Topic 2/12 + NOS /16 Chemistry World

Honey I shrunk the proton

ONE quadrillionth of an inch. If you lost that off your waistline, you wouldn't expect a fuss. Then again, you are not a proton.

Until recently, it was unthinkable to question the size of the proton. Its radius is so well known that it appears on lists of nature's fundamental constants, alongside the speed of light and the charge of an electron. So when Randolf Pohl and his colleagues set out to make the most accurate measurement of the proton yet, they expected to just put a few more decimal places on the end of the official value. Instead this group of more than 30 researchers has shaken the world of atomic physics. Their new measurement wasn't just more accurate, it was decidedly lower. The proton had apparently been on a diet.

Freak results do turn up from time to time in physics. Witness the furore in 2011 over the neutrinos that appeared to travel faster than light and whose unbelievable powers were traced months later to a dodgy cable connection. Yet the proton puzzle first came to light in 2009, and several experiments later we are running out of ways to explain how the particle can have seemingly shrunk. No experimental flaws have been found. The theory has been checked and rechecked. Physicists are now facing the possibility that an unknown phenomenon is at work. Has a big problem with a tiny particle revealed a brand new force of nature?

"As Sherlock Holmes would put it, 'Once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth'," says Itay Yavin, a particle physicist at McMaster University in Hamilton, Canada. "That is new physics."

It wouldn't be the first time we have had to rethink the physics inside the atom. Rewind 100 years and the atom is pictured as a miniature solar system, with negative electrons as planets orbiting a sun-like bundle of positive protons and neutrons at the centre. Holding it all together is a force – not the gravity that influences the whole solar system, but electromagnetism.

After quantum mechanics emerged in the 1920s, electromagnetism came to be seen as particles of light – photons – hopping from electrons to protons, and vice versa. Quantum theory did a fair job of predicting the energy of various electron orbits, but on the fine details it proved a little too crude. So by the end of the 1940s, a more refined theory had taken over: quantum electrodynamics, or QED for short.

QED showed that to predict orbital energies precisely, you had to consider all the ways an electron could emit photons. For instance, an electron might emit a photon then immediately reabsorb it. Or it might emit two photons at once. Or, en route to the nucleus, a photon might temporarily split into a particle-antiparticle pair. In fact, QED showed that there are infinite possibilities, all of which help to determine the electron orbits by varying amounts.

To predict the energy of a particular orbit, you don't need to add up all these possibilities – you would be there forever. Instead, by considering the biggest QED contributions first, then the next biggest and so on, you can progressively make your prediction more accurate. QED is like a box of measuring tools: to get a rough measurement you might start off with a metre stick, but to improve precision you might get out a centimetre rule, and finally a pair of callipers.

Today QED has grown into one of science's most revered theories, largely thanks to the precision with which it can predict orbital energies – in some cases to just a few parts in a million. But physicists are never satisfied. "Just because a theory is good at explaining all current measurements, doesn't mean it's the 'true' one," says Pohl, who works at the Max Planck Institute for Quantum Optics in Garching, Germany.

Pohl's group set out to develop even more precise QED predictions, to see if they would still withstand experimental scrutiny. But it wasn't a case of simply getting out the QED callipers. According to quantum mechanics, particles such as electrons and protons are vague creatures, more like clouds of charge than solid objects. This means that an electron can » even veer inside a proton, where it will feel less of the electromagnetic attraction it feels on the outside. The net result is that the proton's size subtly changes the electron's energy.

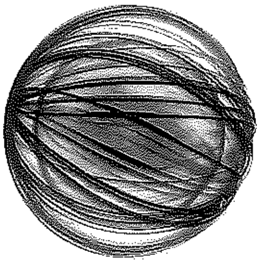
Getting the finest QED predictions, then, requires taking into account the proton's size. In fact, QED itself offers a way to size up the proton, by making use of the hydrogen atom and a difference in the energies that its lone electron can take. First measured in 1947 by US physicists Willis Lamb and Robert Retherford, this shift is called the Lamb shift.

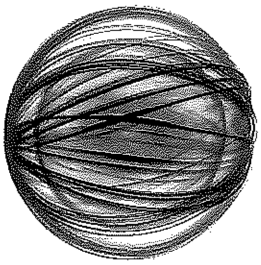
All you have to do is predict the Lamb shift via QED, measure its actual value, then put any "error" down to the size of the proton. Since the late 1990s, experimenters have used this trick to nail down the proton radius to within 0.1 per cent of 0.877 femtometres – about one 10-billionth the thickness of a human hair.

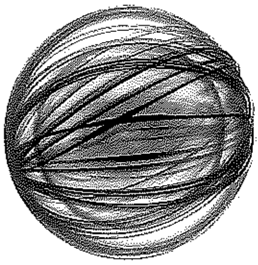
It's an impressive feat, but not so good for testing QED. The trouble is that the energy shift due to the proton size is about the same size as the QED corrections under test, a bit like using a ruler with millimetre divisions to measure something that's about a millimetre long and expecting the result to be accurate. What's needed is an atom in which the proton has a much bigger influence on the Lamb shift.

Enter a very different kind of hydrogen atom: "muonic" hydrogen in which the electron is replaced by its weightier cousin the muon. Muons have the same electrical charge as electrons, but they are 200 times heavier. As a result, the muon orbits hydrogen's central proton 200 times closer than an electron and therefore spends longer inside the proton's cloud. This means that the proton has a bigger effect on the Lamb shift in muonic hydrogen than normal hydrogen. "You can measure the proton radius in muonic hydrogen 10 times better than anywhere else," says Pohl.

"Electrons and protons are vague creatures, more like clouds than solid objects"







Muon mystery

To test their idea, Pohl's group set off for the Paul Scherrer Institute (PSI) in Villigen, Switzerland. Here, a special low-energy particle accelerator fed muons into hydrogen gas, so that they swapped places with the electrons normally orbiting the hydrogen atoms. It was a laborious process, and it wasn't until seven years later, in June 2009, that the Lamb shift finally appeared in their results.

It wasn't where Pohl's team expected it. The result implied that the proton radius was 0.841 femtometres, some 4 per cent lower than in regular hydrogen. "We were running around for four days in a manic depression," says Pohl. "Like, is it a background signal? Or could it really be?"

Others were just as shocked. Suddenly, precision testing of QED had been yanked from the spotlight and replaced with a bit-part actor – the proton's size. "My first reaction was doubt – it was a new technique, there was easily something going wrong," says Jan Bernauer at the Massachusetts Institute of Technology. "It was clear, pretty soon after, that this was not the case."

Because the proton has such a big effect in muonic hydrogen, Pohl and his colleagues were able to measure the radius accurately and so their measurement was unlikely to be wrong. But there is little urge to point the finger at the measurements based on regular hydrogen, either: they have back up. Since the 1950s, physicists have fired electrons at a stationary hydrogen atom to measure the proton's size (see "Proton problem", below right). By angling the gun towards the proton from either side, they can detect when the electrons begin to scatter, and thereby mark out the proton's boundary.

Electron-scattering measurements of the proton radius were never accurate enough for precision tests of QED. Still, at least three independent measurements have been made, all of which support the value of the proton radius extracted from the Lamb shift in regular hydrogen. Bernauer has performed some of them and is sure they are correct. He has equal faith in the PSI group's work. "I'm convinced there's nothing wrong with their experiment," he says. "It's really clean. Either you get something out, or you don't."

Perhaps the protons are actually changing size. According to quantum chromodynamics, the theory that describes the inner workings of a proton, the idea isn't totally implausible. It says that a proton can sometimes distort when receiving a photon from an orbiting electron – a bit like how the oceans gravitate towards our orbiting moon to form tides. Such a distortion can unsettle the normal hopping of photons from electrons or muons to protons, and in turn affect the Lamb shift.

In 2012, theorists Judith McGovern and Michael Birse at the University of Manchester in the UK decided to see if such distortion could explain away the proton puzzle, but found that it was dozens of times too feeble. "It wasn't well known before, and some people had speculated that it might conceivably be large enough," says McGovern. "To my mind, we've pretty convincingly shown that it can't."

The mathematics of QED has also come under scrutiny, but here an answer seems even less likely. QED has established itself as such a bedrock theory that one of its creators, the US theorist Richard Feynman, once called it "the jewel of physics". In any case, says Krzysztof Pachucki at the University of Warsaw in Poland, the calculations have been repeated by hundreds of scientists worldwide. "People tend to ask, are the QED calculations wrong?" he says. "But for muonic hydrogen, the calculations are very elementary. It's hard to believe there's a mistake."

As if to rub salt into the wound, in January 2013 Pohl and colleagues published a new

"To rub salt into the wound, the new, smaller, measure of the proton radius is twice as accurate"

measurement that almost doubles the accuracy of their smaller value of the proton radius. Now, with all traditional avenues of explanation blocked, there seems to be only one route left: physics beyond the current standard model of particle physics.

A fresh force

Ever since the standard model was formulated in the early 1970s, physicists have known it isn't the last word on particles and forces. Yet evidence of new phenomena has proved frustratingly hard to come by. Has the orbit of muons in and around protons revealed clues where other experiments, even those at powerful accelerators, have failed?

There is already a good reason to think something is amiss with muons. For the past 15 years, physicists at Brookhaven National Laboratory in New York have been measuring the muon's "g-factor", an abstract parameter that is related to another fundamental quantum property of particles called spin. Like the Lamb shift, the g-factor is predicted by QED, and for the electron this prediction agrees with experiment to a whopping 10 significant figures, making it the best agreement between theory and experiment in all of physics. However, that's not the case for the muon's g-factor: this disagrees with predictions so much that there's a 99.9 per cent chance that new physics is at work.

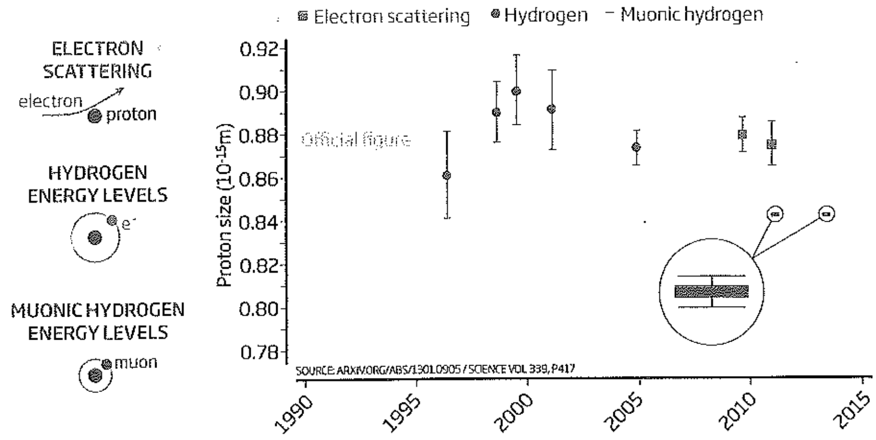
Combine these odds with the proton puzzle, and the muon appears to be telling us something. Theorists believe that a new force could be binding the muon extra tightly to the proton. Such a force would skew the Lamb shift in muonic hydrogen, making the proton appear smaller than it actually is. But modelling such a force is like trying to satisfy an impossibly fussy customer.

For starters, the force needs to affect muons much more than electrons. Next, it needs to be strong enough to account for the proton puzzle, but not so strong as to override the dominant force of electromagnetism in QED. Finally, there is the thorny matter of neutrinos. These fleeting particles hardly interact with other matter, so there cannot be any extra force acting on them we are not aware of already. "The moment you touch neutrinos, your model is dead," says theorist Maxim Pospelov at the University of Victoria in Canada.

Despite these tough constraints, various new forces that would fit the bill have been proposed. In 2011, Yavin and his colleague David Tucker-Smith at Williams College in Williamstown, Massachusetts, came up with a force that could explain not just the proton puzzle, but the g-factor discrepancy too. The force would be carried by a new particle with about one-tenth the mass of the proton.

Proton problem

Three techniques have been used to measure the proton's radius, but the most accurate way – using muonic hydrogen – gives a much smaller result than the others



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Later in 2011, Pospelov and others proposed a more intriguing force-carrier: the dark photon. This particle would be invisible to humans, but it would act as the glue that binds dark matter, an elusive substance thought to make up about 85 per cent of all matter in the universe. Dark photons are already being searched for in the debris of certain particle smashers, such as at Jefferson Laboratory in Newport News, Virginia.

Or perhaps the answer isn't a new force at all. In 2013, Li-Bang Wang and Wei-Tou Ni at the National Tsing Hua University in Taiwan suggested that the muon might be bound tighter to the proton by some extra gravity leaking in from another dimension. That would help to explain the errant proton radius, though not the g-factor result.

Yet all of these explanations have something missing: elegance. "I find them all a little contrived," says Pospelov. "The explanations are not very economical, not very natural."

And this is the problem with the proton puzzle. Whichever way physicists turn, the path looks as if it will lead them right back to where they started. There is some hope in the next round of experiments at PSI, which employ the scattering method to determine the proton radius, using muons in place of electrons. In principle, this is the final piece of the jigsaw and will be able to show whether the issue is with the mathematics, or with the proton itself. But the results are yet to come in.

"None of the explanations seems likely, which is what makes the puzzle so interesting," says Ron Gilman at Rutgers University in New Jersey. "It's like a horse race – but not only can you not tell which horse is likely to win, you're worried none of them will even finish." ▨