Editorial

The Proton Radius Puzzle

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Occasionally, "revolutions" are caused in physics when new measurement techniques become available and cause us to rethink what we thought we knew. This has recently happened in the field of proton structure physics, where researchers have had to revisit fundamental assumptions used in their determinations of the proton's mean electric charge radius.

Until 2010, our knowledge of the proton's electric charge radius came exclusively from electron-proton interactions. One method is to scatter an electron beam of energy <1 GeV from a liquid hydrogen target and measure the *ep* elastic scattering differential cross section, $d\sigma/d\Omega$. By combining a series of measurements at different electron beam energies and scattering angles, a "Rosenbluth separation" can be performed which allows the electric and magnetic form factors of the proton to be determined at low four-momentum transfer Q^2. The rate of decrease of the electric and magnetic form factors at $Q^2 = 0$ are directly proportional to the rms electric and magnetic radii. For an example of a detailed study using this technique, see Bernauer *et al*. (2014).

Precision measurements of hydrogen atomic spectra can also be used to determine the proton's electric charge radius. In this case, the hyperfine 1S Lamb shift of atomic hydrogen is sensitive to the proton's finite charge radius since there is a small (but nonzero) probability that the electron's orbit will be inside the proton. Since the effect is small, a careful bound-state QED calculation of the many radiative effects must be performed to yield the proton charge radius (Melnikov and van Ritbergen, 2000). The accuracy of the proton form factor measurements in *ep* elastic scattering ultimately limits the precision of the radius determination from atomic spectroscopy, but the two methods give electric charge radius values in good agreement within respective uncertainties of about 1% (Particle Data Group, 2012).

Thus, it came as a considerable surprise when a very precise determination of the proton's charge radius via Lamb shift measurements on muonic hydrogen gave results that differed from the accepted value by more than five standard deviations (Pohl *et al*., 2010). When a proton is orbited by a negative muon, its much smaller Bohr radius compared to ordinary atomic hydrogen causes an enhancement of effects related to the finite proton size. The μp Lamb shift between the $2S\frac{1}{2}$ and $2P\frac{1}{2}$ states is affected by as much as 2%, which is dramatically larger than the equivalent shift in ordinary hydrogen. This measurement was only recently made possible through advancements in laser technology and muon beams and is a real *tour-de-force* experimentally.

Not surprisingly, this pioneering muonic Lamb shift measurement caused intense speculation in the proton structure field and many prior assumptions were investigated. Were the fields of atomic and nuclear physics using the same definition of proton charge radius? Is the modeling of muonic hydrogen sufficiently accurate? Was there any systematic uncertainty in any of these measurements that was significantly underestimated? For a recent review of these investigations, see Pohl *et al*. (2013). None of these investigations have yielded anything obviously wrong and after the most recent muonic hydrogen measurements the discrepancy has in fact increased from five to seven standard deviations (Antognini *et al*., 2013).

As a result, the urgency to find a solution to the proton radius puzzle has only increased and even more fundamental assumptions are now under investigation. For example, the possibility that the proton radius puzzle might be caused by a difference between the muon-proton and electron-proton interactions has generated much interest because such an effect is not anticipated in the Standard Model of particle physics. A fundamental tenet of the Standard Model is *lepton universality*, which states that after one corrects for the obvious mass differences between the electron, muon and tau leptons, their interactions should in every other manner be identical. Lepton universality has been tested to the sub-percent level by comparing the decay rates of τ and μ leptons to electrons (Martin and Shaw, 2008). However, the interactions between electrons and protons and muons and protons, have never been directly compared with precision. This will be tested for the first time in 2016-17 with the MUSE experiment (MUSE Collaboration, 2014), which will scatter a mixed beam of electrons and muons from liquid hydrogen and simultaneously compare their scattering cross sections.

To me, it appears that a fundamental flaw of the electron scattering method to determine the proton charge radius is that it invariably involves an extrapolation to $Q^2 = 0$ whose polynomial form is not previously determined by theory. A recent investigation indicates that the choice of extrapolation function has a potentially significant impact (Lorenz and Meissner, 2014). Another issue is the 4 standard deviation difference between the average of the spectroscopic

measurements in ordinary hydrogen and those in muonic hydrogen. To resolve this, further spectroscopic measurements in ordinary hydrogen are also underway (Beyer *et al*., 2013).

The bottom line is that physical systems that were commonly thought to be reasonably well understood can always yield considerable surprises when technical developments thrust revolutions upon the scientific community. Just as at the beginning of the 20th century, we should pray for continuing innovations and future "revolutions" to force us to rethink our fundamental assumptions and cause further advancements in our knowledge of physics.

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