Charge radii from hydrogen-like muonic atoms

- Shedding light on the Proton Radius Puzzle -

Julian J. Krauth

on behalf of the CREMA Collaboration

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CREMA Collaboration

(Charge Radius Experiment with Muonic Atoms)

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Shrinking the proton

$$r_p^{\mathrm{CODATA}} = 0.8775(51)\,\mathrm{fm}$$
$$\Downarrow$$
$$r_p^{\mathrm{CREMA}} = 0.84087(39)\,\mathrm{fm}$$

- 4% smaller
- > 10fold precision
- 7σ discrepant

[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)]

About the proton radius

The proton radius r_p is the

rms charge radius of the proton

which is given by the slope of the electric form factor:

$$r_\mathrm{p}^2 = -6 \frac{dG_\mathrm{E}}{dQ^2}\Big|_{Q^2=0} \quad \left(\simeq \int r^2 \rho(r) d^3 r \right) \tag{1}$$

r_p is therefore a parameter of the charge distribution of the proton.

Its measurement is necessary for

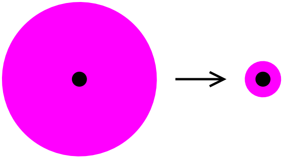
- understanding the proton
- testing higher order bound-state QED in hydrogen
- checking R_∞

It can be measured in several ways...

Proton radius from muonic hydrogen (μp)

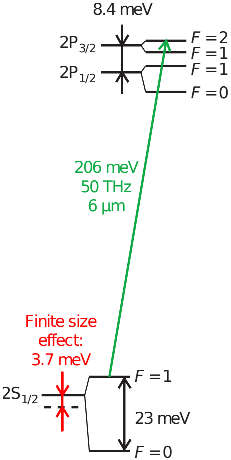
$$m_\mu \approx 200 \times m_e \tag{2}$$

$$|\Psi_S|^2 \propto \frac{1}{a_0^3} \tag{3}$$

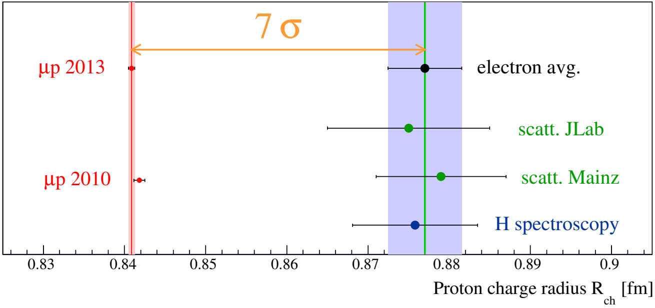


$\Rightarrow$ Probability to be inside the nucleus enhanced by $200^3 \simeq 10^7$!

$$E(2S - 2P) = 206.0336(15)\,\text{meV} - 5.2275(10)\,\text{meV}\; r_p^2[\text{fm}^2] \tag{4}$$



The Proton Radius Puzzle



Summarizing all *electronic* measurements of r_p (spectroscopy and scattering), yields a $7\,\sigma$ discrepancy to the CREMA measurement.

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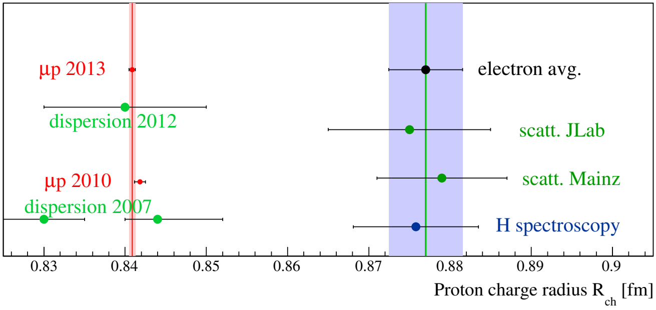

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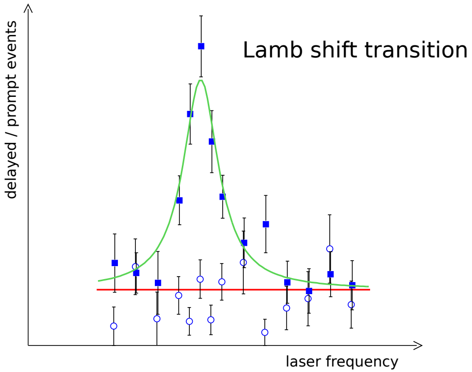
muonic deuterium



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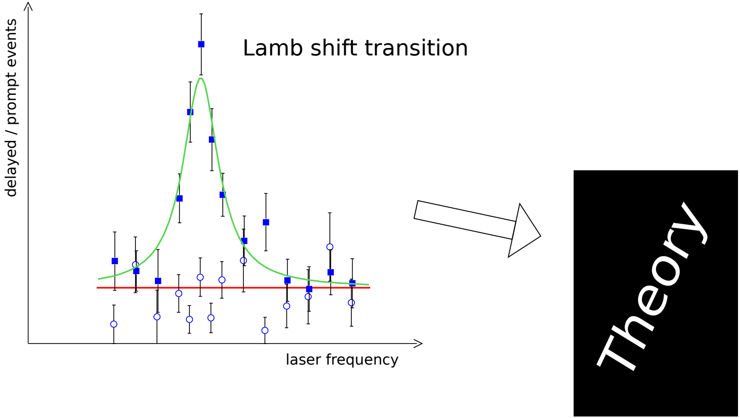

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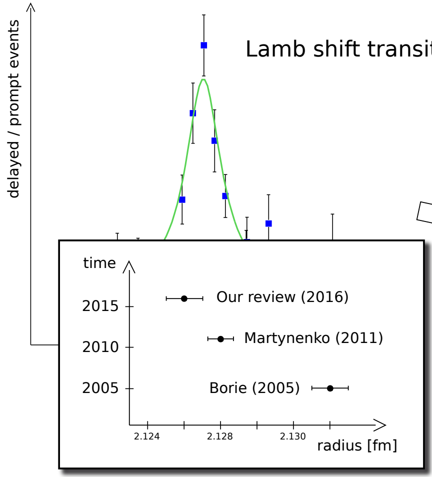
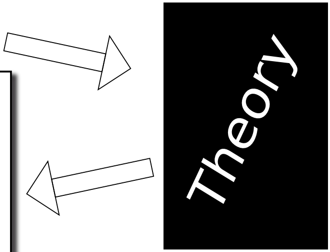


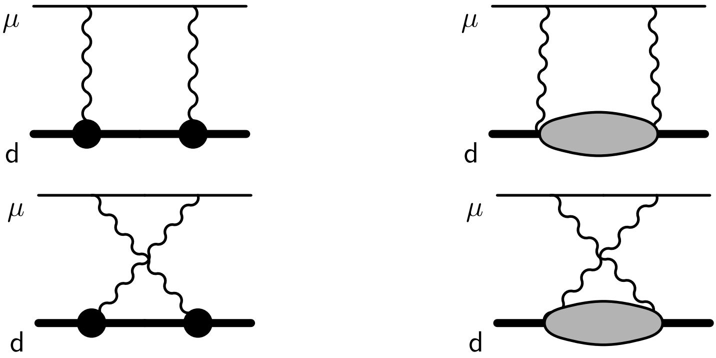


Borie: PRA72, 052511 (2005)
Martynenko: PRA84, 052514 (2011)

two-photon exchange (TPE)

$$\Delta E^{\mathrm{LS}}_{\mathrm{TPE}} = \Delta E^{\mathrm{LS}}_{\mathrm{Friar}} + \Delta E^{\mathrm{LS}}_{\mathrm{inelastic}} \quad (5)$$

elastic (Friar moment) inelastic (polarizability)



→ TPE: main limitation for determination of r_{d}!

muonic deuterium

TPE in the Lamb shift

TPE in history (huge deviations!!!)

Year	Source	Value [meV]	Uncert.
1992	Fukushima *et al.*	1.24 + el.	
1994	Lu and Rosenfelder	1.450 + el.	0.060
1995	Leidemann and Rosenfelder	1.500 + el.	0.025
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2014	TRIUMF/Hebrew group	1.690	0.020
2015	Pachucki and Wienczek	1.717	0.020
2014	Carlson *et al.*	2.011	0.740
2016	our compiled theory value	1.7096	0.0200

green: modern determinations

Table 3

Deuteron structure contributions to the Lamb shift in muonic deuterium. Values are in meV. For source 4, the N^3LO calculation by Hernandez et al. [58] we use their value from the rightmost two columns of their Tab. 3 that differs most from their "AV18" value. Their terms $\delta^{(1)}_{Z1}$, $\delta^{(1)}_{Z3}$, and δ_{Zem} (Friar term) are not listed because they cancel (see text). Items with a diamond ♦ are corrected from the published values, see footnotes.

Item	Contribution	Pachucki [55]		Friar [60]		Hernandez *et al.* [58]			Pach.& Wienczek [65]		Carlson *et al.* [64]		Our choice		
		AV18		ZRA		AV18	N^3LO †		AV18		data		value		source
	Source	1		2		3	4		5		6				
p1	Dipole	1.910	$\delta_0 E$	1.925	Leading C1	1.907	1.926	$\delta^{(0)}_{D1}$	1.910	$\delta_0 E$			1.9165	± 0.0095	3-5
p2	Rel. corr. to p1, longitudinal part	−0.035	$\delta_R E$	−0.037	Subleading C1	−0.029	−0.030	$\delta^{(0)}_L$	−0.026	$\delta_R E$					
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta^{(0)}_T$							
p4	Rel. corr. to p1, higher-order								0.004	$\delta_{HO} E$					
sum	Total rel. corr., p2+p3+p4	−0.035		−0.037		−0.017	−0.017		−0.022				−0.0195	± 0.0025	3-5
p5	Coulomb distortion, leading	−0.255	$\delta_{C1} E$						−0.255	$\delta_{C1} E$					
p6	Coul. distortion, next order	−0.006	$\delta_{C2} E$						−0.006	$\delta_{C2} E$					
sum	Total Coulomb distortion, p5+p6	−0.261				−0.262	−0.264	$\delta^{(0)}_C$	−0.261				−0.2625	± 0.0015	3-5
p7	El. monopole excitation	−0.045	$\delta_{Q0} E$	−0.042	C0	−0.042	−0.041	$\delta^{(2)}_{R2}$	−0.042	$\delta_{Q0} E$					
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta^{(2)}_{D1D3}$	0.139	$\delta_{Q1} E$					
p9	El. quadrupole excitation	−0.066	$\delta_{Q2} E$	−0.061	C2	−0.061	−0.061	$\delta^{(2)}_Q$	−0.061	$\delta_{Q2} E$					
sum	Tot. nuclear excitation, p7+p8+p9	0.040		0.034	C0 + ret-C1 + C2	0.036	0.038		0.036				0.0360	± 0.0020	2-5
p10	Magnetic	−0.008 ◇[a]	$\delta_M E$	−0.011	M1	−0.008	−0.007	$\delta^{(0)}_M$	−0.008	$\delta_M E$			−0.0090	± 0.0020	2-5
SUM_1	Total nuclear (corrected)	1.646		1.648 [b]		1.656	1.676		1.655				1.6615	± 0.0103	
p11	Finite nucleon size			0.021	Retarded C1 f.s.	0.020 ◇[c]	0.021 ◇[c]	$\delta^{(2)}_{NS}$	0.020	$\delta_{FS} E$					
p12	n p charge correlation			−0.023	pn correl. f.s.	−0.017	−0.017	$\delta^{(1)}_{np}$	−0.018	$\delta_{FZ} E$					
sum	p11+p12			−0.002		0.003	0.004		0.002				0.0010	± 0.0030	2-5
p13	Proton elastic 3rd Zemach moment	} 0.043(3)	$\delta_P E$	0.030	$\langle r^3\rangle^{pp}_{(2)}$				} 0.043(3)	$\delta_P E$			0.0289	± 0.0015	Eq.(13)[d]
p14	Proton inelastic polarizab.					} 0.027(2)		δ^N_{pol} [64]			} 0.028(2)	ΔE^{hadr}	} 0.0280	± 0.0020	6
p15	Neutron inelastic polarizab.								0.016(8)	$\delta_N E$					
p16	Proton & neutron subtraction term												−0.0098	± 0.0098	Eq.(15)[e]
sum	Nucleon TPE, p13+p14+p15+p16	0.043(3)		0.030		0.027(2)			0.059(9)				0.0471	± 0.0101	[f]
SUM_2	Total nucleon contrib.	0.043(3)		0.028		0.030(2)			0.061(9)				0.0476	± 0.0105	
	Sum, published	1.680(16)		1.941(19)		1.690(20)			1.717(20)		2.011(740)				
	Sum, corrected			1.697(19) [g]		1.714(20) [h]			1.707(20) [i]		1.748(740) [j]		**1.7096**	**± 0.0147**	

[a] Corrected from -0.016 meV, see Ref. [65] below Eq. (45).
[b] The Coulomb distortion contribution p5+p6 of -0.263 meV (our choice) has been added to Friar's sum of 1.911 meV to make the numbers comparable.
[c] Corrected from +0.015 meV [70, 71].
[d] Rescaled from the muonic hydrogen values from Refs. [66, 74]. See text.
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limiting factors of accuracy: dipole term, subtraction term

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muonic deuterium

TPE in the Lamb shift

extract TPE from muonic data:

- 3 measured transitions, 2 fit parameters (LS, 2S HFS)
- $\Delta E_{\mathrm{LS}} = \Delta E_{\mathrm{QED}} + \Delta E_{\mathrm{fin.size}}(coeff \times r_{\mathrm{d}}^2) + \Delta E_{\mathrm{TPE}}^{\mathrm{LS}}$

use

- $r_{\mathrm{p}}(\mu\mathrm{p}) = 0.84087(39)$ fm
- electronic iso-shift: $r_{\mathrm{d}}^2 - r_{\mathrm{p}}^2 = 3.82007(65)$ fm^2

$\rightarrow$ $r_{\mathrm{d}}(\mu\mathrm{p} + \mathrm{iso})$

insert deuteron radius in Lamb shift and extract TPE.

muonic deuterium

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TPE in history (huge deviations!!!)

Year	Source	Value [meV]	Uncert.
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2014	Carlson *et al.*	2.011	0.740
2016	our theory value	1.7096	0.0200
2016	our exp. value	1.7638	0.0068

green: modern determinations

muonic deuterium

TPE in 2S HFS

- estimated by Faustov *et al.*, PRA90, 012520 (2014):
  $0.2226(49)\,\mathrm{meV}$ (3.5% of total 2S HFS)
  single-sourced!!!
- using
  $\Delta E_{\mathrm{HFS}} = \Delta E_{\mathrm{QED}} + \Delta E_{\mathrm{Zemach}}(coeff \times r_{\mathrm{Z}}) + \Delta E^{\mathrm{HFS}}_{\mathrm{TPE}}$
  and
  current deuterium theory, the Sick Zemach radius,
  and the μd measurements, we get:

$$\Delta E^{\mathrm{HFS}}_{\mathrm{TPE}} = 0.2178(74)\,\mathrm{meV}$$

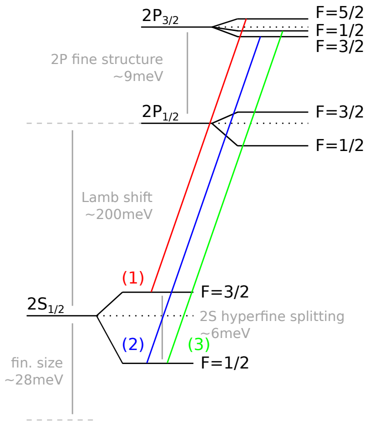
[R. Pohl *et al.* (CREMA-coll.), submitted]

→ Agreement in 2S HFS!

muonic deuterium

experimental results

measured transitions:



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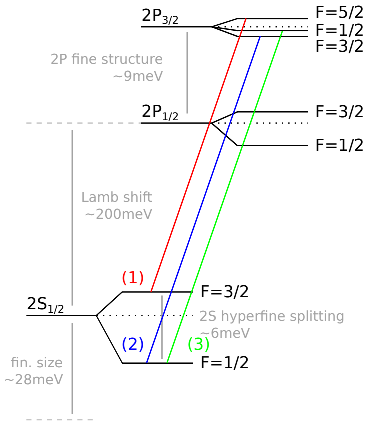

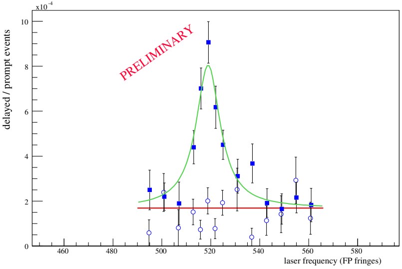

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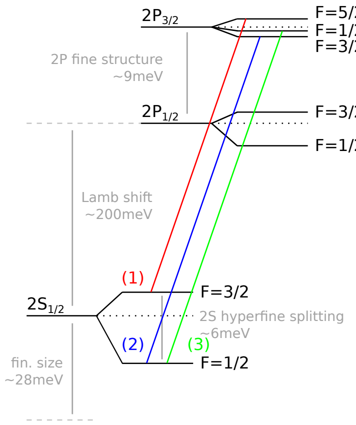

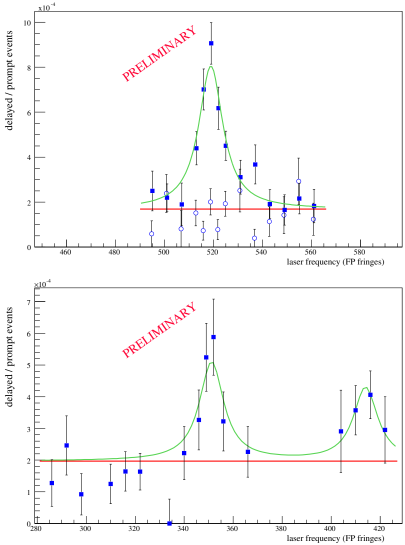

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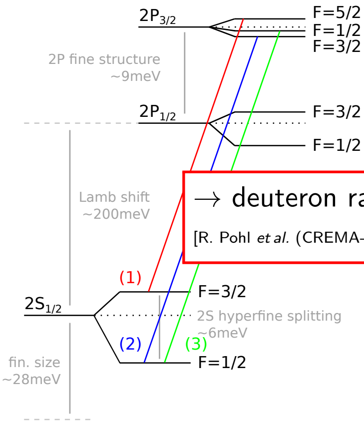
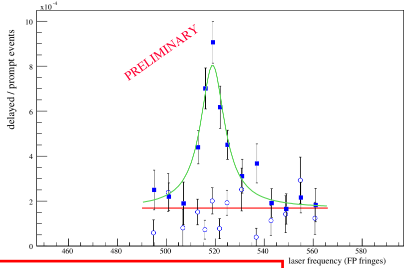
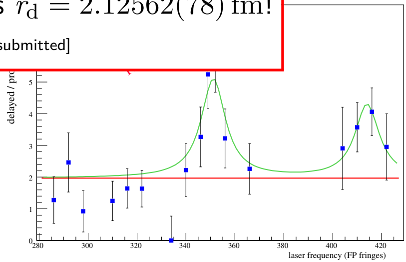




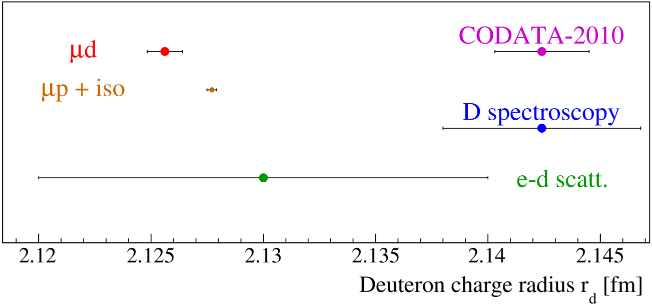


→ deuteron radius $r_{\mathrm{d}} = 2.12562(78)\,\mathrm{fm}$!

[R. Pohl *et al.* (CREMA-coll.), submitted]

muonic deuterium

the size of the deuteron



→ 7.5σ deviation between $r_d(\mu d)$ and CODATA-2010.

[R. Pohl *et al.* (CREMA-coll.), Measurement of the deuteron charge radius, submitted]

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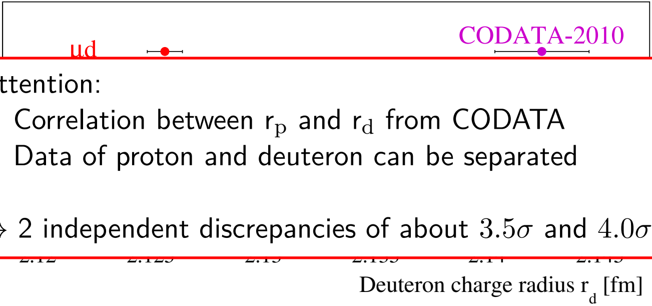

Attention:

- Correlation between r_p and r_d from CODATA
- Data of proton and deuteron can be separated

$\rightarrow$ 2 independent discrepancies of about 3.5σ and 4.0σ!

$\rightarrow$ 7.5σ deviation between $r_d(\mu d)$ and CODATA-2010.

[R. Pohl *et al.* (CREMA-coll.), Measurement of the deuteron charge radius, submitted]

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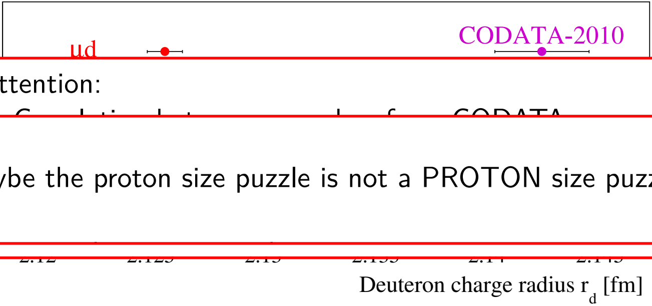


Attention:

Maybe the proton size puzzle is not a PROTON size puzzle.

$\rightarrow$ 7.5σ deviation between $r_d(\mu d)$ and CODATA-2010.

[R. Pohl *et al.* (CREMA-coll.), Measurement of the deuteron charge radius, submitted]

muonic helium-4

theory

- μ^4He$^+$ theory summary (Diepold *et al.*, to be submitted)
  - main sources of uncertainty: polarizability contributions
    - nuclear Friar-moment, 77 μeV
    - inelastic nuclear polarizability contribution, 100 μeV

    - proton Friar-moment, $28\,\mu$eV
    - inelastic nucleon polarizability contribution, 97 μeV
    - proton-neutron subtraction term, 86 μeV

  - Lamb shift (without pol.) and Fine Structure, each $\leq$ 16 μeV
  - experimental uncertainty, 48 μeV

muonic helium-4

theory

- μ^4He$^+$ theory summary (Diepold *et al.*, to be submitted)
  - main sources of uncertainty: polarizability contributions
    - nuclear Friar-moment, 77 μeV
    - inelastic nuclear polarizability contribution, 100 μeV

Special thanks to Ji *et al.*!

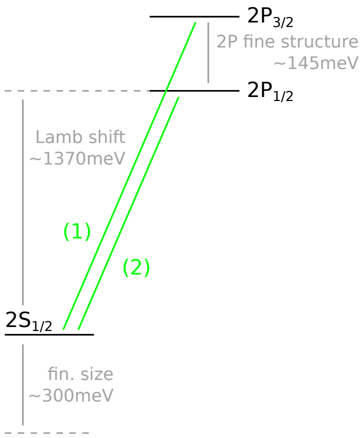
    - proton Friar-moment, 28 μeV
    - inelastic nucleon polarizability contribution, 97 μeV
    - proton-neutron subtraction term, 86 μeV

  - Lamb shift (without pol.) and Fine Structure, each $\leq 16\,\mu$eV
  - experimental uncertainty, 48 μeV

muonic helium-4

preliminary experimental results

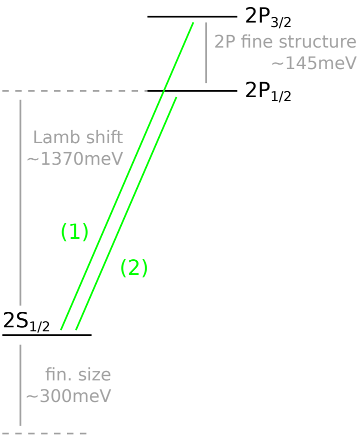
measured transitions:

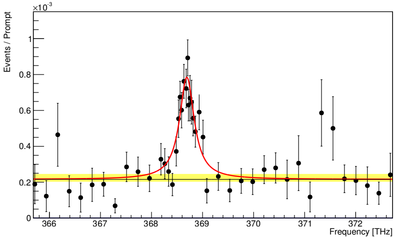


muonic helium-4

preliminary experimental results

measured transitions:

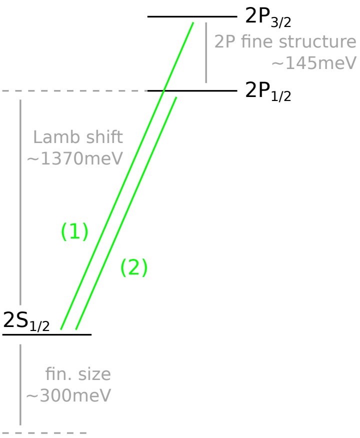


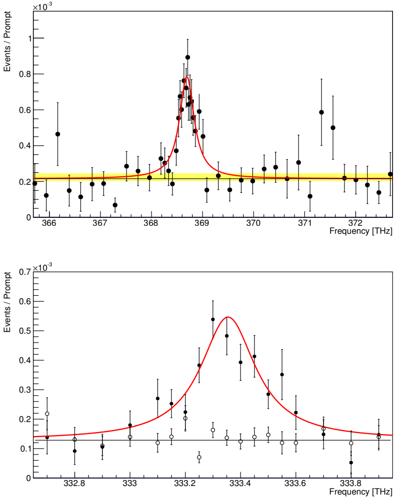


muonic helium-4

preliminary experimental results

measured transitions:

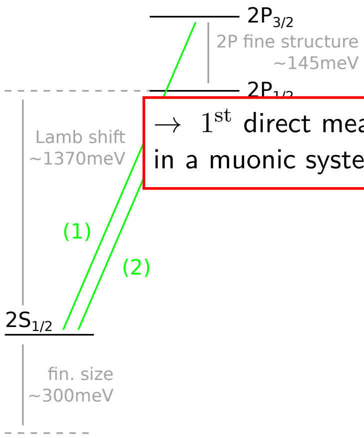


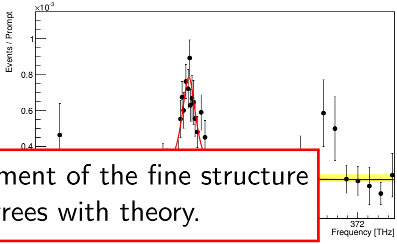


muonic helium-4

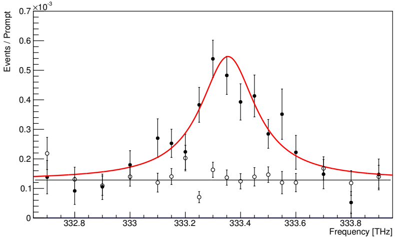
preliminary experimental results

measured transitions:





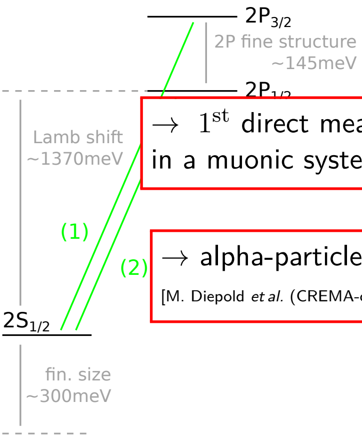
→ 1^{st} direct measurement of the fine structure in a muonic system agrees with theory.

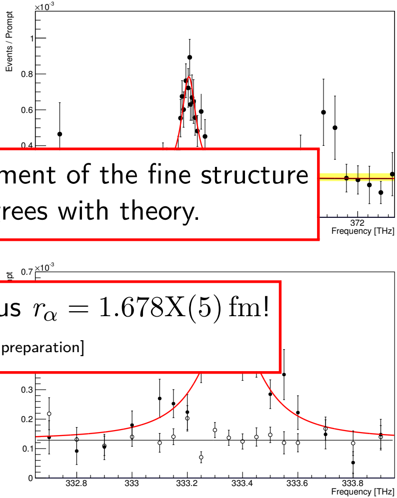


muonic helium-4

preliminary experimental results

measured transitions:





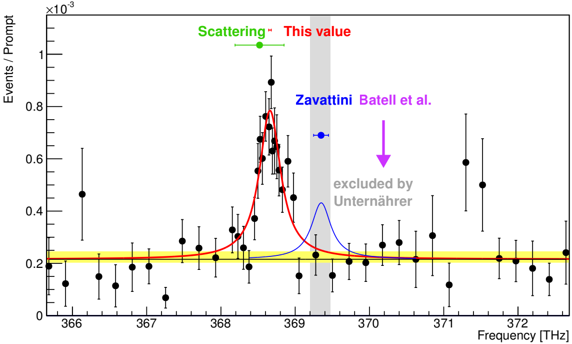
→ 1^{st} direct measurement of the fine structure in a muonic system agrees with theory.

→ alpha-particle radius $r_\alpha = 1.678\mathrm{X}(5)\,\mathrm{fm}$!

[M. Diepold *et al.* (CREMA-coll.), in preparation]

muonic helium-4

previous measurements / predictions



- agrees with $e - \mathrm{p}$ scattering value of $1.681(4)$ fm
- previous Zavattini value (CERN) was disproved, $> 5\sigma$ off
- radii from Zavattini and CREMA do not differ a lot: incomplete theory cancels wrong measurement

muonic helium-3

theory

- μ^3He$^+$ theory summary (Franke *et al.*, in preparation)
  - main sources of uncertainty: polarizability contributions
    - nuclear Friar-moment, 190 μeV
    - inelastic nuclear polarizability contribution, 160 μeV

    - nucleon Friar-moment, 26 μeV
    - inelastic nucleon polarizability contribution, 123 μeV
    - TPE contributions to 2S HFS not calculated yet!
      (needed for extraction of the Zemach radius)
  - experimental uncertainty similar to helium-4.

muonic helium-3

theory

- $\mu^3\text{He}^+$ theory summary (Franke *et al.*, in preparation)
  - main sources of uncertainty: polarizability contributions

Special thanks to Nevo Dinur *et al.*!

(first *ab initio* calc. of nucl. struc. in μ^3He)

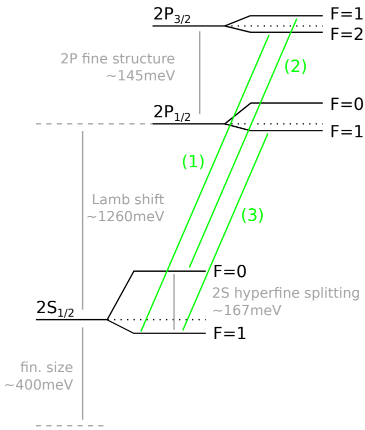
eV

    - nucleon Friar-moment, $26\,\mu$eV
    - inelastic nucleon polarizability contribution, 123 μeV
    - TPE contributions to 2S HFS not calculated yet! (needed for extraction of the Zemach radius)
  - experimental uncertainty similar to helium-4.

muonic helium-3

very preliminary

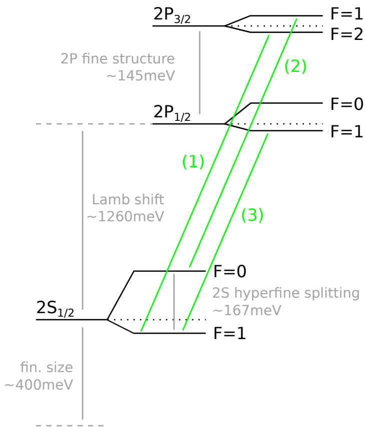
measured transitions:

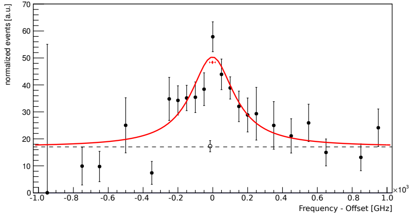


muonic helium-3

very preliminary

measured transitions:

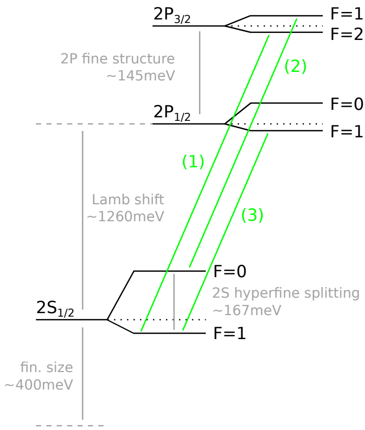


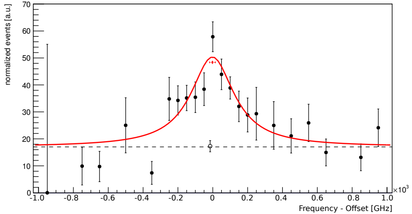


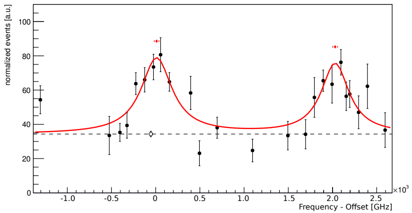
muonic helium-3

very preliminary

measured transitions:



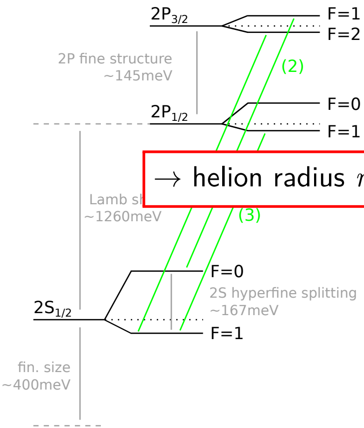


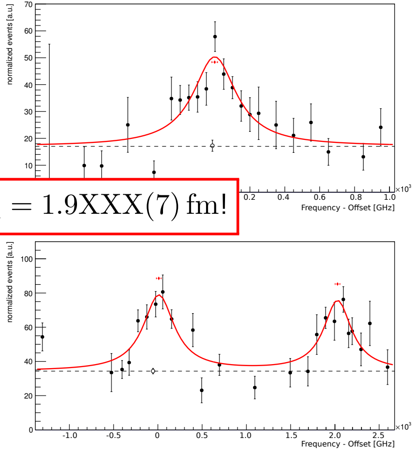


muonic helium-3

very preliminary

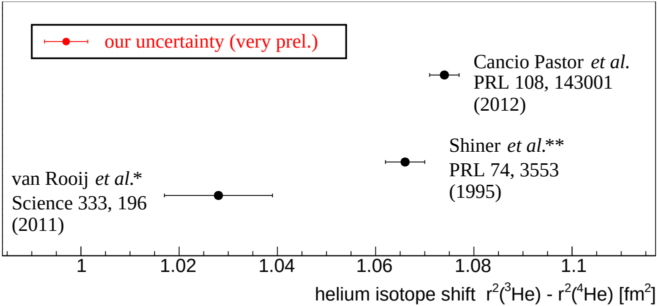
measured transitions:





→ helion radius $r_{\text{helion}} = 1.9XXX(7)\,\text{fm}$!

helium isotope shift



value from re-evaluated theory in

- * Cancio Pastor et al., PRL 108, 143001 (2012)
- ** Pachucki et al., PRA 85, 042517 (2012)

Current situation and outlook

- proton smaller (*Pohl et al. Nature 2010, Antognini et al. Science 2013*)
- deuteron smaller (*Pohl et al. (CREMA), submitted*)
- r_α agrees with e^--scattering
- analysis of helium-3 nearly finished, theory still incomplete

- give an independent value for the helium isotope shift
- extract polarizability in 2S HFS of μ^3He

- more experiments to come: H(2S-4P), H(2S-2P), MUSE, He^+, μp(HFS), ISR, PRAD, and many more

Thank you for your attention!