Is the proton as “big” as we thought?

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Journal Club Presentation
PHYS 596

“Proton Structure from the Measurement of 2S-2P Transition Frequencies of Muonic Hydrogen”

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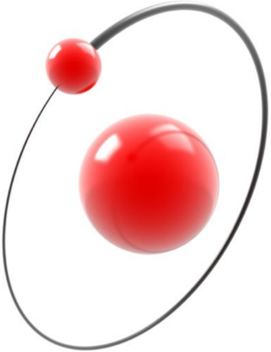
The proton-size puzzle

- “Radius” of the proton can be *defined* and *determined* in various ways



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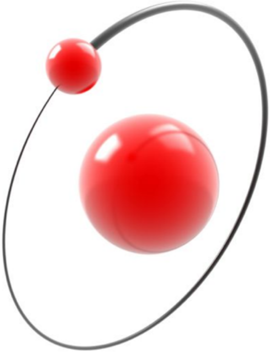
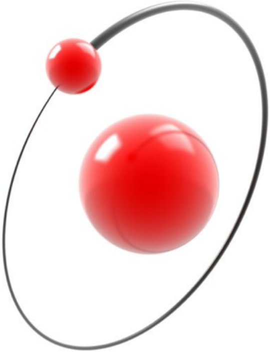
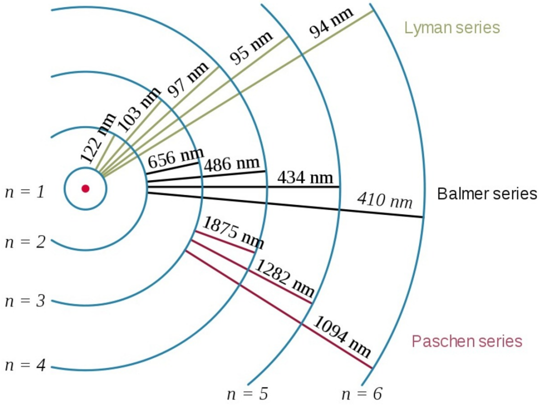


The proton-size puzzle

- "Radius" of the proton can be *defined* and *determined* in various ways
- One attempt to do so runs into trouble - it seems inconsistent with everything else!
- Is this a window for new physics, or another experimental goof-up?



Preliminaries : how things got dirty!



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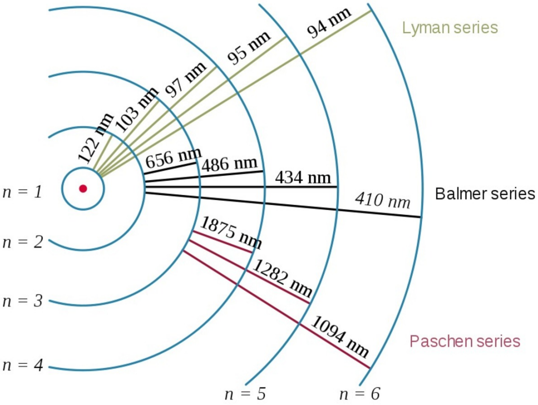

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- ✓ Lamb† shift
- ✓ Hyperfine splitting

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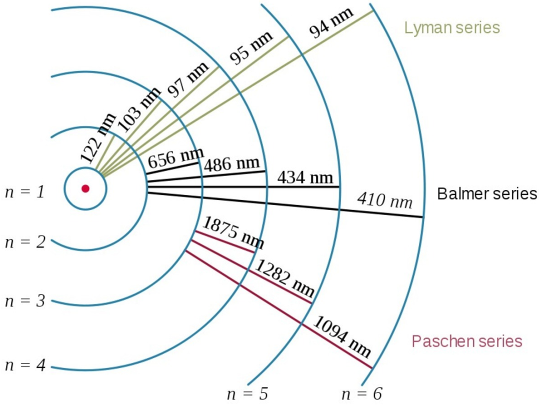

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† lamb = a small sheep ;)

Digression : the spectroscopic notation

✓ Standard way to write down the angular momentum quantum numbers of a state.

$$N\,^{2S+1}L_J$$

L : Orbital angular momentum (S, P, D, F . . . for $\ell = 0, 1, 2, 3, \ldots$)
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e.g. : single electron states (spin-$\frac{1}{2}$ system!), like in Hydrogen

$$1\,^2S_{\frac{1}{2}} \quad 2\,^2S_{\frac{1}{2}} \quad 2\,^2P_{\frac{3}{2}} \quad 2\,^2P_{\frac{1}{2}} \quad 3\,^2S_{\frac{1}{2}} \quad 3\,^2P_{\frac{3}{2}} \quad 3\,^2P_{\frac{1}{2}} \quad 3\,^2D_{\frac{5}{2}}$$

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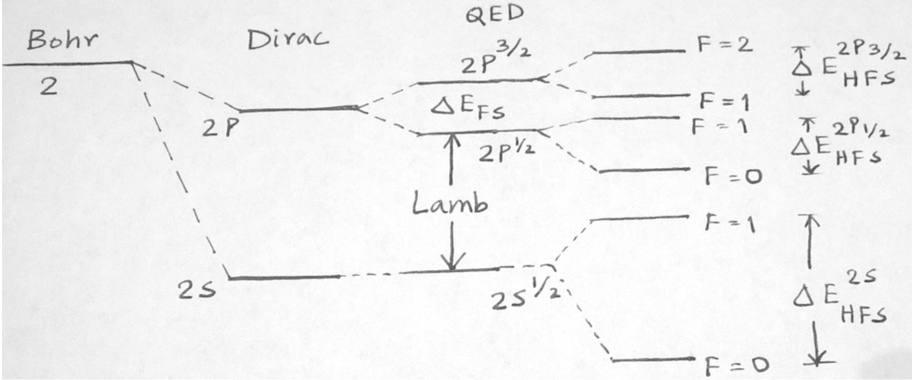


Fig: A subtle structure of the n=2 level in hydrogen according to Bohr's, Dirac's and QED with Lamb Shift.

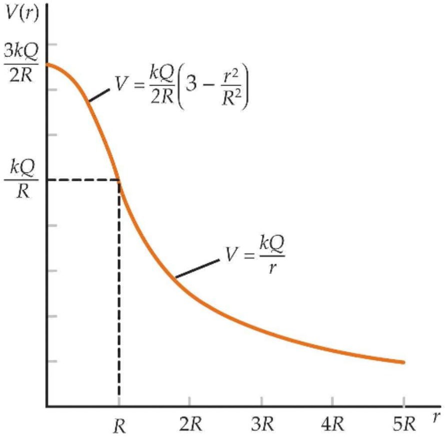
Thou art not solid, proton!

✓ Finite probability of electron to be found inside the nucleus.

$$P(r \leq R) = \frac{1}{\pi a^3} \int_0^{2\pi} \int_0^{\pi} \int_0^{R} e^{-2r/a} r^2 \sin\theta \, dr d\theta d\phi \approx \frac{4}{3} \left(\frac{R}{a} \right)^3$$

V inside charge distribution is smaller than the corresponding field produced by a point charge.

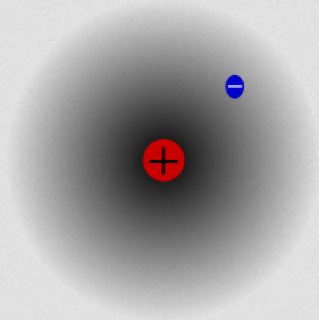
$\Longrightarrow$ measured transition frequencies depend on proton size!



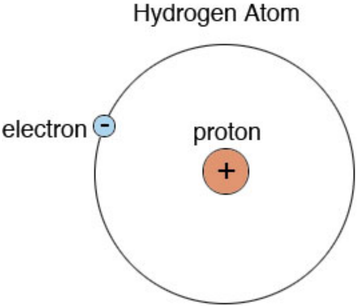
Two ways of defining the "radius" of the proton

✓ Neither atoms nor their nuclei have definite boundaries - we define a

- Charge radius (r_E, based on the distribution of charge) and a
- Zemach radius (r_Z, reflects the spatial distribution of $\vec{\mu}$ smeared out by $\rho(\vec{r})$).



$\approx$



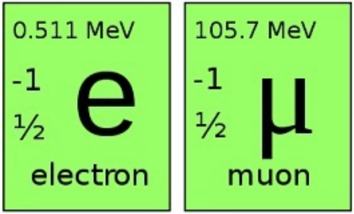
Working with exotic atoms

✓ Historically, r_E and r_Z were determined using measurements of the **differential cross section** in elastic e-p scattering.

✓ A more accurate measurement is expected from **laser spectroscopy** of "Muonic Hydrogen". (Why?)

Muon (e^-'s heavier twin) orbiting the proton instead of electron.

$$m_\mu = 207 m_e$$
$$r_\mu = \frac{1}{186} r_e$$

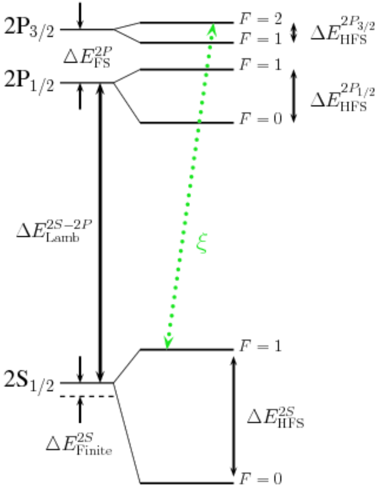


The experiment

(We'll try not to make it boring!)

The experiment

We're measuring r_E from spectroscopy of the $2S_{1/2} - 2P_{3/2}$ transition.

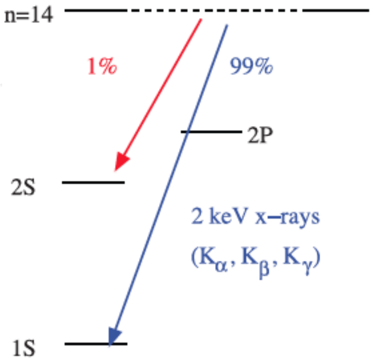


Step 1/3: prepare muonic hydrogen in 2S state

✓ Highly energetic μ^- stopped in H_2 gas

✓ Highly excited μ-p atoms form (n $\approx$ 14)

✓ $\sim$ 1% populate long-lived $2S$ state



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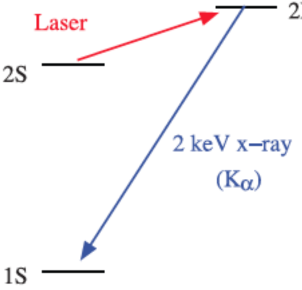
Step 2/3: induce $2S \rightarrow 2P$ transitions

✓ Laser pulse induces $2S \rightarrow 2P$ transitions

✓ Immediately follows $2P \rightarrow 1S$ de-excitation



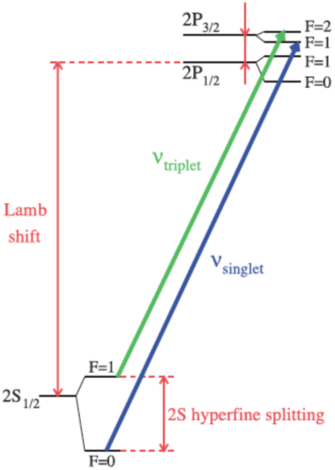
Step 3/3: measure the transition frequencies, what else!

Two 2S $\rightarrow$ 2P transitions measured

✓ $\nu_s \equiv \nu(2S_{1/2}^{F=0} \rightarrow 2P_{3/2}^{F=1})^\dagger$

✓ $\nu_t \equiv \nu(2S_{1/2}^{F=1} \rightarrow 2P_{3/2}^{F=2})$

† $N^{2S+1}L_J \qquad F = J + \mathcal{I}$



Do they conform with known data?

✓ Finite proton size significantly affects Lamb shift and 2S HFS

✓ Some linear combinations of $\hbar\nu_s, \hbar\nu_t, \Delta E^{2P}_{\mathrm{FS}}, \Delta E^{2P}_{\mathrm{HFS}}$ yield Lamb shift and 2S HFS

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✓ From 2S hyperfine splitting, we get r_{Z}, the **Zemach radius**.

$$\Delta E^{\mathrm{th}}_{\mathrm{HFS}} = \ldots + (\ldots)\, r_{\mathrm{Z}} + (\ldots)$$

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$$r_Z = 1.082(37)\ \mathrm{fm}, \qquad r_Z^{\mathrm{Friar}} = 1.086(12)\ \mathrm{fm}, \qquad r_Z^{\mathrm{Distler}} = 1.045(40)\ \mathrm{fm}$$

Experimental limit for measuring $r_Z \sim 3.4\ \%$

✓ So far, so good!

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✓ From Lamb shift, we get the **charge radius**.

$$\Delta E_{\mathrm{L}}^{\mathrm{th}} = \ldots + (\ldots)\, r_{\mathrm{E}}^{2} + (\ldots)$$

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At 7 σ variance with CODATA!

Did we miss something?

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! Maybe we should try a different $\rho(\mathbf{r})$? $\implies$ changes r_E by less than the quoted uncertainty! (more on a later slide.)

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! Yet other recent e-p scattering measurements support the CODATA value.

For the thinking layman . . .

? Is the μ-p interaction different (in what way?) from the e-p interaction?

? Is this a window (albeit possibly small) of new physics?

? Do new force carriers (MeV-mass) exist? (In conformity with other results)

More serious attempts at resolution

$\times$ Gorchtein: uses finite-energy sum rule to find the correction to the proton-polarizability of -(40 +/- 5) μeV. Not enough to explain the 300 μeV difference.

$\times$ Griffith: uses bound-state field theory on proton structure in μ-p. No positive results yet.

? Moumni: Corrects for the noncommutativity in space-space and space-time versions. Says discrepancy is solved by the corrections depending on m^3 giving shifts in the spectrum. New paper though, hasn't been reviewed yet.

Citation Evaluation

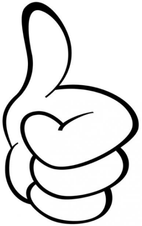
No. of citations : 24

- **13** new proposals, theories, or experiments : Trying to explain the "proton radius puzzle".
- **2** were self-citations (by someone among the authors)
- **9** were papers using the determined values or similar techniques as this experiment.

From the reviewer's POV

What we thought was good :

- Attention to detail - sources of experimental errors; possible sources of discrepancy
- Clear flow of reasoning



What we thought wasn't :

- Talk about changing $\rho(\mathbf{r})$ out of the blue LOOK UP
- No obvious reason for de-excitation into 1S and 2S only LOOK UP

Questions?

... and apart from that, the world is still as beautiful.

GO TO SUMMARY

Definitions of the radii

The charge radius is defined as

$$r_{\mathrm{E}}^2 = \int_0^\infty r^2 \rho(r) dr$$

In general, of course, we could define it in any way, for e.g.

$$r_{\mathrm{E}} = \left(\int_0^\infty r^n \rho(r) dr \right)^{1/n}$$

GO BACK

What we should retain!

- We aim to measure the **charge** and **Zemach** radii of the proton.
- Useful as inputs for tests of bound-state QED
- Earlier experiments with e-p scattering in H-atom - this time, laser spectroscopy of muonic Hydrogen
- From spectroscopy, we deduce **Lamb shift** and **2S hyperfine splitting** - and from them the charge and Zemach radii.
- Turn out to be significantly smaller than accepted proton radius
- Consequences? Window for new physics?

PROTON SIZE PUZZLE