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Researchers Overcome the Space Between Protons and Neutrons to Study Heart of Matter

In the first direct probes of the core of the nuclear interaction, researchers find that leading theories on interactions between protons and neutrons describe them well, even in conditions where the protons and neutrons strongly overlap, such as in neutron stars

NEWPORT NEWS, VA – Nuclear physicists have entered a new era for probing the strongest force in the universe at its very heart with a novel method of accessing the space between protons and neutrons in dense environments. The research, which was carried out at the Department of Energy's Thomas Jefferson National Accelerator Facility, has been published in the journal *Nature* and opens the door for more precision studies of the strongest part of the strong nuclear force and the structure of neutron stars.

"Until this work, the forces between protons and neutrons at very, very short distances comparable to the size of the proton and neutron itself were very model dependent," explains Axel Schmidt, a former MIT postdoctoral researcher and the paper's lead author, who has since moved to George Washington University. "We've come up with a new way to analyze data from Jefferson Lab to look at these forces at distances that are much, much shorter."

The strong force is one of the four fundamental forces of nature, which also include gravity, electromagnetism and the weak nuclear force. The strong force is responsible for binding together the protons and neutrons that form the nucleus of the atom, and thus the core of every atom that builds our visible universe.

"What we have presented in this paper is a new approach in learning about that force by using protons and neutrons in nuclei that happen to get close together, and using this natural occurrence within nuclei to learn about these forces," says Schmidt.

As pairs of protons and neutrons get very close together, they may engage in a short-range correlation, forming a brief partnership. While in this correlation, they overlap momentarily before the particles part ways.

In their analysis, the researchers captured snapshots of these correlations to study as microcosms of dense nuclear matter. They then tested different state-of-the-art models for the strong nuclear force to see how well the models explain the data.

They found that the most successful models describe the strong nuclear force at short distances as having a so-called tensor interaction, where protons interact with other protons very differently than they interact with neutrons. Then, as the distance between the correlated particles shrinks even further, the nuclear force interaction changes to a so-called scalar interaction, where proton-proton and proton-neutron interactions are very similar.

“And we find that these models of the force that have a harder repulsive (scalar) core seem to do a better job of explaining the data,” Schmidt explains.

This hard, repulsive core of the strong nuclear force has never before been directly accessed experimentally inside a nucleus. The researchers say that’s because as experimenters attempted to reach these short distance scales in particle accelerators using higher and higher energies, the data became muddled with production of other particles that complicated the interactions, as a direct consequence of the higher energies needed to access the short distance scales.

The researchers say they were surprised to find that even though the protons and neutrons overlapped in these interactions, the models that treat them as individual particles were still successful in describing their behavior. This was verified across the range of different nuclei used in the experiment, from carbon to lead.

“We find that we can still model the data using protons and neutrons, even though they are clearly at distance scales that are smaller than their own size and therefore quarks and gluons might need to be explicitly accounted for,” says Jackson Pybus, an MIT graduate student and the paper’s second author. “They are clearly overlapping to a large degree, but it doesn't seem to invalidate our models and our calculations."

Further, the result also has implications for the structure of neutron stars, where it’s expected that protons and neutrons overlap much as they do as in the short-range correlations studied in the experiment.

“That's a huge triumph for modern nuclear physics, because nobody expected this model to have any connection to reality at this distance scale,” says Or Hen, an assistant professor of physics at MIT and spokesperson for collaboration.

They say the next step is see if these results hold up when they can run the experiment again on a wide range of nuclei and at higher precision with the newly upgraded CEBAF accelerator and experimental equipment in Jefferson Lab’s Experimental Hall B. The experiment has been approved for running and is awaiting scheduling.

To study the short-range correlations, the researchers re-analyzed data taken at the Department of Energy's Thomas Jefferson National Accelerator Facility from an experiment conducted in 2004 using Jefferson Lab’s Continuous Electron Beam Accelerator Facility, a DOE Office of Science User Facility. CEBAF produced a 5.01 GeV beam of electrons to probe nuclei of carbon, aluminum, iron and lead.

This analysis was carried out as part of the Jefferson Lab Hall B Data-Mining project. The project is supported by DOE's Office of Science. The research was also supported by the National Science Foundation, the Israel Science Foundation, the Pazy Foundation, the Chilean Comisión Nacional de Investigación Científica y Tecnológica, the French Centre National de la Recherche Scientifique and Commissariat a l'Energie Atomique, the French-American Cultural Exchange, the Italian Istituto Nazionale di Fisica Nucleare, the National Research Foundation of Korea, and the UK's Science and Technology Facilities Council.

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