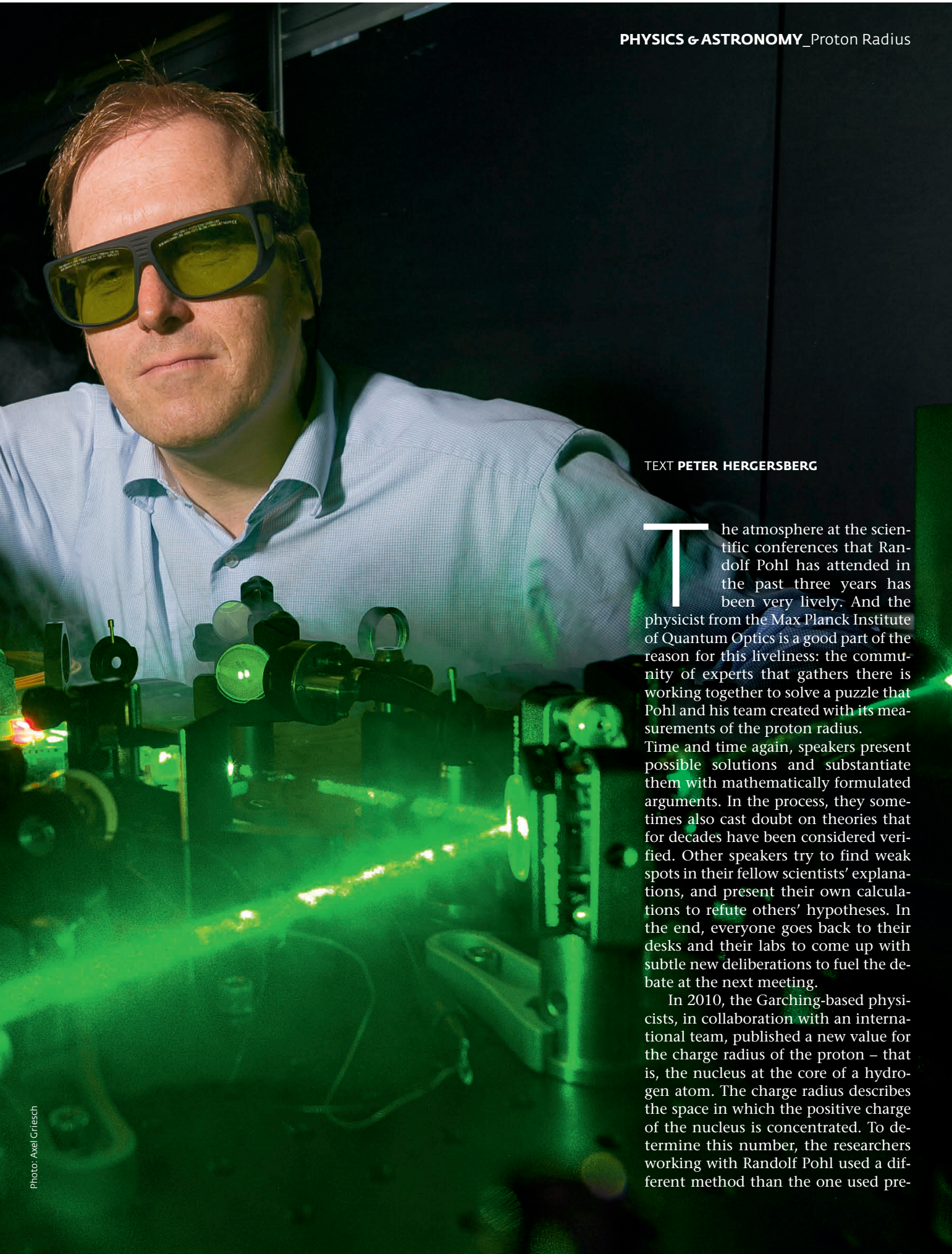


# Physics Has a Core Problem

Physicists can solve many puzzles by taking more accurate and careful measurements. **Randolf Pohl** and his colleagues at the **Max Planck Institute of Quantum Optics** in Garching, however, actually created a new problem with their precise measurements of the proton radius, because the value they measured differs significantly from the value previously considered to be valid. The difference could point to gaps in physicists' picture of matter.

Measuring with a light ruler: Randolf Pohl and his team used laser spectroscopy to determine the proton radius – and got a surprising result.



TEXT **PETER HERGERSBERG**

**T**he atmosphere at the scientific conferences that Randolph Pohl has attended in the past three years has been very lively. And the physicist from the Max Planck Institute of Quantum Optics is a good part of the reason for this liveliness: the community of experts that gathers there is working together to solve a puzzle that Pohl and his team created with its measurements of the proton radius. Time and time again, speakers present possible solutions and substantiate them with mathematically formulated arguments. In the process, they sometimes also cast doubt on theories that for decades have been considered verified. Other speakers try to find weak spots in their fellow scientists' explanations, and present their own calculations to refute others' hypotheses. In the end, everyone goes back to their desks and their labs to come up with subtle new deliberations to fuel the debate at the next meeting.

In 2010, the Garching-based physicists, in collaboration with an international team, published a new value for the charge radius of the proton – that is, the nucleus at the core of a hydrogen atom. The charge radius describes the space in which the positive charge of the nucleus is concentrated. To determine this number, the researchers working with Randolph Pohl used a different method than the one used pre-



viously, and obtained a result that differs significantly from the figure that used to be considered valid. So significantly, in fact, that the difference can't be explained by the measurement accuracies of the two methods. And to keep the tension from subsiding, Randolph Pohl and his colleagues recently refined their measurement result further, thus making it clear: more precise analyses don't make the problem go away.

For years, Randolph Pohl and his colleagues thought that their measuring instrument wasn't sufficiently accurate: they first conducted an experiment in 2003 to determine the size of a proton. However, they didn't discover the signal that would give them information about it. "But this wasn't due to the inaccuracy of our method, but rather to the fact that we hadn't expected such a large deviation," says Randolph Pohl. The researchers had selected too small a window for their measurements.

According to the latest measurements by Pohl's team, the charge radius of the proton is 0.84087 femtometers (one femtometer is a millionth of a millionth of a millimeter) and the measuring uncertainty here is just  $\pm 0.00039$  femtometers. With the previously common measuring method, two independent groups recently determined that the charge radius must be  $0.879 \pm 0.009$

femtometers and  $0.875 \pm 0.011$  femtometers, respectively.

In other words, the difference between the measurements is 0.036 femtometers, or 4 percent. That doesn't sound like much, but in the context of the given uncertainty of the measuring accuracy, it is actually a lot. The discrepancy corresponds to seven combined error bars and is thus significantly larger than one would expect if different experiments merely yielded slightly different results in the context of statistical fluctuations.

### NO SYSTEMATIC ERROR WAS FOUND

Just how great the difference is between the results and uncertainties of the two different methods of measuring the proton radius can be illustrated by transferring them to a map of Germany. Suppose one were to put the result obtained by Randolph Pohl's team in the center of Munich, and the competing measurement in the center of Hamburg. Then the uncertainty of the Munich value would correspond to the distance between the two Munich neighborhoods Pasing and Trudering. The Hamburg measurement, in contrast, would be so imprecise that the actual value might very probably even lie somewhere between Flensburg and Ha-

nover. Clearly, this is going to cause problems – it would be no different than if one were to suddenly look for Hamburg's St. Michael's church on Munich's main square, Marienplatz.

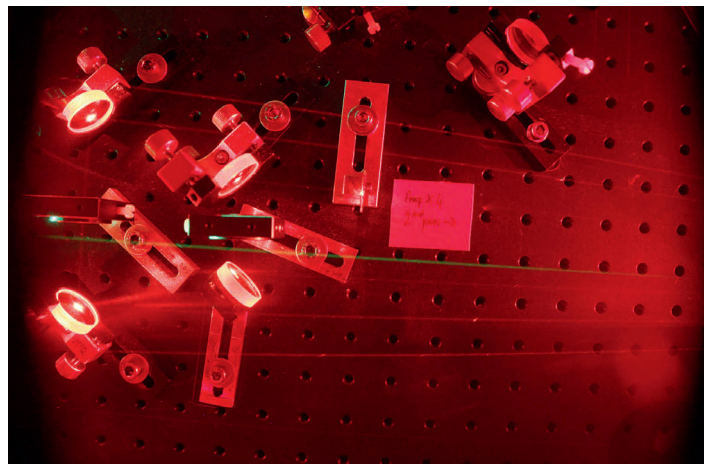
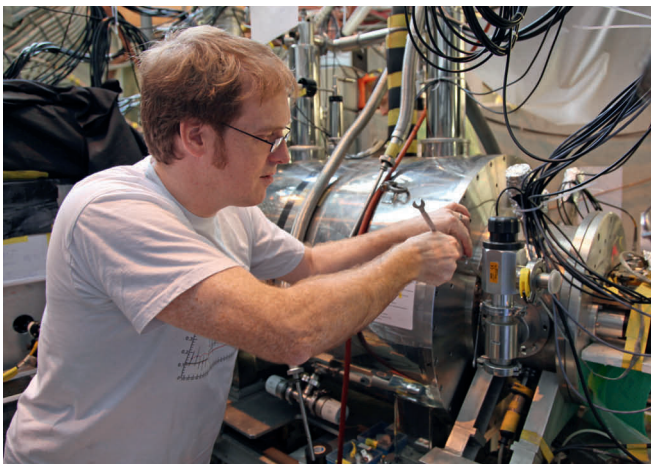
To explain the great difference between the two measurements, physicists initially scoured the two methods for systematic errors that might skew the result. "It could, of course, be the case that we overlooked such an error, but we searched very carefully and found nothing," says Randolph Pohl, whose team took a new approach to measuring the proton radius some 15 years ago, and published the first result of this work in 2010.

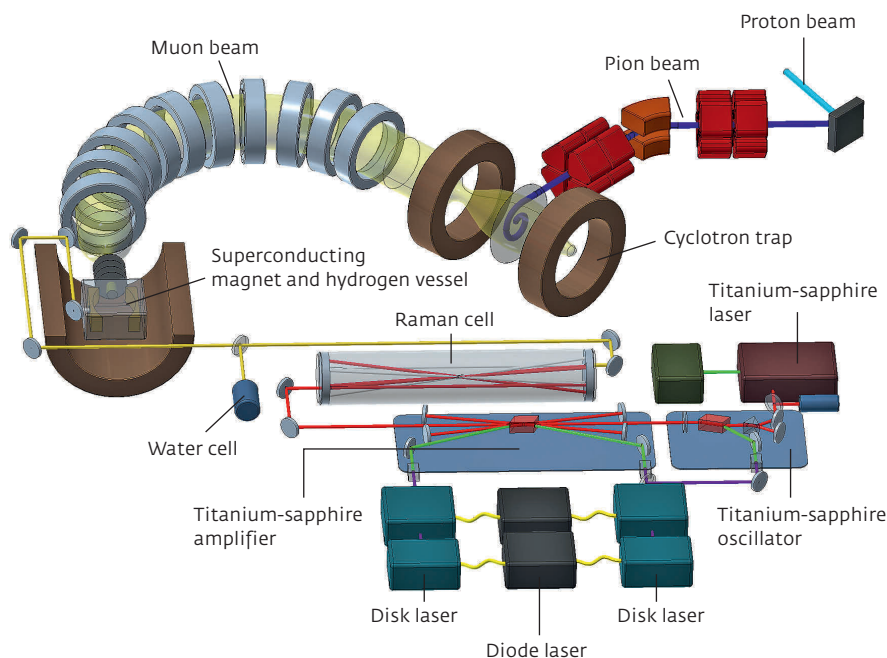
The researchers used laser spectroscopy to determine how high the energy of a photon has to be to transport an exotic hydrogen atom from one special energy state to another. The energy of some of these states depends on the proton radius, and that of others doesn't. If the atom is taken from one state that appears to be sensitive to the proton radius to one that is not sensitive to it, then the radius can be calculated. However, this requires physicists to know all the other effects that influence the position of the states.

In ordinary hydrogen, where one electron whizzes around the proton, the influence of the proton radius is very small because the lightweight elec-

left: Final preparations for the measurement: Randolph Pohl calibrates the apparatus through which muons are directed into a vessel containing hydrogen. A superconducting magnet in the silver cylinder produces the strong magnetic field required for this.

right: The green light produces intense red light in a titanium-sapphire crystal. This is subsequently converted to invisible infrared light and used to perform spectroscopy of muonic hydrogen.





Experiment design: A proton beam strikes a carbon disk, producing negative pions that decay into muons in a magnetic bottle (cyclotron trap). The muons are slowed down and directed through a curved channel to the hydrogen vessel, which is located in a superconducting magnet.

This part of the apparatus would fill a spacious living room. The extremely intense laser beam is directed into the hydrogen vessel. The researchers produce this beam a few meters away in the "laser hut," which is shielded from the muon beam. There, diode lasers pump two parallel ytterbium-YAG disk lasers with energy.

Upon entering the hydrogen vessel, muons produce a signal that, in less than 200 nanoseconds, causes the disk laser to emit intense light pulses. Their frequency is doubled in order to pump a titanium-sapphire laser. Finally, in the Raman cell, the laser's pulses are converted into light of the appropriate color to allow the muonic hydrogen atom in the hydrogen vessel to be examined. The entire process lasts less than one microsecond.

tron usually hangs out far away from the nucleus. In an exotic variant of the element, in contrast, in which a muon, rather than an electron, orbits the nucleus, the effect is far greater.

Physicists produce muonic hydrogen at the Paul Scherrer Institute in Villigen, Switzerland, where they can use the world's strongest muon beam. The muons come about when protons are shot at a carbon disk in a particle accelerator. Using magnetic fields, the researchers direct the muons into a vessel containing hydrogen gas, which halts the exotic elementary particles. Some muons are captured by hydrogen molecules, displace their electrons and form muonic hydrogen atoms.

Now physicists have to step up the pace with their laser experiments that reveal the energies of the states, as muonic hydrogen remains in the state they need for their experiments for only one microsecond. But the haste pays off: muonic hydrogen is ideal for measuring the proton, and for other experiments, as well, because muons, like electrons, carry a negative charge but are around 200 times heavier.

Due to their greater mass, muons are located closer to the nucleus and are thus more sensitive to the proton radius than are normal electrons. This makes it possible to determine the charge radius with great accuracy – or in any case more accurately than previous experiments permitted, which had put the proton radius at approximately 0.88 femtometers: spectroscopy of normal hydrogen and electron scattering measurements. For the latter, scientists shoot electrons at hydrogen nuclei and observe how they are deflected by the protons.

### THE MUON EXPERIMENTS DISREGARD EXOTIC SPECIMENS

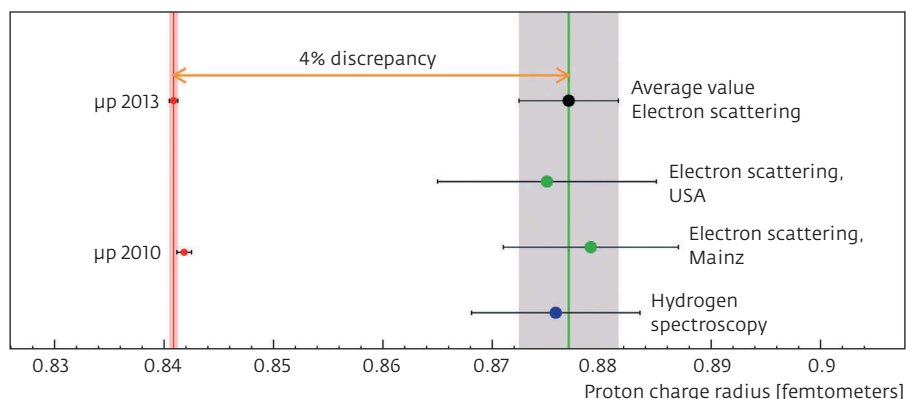
What favors the measurements on muonic hydrogen is the fact that they are more than ten times more precise than the results of the spectroscopy on normal hydrogen and the electron scattering. And the more precise a measurement is, the more reliable it is considered to be. Moreover, physicists have since discussed – and excluded – some of the potential systematic errors

of the experiments with muonic hydrogen. Some skeptics had speculated, for example, whether Pohl's team might, without realizing it, have observed negatively charged muonic hydrogen ions that contain a muon and an electron, or molecules composed of two protons and a muon. However, physicists from Paris performed calculations that have since undermined the basis for this suspicion: even if both of these exotic entities are created, they don't remain stable long enough to permit examination.

In the meantime, the team working with the Max Planck physicists used spectroscopy of muonic hydrogen to measure not only the charge radius of the proton, but also the magnetic radius. The magnetic radius indicates the region in which the magnetization is distributed. This results from the spin of the proton – that is, from the fact that the charged particle is constantly rotating about itself. The electrical and magnetic radius needn't necessarily be the same size. While the charge radius describes the space in which the charge is found, one can imagine the magnet-



The proton radius puzzle: New measurements with the elastic electron scattering from Mainz (Germany) and the US establish the charge radius of a hydrogen nucleus at about 0.88 femtometers, with relatively large error bars (horizontal lines). This value fits very well with the average value of the spectroscopic measurements of normal hydrogen. The spectroscopic results for muonic hydrogen ( $\mu p$ ) obtained in 2010 and 2013 have much smaller error bars, but their values, at 0.84 femtometers, are 4 percent lower than the average of all measurements obtained with electron scattering. No explanation has yet been found for this great discrepancy.



ic radius as the region in which the circulating currents flow that give a proton its magnetic moment.

For the magnetic radius, the researchers now obtain  $0.87 \pm 0.06$  femtometers. This value is currently still so imprecise that the two controversial values of the charge radius fit with it. “What is important is that we actually determined the magnetic radius using spectroscopy of muonic hydrogen in the first place,” says Randolph Pohl. “It will become interesting when we later increase the accuracy.” Only then will the researchers be able to decide whether their method yields a different value than electron scattering for the magnetic radius, as well.

In any case, for the time being, the magnetic radius isn’t causing such a

great stir – unlike the charge radius. Even the latter wouldn’t have been an issue if the new measurements had further narrowed the range of the charge radius as indicated by less accurate experiments. However, the fact that they put the radius in a different range altogether raises fundamental questions.

The story takes on added zest when one considers that the contradictory measurements could indicate fundamental gaps in our understanding of the atoms in hydrogen. This is particularly piquant because, of all the elements, hydrogen is the one quantum physicists know the most about. Since it consists of just one proton and one electron, it is, in fact, the atom that they can describe best in mathematical terms. In other atoms with more electrons, they

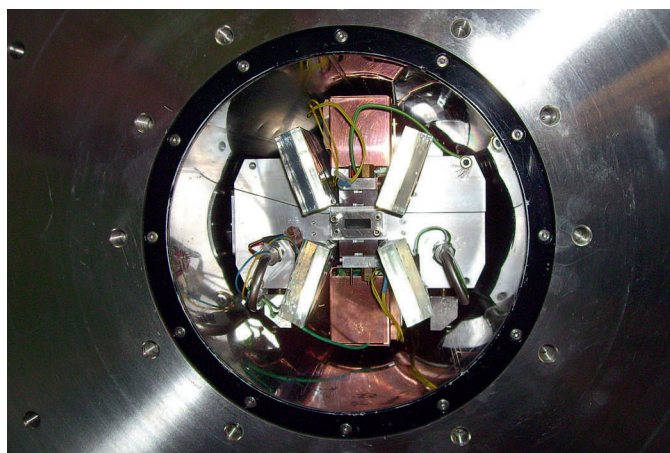
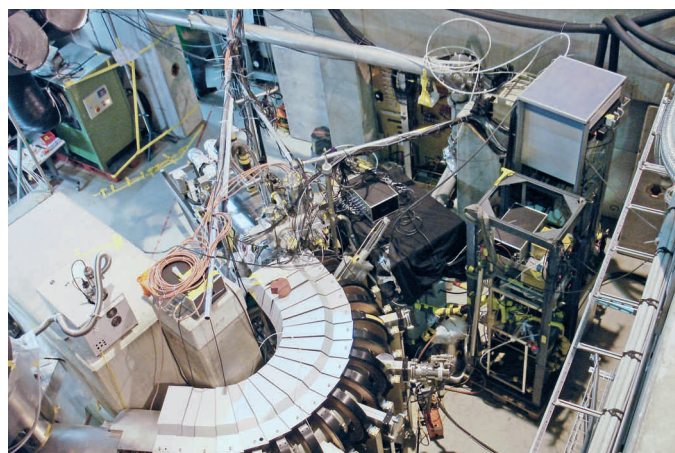
have to rely on approximations. That’s why they use hydrogen to test their theories, and also why many groups around the world are constantly competing to see who can characterize this atom more and more accurately with increasingly precise measurements. They don’t do this out of a sporting ambition but because, in doing so, they have continually made fundamental discoveries – quantum electrodynamics (QED), for instance.

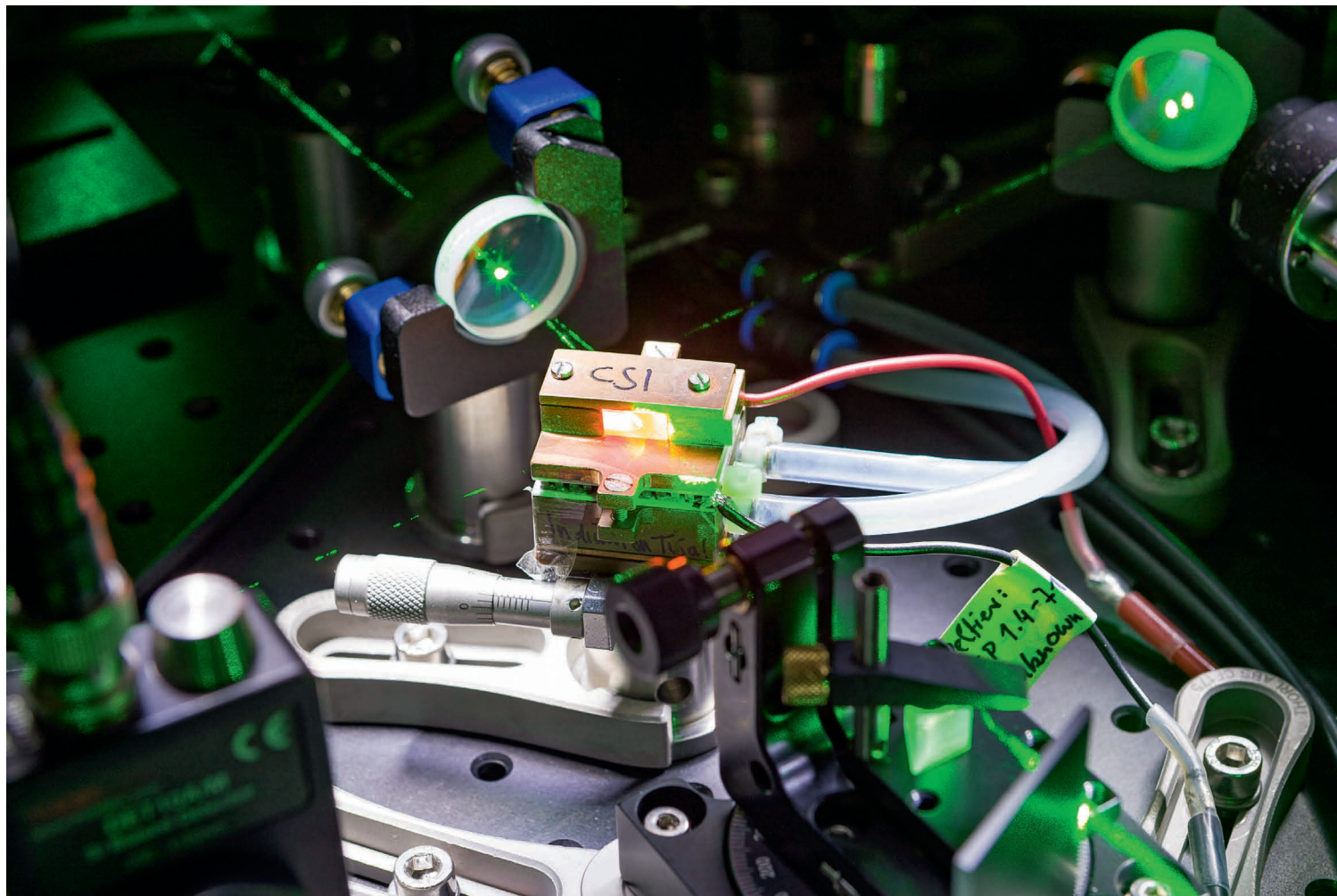
## PLENTY OF ROOM FOR AS-YET-UNKNOWN PHYSICS

QED describes how matter – so, for example, atoms – interact with light, and is considered to be exceptionally well substantiated. Still, it seemed, at first,

left: The muons pass through the curved channel to a strong magnet (left of center).

right: The magnet contains the dumbbell-shaped hydrogen vessel, flanked above and below by detectors and electronics.





Light color converter: In the crystal, which is enclosed in the rectangular device in the center of the image, the green light of the titanium-sapphire laser is converted to red light.

as if the new, more precise measurements of the proton radius might challenge this theory. Specifically, it would be possible to resolve the mystery of the differing proton radii in electronic and muonic hydrogen if QED were to ignore an effect that has a much stronger impact on the energy states in muonic than in electronic hydrogen. “But this effect would have to be very large,” says Randolph Pohl. “And it is extremely unlikely that such a large effect has been overlooked up to now.”

Even if a shortcoming of QED has since been nearly discarded as a possibility, Randolph Pohl and his colleagues hope that their measurements will point to as-yet-unknown physical relationships. There is plenty of room for such explanations. Some nuclear physicists, for instance, questioned the concept of how the charge is distributed in the proton. The previous models assumed that the charge decreases approximately exponentially at the boundary of the proton. But what if it decreases more slowly? Or has a cusp

somewhere? These are legitimate questions, but they haven’t solved the proton puzzle. Experiments with scattered electrons characterize the charge distribution very reliably – and confirmed the established assumption of an approximately exponential decrease.

### AN ELECTRICAL CHARGE DISTORTS THE PROTON

Another suggestion that is currently quite popular takes a similar direction. “Perhaps the proton is polarized differently than previously assumed when it sees the negative electrical charge of the muon,” says Randolph Pohl: the electrical charge distorts the charge cloud of the proton, and does so all the more the heavier the particle is that pulls on it. Physicists factor this in when calculating the proton radius from their laser spectroscopic analyses. If the corresponding formulas currently don’t correctly account for the polarization, this will be most noticeable in muonic hydrogen.

“What would be most interesting, however, is if our result were to point to a physics beyond the standard model,” says Randolph Pohl. The standard model of particle physics describes all elementary particles and most of the forces between them. It covers most observations very well, but it also has some weaknesses. For instance, it doesn’t explain gravitation. Nor does it answer the question about dark matter, which accelerates the movements of stars but is otherwise practically unnoticeable and therefore hasn’t yet been identified either.

Although the shrunken proton can’t directly be of any help in the search for the mysterious substance, it could generally contribute to expanding the standard model: “It’s conceivable that an as-yet-unknown particle is responsible for the muon being more tightly bound to the proton than we assume,” says Randolph Pohl. The muon then moves about at closer range to the nucleus than assumed. But if physicists aren’t aware of the particle and don’t know





Searching for the decisive data: Randolph Pohl (left) and Marc Diepold discuss the results of a measurement campaign that acquired enormous amounts of data, of which, however, only a fraction is based on signals from muonic hydrogen.

that it forces the muon closer to the nucleus, the proton of muonic hydrogen will appear to them to be smaller than that of electronic hydrogen. As attractive as Pohl finds the thought of having found a door to the world beyond the standard model, he remains realistic: "That isn't very likely," says the researcher.

### RYDBERG CONSTANT MUST BE DETERMINED MORE ACCURATELY

While theoretical physicists are busy formulating possible explanations, the experimenters are not sitting idly about. "A more precise determination of the Rydberg constant would allow us to verify whether our measurement is correct," explains Pohl. Physicists use this constant to calculate the different energy levels of atoms and molecules. If Randolph Pohl and his colleagues are right about the smaller proton radius, then also this constant would change – and perhaps a few other physical constants, as well. No other physical constant is known as precisely as the Rydberg constant. If one could use electronic hydrogen to determine it even more precisely, then it would be possible to indirectly verify the result of the proton measurement. Several researchers around the world are working on this, including a group at the Max Planck Institute of Quantum Optics.

In the meantime, Randolph Pohl and his team are also continuing their experiments with muonic atoms at the Paul Scherrer Institute. The researchers will soon perform spectroscopy of muonic helium ions. For one thing, this will al-

low them to test once again whether the QED models are actually complete. "Helium is better suited for this, because it is easier to observe weaker QED effects in heavier nuclei," explains Pohl. For another, the measurements on muonic helium are better suited for comparison with the results of electron scattering. "The electron scattering data for helium is more precise," says Pohl.

A new elementary particle would also have to be noticeable in muonic helium. Then, in helium, there would likewise have to be a discrepancy between the two different measurements of its nuclei. Otherwise, the door to a physics beyond the standard model would close again before it really even opened. ◀

### TO THE POINT

- An international team working with researchers from the Max Planck Institute of Quantum Optics measured the charge radius of the proton very precisely for the first time. To do so, the scientists performed spectroscopy of the energy states of muonic hydrogen.
- The results of the measurements on muonic hydrogen differ significantly from the results of the spectroscopy of normal hydrogen and the results of electron scattering, the method that was previously commonly used to determine the proton radius – indicating that the proton is smaller than had been thought.
- The difference between the results of the two measuring methods could indicate that the picture that physicists had of the proton is incomplete. But it could also point to an as-yet-unknown elementary particle.

### GLOSSARY

**Electron scattering:** When an electron is fired at a positive charge, such as a nucleus, the positive charge deflects it. Electron scattering uses this to advantage: the distribution of the charge, and thus its radius, can be deduced from an analysis of the electron paths.

**Charge radius:** Quantum particles aren't as precisely delimited as billiard balls – their boundaries are rather fuzzy. The same is true for the charge radius of the proton. It is defined as the radius within which about two-thirds of the positive charge of the proton is concentrated.

**Muon:** This elementary particle has the same negative charge as an electron. It can thus replace an electron in hydrogen, or also in a helium ion. But since a muon is about 200 times as heavy as an electron, it comes much closer to the nucleus, and certain effects more readily come to light in muonic atoms.

**Quantum electrodynamics (QED):** This theory describes how matter – atoms, for example – interacts with light. It is considered to be exceptionally well substantiated.

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