UT Physicists Are Part of an Award-Winning Collaboration Working Their Way across the Nuclear Landscape

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If no one had ever been curious about what makes a nucleus work, there would be no MRIs, no nuclear energy programs, and no detailed understanding of how stars are born and die. Fortunately, the engine of matter has both charmed and challenged scientists for decades, and recent work involving UT physicists can help make the properties of the nucleus—its size, its shape, the energy that holds it together—a bit more easy to predict.

The collaborative team of Gaute Hagen, Thomas Papenbrock, David Dean, and Morten Hjorth-Jensen has moved a little farther across the chart of the nuclides, the map that arranges nuclei from light to heavy. Over the past decade, scientists have been able to compute the properties of the lighter nuclei, up to the carbon isotope 12C or so, starting from first principles—the established laws of physics. But beyond nuclei with relatively few protons and neutrons, it has been frustrating to make calculations across the chart because the systems become much heavier. Added nucleons mean more and more interactions and configurations, and make nuclei increasingly difficult to compute—an obstacle scientists call the many-body problem. It's the equivalent of taking every high school soccer team in Tennessee and putting together as many player combinations as possible with a complete dossier on each combination's strengths, bonds, temperaments, and probabilities. Expanding that data set to include every team in the Southeast, then the United States, and so on, is much like the increasing number of protons and neutrons across the nuclear chart. It takes a massive amount of computer power and time to sort out all the possibilities.

There are promising techniques to describe nuclei from first principles that consider the forces between their protons and neutrons. Effective field theory (EFT), for example, provides a framework for understanding nuclei in terms of quantum chromodynamics, the theory of strong interactions. Unfortunately, the dominant methods employed in first-principle calculations have not scaled favorably with increasing mass numbers and cannot easily reach beyond the region of light nuclei.

To move into the territory of medium-mass nuclei, researchers from UT, Oak Ridge National Laboratory, and the University of Oslo decided to use coupled-cluster theory. First developed in the 1950s, coupled-cluster theory is a numerical technique that solves many-body problems. Among its advantages is that it has a low computational cost and that it is size extensive, meaning it's scalable across the chart of nuclides. The theory is also microscopic, taking into account individual nucleons rather than simply the nucleus as a whole. And it is a method well-suited for working with doubly-magic nuclei, those having both protons and neutrons in so-called "magic numbers" (2, 8, 20, 28, 50, 82, 126), which are particularly stable.

Using this approach, the team computed the binding energies, radii, and density for doubly-magic isotopes of helium, oxygen, calcium, and nickel. They reported their findings in "Medium-Mass Nuclei from Chiral Nucleon-Nucleon Interactions," published in *Physical Review Letters* in late August. The group's most recent computations show that inter-nucleon forces can account for up to 90 percent of the binding energy in nuclei, a first look at what role EFT-based forces play in holding a nucleus together.

For their efforts, Oak Ridge National Laboratory honored the group at its annual Awards Night on November 14. They were recognized in the Scientific Research category "for their development and implementation of coupled-cluster theory for medium mass and neutron-rich nuclei." Papenbrock is an assistant professor of physics at UT who holds a joint appointment with the ORNL Physics Division. Dean and Hagen are both with the ORNL Physics Division, and Dean is an adjunct associate professor with UT Physics. Hjorth-Jensen is with the University of Oslo Department of Physics and Center of Mathematics for Applications.

Also honored at the ORNL Awards Night ceremony was David J. Singh, who was recognized as ORNL's top scientist "for outstanding scientific impact on condensed matter physics through development of effective theoretical approaches and the application to key problems associated with novel and complex materials for basic science as well as technical advances." Singh is with the ORNL Materials Science and Technology Division and is an adjunct professor of physics at UT.