Nuclear Polarizability Corrections to the Lamb Shift of μD

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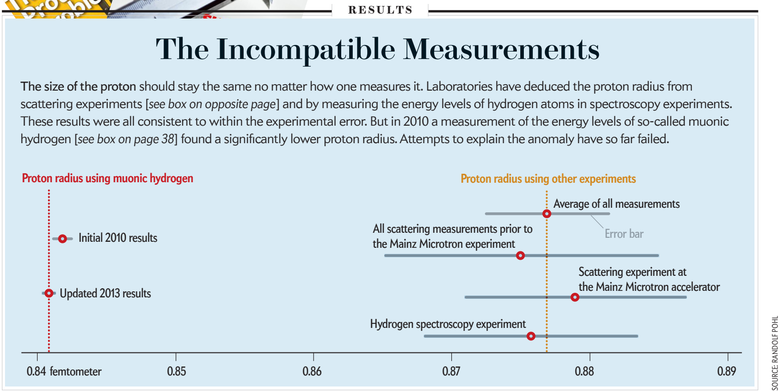
The Proton Radius Puzzle

- New measurements of proton charge radius in μH disagree with CoData determination.



RESULTS

The Incompatible Measurements

The size of the proton should stay the same no matter how one measures it. Laboratories have deduced the proton radius from scattering experiments [*see box on opposite page*] and by measuring the energy levels of hydrogen atoms in spectroscopy experiments. These results were all consistent to within the experimental error. But in 2010 a measurement of the energy levels of so-called muonic hydrogen [*see box on page 38*] found a significantly lower proton radius. Attempts to explain the anomaly have so far failed.

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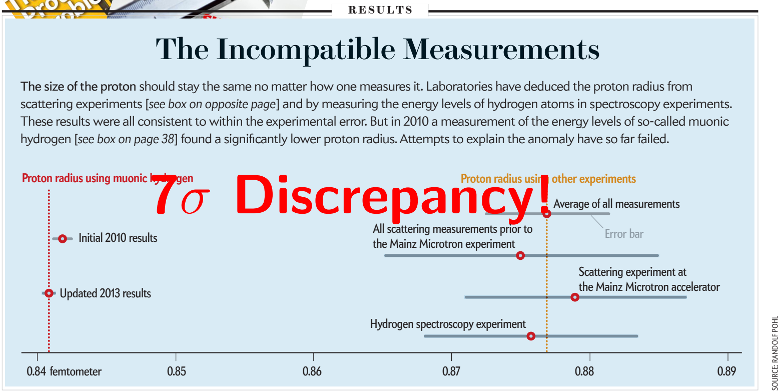
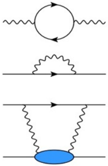


7σ Discrepancy!

Extraction of $\langle r_{ch}^2 \rangle$ from the Lamb Shift

Expansion up to α^5

$$\Delta E(2S-2P) = \delta_{QED} + \delta_{Pol} + \delta_{Zem} + \frac{m_r^3 \alpha^4}{12} \langle r_{ch}^2 \rangle$$



- δ_{QED} corrections arise from vacuum polarization and muon self-interaction
- δ_{Pol} arises from 2γ exchange process
- CREMA collaboration has measured the Lamb shift in μD
- Previous estimates of δ_{Pol} by Pachucki used only AV18 potential
- Use chiral EFT at different orders and vary cuttoff at each order to better estimate error

Nuclear Polarizability

- **The δ_{Zem} term is given by:**

$$\delta_{Zem} = -\frac{\pi(Z\alpha)^2}{3}|\phi(0)|^2 \int d^3r \int d^3r' r^3 \rho(r')\rho(|r - r'|)$$

- **The δ_{Pol} term is expanded as:**

$$\delta_{Pol} \sim \sum_i \delta_{\hat{O}_i} \;\Rightarrow\; \delta_{\hat{O}} \propto \int g(\omega) S_{\hat{O}}(\omega) d\omega$$

The Nuclear Response Function

$$S_{\hat{O}}(\omega) = \frac{1}{2J_0 + 1} \sum_{f \neq i} |\langle i|\hat{O}|f\rangle|^2 \delta(\omega - E_f + E_i)$$

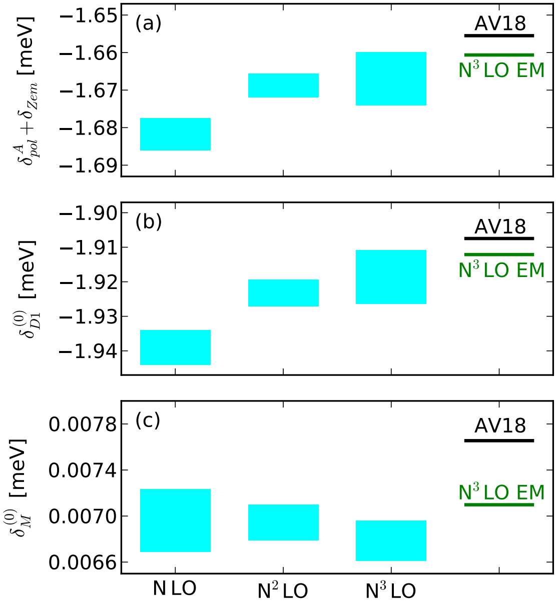
Comparison to Other Work and Experimental Data

		E_0 [MeV]	$\langle r^2_{str} \rangle^{1/2}_d$ [fm]	Q_d [fm^2]	α_E [fm^3]
AV18	**Our**	2.2246	1.967	0.270	0.633
	Wiringa *et al.*	2.2246	1.967	0.270	
N^3LO-EM	**Our**	2.2246	1.974	0.2750	0.633
	Our+RC+MEC		1.978	0.285	
	Entem\Machleidt	2.2246	1.978	0.285	
Experiment		2.224575(9)	1.97507(78)	0.285783(30)	0.70(5) 0.61(4)

Nuclear Polarizability Corrections: AV18

		Pachucki '11	Our work '14	Pachucki '15
$\delta^{(0)}$	$\delta^{(0)}_{D1}$	-1.910	-1.907	-1.910
	$\delta^{(0)}_{L}$	0.035	0.029	0.026
	$\delta^{(0)}_{T}$	–	-0.012	–
	$\delta^{(0)}_{C}$	0.261	0.262	0.261
	$\delta^{(0)}_{M}$	0.016	0.008	0.008
$\delta^{(1)}$	$\delta^{(1)}_{Z3}$	–	0.357	–
$\delta^{(2)}$	$\delta^{(2)}_{R2}$	0.045	0.042	0.042
	$\delta^{(2)}_{Q}$	0.066	0.061	0.061
	$\delta^{(2)}_{D1D3}$	-0.151	-0.139	-0.139
δ_{NS}	$\delta^{(1)}_{Z1}$	–	0.064	–
	$\delta^{(1)}_{np}$	–	0.017	–
	$\delta^{(2)}_{NS}$	–	-0.015	-0.020
$\delta^{A}_{\rm pol}$		–	-1.235	–
$\delta_{\rm Zem}$		–	-0.421	–
$\delta^{A}_{\rm pol} + \delta_{\rm Zem}$		-1.638	-1.656	-1.671

Nuclear Polarizability Corrections: Chiral EFT



Error Budget	
Pot. Dep.	0.5%
Chiral Conv.	0.3%
Atomic Phys.	1%
Total	**1.16%**

⇒ Well within the exp. requirement!

Thank You For Listening!