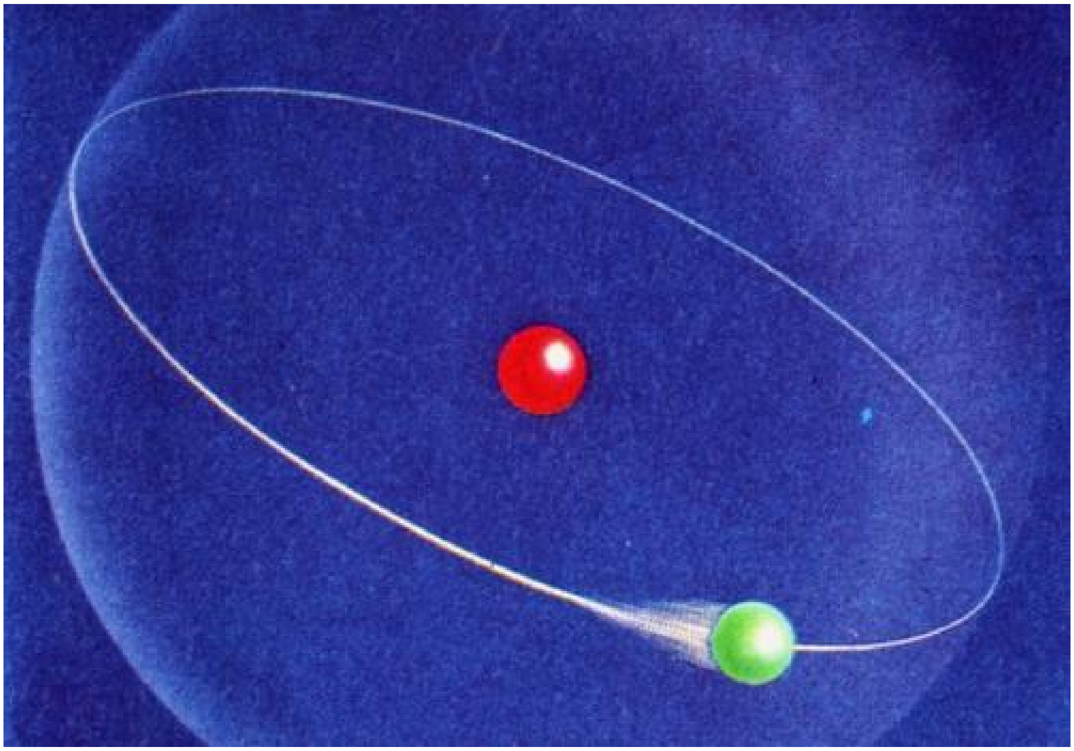
Updating the textbook: Is the radius of a proton wrong?

February 26 2013, by Jonathan Carroll



We thought we knew the radius of the proton to within 0.8%. Perhaps not. Credit: Ludie Cochrane/Flickr

Striving for agreement between theory and experiment and pushing the boundaries of precision are important parts of the scientific process.

With each step in this process we move closer to enlightenment but things get interesting when theory and experiment diverge.

Such was the case following a series of recent experiments investigating the radius of the proton.

As the author Isaac Asimov once said:

The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka!" ("I found it!") but rather "hmm … that's funny …"

The simplest atom

Hydrogen is a simple atom, right? It's an electron bound to a proton. Who knew it would cause such a stir in the physics community?

A recent article in *Science* provides an update to a 2010 announcement that fit the usual pattern: a grand claim of a large discrepancy between established theory and a new experiment, followed by a wide range of explanations of varying levels of credibility.

Usually these updates are to clarify that the problem has been resolved and that, once again, something innocuous was to blame for the unexpected result. Updating three years later to say "it's still broken!" is something of an oddity.

The announcements in question here are about a finding that the radius of the proton differed from the "textbook" value by 4%. This doesn't sound like much, but we thought we knew the radius to within 0.8%, making 4% sort of a big deal.

Physicists only count something as a "discovery" if it's five "standard deviations" (5σ) significant. This measurement is now at 7σ and more than ten times more precise than the previous value, with an error of just 0.05%.

What made it all the more important though, was that the radius of the proton wasn't some value that comes from reading it off a ruler. The theory behind the textbook value is quantum electrodynamics (QED), probably the most refined and accurate theory in all of physics. It describes the way that light and matter interact at the fundamental scale.

Quantum electrodynamics

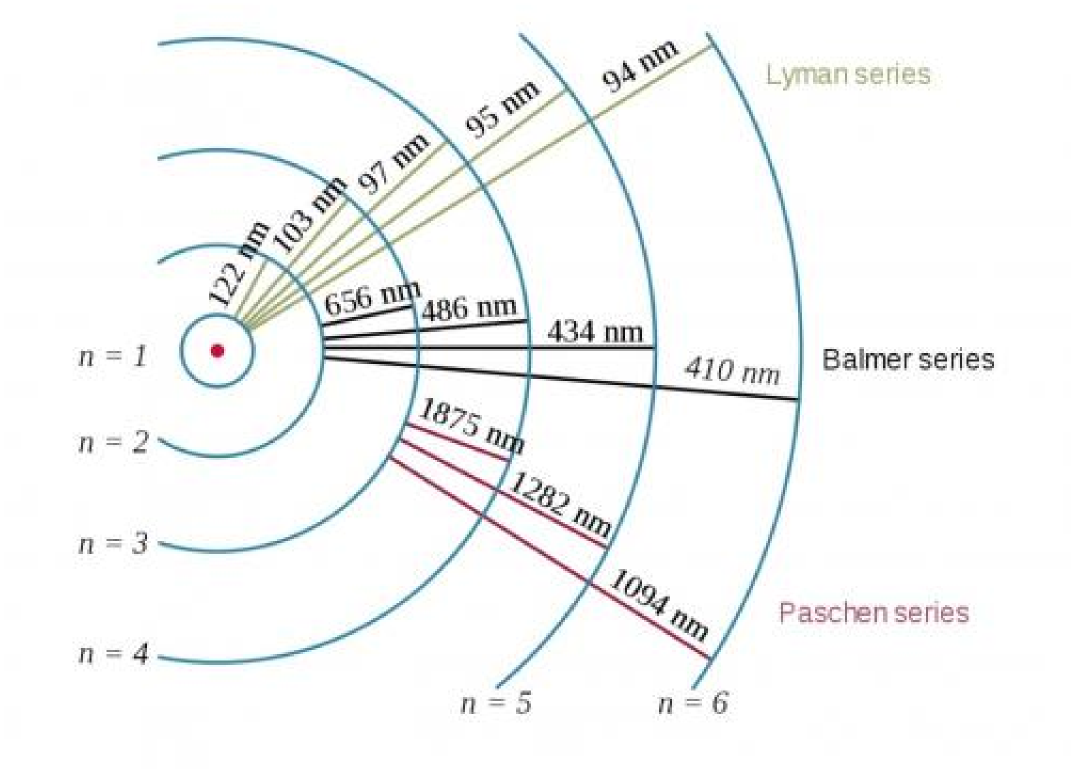
This is the theory that leads to predictions of the "anomalous magnetic dipole moment" of the electron (and muon), one of the most precisely measured quantities in physics. In a perfect world, electrons would have a "g-factor" of exactly g=2. Combining theory with experiment for this value leads to a unitless quantity that differs from g=2 by a very well understood amount:

$$g/2 = 1.001\ 159\ 652\ 180\ 76 \pm 0.000\ 000\ 000\ 000\ 27$$

That is, we know g/2 to better than one part in $3\text{x}10^{13}$, equivalent to knowing the distance of the heliopause (the "edge" of our solar system) to the nearest metre.

This also has implications for the fine structure constant – a quantity for which even a minute change would render life in our universe impossible. This constant has also been verified experimentally to better than one part in a billion.

The point here is that QED works really well. So it's a really, really big problem if it's broken.



Hydrogen spectrum. Credit: http://en.wikipedia.org/wiki/File:Hydrogen_transitions.svg

Radius of the proton

Science wins when theory agrees with experiment. But it moves ahead when they don't. In the case of the proton radius, the theory involves a quantity known as the Rydberg constant, R_∞.

We thought we had a good idea about its value. In fact, it is the most accurately measured fundamental constant.

The beauty of this constant is that it can be related to just a few other basic fundamental constants such as the mass and charge of an electron, and also a unit of energy:

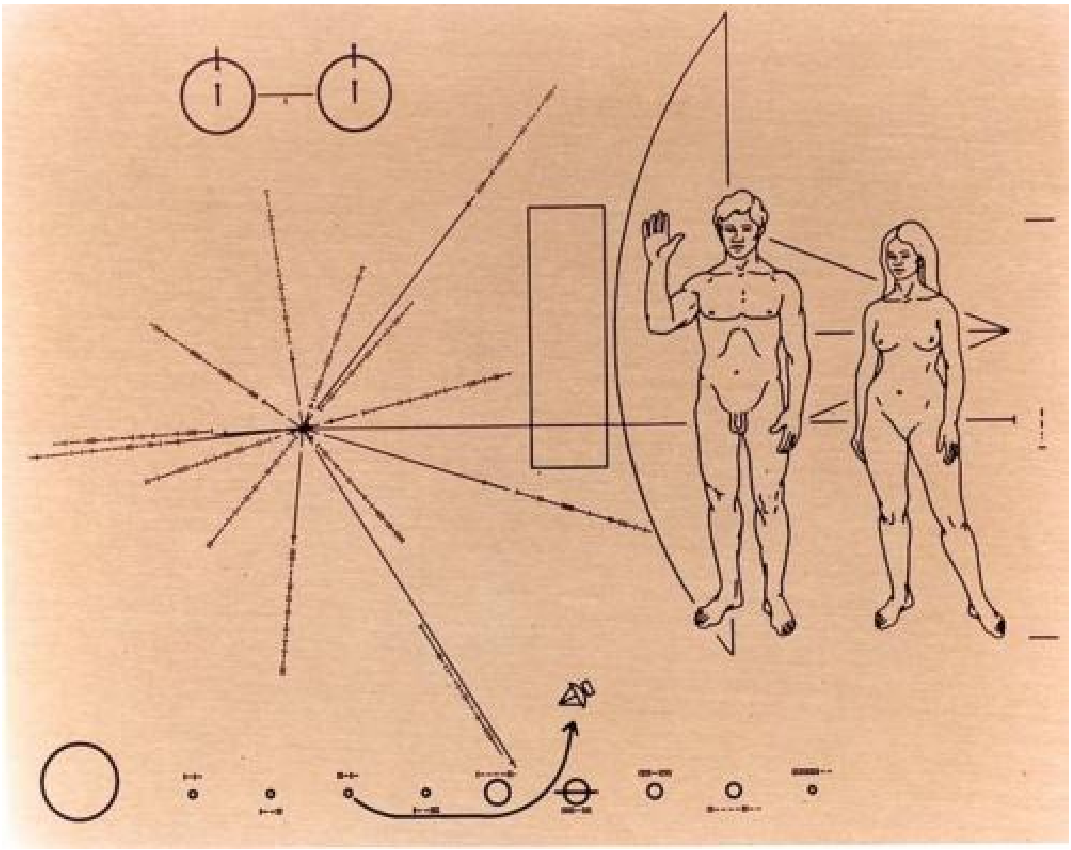
$1\ Ry = h\ c\ R_\infty = 13.605\ 692\ 53\ (30)\ eV.$

That energy might be familiar to you if you've studied hydrogen at all – it's the energy of the ground (lowest energy) state, and it's critical to our understanding of atomic spectra – the range of discrete frequencies given out or absorbed by atoms based on their electrons' energy levels.

Atomic spectra

We think we understand spectra pretty well. The "21cm" line of hydrogen is reasonably well known in science culture. It's the wavelength that SETI scans in looking for signals from other worlds.

It was also used as the standard scale for the diagrams on the gold plaques sent out on Pioneer 10 and 11 and gold records on Voyager 1 and 2, along with a diagram explaining its significance (in case you're wondering, it's the energy of a spin-flip of the ground-state electron in hydrogen, also known as the hyperfine splitting).



Pioneer 10 plaque showing (top-left) the hydrogen spin-flip (hyperfine) scale (marked |) on which all other distances in the images are based in binary (e.g. | – – – for 8 x 21cm = 1.68m for the heights of the people). Credit: http://en.wikipedia.org/wiki/File:Pioneer10-plaque.jpg

Calculating the hydrogen ground state energy, or the 21cm line, precisely relies on quantum electrodynamics, but these don't depend on the value of the proton radius very strongly. Why? Because in the case of hydrogen, the electron spends most of its time a very long way away from the proton.

On average (and we're talking quantum mechanics here) the electron sits about 50,000 proton radii away from the proton itself when in the energy state relevant to the 21cm line. This is why we say that atoms are "mainly empty space".

The important difference comes when you replace the electron in hydrogen with a muon, the electron's heavier cousin. The muon's mass is about 200 times that of the electron, and because of this it spends a lot of its time 200 times closer to the proton.

Being so much closer, its energy levels are more sensitive to the radius of the proton (specifically, how the proton's charge is distributed over its volume).

People have been making predictions of the spectrum for 40 years using the "textbook" radius as an input, but we lacked experimental verification.

In review

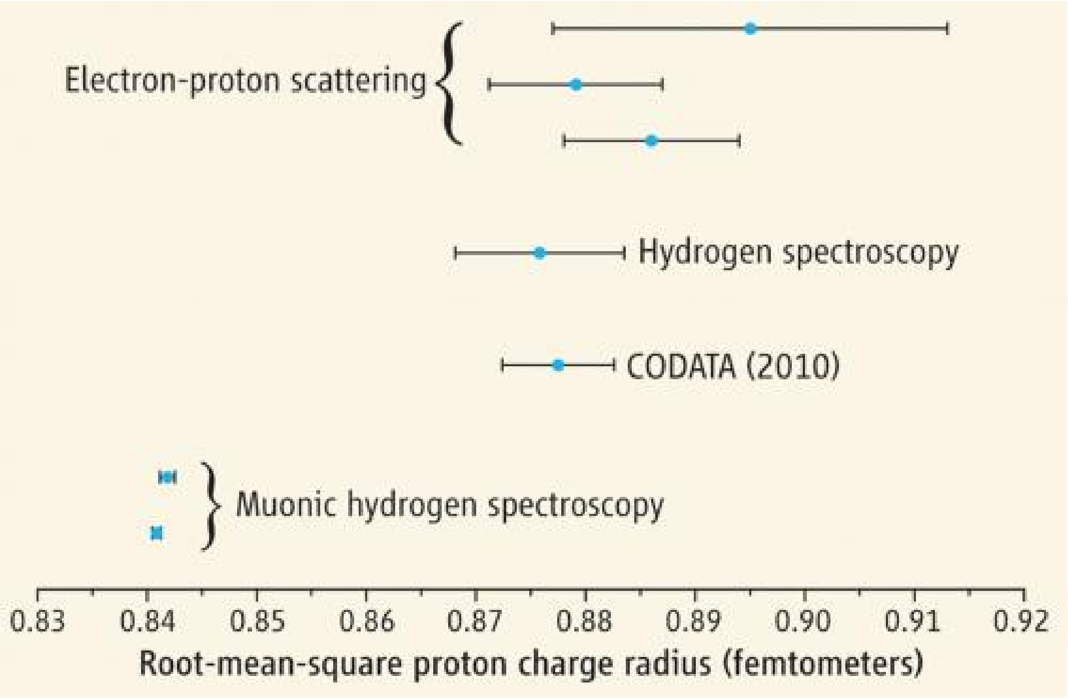
Which brings us back to what a team of physicists did at the Paul Scherrer Institute (PSI) in Switzerland in 2010 and again recently – they measured the energy spectrum of muonic hydrogen very precisely and found that it didn't match what they expected.

Using quantum electrodynamics, they unravelled the dependence on the proton radius, and found that a value 4% smaller than the "textbook" value fixes the problem entirely.

Previous experiments which led to that value all involved "normal" hydrogen, mostly extracting the proton radius from energy shifts in the same way as muonic hydrogen. A few experiments used electron-proton scattering to determine the proton radius, but there are fundamental issues with this extraction that complicate the matter.

When success isn't …

I myself spent the past two years calculating the QED values more precisely, and reached the same conclusion as the PSI team. I've come to realise during this time that hydrogen is anything but simple, requiring extremely precise calculations at this level.



Diverging results. Credit: http://www.sciencemag.org/content/339/6118/405

The update in Science verifies the PSI team's experiment with a second value which agrees perfectly with their first, suggesting they didn't have a problem with their set-up initially.

In a lot of cases, outrageous claims of beyond-five-standard-deviation discoveries vanish with the discovery of an overlooked contribution or even a loose wire (as some predicted). In this case though, the result has withstood intense interrogation and remains undamaged.

Time to re-evaluate

What comes next is a re-evaluation of the "textbook" value, and updated experiments are underway to probe this. There's still the problem with the Rydberg constant and the other experiments, but there is a horrible phenomenon whereby experiment and theory tend to agree with established values until they are challenged firmly enough, at which point they "drift" towards updated values.

Nonetheless, the journey that has lead to this point encapsulates for me the motivation for science: "Let's measure X and see if it's any different to what people got last time." When things don't agree, we learn something and make progress.

Again, Asimov puts it better than I can:

When people thought the earth was flat, they were wrong. When people thought the earth was spherical, they were wrong. But if you think that thinking the earth is spherical is just as wrong as thinking the earth is flat, then your view is wronger than both of them put together.

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