Physicists solve a beta-decay puzzle with advanced nuclear models

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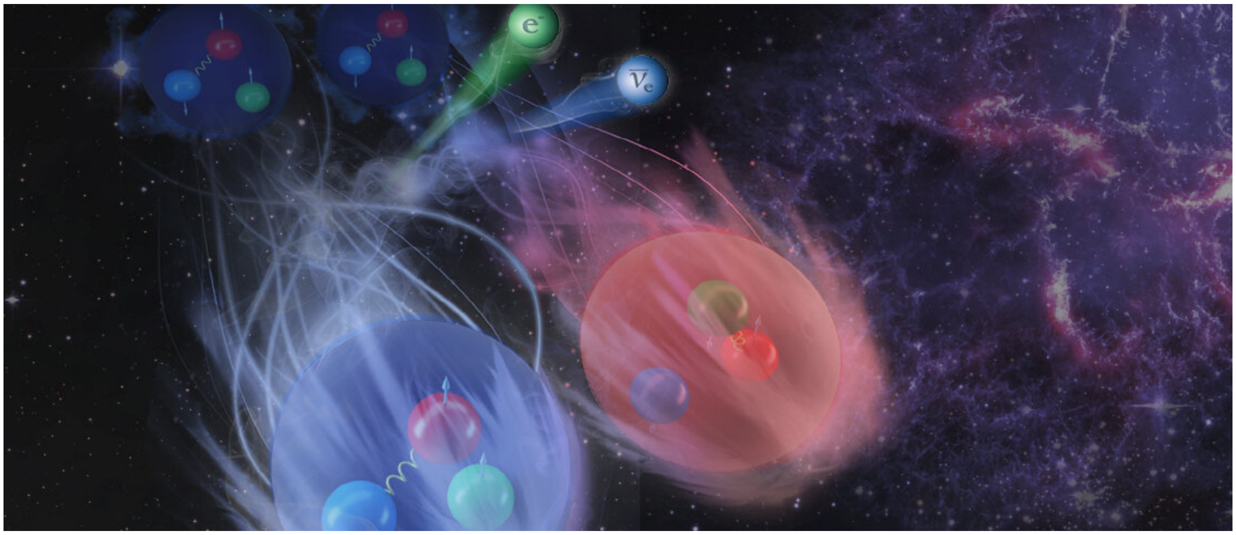

First principles calculations showed that strong correlations and interactions between two nucleons slow down beta-decays in atomic nuclei compared to what's expected from the beta decay of free neutrons. This impacts the synthesis of heavy elements and the search for neutrino-less double-beta decay. Credit: Andy Sproles/ORNL

An international collaboration including scientists at the Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL) solved a 50-year-old puzzle that explains why beta decays of atomic nuclei are slower than what is expected based on the beta decays of free neutrons.

The findings, published in *Nature Physics*, fill a long-standing gap in physicists' understanding of beta decay, an important process stars use to create heavier elements, and emphasize the need to include subtle effects—or more realistic physics—when predicting certain nuclear processes.

"For decades, scientists have lacked a first-principles understanding of nuclear beta decay, in which protons convert into neutrons, or vice versa, to form other elements," said ORNL staff scientist Gaute Hagen, who led the study. "Our team demonstrated that theoretical models and computation have progressed to the point where it is possible to calculate some decay properties with enough precision to allow for direct comparison to experiment."

To solve the problem, the team simulated tin-100 decaying into indium-100, a neighboring element on the periodic table. The two elements share the same number of nucleons (protons and neutrons), with tin-100 possessing 50 protons to indium-100's 49.

Calculating beta decay precisely required the team to not only accurately simulate the structure of the mother and daughter nuclei but also account for the interactions between two nucleons during the transition. This additional treatment presented an extreme computational challenge due to the combination of strong nuclear correlations and interactions involving the decaying nucleon.

In the past, nuclear physicists worked around this problem by inserting a fundamental constant to reconcile observed beta-decay rates of neutrons inside and outside the nucleus, a practice known as "quenching." But with machines like ORNL's Titan supercomputer, Hagen's team demonstrated that this mathematical crutch is no longer necessary.

"Nobody really understood why this quenching factor worked. It just did," said ORNL computational scientist Gustav Jansen. "We found that it could largely be explained by including two nucleons in the decay—for example, two protons decaying into a proton and a neutron, or a proton and a neutron decaying into two neutrons."

The team, which included partners from Lawrence Livermore National Laboratory, University of Tennessee, University of Washington, TRIUMF (Canada), and Technical University Darmstadt (Germany), performed a comprehensive study of beta decays from light to medium-heavy nuclei up to tin-100.

The achievement gives nuclear physicists increased confidence as they search for answers to some of the most perplexing mysteries related to the formation of matter in the universe. Beyond regular beta decay, scientists are looking to compute neutrinoless double beta decay, a theorized form of nuclear decay that, if observed, would explore important new physics and help to determine the mass of the neutrino.

Tin to In

Many elements have isotopes that decay over long periods of time. For example, the half-life of carbon-14, the nucleus used in carbon dating, is 5,730 years. Other nuclei, however, exist only for fractions of a second before ejecting particles in an attempt to stabilize.

In neutron beta decay, an electron and an anti-neutrino are emitted. When tin-100 transforms into indium-100, the nucleus undergoes beta-plus decay, expelling a positron and a neutrino when converting a proton to a neutron.

With its equal number of protons and neutrons, tin-100 exhibits an unusually high rate of beta decay, giving the ORNL team a strong signal from which to verify its results. Furthermore, the tin-100 nucleus is "doubly magic," meaning the nucleons fill out defined shells inside the nucleus that make it strongly bound and relatively simple in structure. The ORNL team's NUCCOR code, which is programmed to solve the nuclear many-body problem, excels at describing doubly magic nuclei up and down the nuclear chart.

"A doubly magic nucleus like tin-100 isn't as complicated as many other nuclei," said Thomas Papenbrock, a researcher at the University of Tennessee and ORNL. "This means we can reliably compute it using our coupled cluster method, which calculates properties of large nuclei by accounting for forces between the individual nucleons."

To model beta decay, however, the team also had to calculate the structure of indium-100, a more complex nucleus than the doubly magic tin-100. This required a more precise treatment of the strong correlations between the nucleons. By borrowing ideas from quantum chemistry, which treats electrons as waves, Hagen's team successfully developed techniques to model these processes.

"In our case we are dealing with nucleons instead of electrons, but the quantum chemistry concepts have helped us branch out from doubly magic nuclei and expand into these open-shell regions," said ORNL physicist Titus Morris.

Guiding experiment

Now that Hagen's team has shown its understanding of beta decay is on par with experiment, it's looking to take advantage of new supercomputers like ORNL's Summit, the world's most powerful, to guide current and future experiments.

Researchers are currently using Summit to simulate how calcium-48, another doubly magic nucleus, would undergo neutrinoless double beta decay—a process in which two neutrons beta decay into protons, but without emitting any neutrinos. The results could aid experimentalists in the selection of an optimal detector material for the potential discovery of this rare phenomenon.

"Currently, calculations using different nuclear models of neutrinoless double beta decay may differ by as much as a factor of six," Hagen said. "Our goal is to provide a benchmark for other models and theories."

More information: Discrepancy between experimental and theoretical β-decay rates resolved from first principles, *Nature Physics* (2019). DOI: 10.1038/s41567-019-0450-7,
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Provided by Oak Ridge National Laboratory

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