Accurate spectroscopy of protonium and light antiprotonic atoms

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Searching for New Physics with light antiprotonic atoms

- theoretical predictions for $\bar{p}\,p$ and $\bar{p}\,N$ systems can be almost as accurate as values of fundamental constants $\sim 10^{-12}$ for highly excited circular states
- for lower circular states: the limitation comes from the electric dipole polarizability of the nucleus
- antiprotonic helium atom: $\bar{p}\,\alpha\,e$: accurate calculations $\sim 10^{-10}$ and measurements for $n \sim 38$, ASACUSA + V. Korobov
- a good agreement leads to constraints on exotic interactions for distances $\gg 200$ fm (the size of the electron vacuum polarization interaction potential)
- similarly the precise spectroscopy of H_2, H_2^+ gives strong constraints at a distance of a Bohr radius $\sim 0.5 \cdot 10^{-10}$ m

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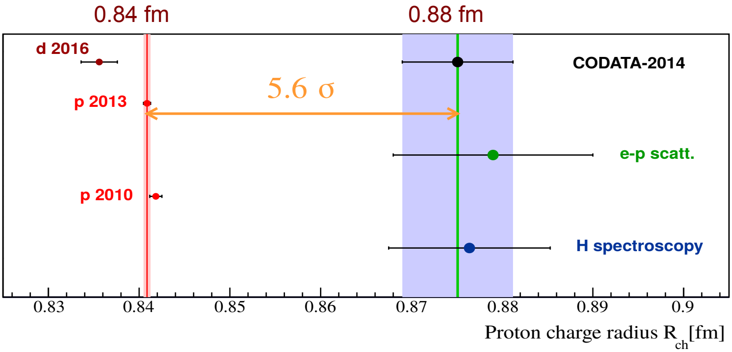
- terra incognita: from 10 fm to 200 fm, there are no experiments which probes these distances between hadrons with a high precision
- precision spectroscopy of $\bar{p}\,N$ can probe the long range hadronic interactions from distances where annihilation is negligible
- can we expect anything interesting in this region ?
- a recent experiment on forbidden electromagnetic decay: arxiv:1910.10459 *New evidence supporting the existence of the hypothetic X17 particle*, by Krasznahorkay *et al*. suggests the existence of a pseudoscalar or a vector boson particle with $M \sim 17$ MeV, what corresponds to ~ 12 fm distance
- The vector boson particle will be visible in spectra of $\bar{p}N$

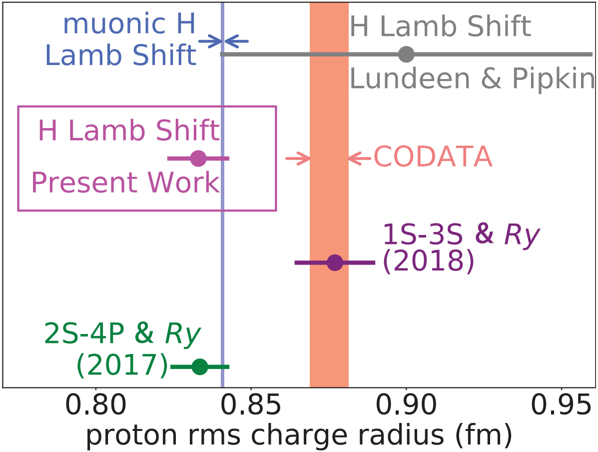
Muonic Hydrogen



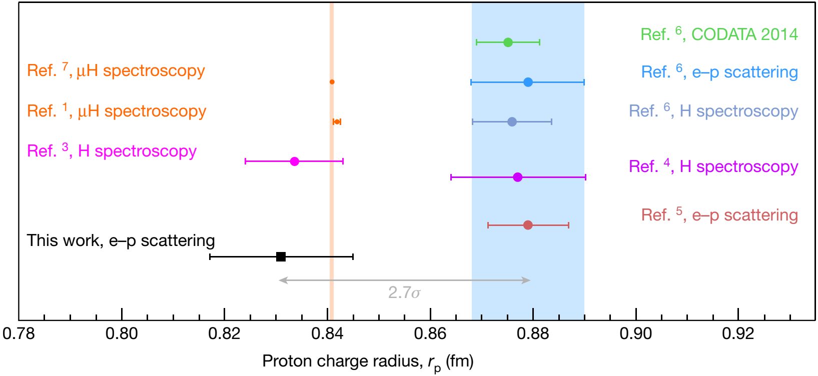
muonic hydrogen: 0.8409 ± 0.0004 fm
electronic hydrogen: 0.876 ± 0.008 fm
electron scattering 0.879 ± 0.011 fm

20x more precise

2S-2P by E. Hessels, Science 365, 1007 (2019)



JLAB, Nature 575, 147 (2019)



Theory of antiprotonic circular levels

(unpublished) PhD dissertation, *QED correction to positronium and antiprotonic atoms*, Warsaw (2009)

$$E(\alpha) = m_1 + m_2 + \alpha^2 E^{(2)} + \alpha^4 E^{(4)} + \alpha^5 E^{(5)} + \alpha^6 E^{(6)} + \dots$$

$$H^{(2)} = \frac{p^2}{2\,m_1} + \frac{p^2}{2\,m_2} + V(r),$$

$$V(r) = -\frac{Z\,\alpha}{r} - \frac{\alpha}{\pi}\int_2^\infty d\rho\,\frac{2}{3\,\rho}\sqrt{1-\frac{4}{\rho^2}}\left(1+\frac{2}{\rho^2}\right)\frac{Z\,\alpha}{r}\,e^{-\rho\,m_e\,r}$$

$$\begin{aligned} H^{(4)} = & -\frac{p^4}{8}\left(\frac{1}{m^3}+\frac{1}{M^3}\right) + \frac{1+2\kappa}{8\,m^2}\nabla^2 V + \\ & \left(\frac{1+2\kappa}{4\,m^2}+\frac{1+\kappa}{2\,m\,M}\right)\frac{V'}{r}\,\vec{L}\cdot\vec{\sigma} + \frac{1}{2\,m\,M}\nabla^2\left[V-\frac{1}{4}(r\,V)'\right] \\ & + \frac{1}{2\,m\,M}\left[\frac{V'}{r}L^2 + \frac{p^2}{2}(V-r\,V') + (V-r\,V')\frac{p^2}{2}\right] \end{aligned} \tag{1}$$

Theory of antiprotonic circular levels

$$E^{(5)} = -\frac{2\,\alpha}{3\,\pi}\left(\frac{Z}{m_1}+\frac{1}{m_1}\right)^2\left\langle\vec{p}\,(H-E)\ln\frac{(H-E)}{\mu\,(Z\,\alpha)^2}\,\vec{p}\right\rangle - \frac{7}{6\,\pi}\,\frac{Z^2\,\alpha^2}{m_1\,m_2}\left\langle\frac{1}{r^3}\right\rangle$$

$$E^{(6)} = \ldots \text{PhD dissertation}$$

- α^7 corrections can also be calculated in a straightforward way
- in conclusion: one can obtain highly accurate results for circular states, similarly to $\bar{p}\mathrm{He}^+$, but at smaller inter-hadronic distances
- can one reach a similar accuracy for measurements ?