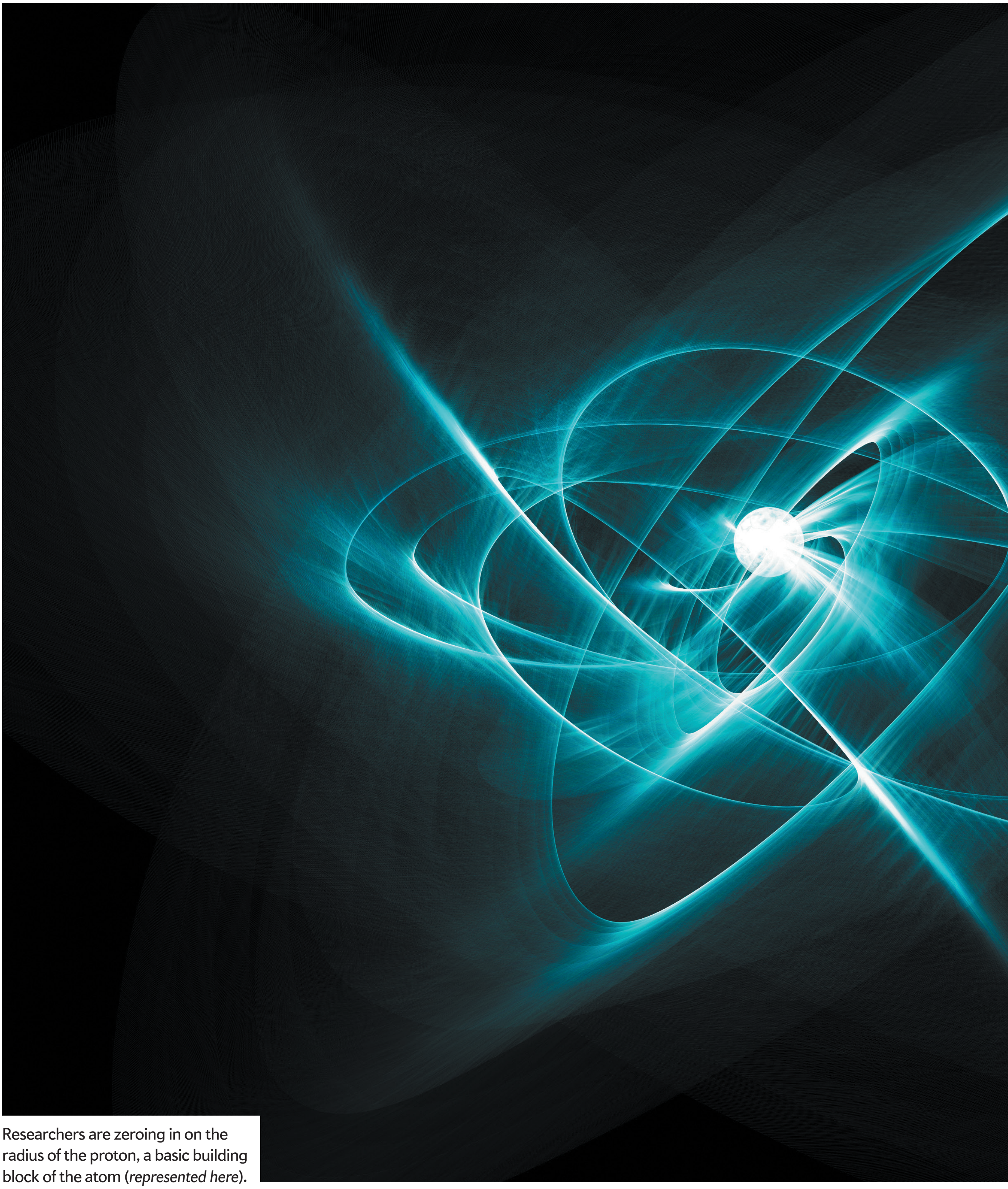
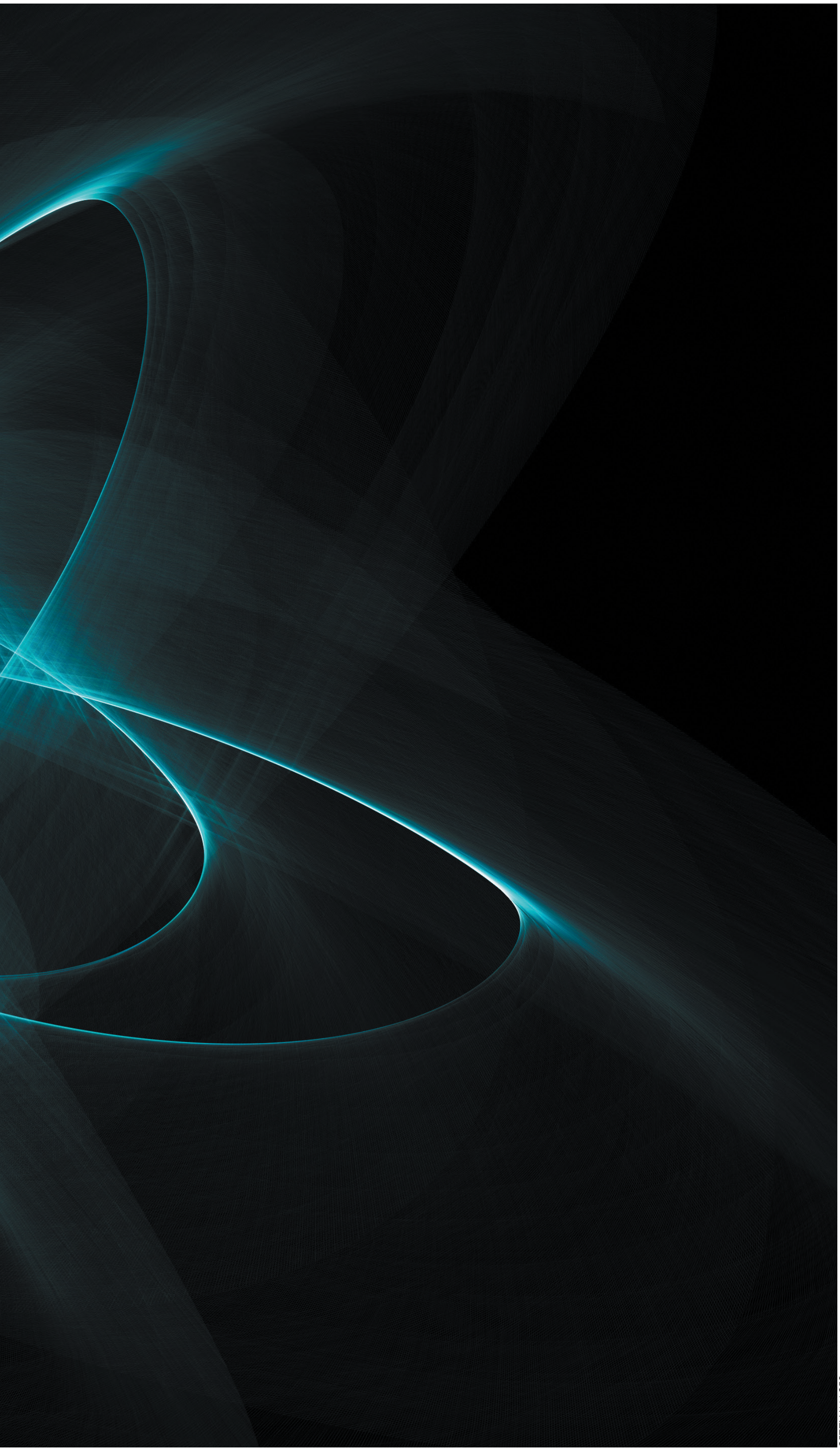
ADVANCES



Researchers are zeroing in on the radius of the proton, a basic building block of the atom (*represented here*).



GETTY IMAGES

NUCLEAR PHYSICS

Proton Size Puzzle

New work may solidify a critical benchmark

Scientists love precision. They can measure the distance from Earth to the moon to within a couple of centimeters and the spins of far-off pulsars to fractions of a millisecond. When peering inside a nearby atom, however, that kind of precision is harder to come by. Consider protons, the positively charged chunks of matter found in every atomic nucleus. Physicists have been trying to pin down their size for more than half a century, but it has proved fiendishly difficult—and conflicting measurements have left researchers scratching their heads. Now an ultraprecise measurement at York University in Toronto may finally have tamed the proton.

Protons are, of course, tiny—less than two trillionths of a millimeter across—so teasing out their radius requires exacting techniques. Researchers can fire a beam of electrons at a hydrogen atom, whose nucleus consists of a single proton; the angles at which the electrons bounce off the proton are determined by its size. Another strategy relies on spectroscopy, which measures the intensity of the radiation at various frequencies that an object emits. Scientists can excite a hydrogen atom's electron so it jumps from one energy state to the next and then carefully track the frequency of the radiation needed to drive this transition. The size of the "gap" between the energy levels depends on the proton's size.

Measurements dating back to the 1950s, from work using both methods, set the proton's radius at an apparent 0.88 femtometer (a femtometer is 10^{-15} meter). In 2010 researchers led by Randolf Pohl, then at the Max Planck Institute for Quantum Optics in Garching, Germany, tried something different. They used the spectroscopic method but with special "muonic" hydrogen: instead of an electron, this atom contains a muon, a particle with about 200 times the mass of an electron. Because the muon hugs the proton more tightly than an electron would, its energy levels are more sensitive to proton size, promising more accurate results. Plus, the particular transition they studied (in which the muon jumps from its first excited state to its second) leads more directly to the proton radius than other transitions. Pohl and his team were surprised to find a lower value for the radius, pegging it at 0.84 femtometer—well outside the range of potential sizes established by earlier measurements.

Pohl's result sent the head-scratching into high gear. Was something wrong with the earlier experiments? Or is there something peculiar about how protons interact with muons, compared with their behavior around electrons? That was the most intriguing possibility: that some as yet unknown physics, which might require a tweak to the so-called Standard Model, was at play.

"When there's a discrepancy in the data, it really gets people excited," says David Newell, a physicist at the National Institute of Standards and Technology in Gaithersburg, Md., whose work has focused on pinning down the value of Planck's constant, another crucial parameter in atomic physics.

The discrepancy caught the attention of Eric Hessels, head of the York team, who a decade ago was at the workshop where Pohl first presented his results. Hessels took Pohl's findings as something of a personal challenge and worked to replicate the experiment—right down to the particular energy-level transition—using regular instead of muonic hydrogen. This jump is known as the Lamb shift (for physicist Willis Lamb, who first measured it in the 1940s). A precise measurement of the Lamb shift in regular hydrogen seemed guaranteed to reveal something of interest. If it matched the earlier, larger value, it might point the way to new physics; if it matched the lower value, it would help pin down the size of the proton, solving a decades-old puzzle.

It took Hessels eight years to find the answer. "It was a more difficult measurement than I anticipated," he says, "and more difficult than any other measurement that we've taken on in our lab." He used radio-frequency radiation to excite hydrogen atoms, noting the precise frequency at which the radiation drove the electron energy jump associated with the Lamb shift. In the end, his team determined that the proton's radius is 0.833 femtometer, plus or minus 0.010 femtometer—which agrees with Pohl's measurement. *Science* published the results in September.

In an age of "big science"—think of the Large Hadron Collider and its tunnel's 27-kilometer circumference—physicists may take some comfort in the fact that such important results can still be obtained with tabletop experiments. Hessels's setup fit in a single room on York's campus.

It is unclear why previous experiments produced a larger value for the proton's radius. Errors in experimental design are one possibility, researchers suggest. Another possibility—seemingly less likely, in light of Hessels's measurement—is that unknown physics still skews the results.

MEDICINE

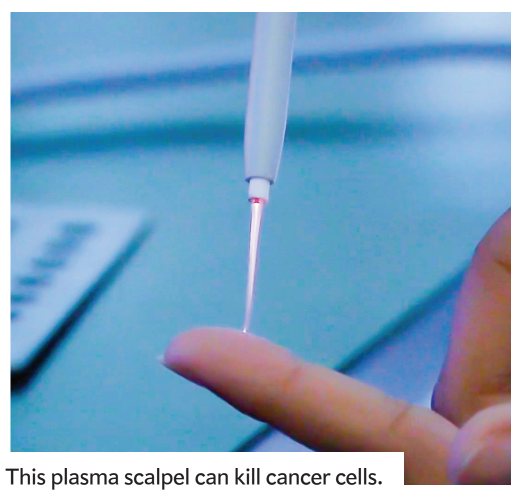
Plasma Power

New supercharged scalpel takes on cancer

When a surgeon removes a tumor, some cancer cells may get left behind, threatening to seed another malignant growth. Researchers have just begun the first clinical trial of a new anticancer tool that they hope will kill these stubborn cells: a plasma scalpel.

The pen-size scalpel emits a small jet of helium whose charged particles glow with a vivid lilac hue. An electrode at the scalpel's tip splits some of the helium atoms into a plasma soup of positive ions and electrons.

Unlike in the sun's blazing plasma, the scalpel's ions are relatively slow-moving—so the jet feels like a cool breeze to the touch. But its fast electrons are packed with energy and can convert atmospheric oxygen and nitrogen into reactive forms, including superoxide, nitric oxide and atomic oxygen. These substances can interrupt key metabolic processes and hamper cell reproduction, and researchers have found that cancer cells are much more vulnerable to such effects than healthy cells are. The scalpel can be used on a tumor site for just a few minutes during surgery, says Jerome Canady, a surgeon in Washington, D.C., and part of the team that developed the tool. "We just spray that area with plasma to kill any microscopic tumors," he says.


This plasma scalpel can kill cancer cells.

Cold plasma is already used to treat infections and sterilize wounds, and more energetic plasma can neatly cut or cauterize tissue. Turning it against cancer has long been a goal, and the new trial is a major milestone, says Mounir Laroussi, who studies the biological effects of cold plasma at Old Dominion University. "I think this is huge," he says.

In the past few years doctors have used plasma scalpels on three cancer patients on a "compassionate use" basis, after all other

The York finding's precision and closeness to the 2010 figure suggest a consensus forming around the lower value for the proton radius. "There are now a number of measurements, and they're starting to line up with the muonic-hydrogen measurement," Hessels says. "So the controversy is starting to diminish."

Diminish but not disappear: As good as Hessels's result is—it is one of the best spectroscopic measurements achieved with normal hydrogen—Pohl's measurement is more precise because of the greater sensitivity of the muonic-hydrogen method. This finding means there is room for even more sensitive experiments, researchers say.

Meanwhile there are other secrets the proton has yet to give up. For starters, we know protons and neutrons both consist of three quarks bound by the strong nuclear force—but the exact nature of that binding is poorly understood, says Nilanga Liyanage, a physicist at the University of Virginia.

"Protons are the stuff we're made of," says Liyanage, who has tackled the proton radius puzzle through electron-scattering experiments at the Jefferson Lab in Virginia. And "99.9 percent of our mass—of ourselves, of everything in the universe—comes from protons and neutrons." The proton radius is a critical benchmark quantity, he adds: "It's a very important particle, and we need to understand it." *—Dan Falk*

treatment options had failed. The plasma successfully killed residual cancer cells in these people, Canady says, but a full clinical trial will provide vital data about safety and longer-term effects. As *Scientific American* went to press, Canady and his colleagues were due to perform the first surgery of their trial in late October 2019. They aim to use the plasma scalpel on 20 patients with late-stage solid cancers, including those affecting the pancreas, ovary or breast.

Laroussi says it took more than a decade of laboratory work on cell cultures and animals to prepare the plasma scalpel for the clinic. The process involved identifying the chemicals it generates, measuring their penetration into tissue and understanding how the disruption of cancer cells works. "You also have to stay below a certain dose—otherwise you kill both cancer cells and healthy cells," he says. Laroussi hopes the trial will show that the device can be fine-tuned to take out its cancerous quarry without causing unwanted damage. *—Mark Peplow*

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