# Particle physics: 'Honey, I shrunk the proton'

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In a measuring chamber for protons: the muon beam moves through the ring-shaped electrodes from the left. In the space between the two grey-metallic bars under the pane of glass the muons impact on gaseous hydrogen -- and displace the electrons from some of the atoms. The apparatus registers this process and fires a laser through the hole in the bottom bar onto the muonic hydrogen in order to reveal details of the atomic structure and thus ultimately the radius of the proton. Credit: Image: Randolf Pohl / MPI of Quantum Optics

Scientists lobbed a bombshell into the world of sub-atomic theory on Wednesday by reporting that a primary building block of the visible Universe, the proton, is smaller than previously thought.

Big problems sometimes come in small packages. The problem with which physicists must now concern themselves measures a mere 0.0350 millionth of a millionth of a millimetre. This is precisely the difference between the new, smaller, dimension of the proton, the nucleus of the hydrogen atom, and the value which has been assumed so far. Instead of 0.8768 femtometres it measures only 0.8418 femtometres. At the Paul Scherrer Institute in Switzerland, an international team of researchers including physicists from the Max Planck Institute of Quantum Optics has now measured this in experiments which are ten times more accurate than all previous ones. They thus present physics with some tough problems: at least one fundamental constant now changes. And physicists have also to check the calculations of quantum electrodynamics. This theory is assumed to be very well proven, but its predictions do not agree with these latest measurements. (*Nature*, July 8, 2010)

For many years, Randolf Pohl and his colleagues believed their measuring instrument was not accurate enough: they first performed an experiment to determine the size of the proton back in 2003, but they had not discovered the signal which would provide them with the relevant insight. "This was not down to the accuracy of our method, but to the fact that we did not expect such a large deviation," says Randolf Pohl. The researchers had therefore chosen too small a window for their measurements. "It is good, nevertheless, that we have significantly improved our method yet again, otherwise people might not believe us now," continues Pohl.

Randolf Pohl and his colleagues in an international collaboration have measured the charge radius of the proton with an accuracy of better than one thousandth of a femtometre. This is the radius which the charge of the positive hydrogen nucleus assumes. To this end, they have investigated tiny details in the atomic structure, using muonic hydrogen, where it is not an electron but a heavier muon which orbits the nucleus (see 'Background: a ruler for a proton'). Their measurements show that the hydrogen nucleus measures 0.8418 femtometre. A result which is outside the margin of error which physicists had applied to the previous measurements for the proton radius by a factor of five.

Even if the deviation is negligible on a day-to-day scale, it possibly has significant consequences. Researchers are unable to say precisely what these may be, however. What is certain is that this changes the Rydberg constant. Quantum physicists use this constant to calculate which energy packets atoms and molecules absorb and emit when they change their states. These energy packets correspond to the spectral lines of the elements. The calculations for the spectral lines now shift noticeably and no longer match the experimental findings.

## The theoreticians are now searching for the error in the calculation

"Since the Rydberg constant is the most accurately determined fundamental constant so far, it is as solid as a rock," says Randolf Pohl. If physicists draw a self-consistent picture of all fundamental constants, the other fundamental constants such as Planck's constant or the mass of the electron can only move around the Rydberg constant. The fact that this rock has been moved slightly will hardly impress the other fundamental constants: they have been determined just as exactly as the Rydberg constant so they will probably not feel the jerk at all. The test for this is still pending, however.

"We also have to be very careful with more far-reaching consequences," says Pohl. Many theoreticians all over the world are now recalculating the predictions of quantum electrodynamics with the new proton radius. This quantum theory describes how atoms, electrons, elementary particles and other players move in this diminutive world and which electromagnetic fields are created in the process. It also provides a value for the proton radius for comparison with experimental data - but this is significantly higher than the one measured now. "I assume that an error has been made somewhere in the calculation, because the theory of quantum electrodynamics is very consistent and has been rigorously proven," says Pohl. If this is not the case, the slightly shifted proton radius would trigger an earthquake in physics, which would at least result in considerable 'fault lines' in this theory.

While theoreticians are now trying to get to the bottom of the mystery of the erroneous proton radius in their models, the Garching researchers and their colleagues are checking the new measurement result with further experiments on the hydrogen atom. They also want to redesign their experimental set-up so that they can also measure the charge radius of the helium nucleus. These investigations are also intended to tell them something about how atomic nuclei are deformed when they interact with a negative charge. In this way the physicists want to discover the exact structure of matter step-by-step - and hope, of course, to come across more mysteries of physics.

## Background: A ruler for a proton

In order to measure the charge radius of the proton, the researchers use the electronic interactions in a hydrogen atom and take into account the tiniest details of the atomic structure: the positively charged nucleus attracts the electron, which can move in different shells around the nucleus. The energy of the electron increases when it jumps up to the next highest shell. In the first shell it can only move in one orbital: the s-orbital, which surrounds the atomic nucleus like a sphere. When the electron climbs upwards shell by shell, additional space becomes available to it each time. In the second shell, for example, it can occupy not only the spherical s-orbital but also a p-orbital which forms a dumbbell-shaped structure around the atomic nucleus.

In the simplest model of an atom the electron has the same energy in the s-orbital as it does in the p-orbital. In reality, however, its energy in the p-orbital is slightly higher than in the s-orbital. Physicists call the small energy gap the Lamb shift. The Garching physicists are targeting this small gap. One reason for its existence is that the proton is not an infinitesimally small point, but a tiny sphere. If the electron occupies the p-orbital, the electron does not feel this, because both club-shaped ends of the dumbbell are located outside the atomic nucleus - the electron is therefore never inside the nucleus itself. The situation is quite different in the sphere of the s-orbital: here the electron also repeatedly spends time in the nucleus itself - the charges of nucleus and electron then cancel each other out. This decreases the average attractive force of the nucleus and hence the energy of the electron.

In the conventional hydrogen atom the effect is so small that it is hardly noticeable even in the most accurate measurements. At the Paul Scherrer Institute in the Swiss town of Villingen the Garching physicists have therefore produced muonic hydrogen in which a muon replaces the electron. The muon has the same negative charge as an electron, but is around 200 times heavier. The total diameter of the atom thus shrinks and, on average, the muon spends more time in the nucleus so that the energy of the s-orbital in question also experiences a stronger shift. The researchers measure the energy difference by giving the electron a little energetic nudge with a laser, so that it jumps from the s-orbital of the second shell into the p-orbital.

That is the principle. In order to measure the energy difference, which is still tiny even in muonic hydrogen, the physicists working with Randolf Pohl have to solve some practical problems. They not only need a laser whose wavelength can be set with extreme precision. Little by little they change its energy until it precisely matches the transition between the two orbitals. The laser must also release its pulse in less than one millionth of a second after it has received the command. This is placed as soon as the detectors of the apparatus register a muonic hydrogen atom.

In 99 percent of the cases the muon in the hydrogen atom slips immediately into the s-orbital of the energetically favourable first shell. The laser therefore mainly fires at particles which are no use for the researchers' real purpose. The apparatus registers an atom in which the muon remains in the s-orbital of the second shell only six to seven times per hour. "You can sit for hours in front of the screen and hardly anything happens," says Randolf Pohl. And then it takes only a millionth of a second until the muon falls from the second into the first, energetically more favourable shell. The Garching researchers have used a variety of tricks to teach their laser a reaction time of 900 billionths of a second, thus making the measurement possible in the first place.

After the researchers had spent several months setting up and fine-tuning their apparatus at the Paul Scherrer Institute, they finally measured for three weeks without a break. Only then had they moved muons from the s-orbital into the p-orbital of the second shell so often that a marked peak was visible in their spectrum. Then only calculations remained. "The equation for this is pretty difficult," says Pohl, but, finally, they arrived at their value for the proton radius which is ten times more accurate and which now sets a number of new tasks for quantum theorists.

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