# The puzzle of the proton radius

**Will Morrow**
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An article published in this month's edition of the *Scientific American* journal, written by physicists Jan Bernauer and Randolf Pohl, points to the emergence over the past four years of an unexplained and intriguing discrepancy in atomic physics. Two different experimental methods for measuring the same thing, the proton radius, have yielded seemingly incompatible results.

In October 2010, Pohl and an international team of physicists published their findings for the proton radius based on a new and highly accurate experimental method. Their result, which has since been confirmed in further testing published in January 2013, was 0.8049 femtometres (10^-15 metres, or approximately a billion times smaller than the width of a human hair). This figure is 4 percent less than the currently accepted value, consistent with all previous measurements—including the results of Bernauer's group, published separately in October 2010. Statistically, the difference between the two measurements amounts to seven standard deviations, meaning it is virtually impossible for the result to be a fluke.

Since the publication of Pohl's results in 2010, physicists have sought to rule out any experimental errors and incorrect calculations that may have caused the discrepancy. Further experiments have been planned. So far, however, no such flaws have been found, and there has been no successful explanation for the anomaly on the basis of current theories.

It cannot, of course, be ruled out that an error will be discovered. However, the possible existence of two apparently irreconcilable values for the radius of such a fundamental sub-atomic particle as the proton could provide the impetus for further theoretical work and a breakthrough in some outstanding questions of modern physics.

As Pohl and Bernauer write in the *Scientific American*: "Four years after the puzzle came to light, physicists have exhausted straightforward explanations. We have begun to dream of more exciting possibilities."

Previously, the most accurate experimental method for measuring the proton radius was based on an analysis of the angle of deflection of particles fired into protons. Using this technique, Bernauer's group obtained results which fit right in the middle of the accepted value of the proton, and which had the least experimental uncertainty of any measurement to date.

Pohl's research team employed a different experimental method, which relied on a strange effect of quantum mechanics—the laws of motion that govern at an atomic scale. The team analysed the different frequencies of light emitted by an exotic form of the hydrogen atom, the simplest of all elements, which consists of a single proton at its nucleus and a single bound electron.

According to the quantum mechanical description of hydrogen, this electron does not possess a well-defined orbit, as we would expect from our experience with objects on an everyday scale. Rather, the electron's position can be described only by a "wave function," which determines the probability that one would find it at any point in the atom.

Moreover, this wave function can take only very specific forms, known as atomic states, according to the energy of the electron. These energy levels can have only certain discrete values. In other words, the electron can be found in one or another energy level, but not in between. When an electron moves from a higher to a lower energy state, it emits electromagnetic radiation of a characteristic frequency.

Pohl's experiment made use of a bizarre consequence of these laws. At its lowest energy level, the wave function describing the electron's position in hydrogen is actually non-zero at the nucleus. In other words, the minuscule negatively-charged electron spends some of its time inside the comparatively enormous and positively-charged proton. Moreover, the probability that the electron will be inside the proton at any time depends upon the proportion of the atom's volume that is occupied by the proton, and hence on the proton's radius.

As the electron reaches higher energy levels, however, the probability of it being inside the proton drops to zero. This difference, between the lowest and higher atomic states, is known as the "Lamb Shift," after William Lamb, the physicist who discovered the phenomenon in 1947. By measuring the difference in energy between certain atomic states, physicists can infer the radius of the proton.

While this technique has been used before, Pohl's group made the new proposal in 1997 to replace hydrogen's electron with a muon—an atomic particle that has the same negative charge but is 207 times more massive. This proposal was technically impossible until the late 1990s. Because it is heavier, the muon spends a greater portion of its time inside the proton than would an electron, and is therefore far more sensitive to the size of the proton radius. This allowed Pohl's group to make measurements with 10 times greater precision than all previous experiments.

The use of a muon, however, posed significant technical challenges, making the construction of the experimental apparatus itself a major feat of engineering. The physicists spent the three years from 1999 to 2002 at the Paul Scherrer Institute in Switzerland developing suitable detectors and a muon beam that could provide a steady flow of muons at the correct energy.

The muon beam was directed into a container of hydrogen gas. Every so often, a muon would displace an electron and take its position in a hydrogen atom, forming "muonic hydrogen." This exotic atom, however, is highly unstable, and decays within a few nanoseconds. The experimenters were therefore confronted with the task of timing their apparatus to detect the appearance of muonic hydrogen and take measurements of the frequencies of light that it absorbed and emitted—all within a few nanoseconds, or billionths of a second.

Just how unusual were the results can be gauged from the fact that it took Pohl's group more than seven years of apparently unsuccessful experiments. The experimental apparatus was designed to detect signals in a range calculated from previous measurements of the proton's radius. Over the course of years, the team spent many periods of several weeks each searching for such signals. They carried out a major redesign of the experiment and tried again. Still they found nothing.

Finally, in 2009, Pohl explains: "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 decades-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?"

After discussion, the team eventually decided to retune their detectors to search for a far smaller proton radius—"smaller than anyone had any right to assume." They were stunned by their findings.

Scientific publications have pointed to the potential implications of Pohl's results for modern physics, including the theory of quantum electrodynamics (QED). QED was the first theory to combine the newly-developed theory of quantum mechanics of the 1920s and 1930s with Albert Einstein's theory of special relativity. The theory describes—to an extraordinary degree of accuracy—the interaction of electromagnetic waves—light—with matter. One of its achievements was a full explanation of the Lamb Shift. The Pohl group's calculations of the radius of the proton were based on QED.

Helen Margolis, an optics physicist at the National Physical Laboratory in the UK, remarked in a column for *Science* magazine last year: "If the results of [further] experiments turn out to reinforce the proton size puzzle, then it could become necessary to question the foundations of the world's most precise and best-tested fundamental physical theory, QED itself."

Another possible implication—yet to be investigated—is that the proton radius could differ depending on whether it is orbited by an electron or a muon. If this were the case, it would violate a fundamental precept of what is known as the Standard model, which is also derived from QED. The Standard model has been highly successful in explaining and predicting the existence of sub-atomic particles.

As Pohl and Bernauer write: "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 than electrons." Experiments to investigate this possibility have been planned, combining the Pohl group's use of a muon with the alternative approach for measuring a proton radius based on scattering.

The two pillars of twentieth century theoretical physics—quantum mechanics and Einstein's theory of general relativity—developed from an investigation into apparent experimental anomalies that could not be explained on the basis of previous theories. Both have been extraordinarily accurate within their own spheres—quantum mechanics on the very small scale, general relativity over the very large. However, attempts to harmoniously unify the two theories have so far proven unsuccessful.

That is why the emergence of two measurements for the radius of a proton has been greeted with excitement among physicists. The disparity holds out the tantalising possibility that an investigation of the phenomenon will yield fresh new insights into the fundamental laws of theoretical physics.