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Physicists team up to tackle proton radius problem

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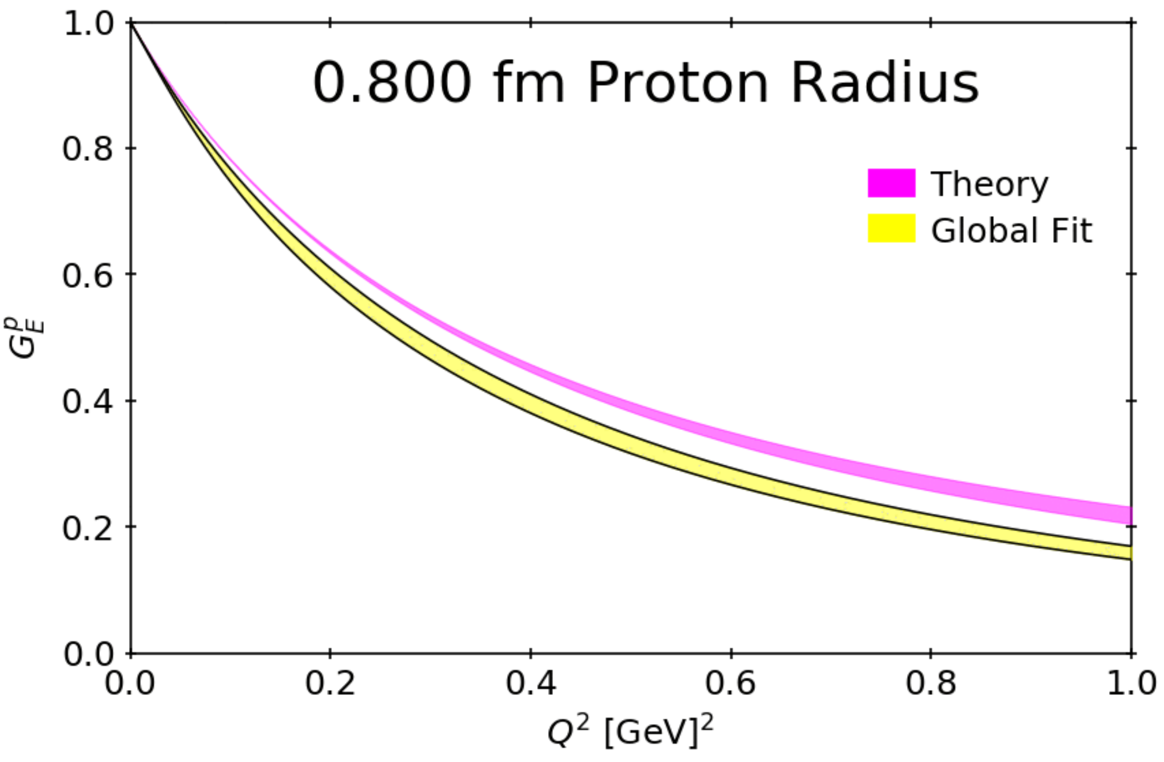

Credit: Jefferson Lab

Ten years ago, just about any nuclear physicist could tell you the approximate size of the proton. But that changed in 2010, when atomic physicists unveiled a new method that promised a more precise measurement. The new quantity came up 4% shorter than expected, setting off a scramble within the nuclear and atomic physics communities to determine if this discrepant result was due to new physics or an indication of problems with the extractions of the quantity from experiments.

Now, four nuclear physicists, two experimentalists and two theorists, think that they've resolved the discrepancy using experimental nuclear physics data and an advanced physical model to obtain a new value for the size of the proton. The result was published in *Physical Review C* in April.

Taking A Yardstick to the Proton

One thing that all of the methods agree on is that the proton is tiny. The proton's charge radius, which measures the size of the distribution of electric charge in the nuclear particle, is a bit less than a femtometer, with a single femtometer registering at one-quadrillionth of a meter.

Stated another way, if you take a meter stick and split its length into one billion equal pieces, and then take just one of those pieces and split its length into another million pieces, the length of each one of those million pieces will be a femtometer.

Because it is so small, the charge radius of the proton can't be measured directly. Instead, nuclear and atomic physicists use sophisticated methods to determine the proton size.

"Basically, it's about the interaction of the proton with electromagnetic fields, that's part of what's called the electromagnetic structure of the proton, or the form factor of the proton," explained Christian Weiss, a staff scientist at the Department of Energy's Thomas Jefferson National Accelerator Facility in the Center for Theoretical and Computational

Physics. "What you are measuring is the size of the spatial distribution of electric charge of the proton."

Two's Company, Three's a Crowd

About 30 years ago, nuclear and atomic physicists came up with two different methods to determine this electric charge radius.

Nuclear physicists conduct experiments via electron scattering, where electrons are hurled at protons, and the proton's charge radius is determined by the change in path of the electrons after they bounce off the proton.

"In some sense, the electron ever-so-gently scatters off that proton," Weiss said.

Atomic physicists also use electrons to measure the proton's radius. They observe, using spectroscopy, the energy levels of electrons as they orbit a small nucleus, such as hydrogen (with one proton) or deuterium (with a proton and a neutron).

Using these two different methods, a radius of about .88 femtometers was established as the world value.

Then, in 2010, an atomic physics research team made a shocking announcement. In a twist on the atomic physics method, the team measured the energy levels of electrons in orbit around lab-made hydrogen atoms that replaced an orbiting electron with a muon. While a muon is the same class of particle as the electron, it has 200 times the electron's mass and so orbits much closer to the proton. This proximity means that the proton's charge radius has a greater effect on its orbit.

The new, more precise method yielded a measurement of .84

femtometers, or about 4% smaller than the world value.

The new result set off a frenzy of activity around a value that most physicists thought had already been settled. Further electron-scattering experiments were planned, additional hydrogen and muonic hydrogen spectroscopy measurements were made, and atomic and nuclear theory were re-examined for clues.

Physicists Face Off

Here at Jefferson Lab, the new efforts galvanized a review of the experiments that were used to establish the world value and a review of nuclear theory for more precise ways to examine the data or predict the value from results. A team of four nuclear physicists came together to work on the science behind the Physical Review C publication.

They began by addressing one of the concerns that experimental nuclear physicists had about electron-scattering data: how the quantity for the proton radius was obtained from experimental data.

"There has been a challenge to extract the radius of the proton from these electron-scattering data, because the actual scattering experiments require some finite momentum transfer from the proton," Weiss explained. "The number that you're interested in is the response of the proton at zero momentum transfer, so that's something that's not directly accessible."

Instead, nuclear physicists analyze the data they get from experiments at the lowest momentum transfers and then use a procedure to extrapolate down to zero. There's an ongoing debate, however, about what momentum transfers are still relevant and how the extrapolation should be done.

Two members of the team are experimentalists: Douglas Higinbotham, a Jefferson Lab staff scientist, and Zhihong Ye, a senior research associate at Argonne National Lab. They resolved the experimental side of the challenge by considering the pre-analysis world data over a wide range of momentum transfers.

Instead of extrapolating from the data to get a value, they instead plotted the data over the full range of measured momentum transfers while taking into account that the proton's charge radius could be any one of many possible values.

"We just fixed the radius in our fits and repeated the analysis many, many times, for every reasonable value of the radius," said Higinbotham. "And then went to theorists and asked them to generate the theoretical curves for those radii, so that we can compare and see if there is agreement."

The other two members of the four-person team are theorists: Weiss and José Manuel Alarcón, a research professor at the Universidad Complutense de Madrid. They worked together to tighten up the theoretical methods used to analyze the problem.

"We used a particular theoretical method called effective field theory to make a model of the structure of the proton for how it responds to electromagnetic scattering at low momentum transfers," Weiss explained. "The theory condenses the relevant structure of the proton to a few numbers. And it allows you to predict the response of the proton to electron scattering at finite momentum transfers, and how that's related to the charge radius that you want to extract."

When the experimentalists and theorists then compared their work, they found that it converged on a new value for the proton's radius, as shown in the animation.

"What is absolutely beautiful and striking is when you look at whether there is a radius where the global fit and the theoretical calculation agree, there is one. It's .845 femtometers," said Higinbotham. "And it's oddly consistent with the muonic radius result and not with many of the previous electron-scattering extraction results."

A Window into New Physics

The quest to solve this discrepancy isn't one of idle curiosity—the value for this quantity has far-reaching effects. For instance, a more precise result may reveal uncharted areas of nuclear and particle physics.

"It can be a window for new physics. If we cannot reconcile different measurements for the proton radius, maybe it's because there is new physics that we don't understand or that we don't have in our theory. That's one of the reasons why this proton radius is so important," explained Alarcón.

When asked if they think this is the final determination for this quantity, all four researchers demurred.

"Science is a process of successive refinement of ideas and methods, in which our present understanding is only a stage from which we move on to more accurate theory and experiments," said Weiss.

For now, they point to several recent experimental studies that use newer technologies to measure the value to even higher precision, including the PRad experiment that took electron-scattering data in Jefferson Lab's Experimental Hall B in 2016. It's named for its goal: an ever-more precise measurement of the proton's radius.

"The PRad result will be out this year. It will be interesting to see whether the new result can confirm our scientific analysis," said Ye.

More information: J. M. Alarcón et al. Proton charge radius extraction from electron scattering data using dispersively improved chiral effective field theory, *Physical Review C* (2019). DOI: 10.1103/PhysRevC.99.044303

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