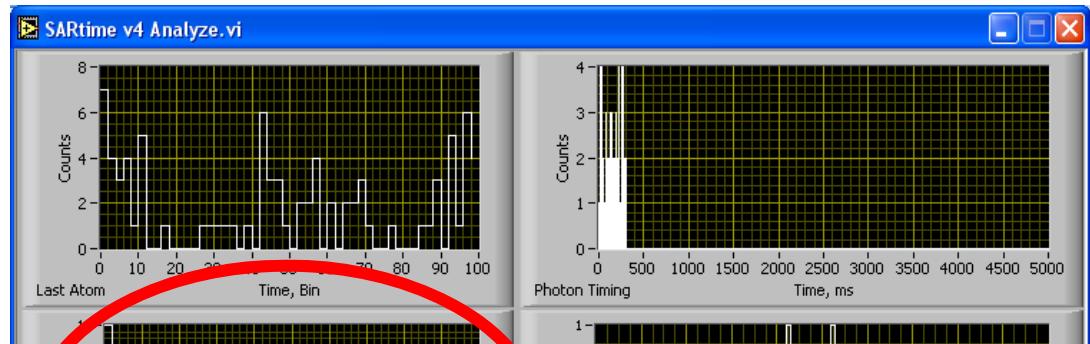


One trapped ${}^6\text{He}$ atom

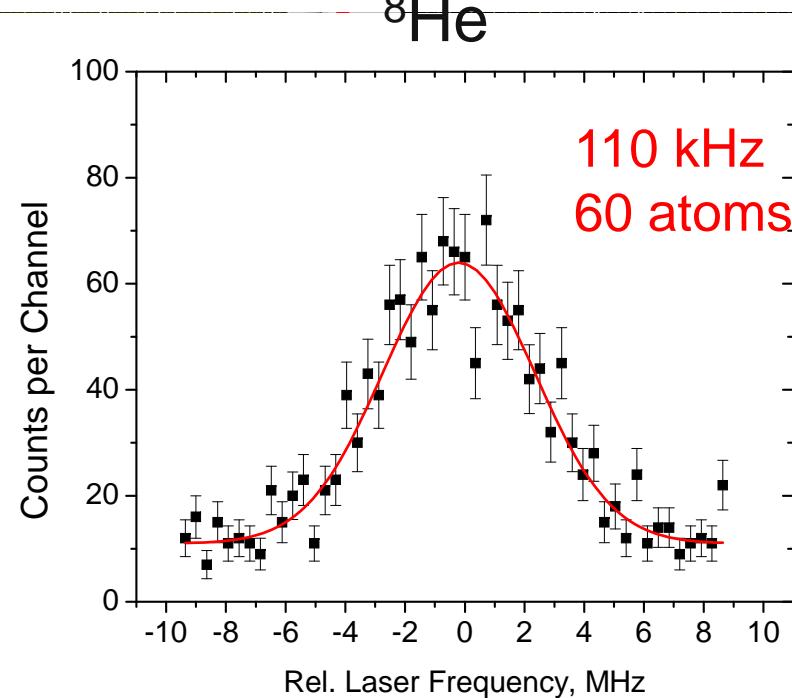


He-8 Trapped!

First He-8 Atom
June 15th 2007

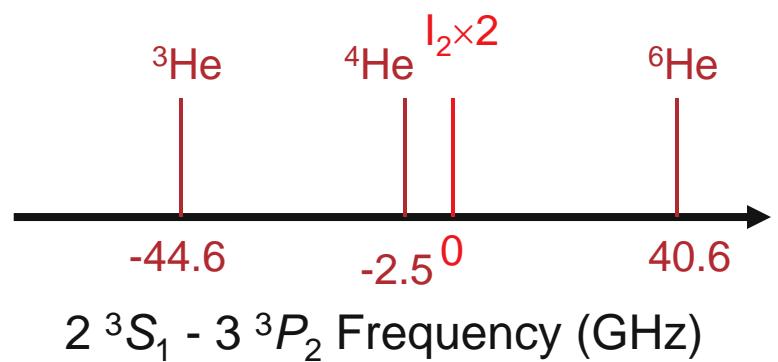
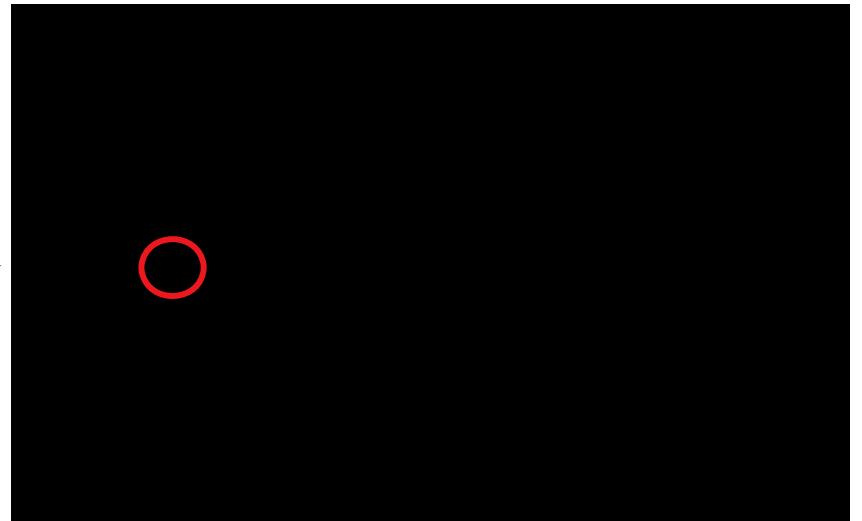
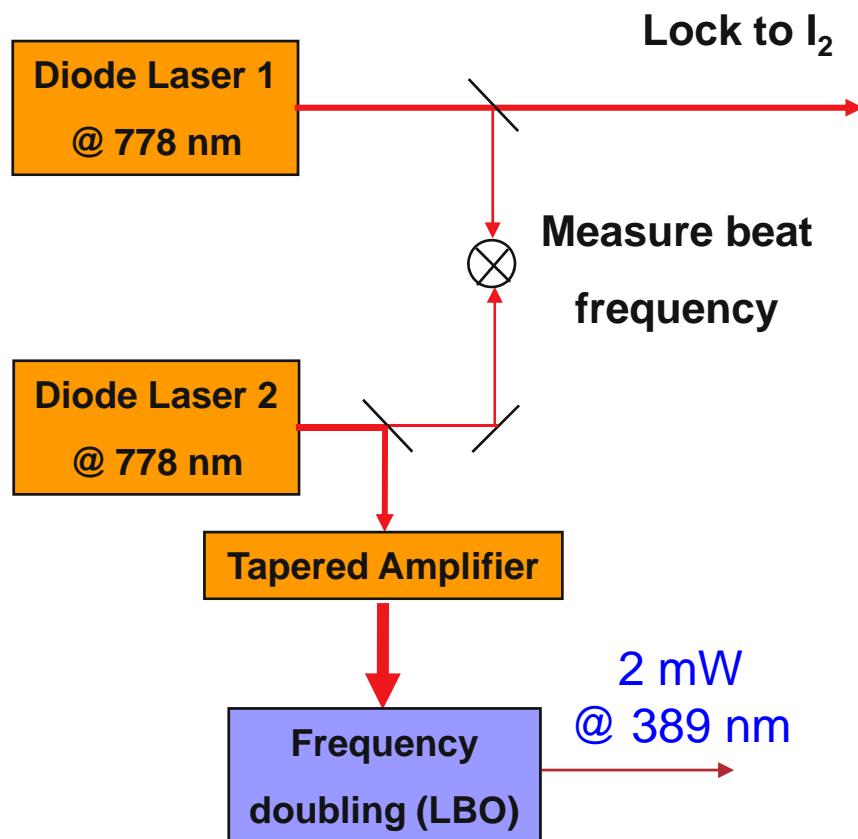


$\sim 30 {}^6\text{He}$ atoms/s

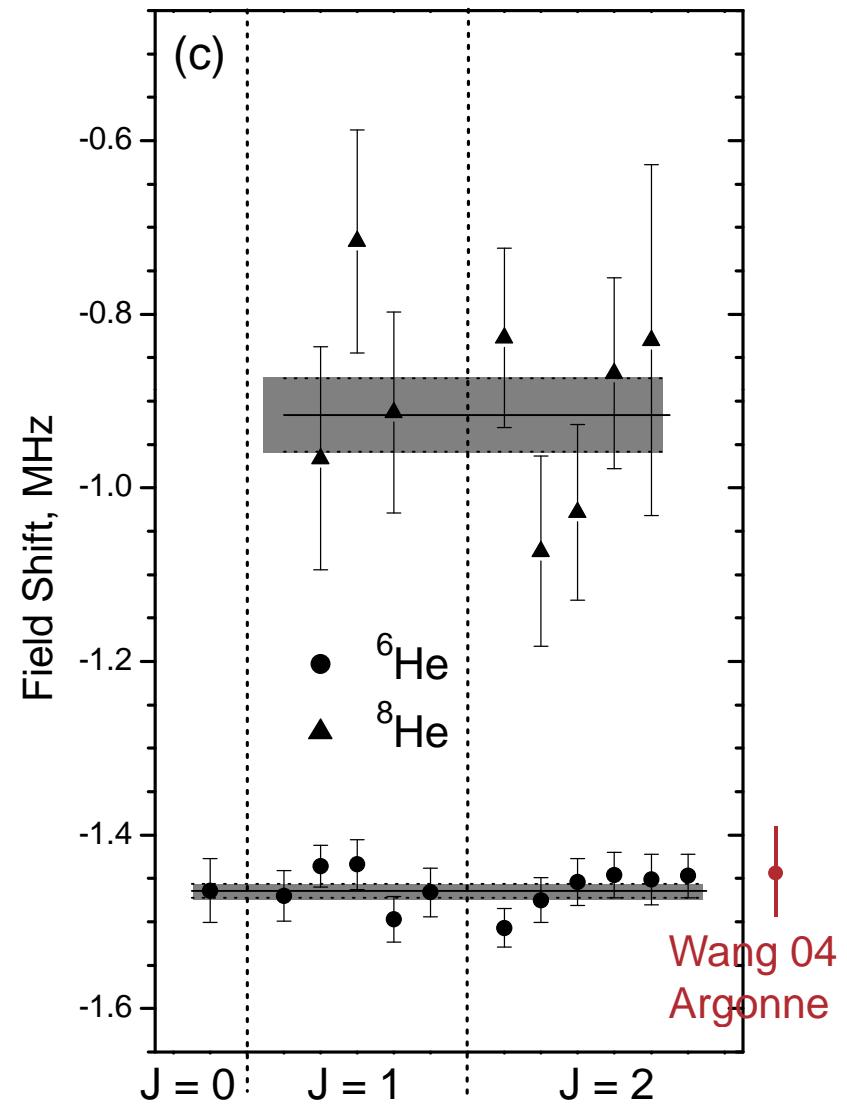
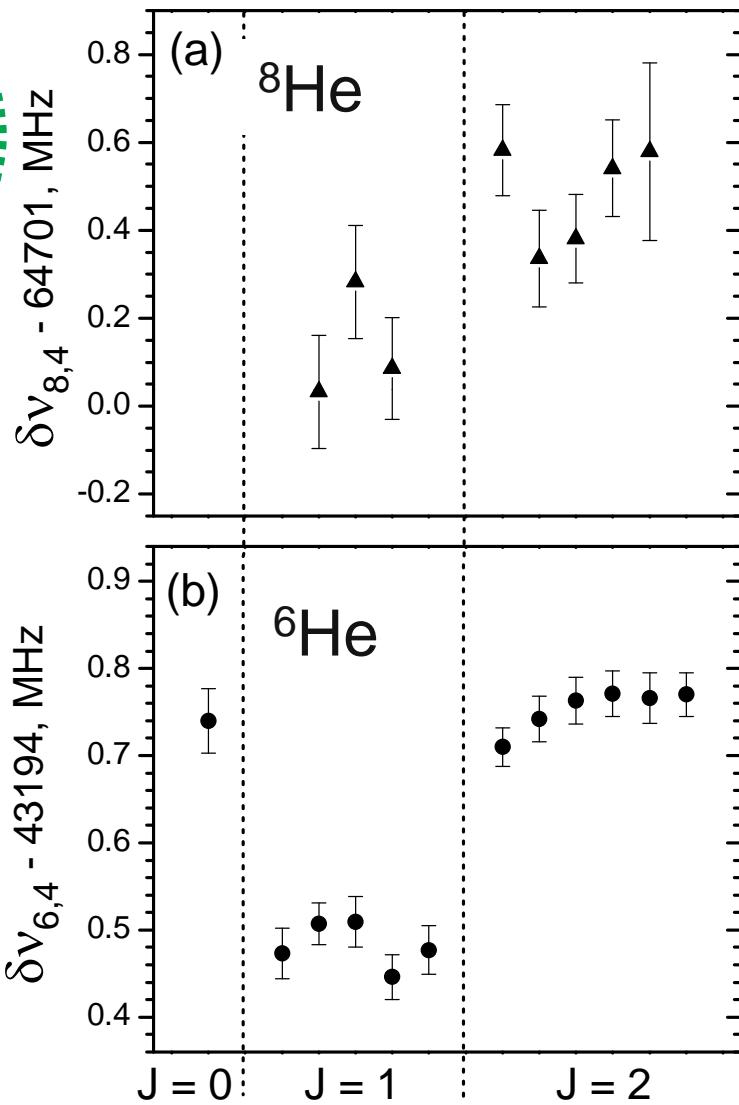
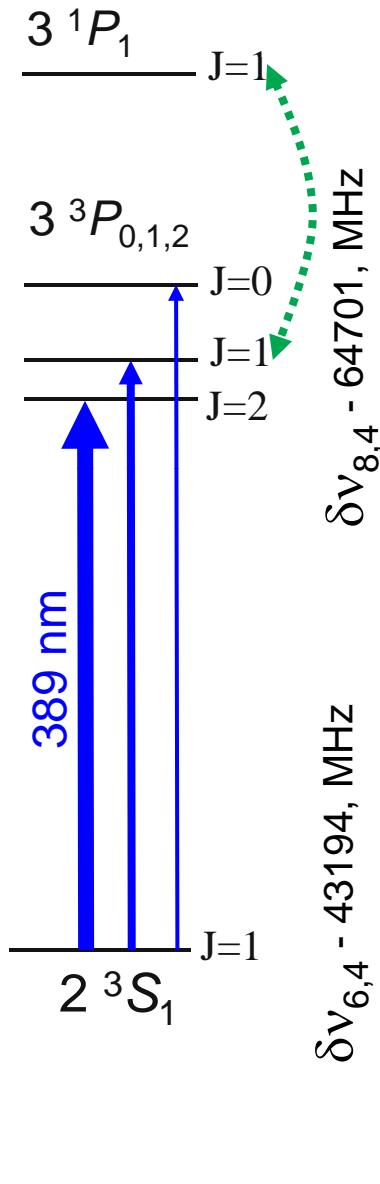


$\sim 30 {}^8\text{He}$ atoms/hr

Laser Setup - 389 nm (778 nm)



Isotope Shift and Field Shift : J - Dependence?



${}^6\text{He}$ & ${}^8\text{He}$ Charge Radii

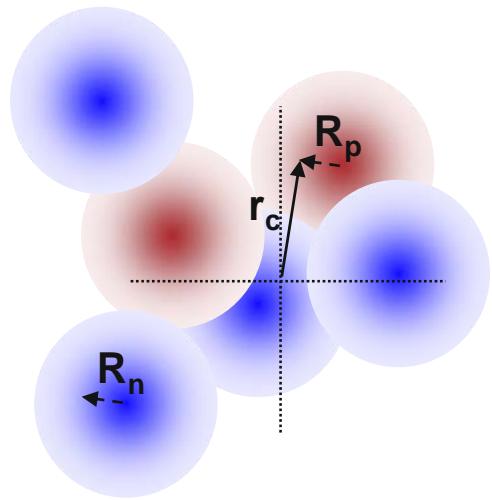
	${}^6\text{He}$	${}^8\text{He}$
Field Shift, MHz	-1.464(34)	-0.916(95)
RMS R_{CH} , fm	2.068(11)	1.929(26)
Total Uncertainty	0.5 %	1.3 %
- Statistical	0.1 %	0.6 %
- Trap Systematics	0.3 %	0.6 %
- Mass Systematics	0.2 %	1.0 %
- He-4: 1.676(8) fm	0.3 %	0.4 %

Recoil Correction

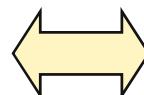
$$E_\gamma = E_{\text{int}} + \frac{P_\gamma^2}{2M_{\text{atom}}}$$



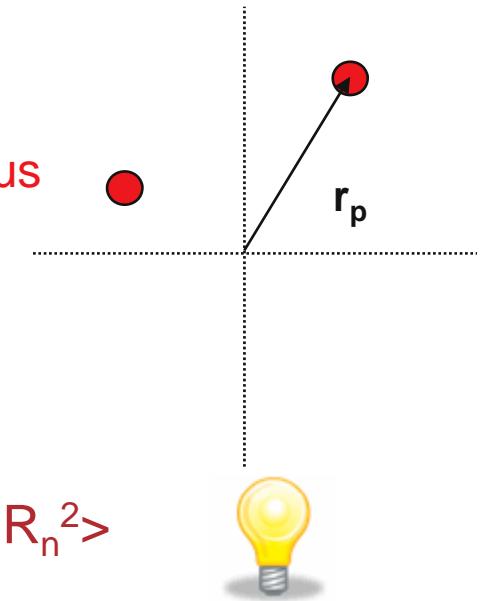
Charge Radius vs. Point-Proton Radius



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



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



$$Z\langle r_c^2 \rangle = Z\langle r_p^2 \rangle + Z(\langle R_p^2 \rangle + 0.75/M_p^2) + N\langle R_n^2 \rangle$$

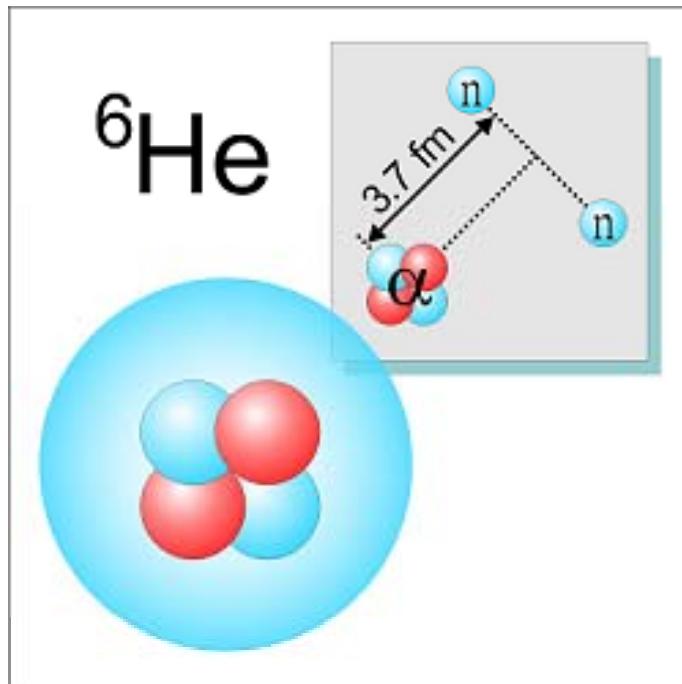
Mean square charge radii of nucleons:

$$\text{Neutron } \langle R_n^2 \rangle = -0.116(2) \text{ fm}^2$$

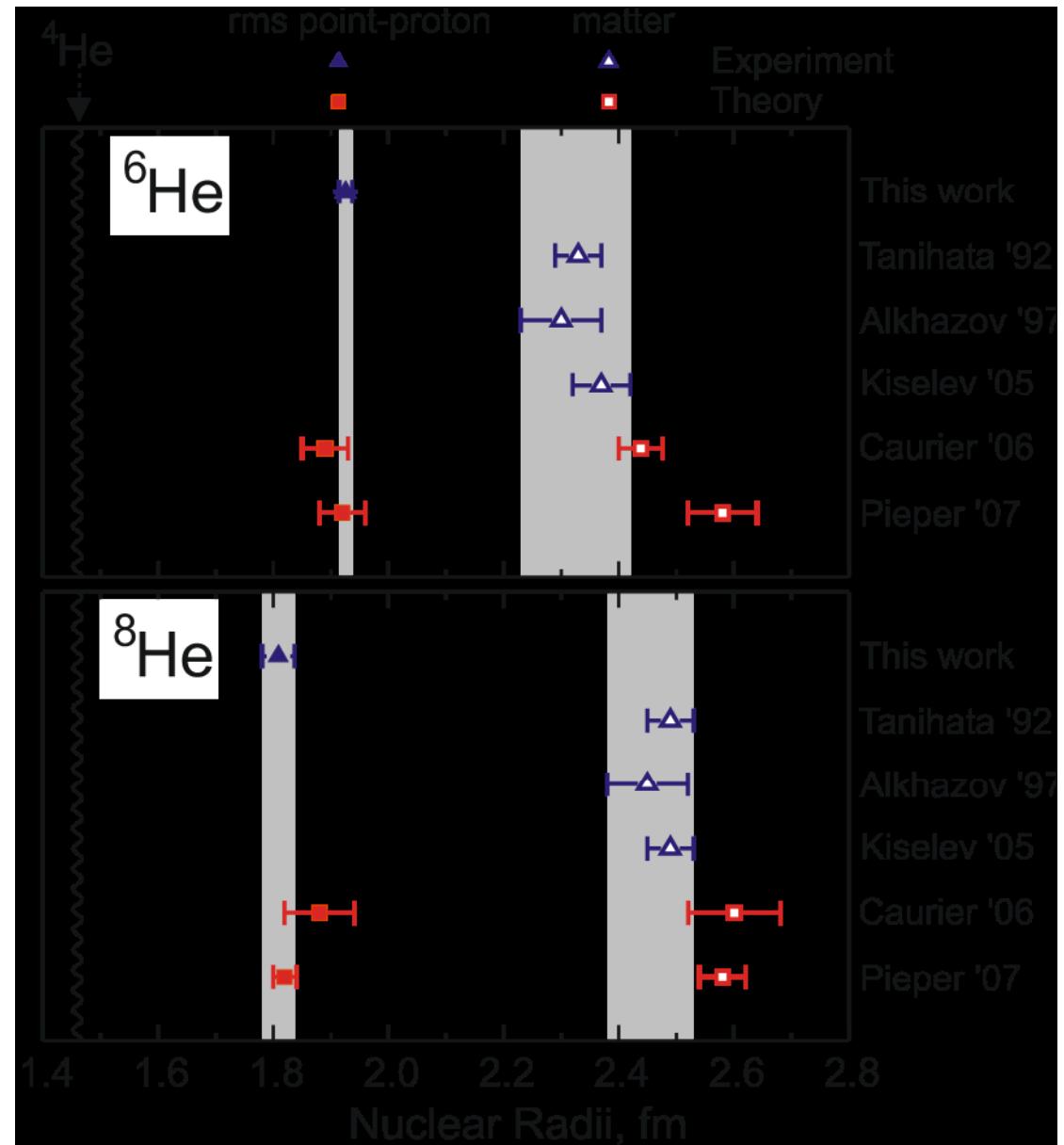
$$\text{Proton } \langle R_p^2 \rangle = 0.769(12) \text{ fm}^2 \text{ (I. Sick)}$$

$$\text{Darwin-Foldy } 0.75/M_p^2 = 0.033 \text{ fm}^2 \text{ (J. Friar)}$$

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



Wang et al., PRL (2004)
Mueller et al., PRL (2007)



He-6 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.P. O'Conner, R.C. Pardo, K.E. Rehm, J.P. Schiffer, X.D. Tang - Physics, Argonne
G. W. F. Drake - Univ of Windsor, Canada

He-8 Collaboration

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

