Physicists calculate proton's pressure distribution for first time

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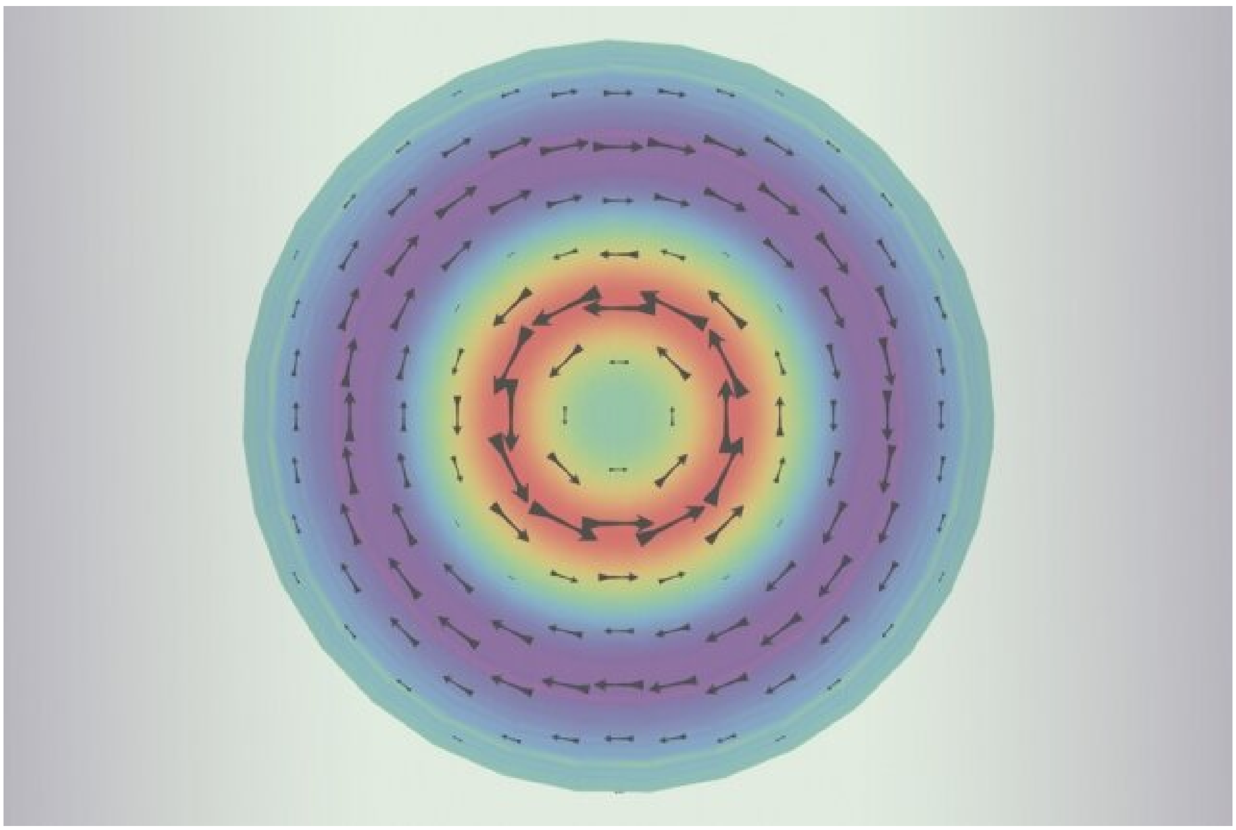

MIT physicists have calculated the pressure distribution inside a proton for the first time. They found the proton’s high-pressure core pushes out, while the surrounding region pushes inward. Credit: Massachusetts Institute of Technology

Neutron stars are among the densest-known objects in the universe, withstanding pressures so great that one teaspoon of a star's material would equal about 15 times the weight of the moon. Yet as it turns out, protons—the fundamental particles that make up most of the visible matter in the universe—contain even higher pressures.

For the first time, MIT physicists have calculated a proton's pressure distribution, and found that the particle contains a highly pressurized core that, at its most intense point, is generating greater pressures than are found inside a neutron star.

This core pushes out from the proton's center, while the surrounding region pushes inward. (Imagine a baseball attempting to expand inside a soccer ball that is collapsing.) The competing pressures act to stabilize the proton's overall structure.

The physicists' results, published today in *Physical Review Letters*, represent the first time that scientists have calculated a proton's pressure distribution by taking into account the contributions of both quarks and gluons, the proton's fundamental, subnuclear constituents.

"Pressure is a fundamental aspect of the proton that we know very little about at the moment," says lead author Phiala Shanahan, assistant professor of physics at MIT. "Now we've found that quarks and gluons in the center of the proton are generating significant outward pressure, and further to the edges, there's a confining pressure. With this result, we're driving toward a complete picture of the proton's structure."

Shanahan carried out the study with co-author William Detmold, associate professor of physics at MIT.

Remarkable quarks

In May 2018, physicists at the U.S. Department of Energy's Thomas

Jefferson National Accelerator Facility announced that they had measured the proton's pressure distribution for the first time, using a beam of electrons that they fired at a target made of hydrogen. The electrons interacted with quarks inside the protons in the target. The physicists then determined the pressure distribution throughout the proton, based on the way in which the electrons scattered from the target. Their results showed a high-pressure center in the proton that at its point of highest pressure measured about 10^{35} pascals, or 10 times the pressure inside a neutron star.

However, Shanahan says their picture of the proton's pressure was incomplete.

"They found a pretty remarkable result," Shanahan says. "But that result was subject to a number of important assumtions that were necessary because of our incomplete understanding."

Specifically, the researchers based their pressure estimates on the interactions of a proton's quarks, but not its gluons. Protons consist of both quarks and gluons, which continuously interact in a dynamic and fluctuating way inside the proton. The Jefferson Lab team was only able to determine the contributions of quarks with its detector, which Shanahan says leaves out a large part of a proton's pressure contribution.

"Over the last 60 years, we've built up quite a good understanding of the role of quarks in the structure of the proton," she says. "But gluon structure is far, far harder to understand since it is notoriously difficult to measure or calculate."

A gluon shift

Instead of measuring a proton's pressure using particle accelerators, Shanahan and Detmold looked to include gluons' role by using supercomputers to calculate the interactions between quarks and gluons that contribute to a proton's pressure.

"Inside a proton, there's a bubbling quantum vacuum of pairs of quarks and antiquarks, as well as gluons, appearing and disappearing," Shanahan says. "Our calculations include all of these dynamical fluctuations."

To do this, the team employed a technique in physics known as lattice QCD, for quantum chromodynamics, which is a set of equations that describes the strong force, one of the three fundamental forces of the Standard Model of particle physics. (The other two are the weak and electromagnetic force.) The strong force is what binds quarks and gluons to ultimately make a proton.

Lattice QCD calculations use a four-dimensional grid, or lattice, of points to represent the three dimensions of space and one of time. The researchers calculated the pressure inside the proton using the equations of Quantum Chromodynamics defined on the lattice.

"It's hugely computationally demanding, so we use the most powerful supercomputers in the world to do these calculations," Shanahan explains.

The team spent about 18 months running various configurations of quarks and gluons through several different supercomputers, then determined the average pressure at each point from the center of the proton, out to its edge.

Compared with the Jefferson Lab results, Shanahan and Detmold found that, by including the contribution of gluons, the distribution of pressure in the proton shifted significantly.

"We've looked at the gluon contribution to the pressure distribution for the first time, and we can really see that relative to the previous results the peak has become stronger, and the pressure distribution extends further from the center of the proton," Shanahan says.

In other words, it appears that the highest pressure in the proton is around 10^{35} pascals, or 10 times that of a neutron star, similar to what researchers at Jefferson Lab reported. The surrounding low-pressure region extends farther than previously estimated.

Confirming these new calculations will require much more powerful detectors, such as the Electron-Ion Collider, a proposed particle accelerator that physicists aim to use to probe the inner structures of protons and neutrons, in more detail than ever before, including gluons.

"We're in the early days of understanding quantitatively the role of gluons in a proton," Shanahan says. "By combining the experimentally measured quark contribution, with our new calculation of the gluon piece, we have the first complete picture of the proton's pressure, which is a prediction that can be tested at the new collider in the next 10 years."

More information: P. E. Shanahan et al. Pressure Distribution and Shear Forces inside the Proton, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.122.072003 , journals.aps.org/prl/abstract/ … ysRevLett.122.072003

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