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Physics researchers question calcium-52's magic

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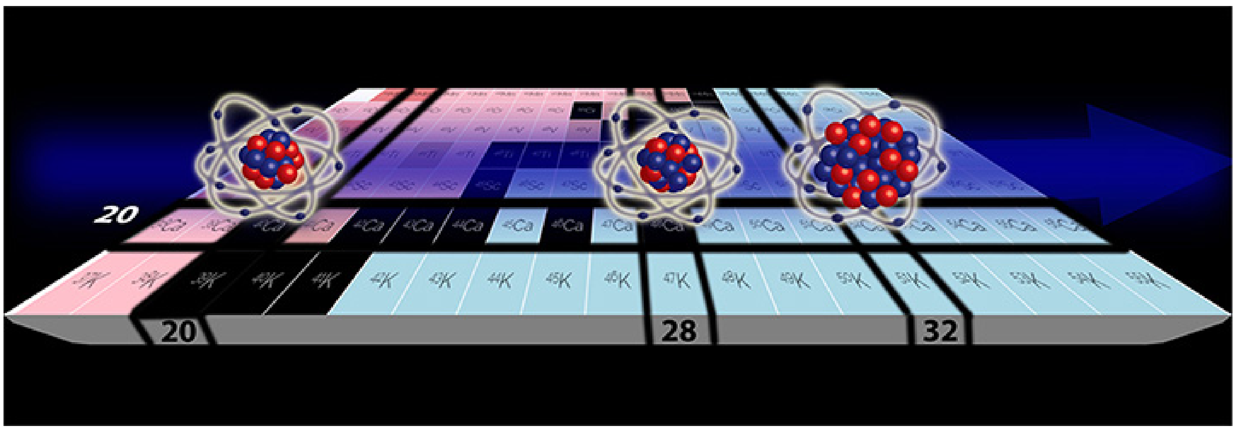

The image above shows the chain of the studied calcium isotopes. The "doubly magic" isotopes with mass numbers 40 (Ca-40) and 48 (Ca-48) exhibit equal charge radii. The first measurement of the charge radius in Ca-52 yielded an unexpectedly large result. Credit: COLLAPS Collaboration/Ronald Fernando Garcia Ruiz

For decades nuclear physicists have tried to learn more about which elements, or their various isotopes, are "magic."

This is not to say that they display supernatural powers. Magic atomic nuclei are composed of "magic" numbers of protons and neutrons—collectively called nucleons—such as 2, 8, 20, and 28. These specific numbers of nucleons define shells inside the nucleus, which, when closed, make it far more strongly bound, and stable, than other nuclei.

If both protons and neutrons have a magic number, the atomic nucleus is said to be doubly magic, making it particularly strongly bound and simple in its structure. For instance, calcium-48, with 20 protons and 28 neutrons, is doubly magic.

Atomic nuclei make up the vast majority of visible matter in the universe, and understanding the interactions between the neutrons and protons that comprise nuclei has an impact on research spanning from the subatomic realm to astrophysical objects such as neutron stars.

For a nucleus to be considered magic, it must exhibit several properties. Researchers look at its excitation energy, the energy needed to move the nucleus to a higher energy state. In addition, researchers measure its separation energy, the energy needed to remove a nucleon from the nucleus. Finally, measuring the charge radius, or the distribution of protons in the nucleus, allows scientists to track trends that would indicate whether a nucleus is magic.

Recently a multi-institution team led by Gaute Hagen at the Department of Energy's Oak Ridge National Laboratory computed the size of the atomic nucleus calcium-48—a magic isotope—and found it had a significantly thinner neutron skin than was previously thought. The results challenge researchers' understanding of the basic properties of atomic nuclei, such as the evolution of shell structure in neutron-rich nuclei and its connection to the distribution of charge and stability. The team's research was published in *Nature Physics*.

After the work on calcium-48, the team continued by moving to a larger, heavier, and more complex isotope—calcium-52—and the results surprised the researchers once again.

"What had been previously known for calcium-52 was that it has a relatively high excitation energy for the 2^+ state and a large neutron separation energy," Hagen said. "These quantities tell us something about how strongly a nucleus is bound and therefore led researchers to believe that calcium-52, much like calcium-48, was magic."

"Those are two observables that only give us partial information on whether a nucleus is magic, though," Hagen continued. "There are more observables we need to look at before we can conclusively claim to have a magic nucleus. In this work a more detailed analysis of the properties of calcium-52 challenged this claim."

Charging Toward Answers

Experimentalists from the Collinear Laser Spectroscopy (COLLAPS) collaboration at the European Organization for Nuclear Research—known as CERN—discovered that calcium-52's charge radius was much larger than those for all lighter isotopes of calcium. The research was performed using CERN's ISOLDE facility (On-Line Isotope Mass Separator).

The electric charge radius determines the size of an atomic nucleus. When looking at the variation of known charge radii in various isotope chains, researchers would normally see a picture that looks like rolling hills as neutrons are added to a nucleus. These hills represent how the charge radii evolve, getting smaller for magic nuclei and larger for the non-magic ones. The very large charge radius measured for calcium-52 called its status as a magic nucleus into question.

To help experimentalists interpret whether calcium-52 had any tricks up its sleeve, Hagen and his collaborators turned to the Titan supercomputer at the Oak Ridge Leadership Computing Facility, a DOE Office of Science User Facility located at ORNL.

Theoretical researchers from ORNL, the University of Tennessee, Michigan State University, Technische Universität Darmstadt in Germany, and TRIUMF in Canada computed the charge radii of calcium isotopes and found the same trend as in the experiment.

"If calcium-52 was magic, you would expect there to be a dip or kink in the graph showing the charge radii of calcium isotopes at calcium-52," Hagen said. "Our theory collaborators agreed with the experimental trend, and there were no signs of this kink."

Unlike the team's prior work with calcium-48, though, even the best-performing nuclear models were unable to perfectly match experimental data, although the overall trend was reproduced. OLCF scientific computing liaison Gustav Jansen, who also played a significant role in developing the team's NUCCOR code and has served as the bridge between nuclear theory and computational science on the project, noted that this outcome resulted from the extremely complex nature of the calculation.

Jansen spearheaded the efforts to optimize the team's code for Titan and organized the workflow in such a way that the team could get the most precise simulations at the lowest computational cost.

Hagen and Jansen agreed that without access to leadership computing, nuclear physics research would not be where it is today.

"There is a revolution in our field, where we can take computing power with improved computational methods to really go to a mass-50 nucleus, which is our current limit," Hagen said. "Without access to supercomputing, I think work like this would be impossible."

As computational power increases, the team looks forward to adding more detail into its simulations and expanding out to increasingly larger nuclei. To help in that effort, the team's NUCCOR code was selected as one of 13 projects for the OLCF's Center for Accelerated Application Readiness (CAAR) project.

In anticipation of the OLCF's next-generation supercomputer, Summit—set to start delivering science in 2018—staff members developed the CAAR project to invite researchers to apply for early access to Summit's test beds and developmental systems. CAAR allows researchers to prepare their codes to run as efficiently as possible on Summit from the very beginning.

Both Jansen and Hagen agree that Summit will help them continue to refine and improve their research, ultimately helping to create more accurate simulations of increasingly larger, more complex nuclei.

"Our results for this simulation really point us back to the fundamental interaction that we're studying," Jansen said. "It's saying that we need to do a better job of approximating this interaction, but also we need to narrow down the associated uncertainties. With our methods right now, the precision in the results is far better than what we have from the inputs, and until we have these two on equal footing, we won't be able to get the most precise answer."

More information: R.F. Garcia Ruiz et al. "Unexpectedly Large Charge Radii of Neutron-Rich Calcium Isotopes," *Nature Physics* (2016). DOI: 10.1038/nphys3645

G. Hagen et al. "Neutron and Weak-Charge Distributions of the ^{48}Ca Nucleus," *Nature Physics* (2016). DOI: 10.1038/nphys3529

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