Update on CREMA's work towards the Proton Radius Puzzle

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Thanks for the graphics to
Randolf Pohl, Julian Krauth, Stefan Schmidt (PSAS2018 poster & TBA proceedings),
and Nir Nevo Dinur

CREMA 'Charge Radius Experiment with Muonic Atoms'

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Paul Scherrer Institut, Switzerland

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Physics Department, National Tsing Hua University, Taiwan

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Root of the Puzzle: the Proton Radius was shrunk 2009

$$r_p^{\mathrm{CODATA}} = 0.88..\,\mathrm{fm} \pm 0.8\%$$

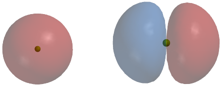
$$\Downarrow$$

$$r_p^{\mathrm{CREMA}} = 0.84...\,\mathrm{fm} \pm 0.04\%$$

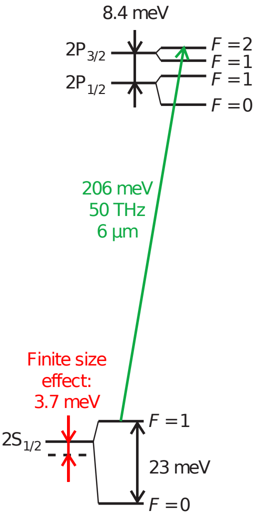
- $4\,\%$ smaller
- > 10 fold precision

[P. J. Mohr *et al.*, Rev. Mod. Phys. 80, 633-730 (2008)]
[R. Pohl *et al.* (CREMA-coll.), Nature 466, 213 (2010)]
[A. Antognini *et al.* (CREMA-coll.), Science 339, 417 (2013)]

- Bound system of one μ^- and a proton
  (or other light nuclei such as the deuteron, helion, α, ...)
- Muon lifetime $\tau_\mu = 2.2\,\mu$s
- $m_\mu \approx 200 \cdot m_\mathrm{e} \quad \Rightarrow \quad a_\mu \approx a_\mathrm{e}/200$
- Probability to be *inside* the nucleus $200^3 = 10^7\times$higher

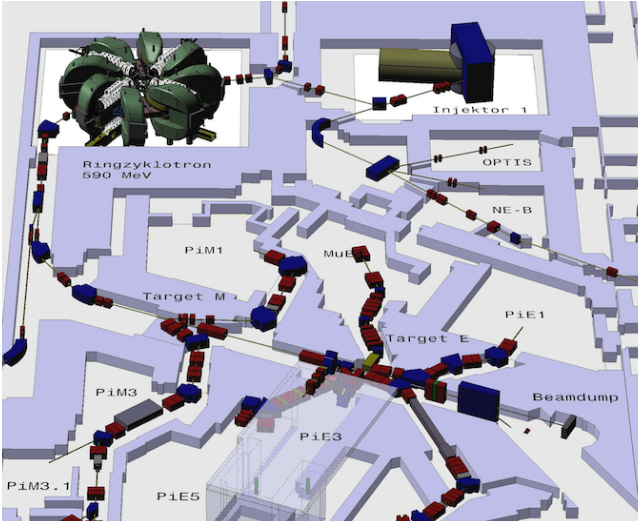


- S-states great probe for nuclear structure:
  - Lamb shift $(\Delta E_{\mathrm{2S}\rightarrow\mathrm{2P}}) \Rightarrow$ charge radius
  - $\mathrm{2S}$ & $\mathrm{2P}$ hyperfine structure $\Rightarrow$ Zemach radius
  - Polarizablity of the nucleus
- Measure Lamb shift transitions between energy levels via laser spectroscopy

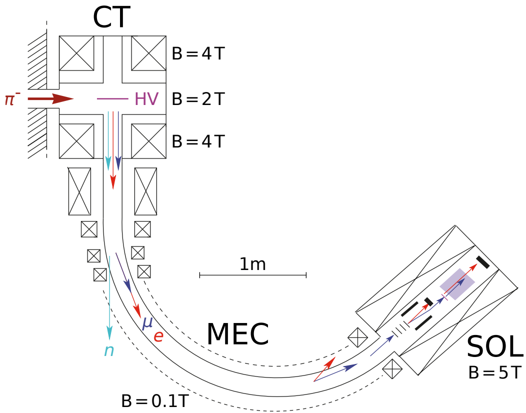


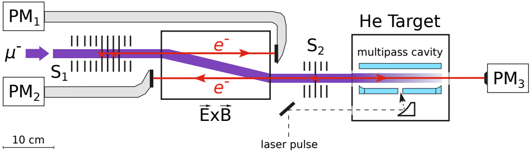
The Paul Scherrer Institute (PSI), Switzerland

HIPA facility at the Paul Scherrer Institute

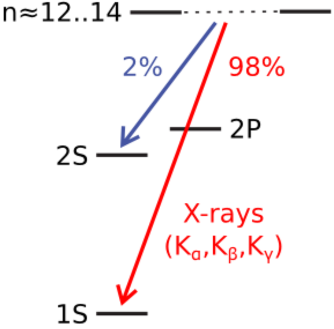


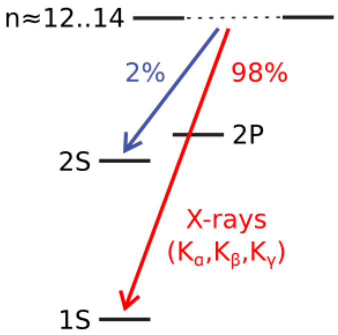
- High Intensity Proton Accelerator
- ~ 2 mA of 590 MeV p^+ are shot on a carbon target to create pions (PiE5 area)
- pions decay to muons
- muons are cooled/slowed down in a special beamline
- non-destructive muon detector provides trigger for laser
- μ^- enter gas target (hydrogen, deuterium, ^{3}He, or ^{4}He)
- bound state is formed between light nucleus and one muon





- Superconducting cyclotron trap (CT $\hat{=}$ magnetic bottle) releases low-energy μ^- to the muon extraction channel (MEC)
- μ^- enter the gas target within supercond. solenoid (SOL)
- Stacks of ultra-thin carbon foils (S1, S2) provide a trigger signal for the laser when a muon enters the target


n≈12..14
2%
98%
2P
2S
X-rays
(Kα,Kβ,Kγ)
1S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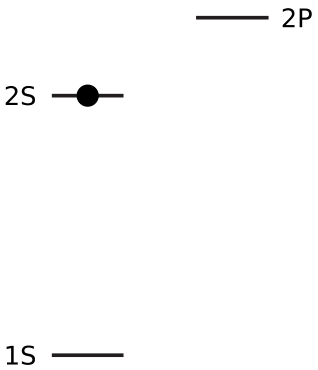
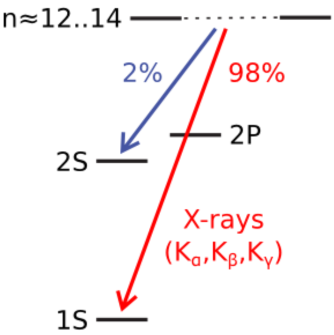
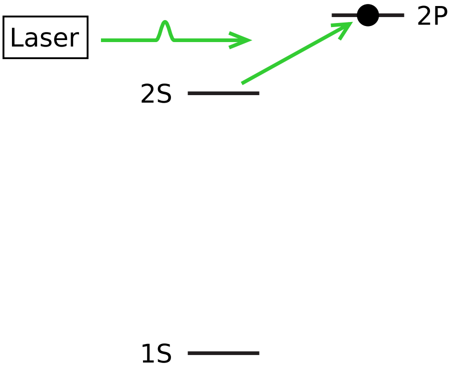
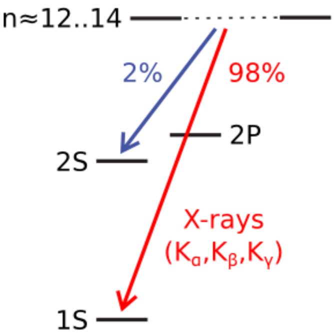

2P
2S
1S

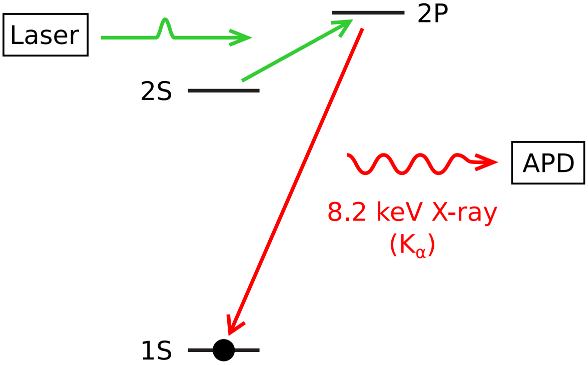
Measurement of muonic Lamb shift transitions





Measurement of muonic Lamb shift transitions





Steps to extract nuclear properties from transition energy

- Make sure systematics are under control
- Most systematics are below our measurement sensitivity
- We needed to check on *Quantum Interference*

- Use theory to extract charge radius from transition frequency
- What are the current state of the art theory term calculations?
- Summarize contributions from several different experts
- Data from hydrogen and deuterium published, helium-3 and helium-4 are underway

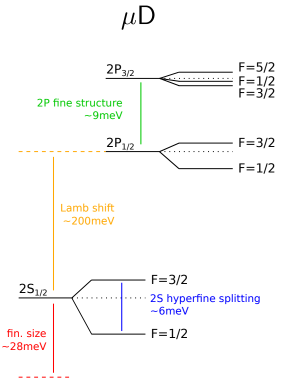
What is Quantum Interference (QI)?
"Coherent excitation of multiple allowed excited states", a polarization & geometry dependent effect (vanishes in 4π)

[eg. E. Hessels, M. Horbatsch, PRA 82, 052519 (2010); R. Brown *et al.*, PRA 87, 032504 (2013); and Refs therein]

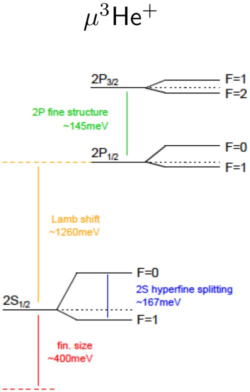
- Investigations on QI in CREMA are published
- Compare point-like detector vs. acceptance angle of CREMA

[Amaro, Franke, et.al., PRA **92**, 022514 (2015)]

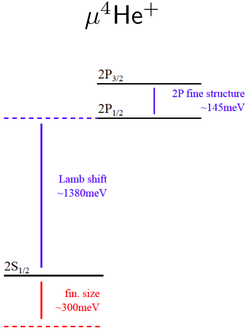
$n = 2$ levels in muonic deuterium, helium-3, and helium-4



[Krauth et.al., Ann. Phys. **366** 168 (2016)]



[Franke, Krauth, et.al., EPJD **71** 341 (2017)]



[Diepold et.al., arXiv:1606.05231, submitted to Ann. Phys.]

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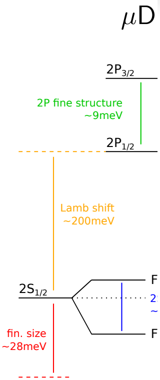
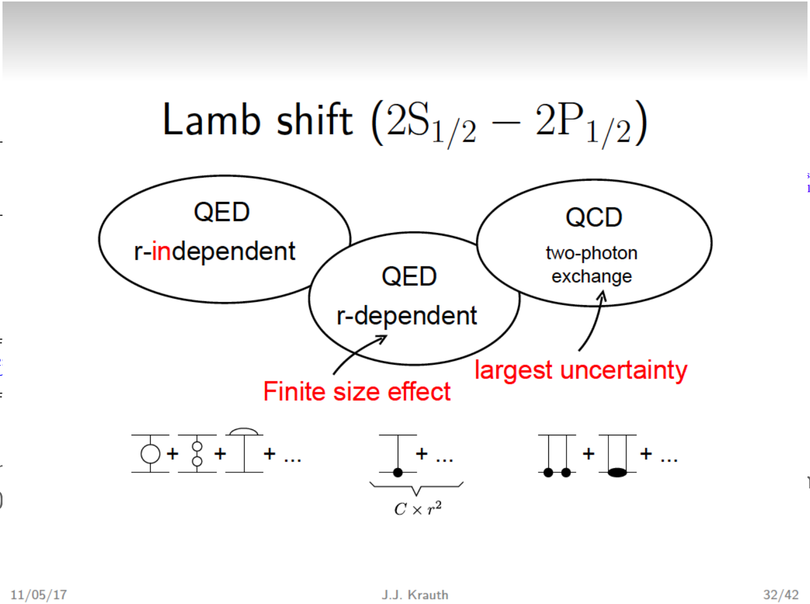
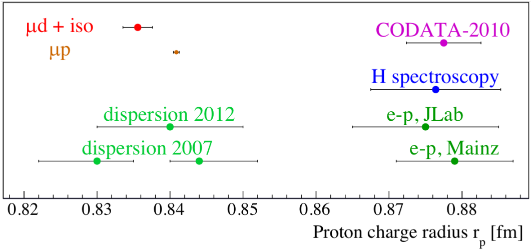


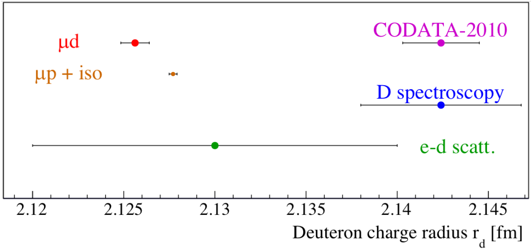


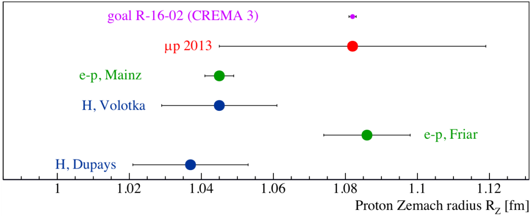
structure
145meV

[Krauth et.al., Ar
168 (20

itted to

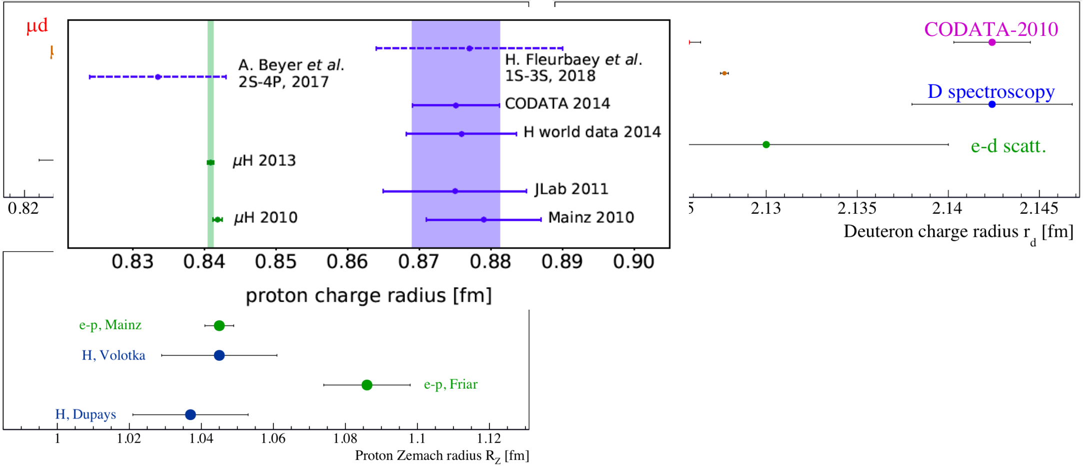






The deuteron is too small as well! Pohl et al., Science **353** 669 (2016)

Some remarks: deuteron radius will be affected once new theory results get incorporated (Hernandez et al., PLB **778** 377 (2018) & Pachucki et al., arXiv:1803.10313)



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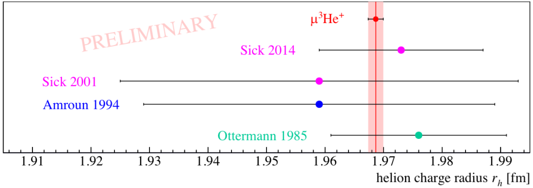
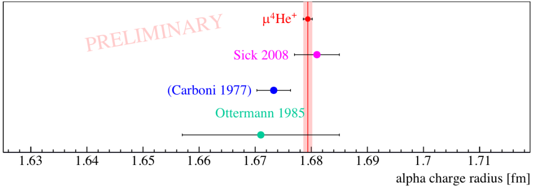
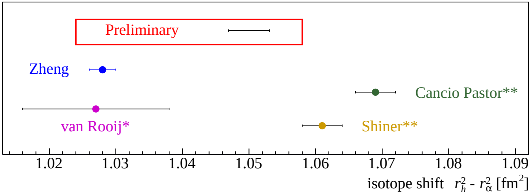
Helion and alpha radii (VERY preliminary)







Remarks: alpha radius will be affected by ongoing work in the CREMA theory summary about to be resubmitted;

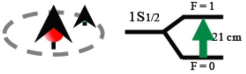
Isotope shift values from reevaluated theory in:

* Patkos et al., PRA 95 012508 (2017) ** Patkos et al., PRA 94 052508 (2016)

1S – HFS spectroscopy

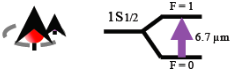
(see also [Adamczak et al. 2012 and 2016] (FAMU collaboration) and [Miyake et al., 2014] (J-PARC μH collaboration))

Hydrogen

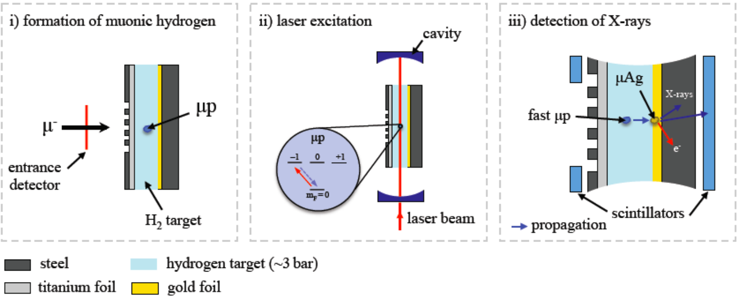


$$\nu_{\text{exp}} = 1\,420\,405.751\,766\,7(10)\ \text{kHz}$$
$$\nu_{\text{theo}} = 1\,420\,403.1(6)_{\text{proton size}}(4)_{\text{pol}}\ \text{kHz}$$

Muonic hydrogen

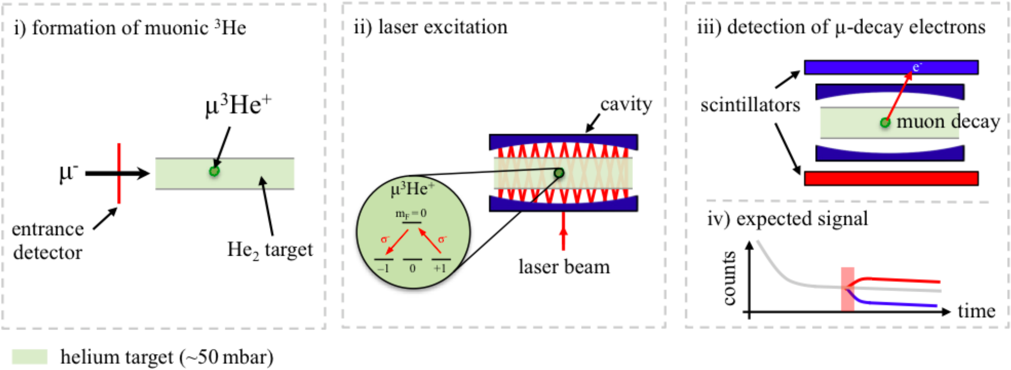


Experimental scheme

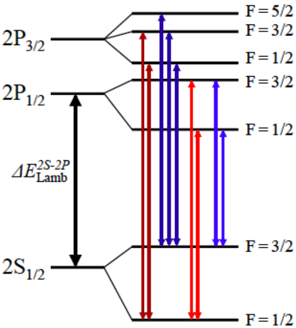


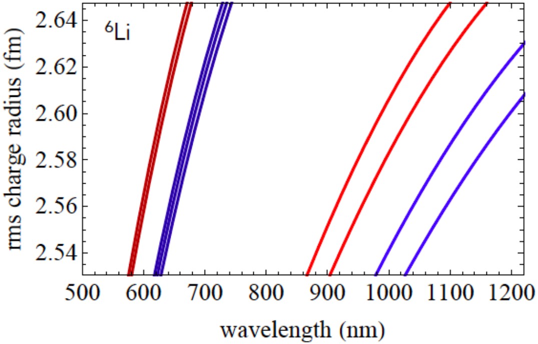
1S – HFS spectroscopy

Experimental scheme



- We aim to improve the current literature values for the nuclear charge radii of ^{6,7}Li by about one order of magnitude.
- Challanges: producing a dense target from a solid.
- Our approach: using a compact hot vapor cell, which is embedded inside the 5 T solenoid of the low-energy muon beamline.
- Additional energy reduction of the 2 keV muon beam is achieved via a pulsed drift tube.

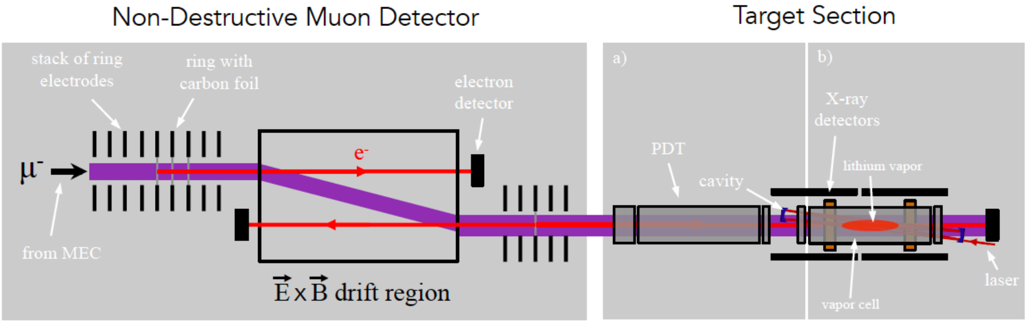




Swainson et al., Phys. Rev. A 34 620 (1986)

Experimental proposal based on theory by Drake (1985) Swainson (1986) and Krutov (2016).

Planned experimental setup

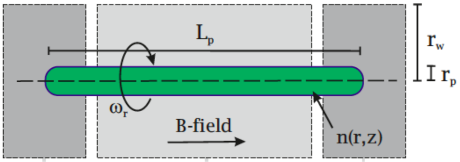


Experimental proposal based on theory by Drake (1985) Swainson (1986) and Krutov (2016).

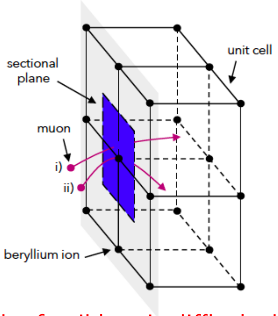
Penning-trap assisted laser spectroscopy

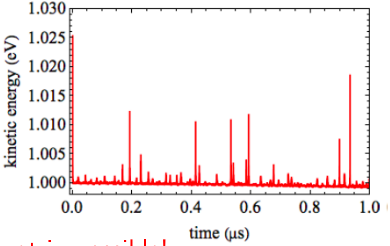
- We intend to use a cold beryllium ion crystal as a dense target.
- Muon capture rate is strongly enhanced for low energies (below few eV).
- First simulations suggest that this approach may be feasible.
- Low muon stop rate – further studies are required.
- Test with antiprotons first.

Penning-Malmberg trap

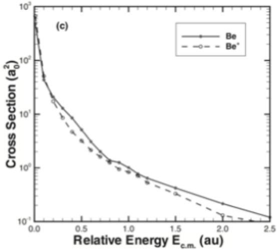


Ion crystal - simulations





Capture cross section



Cohen et al., 67 1769 (2004)

...may be feasible – is difficult, but not impossible!

THANK YOU for your attention!