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PRESS RELEASE (2025/1/28)

An overlooked nuclear force helps keep matter stable

Scientists reveal that the three-nucleon force has a stronger than anticipated impact on the stability of an atom's nucleus, with ramifications across astrophysics and quantum technology.

Fukuoka, Japan – Researchers from Kyushu University, Japan have revealed how a special type of force within an atom's nucleus, known as the three-nucleon force, impacts nuclear stability. The study, published in *Physics Letters B*, provides insight into why certain nuclei are more stable than others and may help explain astrophysical processes, such as the formation of heavy elements within stars.

All matter is made of atoms, the building blocks of the universe. Most of an atom's mass is packed into its tiny nucleus, which contains protons and neutrons (known collectively as nucleons). Understanding how these nucleons interact to keep the nucleus stable and in a low energy state has been a central question in nuclear physics for over a century.

The most powerful nuclear force is the two-nucleon force, which attracts two nucleons at long range to pull them together and repels at short range to stop the nucleons from getting too close. "Scientists have formed a good understanding of the two-nucleon force and how it impacts nuclear stability," says first author Tokuro Fukui, Assistant Professor of Kyushu University's Faculty of Arts and Science. "On the other hand, three-nucleon force, which is when three nucleons interact with each other simultaneously, is much more complicated and poorly understood."

Fukui describes nuclear forces by likening them to a game of catch. With the two-nucleon force, two players, or nucleons, interact by throwing a ball to each other. The ball, a subatomic particle called a meson, can vary in heaviness, with the lightest meson, known as a pion, responsible for the long-range attraction between nucleons. With the three-nucleon force, there are three players, or nucleons, and balls, or mesons, are passed between them. At the same time as throwing and catching the balls, the players, or nucleons, also spin and move in an orbit within the nucleus.

Although the three-nucleon force has historically been considered to be of little significance when compared to the two-nucleon force, a growing number of recent studies have highlighted its importance. Now, this new study clarifies the mechanism of how the three-nucleon force enhances nuclear stability, and demonstrates that as the nucleus grows, the force gains in strength.

In their research, Fukui and his colleagues used advanced nuclear theory and supercomputer simulations to study the exchange of pions between three nucleons. They found that when two pions are exchanged between three nucleons, the nucleons are constrained in how they move and spin, with only four combinations possible. Their calculations revealed that one of these combinations, known as the "rank-1 component," plays a crucial role in promoting nuclear stability.

Increased stability occurs, Fukui explains, due to enhancing a process known as spin-orbit splitting. When nucleons spin and orbit in the same direction, the alignment of these nucleons leads to a reduction in energy. But when nucleons spin and orbit in opposing directions, these nucleons exist in a higher energy state. This means that nucleons "split" into different energy shells, providing the nucleus with a stable structure.

"Our supercomputer simulations showed that while the three-nucleon force increases the energy state of the nucleons with an aligned spin and orbit, it causes the nucleons with opposing spins and orbits to gain even more energy. This results in a larger energy gap between the shells, making the nuclei even more stable," reveals Fukui.

Importantly, this effect becomes more pronounced in heavier nuclei that contain more nucleons. In the heaviest element examined—carbon-12, which has 12 nucleons—the three-nucleon force caused the energy gap to widen by a factor of 2.5.

"This effect is so large that it has almost equal weighting to the impact of the two-nucleon force. We expect the effect to be even stronger for elements heavier than carbon-12, which we plan to study as part of our next steps," says Fukui.

The three-nucleon force could play a key role in understanding how heavy elements form from the fusion of lighter elements in stars. As this force grows stronger in heavier nuclei, it increases their stability by creating larger energy gaps between nuclear shells. This stability makes it more challenging for the nucleus to capture additional neutrons, which is essential for forming heavier elements. In cases where the nucleus already contains a "magic number" of protons or neutrons that completely fills its shells, the nucleus becomes exceptionally stable, which can further hinder the fusion process.

"Knowing the energy gap between different nuclear shells is crucial information for scientists trying to predict the formation of heavy elements, which they cannot achieve without understanding the three-nucleon force. For magic number nuclei, conditions that provide colossal amounts of energy may be needed," says Fukui.

Finally, the researchers discovered another surprising effect of the three-nucleon force on nucleon spins. With only the two-nucleon force, the spin states of both nucleons can be measured individually. However, the three-nucleon force creates quantum entanglement, where two of the three nucleons have spins that exist in both states at once until measured.

"Quantum entanglement of nucleons can occur just like with electrons, although the larger mass of nucleons presents different challenges. These differences may have implications for future research, including in emerging technologies like quantum computing," concludes Fukui.

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For more information about this research, see "Uncovering the mechanism of chiral three-nucleon force in driving spin-orbit splitting" Tokuro Fukui, Giovanni De Gregorio, Angela Gargano, *Physics Letters B*, https://doi.org/10.1016/j.physletb.2024.138839

About Kyushu University

Founded in 1911, Kyushu University is one of Japan's leading research-oriented institutes of higher education, consistently ranking as one of the top ten Japanese universities in the Times Higher Education World University Rankings and the QS World Rankings. The university is one of the seven national universities in Japan, located in Fukuoka, on the island of Kyushu—the most southwestern of Japan's four main islands with a population and land size slightly larger than Belgium. Kyushu U's multiple campuses—home to around 19,000 students and 8000 faculty and staff—are located around Fukuoka City, a coastal metropolis that is frequently ranked among the world's most livable cities and historically known as Japan's gateway to Asia. Through its VISION 2030, Kyushu U will "drive social change with integrative knowledge." By fusing the spectrum of knowledge, from the humanities and arts to engineering and medical sciences, Kyushu U will strengthen its research in the key areas of decarbonization, medicine and health, and environment and food, to tackle society's most pressing issues.

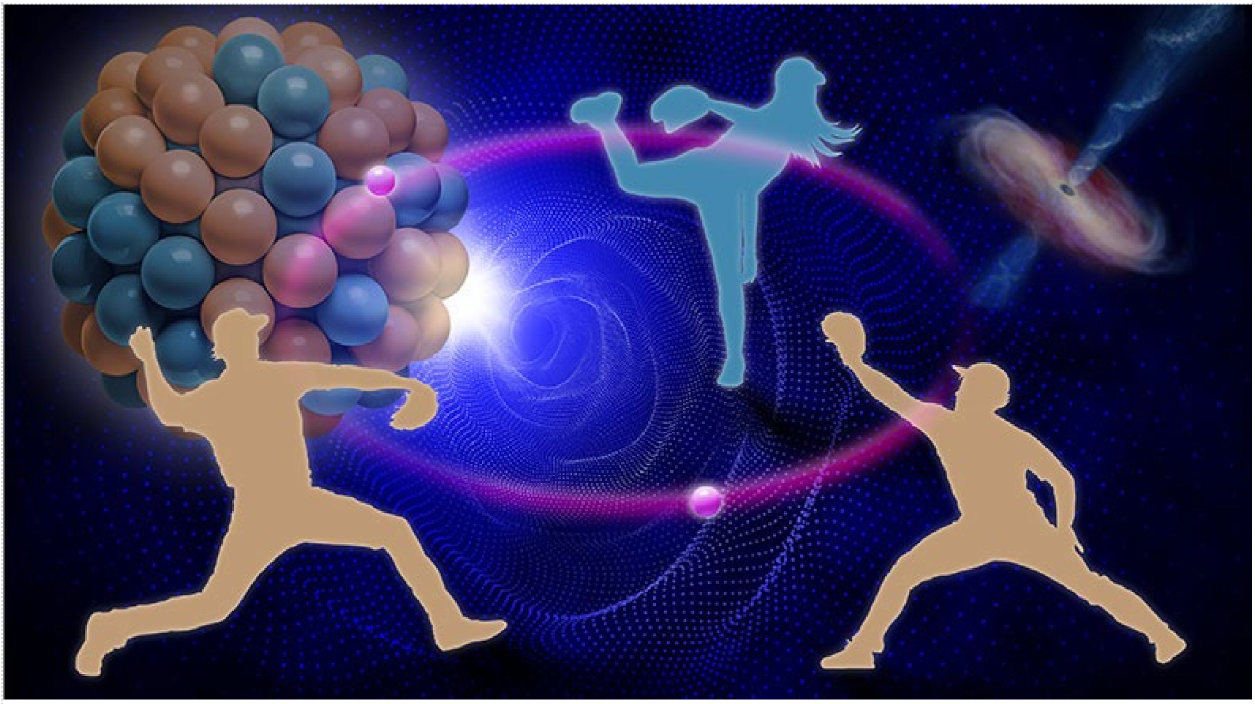

Fig. 1. Nuclear forces are likened to a game of catch.

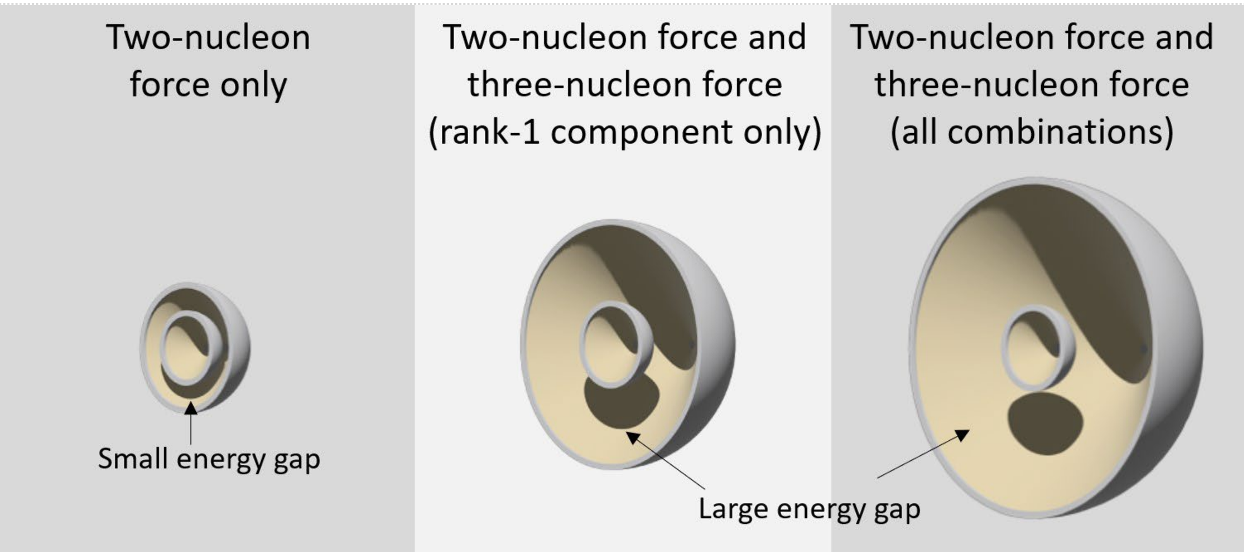

Fig. 2. The three-nucleon force enhances spin-orbit splitting, which causes a larger energy gap between nuclear shells and stabilizes the nucleus.

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