Precise atomic spectroscopy in search for unknown interactions

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Precise atomic spectroscopy in search for unknown interactions

- Measurements of atomic levels can be very accurate, Garching (2010)

  - $\nu(1S-2S)_{\rm H} = 2466\,061\,413\,187\,035(10)$ Hz,

  - higher accuracy 10^{-18} has been reported for clock transitions

- Hydrogen ground state hfs $\delta E_{\rm hfs}(H) = 1\,420\,405.751\,768(1)$ kHz,

  - hadronic contribution 33pm,

  - agreement with $\delta E_{\rm hfs}(\bar{H})$ up to $3\cdot 10^{-9}$ ASACUSA (2017)

  - comparison to μH hfs ? (Antognini, PSI+ETH)

- Accurate calculations are possible only for simple systems like: H, He, Li, and exotic systems: $\bar{p}$ He, $e\,\mu$, ...

  - the best m_e/m_p from HD$^+$spectroscopy (Amsterdam, Düsseldorf, 2020)

- He, H_2: the most accurate μ_D, Q_D from HD spectroscopy

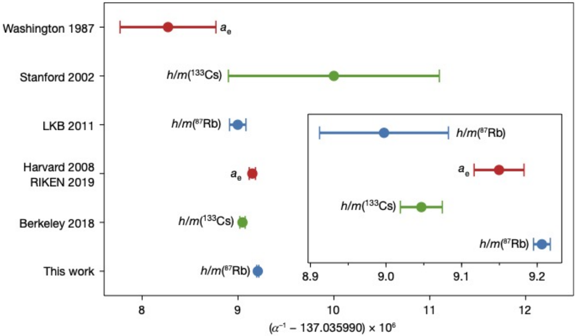
  - collaborators from Praha: V. Patkos (He), from St. Petersburg: V.A. Yerokhin (He), and from UAM: J. Komasa (H_2, Be), M. Puchalski (H_2, He, Li, Be)

electron magnetic moment

- $\delta H = -\vec{\mu}\,\vec{B}$, where $\vec{\mu} = g\left(\frac{e}{2\,m}\right)\vec{S}$ can be measured very precisely
- Dirac theory → $g = 2$, the magnetic moment anomaly $a = \frac{(g-2)}{2} \sim \frac{\alpha}{2\,\pi}$ mainly due to QED effects, calculations up to α^5 order
- determination of the fine structure constant $\alpha = \frac{e^2}{4\,\pi\,\epsilon_0\,\hbar\,c}$ from the measurements of the electron $g-2$ versus the atomic recoil – agreement
- $4.2\,\sigma$ discrepancy for the muonic $g-2$, (FNAL, 2021)

fine structure constant α

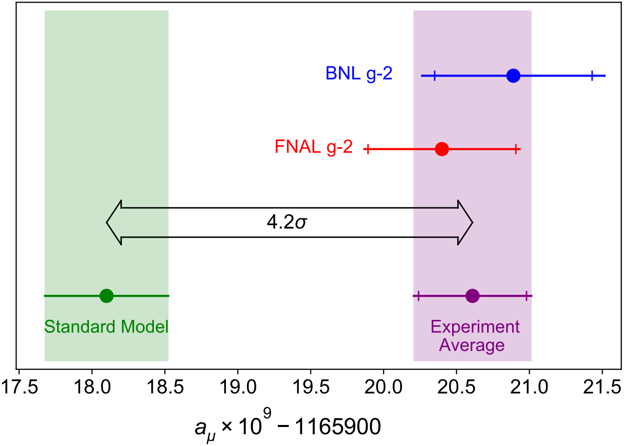
$\alpha^2 = \frac{2\,R_\infty}{c}\,\frac{M}{m_e}\,\frac{h}{M}$ → measurement of h/m leads to determination of α.



from S. Guellati-Khelifa *et al.*, Nature **588**, 3 (2020),

μ magnetic moment anomaly

Phys. Rev. Lett. **126**, 141801 (2021)

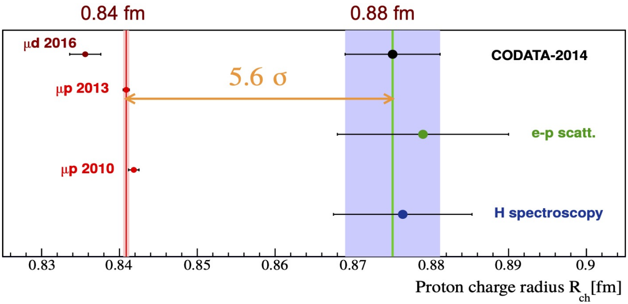


Hydrogen and determination of r_p

- Measurements of transition frequencies can be very accurate, Garching 2010: $\nu(1S-2S)_{\mathrm{H}} = 2466\,061\,413\,187\,035(10)\ \mathrm{Hz}$
- but we need two transitions do determine two unknowns: R_∞ and r_p
- other transitions measured in hydrogen: $2S-2P$, $2S-3S$, $2S-4P$
- hydrogenic systems can be calculated very precisely
  - Dirac equation and finite nuclear mass effects
  - QED radiative corrections
  - nuclear polarizability: limits theory for μH

  up to the finite nuclear size correction: $\delta E = \frac{2\,\pi}{3}\,(Z\,\alpha)\,\phi^2(0)\,\langle r_p^2\rangle$
- high sensitivity to r_p in μH due to ~ 200 heavier muon

Proton charge radius r_p : early results



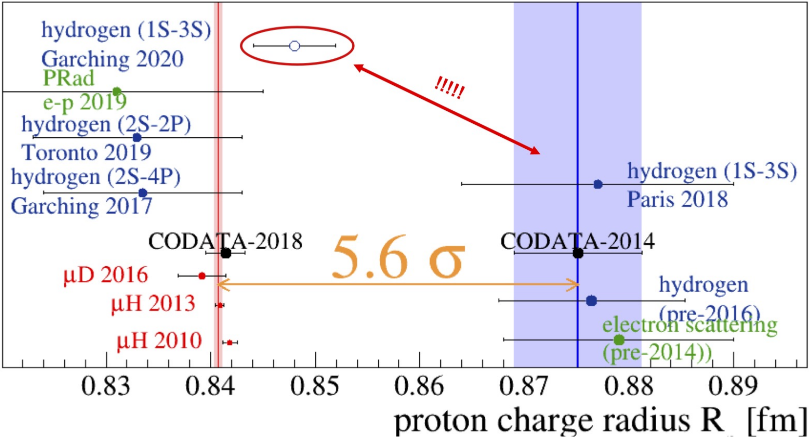
muonic hydrogen: 0.8409 ± 0.0004 fm
electronic hydrogen: 0.876 ± 0.008 fm
electron scattering 0.879 ± 0.011 fm

20x more precise

from Randolf Pohl

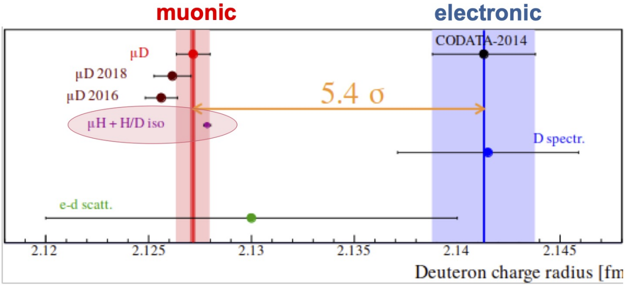
talk at Joint Quantum Institute, April 19, 2021

Proton charge radius r_p : current status



from Randolf Pohl talk at Joint Quantum Institute, April 19, 2021

Deuteron charge radius from μD and H-D isotope shift



μD: 2.12717 (13)$_{exp}$ (82)$_{theo}$ fm (theo = nucl. polarizability)

H/D 1S-2S isotope shift:
$r_d^2 - r_p^2 = 3.82070(31)$ fm^2

μH + H/D(1S-2S): 2.12785 (17) fm

from Randolf Pohl talk at Joint Quantum Institute, April 19, 2021

μD($2S$) hyperfine splitting

$$E_{\rm hfs}({\rm exp}) = 6.2747(70)_{\rm stat}(20)_{\rm syst}\ {\rm meV}$$
$$E_{\rm hfs}({\rm point}) = 6.17815(20)\ {\rm meV}$$
$$\delta E_{\rm nucl} = E_{\rm hfs}({\rm exp}) - E_{\rm hfs}({\rm point}) = 0.0966(73)\ {\rm meV}$$

- The Bohr-Weisskopf effect, charge and magnetic moment distribution within nucleus gives a correction with an opposite sign

$$\delta E_{\rm nucl,BW} = -0.1177(3)\ {\rm meV}$$

.

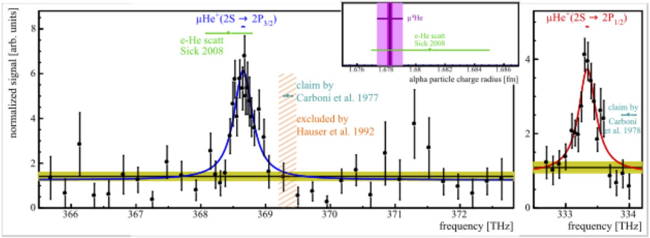
- Nuclear polarizability effects are very important

$$\delta E_{\rm nucl,theo} = 0.0383(86)\ {\rm meV}$$

in 5 σ disagreement with the experimental value

- lack of good understanding of nuclear structure effects to hfs in muonic atoms

$\mu\ ^4$He determination of α-particle charge radius



$2P_{3/2}$: ±17 GHz

$2P_{3/2}$: ±15 GHz

R(^{4}He) = 1.67824 $(13)_{\text{exp}}$ $(82)_{\text{theo}}$ fm

Krauth, RP et al. (CREMA Coll.)
Nature 589, 527 (2021)

Theory: Diepold et al., Ann. Phys. (2018)
incl. 3-photon nuclear polarizability (Pachucki, 2018)

^{4}He atom: theory versus experiments

Very recent measurement of 2^3S_1 ionization energy by F. Merkt *et al.* 2021, and very recent theory V. Patkos *et al.*, Phys. Rev. A 2021.

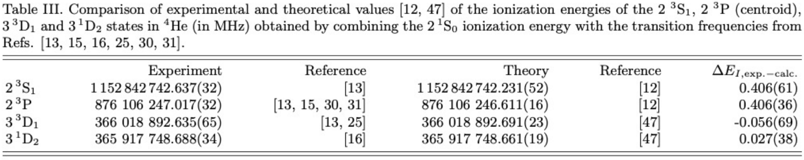


Table III. Comparison of experimental and theoretical values [12, 47] of the ionization energies of the $2\,^3\mathrm{S}_1$, $2\,^3\mathrm{P}$ (centroid), $3\,^3\mathrm{D}_1$ and $3\,^1\mathrm{D}_2$ states in ^{4}He (in MHz) obtained by combining the $2\,^1\mathrm{S}_0$ ionization energy with the transition frequencies from Refs. [13, 15, 16, 25, 30, 31].

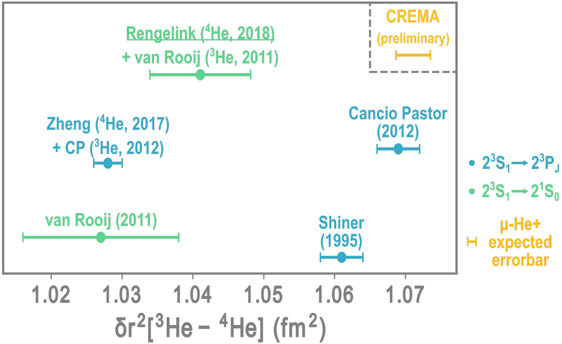
	Experiment	Reference	Theory	Reference	$\Delta E_{I,\mathrm{exp.-calc.}}$
$2\,^3\mathrm{S}_1$	1 152 842 742.637(32)	[13]	1 152 842 742.231(52)	[12]	0.406(61)
$2\,^3\mathrm{P}$	876 106 247.017(32)	[13, 15, 30, 31]	876 106 246.611(16)	[12]	0.406(36)
$3\,^3\mathrm{D}_1$	366 018 892.635(65)	[13, 25]	366 018 892.691(23)	[47]	-0.056(69)
$3\,^1\mathrm{D}_2$	365 917 748.688(34)	[16]	365 917 748.661(19)	[47]	0.027(38)

but a very good agreement with $2^3S_1 - 2^3P$ transition frequency with the charge radius from μHe Lamb shift

$$E(2^3S - 2^3P)_{\mathrm{theo}} = 276\,736\,495.620\,(54)\ \mathrm{MHz}$$

$$E(2^3S - 2^3P)_{\mathrm{exp}} = 276\,736\,495.600\,0\,(14)\ \mathrm{MHz},\ \text{Zheng } \textit{et al } 2017.$$

^{4}He - ^{3}He isotope shift of nuclear charge radii difference



picture by Youri van der Werf

Expected and planned measurements

- $\mu\,{}^3$He Lamb shift, PSI
- $He^+(1S-2S)$ Garching and Amsterdam
- μH ground state hyperfine splitting, ETH
- $\mu^+ e^-$ ETH
- $\mu - p$ scattering with high sensitivity to r_p, AMBER collaboration at CERN, Na66
- $e - p$ versus $\mu - p$ scattering, MUSE collaboration at PSI
- $\bar{p}p$, $\bar{p}\alpha$, AEGIS, CERN