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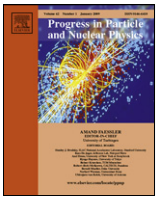

Review

The proton radius puzzle

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ABSTRACT

The proton size, specifically its charge radius, was thought known to about 1% accuracy. Now a new method probing the proton with muons instead of electrons finds a radius about 4% smaller, and to boot gives an uncertainty limit of about 0.1%. We review the different measurements, some of the calculations that underlie them, some of the suggestions that have been made to resolve the conflict, and give a brief overview new related experimental initiatives. At present, however, the resolution to the problem remains unknown.

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1. Introduction

The proton radius conflict is a prime problem in proton structure physics. To state the problem is simple: we measure the proton radius using electrons, and we measure the proton radius using muons, and we get incompatibly different answers.

Measurements made using electrons come either from electron–proton scattering or from atomic spectroscopy, where there are small but measurable shifts in the hydrogen spectrum due to the proton size. The proton charge radius obtained from different electron measurements substantially agree, and gave a result with an uncertainly of order 0.6%.

On the muonic side, there is only one set of measurements, but it is one with a very small uncertainty limit. The announcement came in 2010 [1], with follow-up in 2013 [2], of the proton size measured from its effect on the muonic hydrogen spectrum, specifically the 2S–2P Lamb shift. The muon, because of its mass, orbits closer to the proton than an electron, and its energy levels are more strongly affected by the proton size. This allows a proton radius measurement with an error bar more than 10 times smaller than obtained from the collected electronic measurements, despite the limited lifetime of the muon.

The proton radius from the muonic Lamb shift is a startling 4%, or 7 of the current electronic standard deviations, smaller than the previously accepted result.

The reasons for this are not yet clear. We will make some comments here about what has been thought about, beginning with a brief description of the electron based experiments followed by some remarks about how the muonic Lamb measurements are carried out to give the charge radius. We will then comment on some (but far from all) of the theory calculations needed to interpret the experiments. Much work has been done checking the corrections involved in pulling out the charge radius from the muonic experiment, but nothing big enough to affect the result that has been found. Then we will comment at some length about suggestions that have been made to reconcile the two measurements, including speculation about anomalous QCD corrections, speculation about connections to physics beyond the standard model, and questions raised about the interpretation of the experiments using electrons. The importance of the problem has led to a number of experiments to check aspects of the conflict, and we will catalog some of them in anticipation of their success. We will offer some concluding remarks, but the main concluding remark, unfortunately or otherwise, is that the problem remains.

Previous reviews are found in [3,4].

2. The electronic measurements

Measurements of the proton radius using electrons, either by electron–proton scattering or by careful measurements of atomic energy levels, did not originate the proton radius puzzle. The various electron based measurements of the radius are in agreement and it was not until the muon based measurement appeared that there was a problem. However, we will start with a discussion of the electron based measurements in order to show our notation and delineate one side of the conundrum.

We start with electron scattering. For understanding some definitions, it is even useful to start non-relativistically, where scattering electrons off pointlike protons has the Rutherford cross section

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} = \left(\frac{\alpha}{4E\sin^2(\theta/2)}\right)^2, \tag{1}$$

in the lab system, where E is the energy of the incoming electron, θ is its scattering angle, α is the fine structure constant, $e^2/(4\pi)$. The nonrelativistic cross section result of an extended target is modified, but just becomes

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} \times \left(G(Q^2)\right)^2, \tag{2}$$

where Q is the momentum transfer, the difference between the incoming and outgoing projectile momenta, and $G(Q^2)$ is the "form factor", given nonrelativistically by

$$G(Q^2) \overset{NR}{=} \int d^3r\, e^{i\vec{Q}\cdot\vec{r}} |\psi(r)|^2, \tag{3}$$

where $\psi(r)$ is a wave function describing the density of the target. It is easy to expand the form factor at low Q^2 and obtain,

$$G(Q^2) = 1 - \frac{1}{6}\langle r^2\rangle Q^2 + \cdots, \tag{4}$$

where $\langle r^2\rangle$ is the rms radius squared.

For a electron–proton scattering at the energies under consideration, relativity matters. The lowest order calculation is one photon exchange and proceeds from the Feynman diagram in Fig. 6. The proton vertex involves the matrix element of the electromagnetic current between incoming and outgoing states of definite momentum,

$$\langle p'|J_\mu|p\rangle = \bar{u}(p')\left(\gamma_\mu F_D(Q^2) + \frac{i}{2m_p}\sigma_{\mu\nu}\, q^\nu F_P(Q^2)\right)u(p), \tag{5}$$