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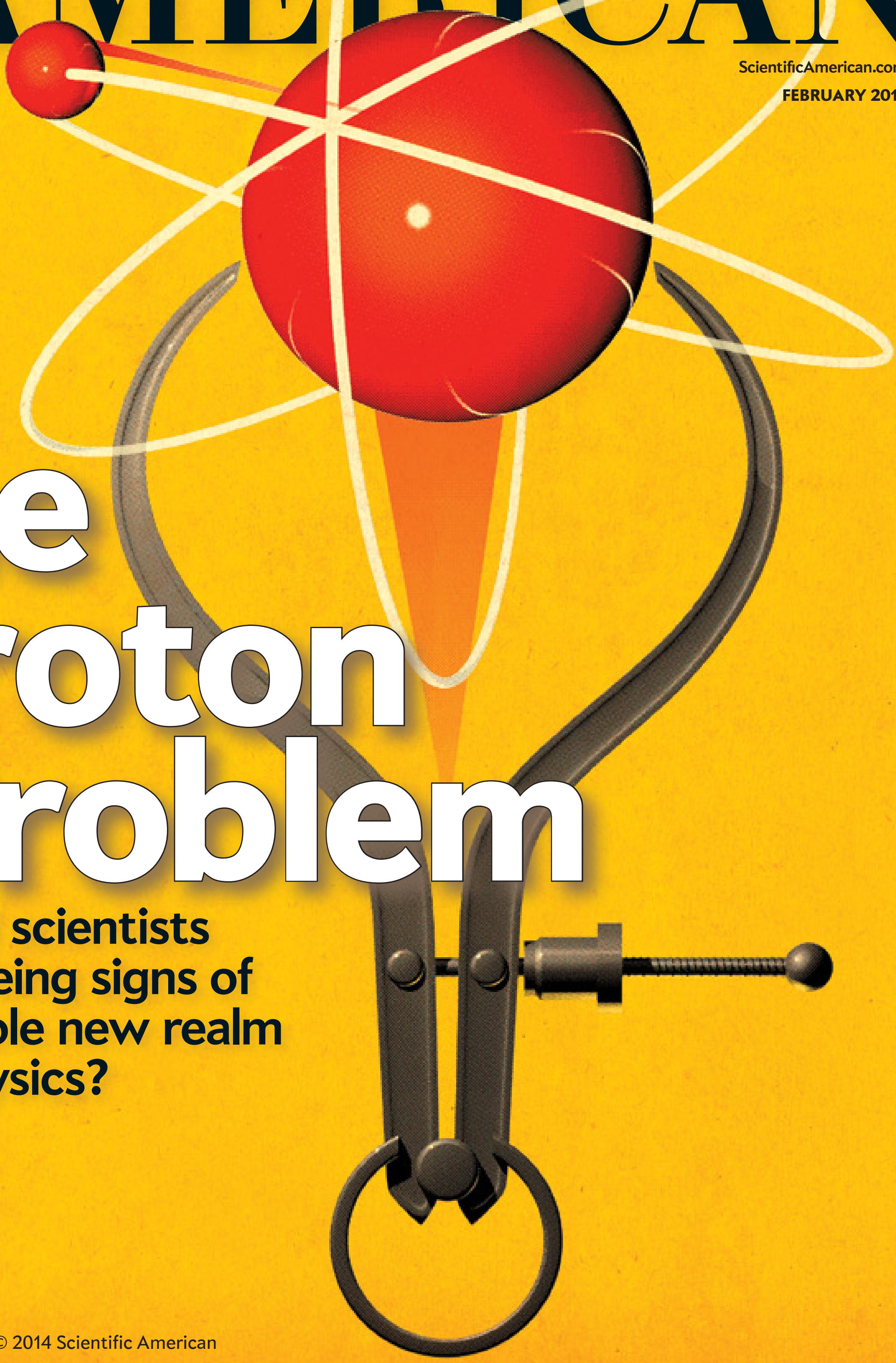


The Proton Problem

Could scientists be seeing signs of a whole new realm of physics?

PHYSICS

The Proton Radius Problem

Two experiments have come up with two wildly different values for the proton's radius. What's going on?

By Jan C. Bernauer and Randolf Pohl

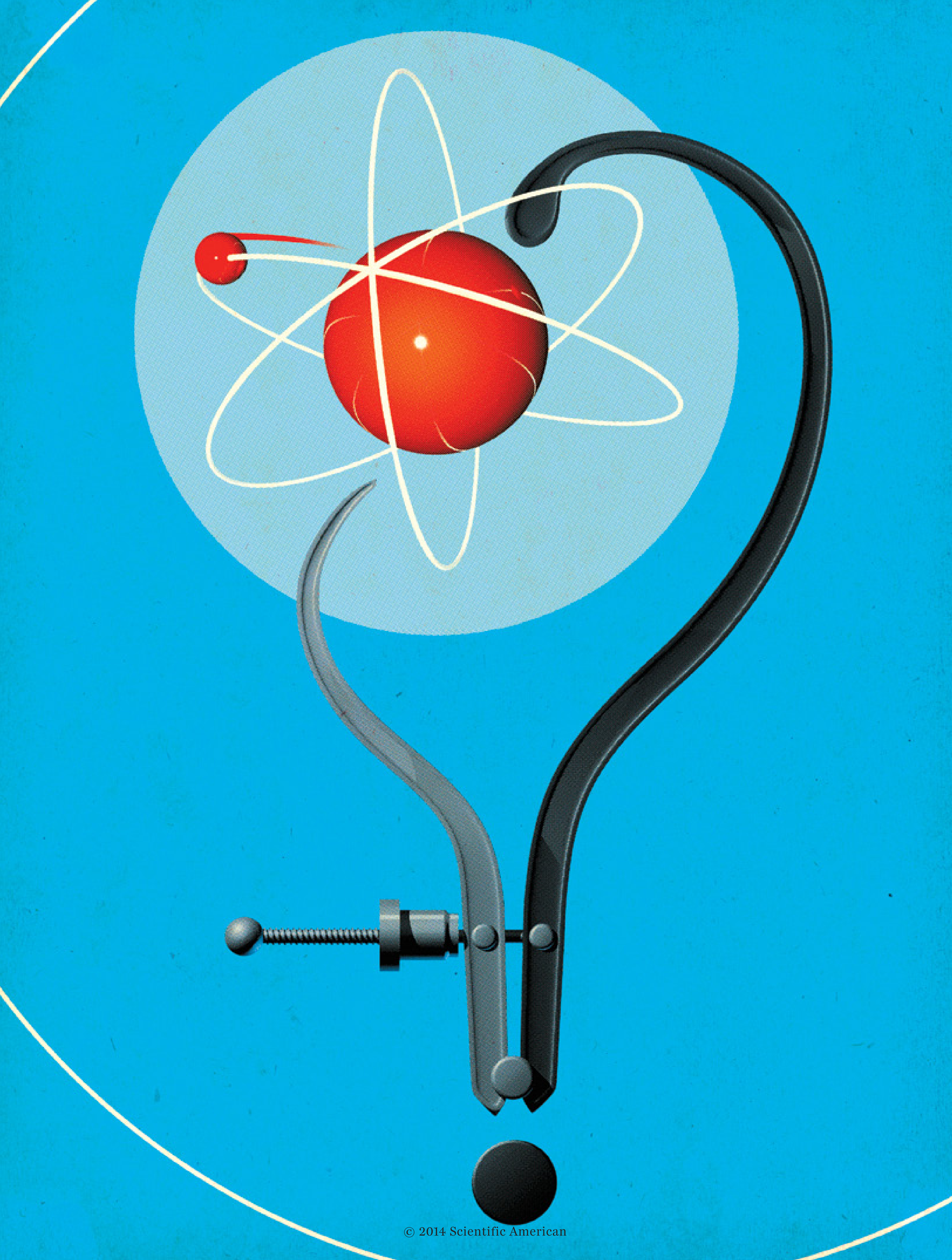
IN BRIEF

A new experiment to measure the proton radius has found it to be much smaller than expected.

The difference suggests that physicists do not understand something important about either the proton itself or the theory of quantum electrodynamics—until now the best-tested and best-understood theory in all of science.

With any luck, the anomaly could lead to a fundamental revision of the laws of physics.

Illustration by Tavis Coburn

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YOU WOULD BE FORGIVEN FOR ASSUMING THAT WE UNDERSTAND THE PROTON.

It is, after all, the main constituent of matter in the observable universe, the fuel of stellar furnaces. Studies of the proton—its positive charge suitably bound up with a negatively charged electron to make a hydrogen atom—initiated the quantum-mechanical revolution a century ago. Today researchers trigger torrents of ultrahigh-energy proton collisions to conjure particle exotica such as the Higgs boson.

Yet recent studies of the proton have surprised us. The two of us (Bernauer and Pohl), along with our colleagues, have made the most precise measurements of the radius of the proton to date, using two complementary experiments. When we began the exercise, we suspected that our results would help add levels of precision to the known size of the proton. We were wrong. Our measurements of the proton's radius differ by a huge gulf. The difference is more than five times the uncertainty in either measurement, implying that the probability that this is all due to chance is less than one in a million.

Clearly, something is amiss. Either we don't fully understand the proton, or we don't understand the physics that goes into the precision measurements of the proton. We have reached out into the universe and pulled back an anomaly. And so we have a great chance to learn something new.

THE MISSING SHIFT

OUR STORY BEGINS on the Italian island of San Servolo, 10 minutes by fast boat from the Piazza San Marco in Venice. The island hosted a hospital for the mentally ill until the late 1970s. Three decades after it closed, a few dozen physicists began to meet on the island to discuss ever more stringent tests of the best-understood theory in all of physics, if not all of science: quantum electrodynamics, or QED.

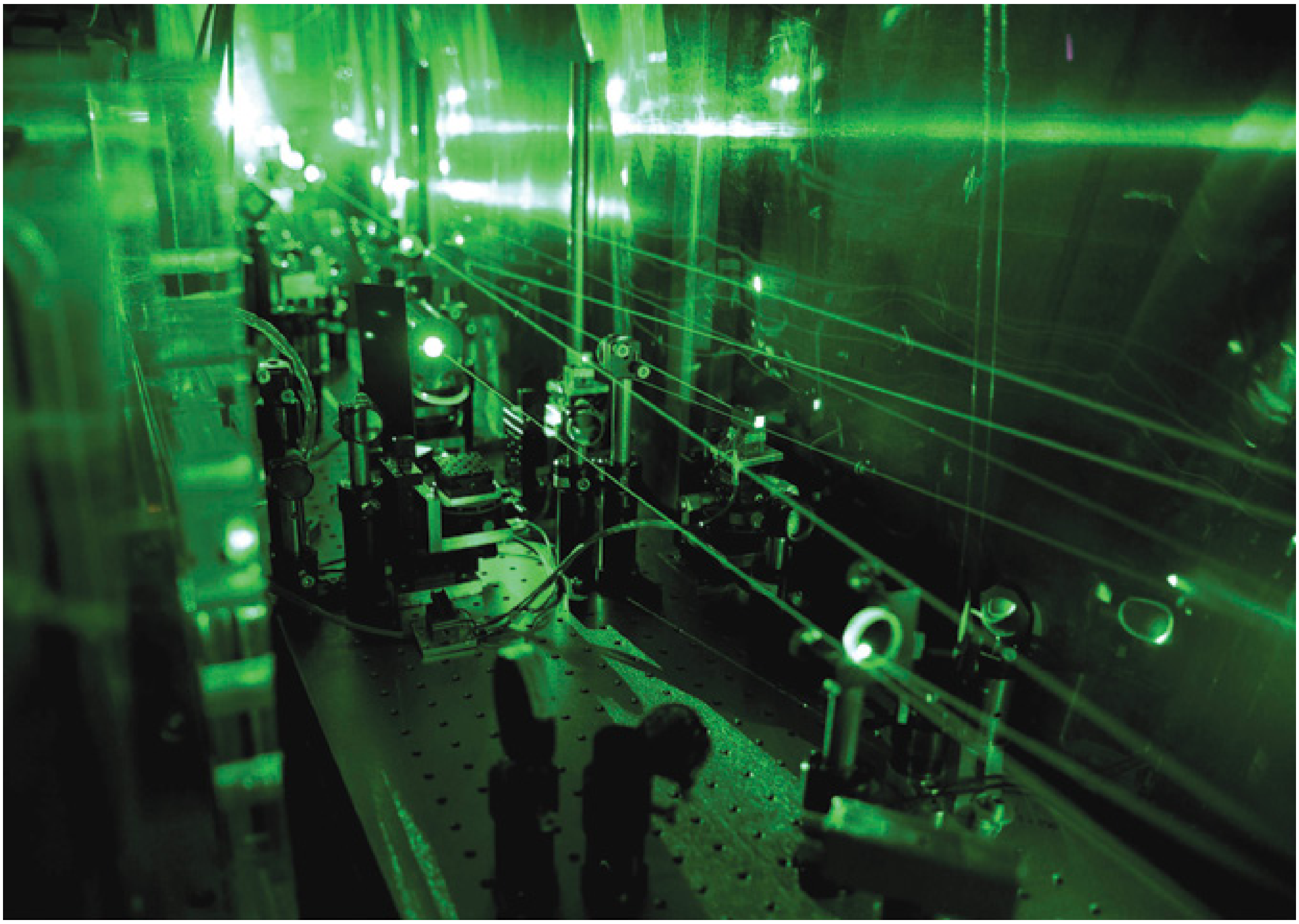
QED traces its history back to 1928, when P.A.M. Dirac combined quantum mechanics and special relativity into what is now known as the Dirac equation. It is our best theory of electricity and magnetism because it fully describes how light interacts with matter. To take just one example, QED explains the structure of atoms using nothing more than the laws of physics and the values of fundamental constants such as the mass of the electron. Because of this, physicists use simple atoms such as hydrogen to test QED. They can predict the outcomes of experiments with an uncertainty of 0.0000000001 percent. Experiments match this precision.

The two of us met on San Servolo for the first time. We were both embarking on measurements of the proton that would help refine our knowledge of QED. Bernauer's experiment was poised to investigate the proton's internal structure using an improved version of a technique that had already resulted in the most accurate measurements to date.

Pohl's group was using a new approach. The group was examining subtle shifts in the energy levels of an exotic, electron-free form of hydrogen—shifts that depend critically on the size of the proton. These shifts were first detected in regular hydrogen back in 1947 by the late Willis E. Lamb, Jr. Even though physicists refer to the phenomena by the singular name "Lamb shift," they have come to understand that two distinct causes are at play.

The first contributor to the Lamb shift comes from so-called virtual particles, phantoms that pop up inside the atom before quickly vanishing again. Scientists can use QED to calculate how these virtual particles affect atomic energy levels to an astonishing precision. Yet in recent years uncertainties in the second contributor to the Lamb shift have begun to limit scientists' predictive powers. This second cause has to do with the proton radius and the bizarre quantum-mechanical nature of the electron.

In quantum mechanics, the electron takes the form of a cloudlike wave function that is spread out over the size of the atom. The wave function (more accurately, the square of it) describes the probability of finding the electron at a given location and



PROTON PROBE: One way to measure the proton's radius is to shoot this precisely tuned laser beam at an experimental sample of so-called muonic hydrogen—atoms made up of one proton and one muon, the heavy cousin to the electron.

COURTESY OF A. ANTOGNINI AND F. REISER *Paul Scherrer Institute*

can only take certain discrete forms, which we call atomic states.

Some of the atomic states, labeled "S states" for historical reasons, have a wave function that is *maximal* at the atomic nucleus. That is, there is a nonzero probability of finding the electron *inside* the proton itself—a probability that grows along with the radius of the proton. When the electron is inside the proton, the electron doesn't "feel" the proton's electrical charge quite as much, which reduces the overall binding strength between the proton and electron.

This reduction in binding strength changes the Lamb shift of the lowest-energy state—the 1S state—by 0.02 percent. This fraction may seem insignificant. But the energy difference between the 1S ground state and the first excited state—the 2S state—has been measured to an incredible precision of a few parts in 10^{15}. Therefore, even the tiny effect of the proton radius must be included if one wants to confront QED theory with precision experiments.

Pohl's group had been trying for eight years to nail down the proton size. Yet at the time of that first conference on San Servolo, its experiment did not appear to be working—much to everyone's puzzlement.

Meanwhile Bernauer's team was about to begin a complementary investigation into the radius of the proton. His approach would not rely on the energy levels of hydrogen. Instead it would use the scattering of electrons off a hydrogen target to infer just how big protons are.

TARGET PRACTICE

HYDROGEN GAS is mostly a swarm of protons. If you shoot a beam of electrons at it, some of the negatively charged electrons will get deflected by a positively charged proton and "scatter" away from the initial direction of the beam. Moreover, this scattering depends strongly on the internal structure of a proton. (Protons, unlike electrons, are made of more elementary components.)

Let's look more closely at how a proton and electron interact when one scatters off the other. When the electron scatters, it transfers some of its momentum to the proton. In QED, physicists describe this interaction as the exchange of a virtual photon between the electron and the proton. If the electron scatters by only a small amount—a glancing blow—it transfers only a small fraction of its momentum. If it scatters close to 180 degrees, we imagine that the electron has hit the proton dead center, transferring a good deal of momentum. In QED, higher momenta mean that the virtual photons have a shorter wavelength.

Similar to a light microscope, if we want to see the smallest structures, we use the shortest wavelengths possible. Part of

Bernauer's work was to use small wavelengths to investigate the distribution of charge inside the proton.

Yet when Bernauer traveled to the conference on San Servolo, the scientists there asked him to extend his experiment. Short wavelengths are good for looking at the structures inside the proton, but if you want to examine the proton as a whole, you must use long wavelengths. In fact, if you want to measure the full extent of the proton (and thus its radius), you need to use an infinite wavelength, which allows the photon to "see" the complete proton. This is the limit at which no scattering happens at all.

Technically, of course, this is not possible—the electrons need to deflect by at least a small amount for anyone to make a measurement. So Bernauer's group measured the lowest momentum transfer his setup allowed and then extrapolated down to zero.

Compared with old experiments, his efforts managed to almost halve the gap between the smallest momentum transfer previously measured and zero, making the extrapolation much more reliable. In the end, the experiment had about twice the number of measurements of all previous measurements combined. After doing the experiment in 2006 and 2007, Bernauer required three years to analyze all the data—work for which he would earn his Ph.D. The radius of a proton, he found, was about 0.879 femtometer—about one ten-billionth the size of a droplet of mist and square in line with previous measurements.

STRANGE HYDROGEN

IN THE MEANTIME, Pohl and his team members continued to struggle. Their experiment replaced the electron in a hydrogen atom with the electron's fat cousin—the muon. Muons are nearly identical to electrons, except for the fact that they are about 200 times more massive. This difference causes the muon in muonic hydrogen to get about 200 times closer to the proton than an electron does.

We were scheduled for just one more week of observations. If those failed, the decade-long experiment would be permanently shut down as a failure.

If the muon is 200 times closer to the proton, it should also be spending considerably more time *inside* the proton. (Indeed, the probability is increased by a factor of 200^3, or eight million.) This, in turn, changes the Lamb shift of the atom by 2 percent—a relatively huge amount that should be easy to spot.

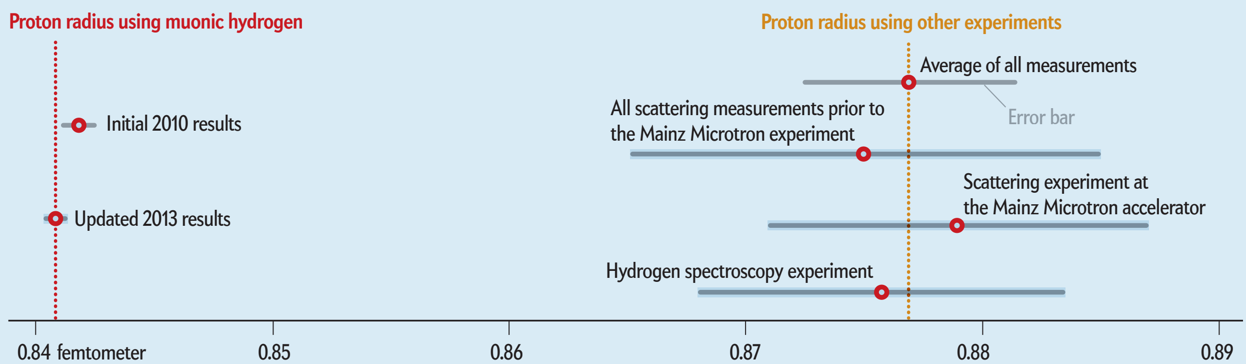
Pohl's experiment shot muons from an accelerator at the Paul Scherrer Institute (PSI) in Switzerland into a vessel containing hydrogen gas. Occasionally a muon would displace an electron, breaking up the hydrogen molecule and forming a muonic hydrogen atom in a highly excited state. Within a few nanoseconds the muonic hydrogen would tumble into lower and lower energy states. The experiment used only the hydrogen atoms that ended up in the first excited energy state (the 2S state).

As each muon entered the hydrogen vessel, it triggered a start signal for the laser system, which delivered a laser pulse about one microsecond later. If the laser had exactly the right amount of energy, as measured by its wavelength, the laser

RESULTS

The Incompatible Measurements

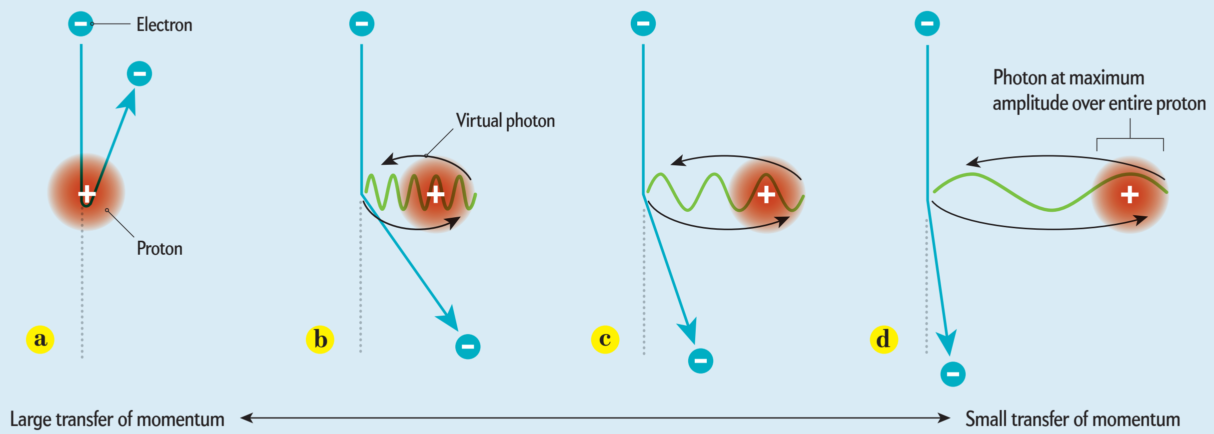
The size of the proton should stay the same no matter how one measures it. Laboratories have deduced the proton radius from scattering experiments [*see box on opposite page*] and by measuring the energy levels of hydrogen atoms in spectroscopy experiments. These results were all consistent to within the experimental error. But in 2010 a measurement of the energy levels of so-called muonic hydrogen [*see box on page 38*] found a significantly lower proton radius. Attempts to explain the anomaly have so far failed.



SOURCE: RANDOLF POHL

Scattershot Proton Measurement

Electron-scattering experiments fire a beam of electrons at hydrogen gas (which is mostly protons) and measure how the electrons scatter. Quantum electrodynamics (QED) describes these interactions using the exchange of "virtual" photons. An electron that hits a proton exchanges an extremely short-wavelength photon **a**. Short wavelengths imply higher energies that vigorously alter the electron's course. Electrons that pass farther from the proton produce progressively longer-wavelength photons (**b** *through* **d**) and smaller deflections. Information about the proton radius is encoded in the longest wavelengths. Imagine that the interaction between the photon and the proton is dependent on the photon's amplitude. To register the whole proton, the wavelength must be so long that the amplitude does not change over the entire extent of the proton's width **d**.



would push the 2S state up in to the higher 2P state. The shape of the 2P state is such that a muon will never be found inside the proton [*see box on next page*], so by measuring the energy difference between the 2S and 2P state, we could infer how much time the muon spent inside the proton—and thus the proton radius.

Here's the key caveat: we had to tune the laser so that it came in with exactly the right amount of energy. The atom would make the jump to the higher state only if the energy of the laser perfectly equaled the energy difference between the 2S and the 2P state. If the wavelength were a bit off, nothing would happen. How did we know if the atoms were making the jump? Any atom bumped up to the 2P state would quickly release a low-energy x-ray photon. If we found these photons, we knew we had the right energy.

Sounds simple enough in theory, but these experiments are notoriously difficult to execute. Similar experiments were first proposed back in the 1960s, when QED was still rather new, as a precision test of the theory. But the experiment was more difficult than complementary experiments on hydrogen and other electronic atoms, so interest faded until the 1990s, when those other tests became limited by the uncertainty of the proton radius.

Pohl's group proposed the muonic hydrogen Lamb shift measurement to administrators at PSI in 1997. The institute approved the project in early 1999, and we spent three years building a laser system, a beam of low-energy muons and detectors for the low-energy x-rays.

After we assembled the experiment at PSI in 2002, we had to deal with several technical issues. By the time we got them straightened out, we had only a few hours to really shoot lasers at muonic hydrogen atoms before our assigned time at the accelerator expired. Some of us were very disappointed because we had really believed that we would find the 2S–2P shift in the first shot. The senior physicists, however, were more realistic about the prospects of the first "machine development" run. They were happy that everything was working and that only a few minor technical issues had cropped up. These could be fixed before the beginning of the "real run," scheduled for 2003, where we would surely see the Lamb shift signal.

Then, after many months of preparation, three weeks of successful data taking revealed … nothing. Not the slightest indication of a signal. Even though the laser had scanned over the entire wavelength region that corresponded to the known experimental values of the proton radius. Nothing.

We assumed the obvious: something in our setup must have been in error. The conclusion at the time was that we needed to improve the laser system. We embarked on a major redesign, which was completed in late 2006. We took data for another three weeks in 2007 and again saw nothing. Luckily, we were given one final chance in the first half of 2009. It took a few months to get the complex apparatus to run. Once more, after a week of collecting excellent data, we found no sign of a signal.

We were scheduled for just one more week of observations. If those failed, we were afraid that some administrators would conclude that we were not up to the task. The decade-long experiment would be permanently shut down as a failure.

We finally started to wonder if something more profound was going on. What if we were searching for the proton radius in the wrong place? We decided to extend the search region. The group made a collective decision to look for a larger proton radius. Late one evening, however, Pohl's colleague Aldo Antognini came into the control room to say that he had a good feeling about looking for a *smaller* proton. With time tight, Pohl and Antognini redirected the search to look for a proton radius smaller than anyone had any right to assume. Very quickly, we found a hint of a signal. But the very next day the accelerator was shut down for a four-day-long scheduled maintenance. We would have to wait.

Then, in the evening hours of July 4, 2009, 12 years after the beginning of the endeavor, an unambiguous signal showed up, telling us that the proton measured in muonic hydrogen was significantly smaller than everybody had believed so far. The group spent a few more weeks doing additional measurements and calibrations and a few months on data analysis. The final result, which we have since confirmed with additional measurements, is a proton charge radius of 0.8409 femtometer, plus or minus 0.0004. That figure is 10 times more accurate than any previous measurement but differs by 4 percent from them—a huge discrepancy!

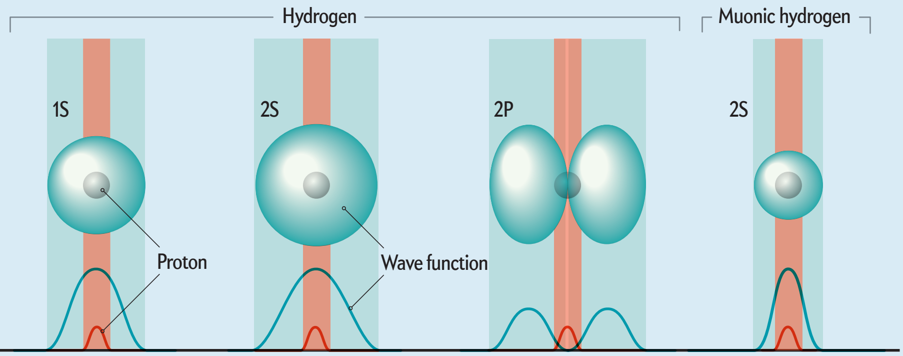
SECOND EXPERIMENT

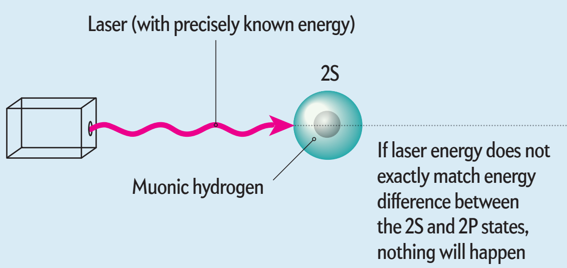
Strange Hydrogen Technique

The electron in a hydrogen atom takes the form of a probability cloud called a wave function. Sometimes the wave function overlaps the proton, implying that the electron may be inside it. This overlap changes the atom's energy. Researchers can measure this "Lamb shift" in energy to deduce the size of the proton, as larger protons will cause a larger shift. They also replace electrons with muons, which have a smaller wave function and so spend more time inside the proton, to enhance the signal.

A Crucial Overlap

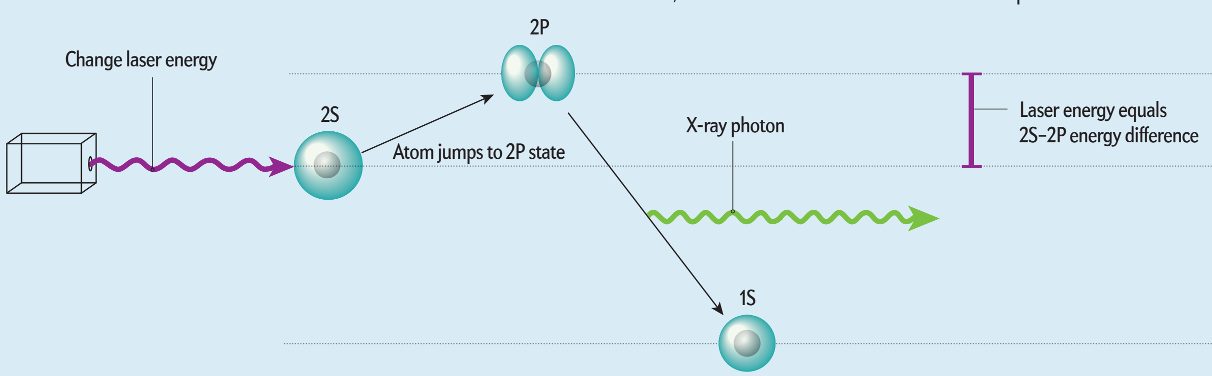
Hydrogen's shape depends on its energy. In the lowest-energy "S states," the wave function and proton overlap. In higher-energy "P states," the two do not. Researchers measure the difference in energy between S states and P states to find the Lamb shift caused by the size of the proton. Muonic hydrogen increases the proton–wave function overlap and amplifies the Lamb shift.





The Experiment

Muonic hydrogen is created by shooting a beam of muons into hydrogen gas (*not shown*). Around 1 percent of the resulting atoms will be in the 2S state. Next a laser beam is sent in with a very precise wavelength (*left*). For most wavelengths, nothing happens. But if the laser wavelength corresponds exactly to the energy difference between the 2S and 2P states (*below*), the atom will jump up in energy, then fall down to the 1S state, releasing an x-ray photon in the process. Because the difference in energy between the 2S and 2P states depends on the Lamb shift, researchers use this measurement to find the proton radius.



In 2010 both of our groups shared their results at the same Precision Physics of Simple Atoms conference in Les Houches in the French Alps. Pohl presented the results of the muonic hydrogen measurement to the scientific community for the first time. In the afternoon of the same day, data from Bernauer's experiment were delivered. Pohl and his colleagues expected that Bernauer's analysis would back up the new, smaller result. Yet to their surprise, the results were nearly identical to the old radius: 0.877 femtometer.

NEW IDEAS

THIS DISCREPANCY created great excitement in the community. Discrepancies are useful because they stimulate new thinking, which leads to new ideas and a better understanding of nature.

At first, most people believed there must be a simple mistake. Perhaps something was off in the experiments, or perhaps the theoretical calculations needed to extract the radius went awry. Shortly after the conference, independent researchers came up with a flurry of possible candidates for straightforward mistakes.

Four years after the puzzle came to life, physicists have exhausted the straightforward explanations. We have begun to dream of more exciting possibilities.

For example, prior to Pohl's experiment, only three individuals had done the complex calculations needed to translate the experimental measurement of the laser wavelength into the proton radius. Many people speculated about errors or omissions in these calculations. Consequently, a large number of theorists repeated and extended the calculations but found no mistakes.

Others reconsidered how Bernauer extrapolated the radius from his scattering data. Could it be possible to reconcile the raw data with the smaller radius from muonic hydrogen? It seems that this fix has also been ruled out.

With every failed suggestion, the impact of the discrepancy has become more severe. Four years after the proton radius puzzle came to life, physicists have exhausted the straightforward explanations such as errors in measurements or in calculations. We have now started to dream about more exciting possibilities.

For example, do we really understand how the proton reacts when the muon pulls on it? The electrostatic force of the muon deforms the proton, in a way similar to how the moon's gravity causes tides on Earth. The crooked proton slightly alters the 2S state in muonic hydrogen. Most people think that we understand this effect, but the proton is such a complicated system that we may have missed something.

The most exciting possibility is that these measurements might be a sign of new physics that go beyond the so-called Standard Model of particle physics. Perhaps the universe contains a heretofore undetected particle that somehow makes muons behave differently from electrons. Scientists have been exploring this option but have found it difficult to model a new particle that does not also produce observable consequences that violate the results of other experiments.

On the other hand, physicists already have another muon puzzle to solve. Fundamental particles such as muons and electrons have a "magnetic moment"—a magnetic field that is much like a bar magnet. Tellingly, the muon's magnetic moment does not match the QED calculations. Perhaps new physical phenomena will explain both the proton radius measurement and the muon's anomalous magnetic moment.

To end these speculations, several new experiments have been proposed. At least two scattering experiments—one at Thomas Jefferson National Accelerator Facility in Newport News, Va., and another at the Mainz Microtron accelerator at the Johannes Gutenberg University Mainz in Germany, where Bernauer did his original experiment—aim to improve the accuracy of the earlier scattering experiments. These measurements will give independent verification and test some of the proposed explanations.

Both Pohl's group and the Mainz team are looking to measure the radius of deuterium—the nucleus formed from a single proton and a single neutron—to see if the difference shows up here, too. Pohl is also going to remeasure standard electronic hydrogen with better precision.

In addition, many physicists have noted that researchers have performed atomic measurements using both muons and electrons but have performed scattering experiments with only electrons. Missing is the combination of muons and scattering. Bernauer is involved in a project that aims to fill this gap. Using one of the muon beams at PSI, the same institute where Pohl's group performed its experiment, the Muon-Proton Scattering Experiment (MUSE) will scatter both electrons and muons off protons to make a direct comparison. The experiment will be able to check for some of the most viable proposed explanations.

Time will tell if the radius puzzle gets resolved as a freak mistake or as the gateway to a deeper understanding of the universe. It just might be the thread we have to pull to unravel the next chapter in the book of nature. Pull we will. SA

MORE TO EXPLORE

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