The curious case of germanium-72: An unusual isotope changes phases as temperature rises

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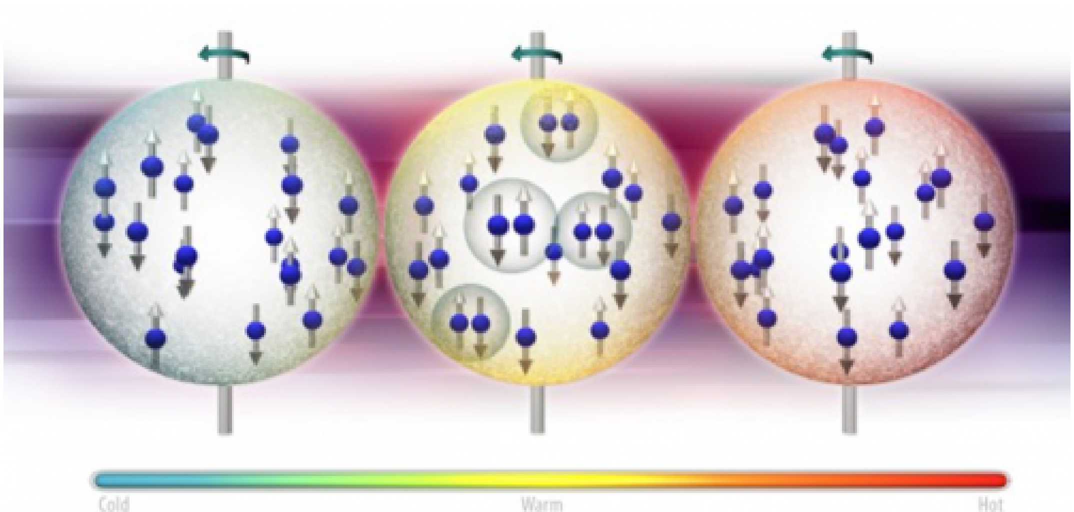

As a rapidly rotating gemanium-72 nucleus gets hotter, pairing among the protons and neutrons within the nucleus tends to decrease steadily. At one critical temperature, however, the pairing spikes back up, as represented in the center illustration. This odd behavior marks a phase transition within the germanium-72 nucleus. (Illustration by Andy Sproles, ORNL)

(PhysOrg.com) -- There's a lot we don't know about the atomic nucleus, even though it was discovered a century ago this year.

We have, of course, learned much. We can get energy by splitting the nucleus in a process known as fission or smashing nuclei together in a process known as fusion. While we can't say exactly when an unstable nucleus will decay on its own—spontaneously transforming from one isotope to another—we can say how fast a large group of nuclei will do so. In fact, we can confidently determine the half-life of a nucleus—the time in which 50 percent will decay—even in cases in which that half-life is greater than the age of the universe. The nucleus displays oddities the understanding of which will help explain our world. One of these is the tendency of protons and neutrons that make up the atomic nucleus —known collectively as nucleons—to bond together in pairs.

Physicists from Oak Ridge National Laborator, the University of Tennessee, and Germany's GSI in Darmstadt recently used ORNL's Jaguar supercomputer to explore the pair bonding of neutrons in one uncommon isotope—germanium-72. In doing so they discovered that changes in temperature and rotation take the nucleus through at least two physical phases. Their work, which offers the first realistic description of this kind of phase transition in an atomic nucleus, was featured in the Nov. 19, 2010, edition of *Physical Review Letters*.

In our mundane lives we witness phase transition anytime we see water chill into ice or boil into steam. Those three states of water—solid, liquid and gas—are the three phases, and the transitions depend on both pressure and temperature. In the concealed quantum world of the atomic nucleus, however, phase transitions are more subtle.

Germanium-72 has 32 protons (like all germanium isotopes) and 40 neutrons. Those 40 neutrons pair off strongly when the nucleus is cold and calm, but pairing weakens as you increase the temperature or rotation. What the team discovered, however, was that the relationship is not straightforward. When rotation is high, the pairing weakens as temperature rises, spikes back up at one small range of temperatures, and then weakens as temperature continues to rise. That spike indicates the transition between phases.

"The phase transition is an outgrowth of the pairing, the rotation, and the temperature," noted team member Hai Ah Nam of ORNL. "What we saw was that at the highest rotation, there was a critical temperature where all of a sudden pairing was favored again. That was interesting."

She said the discovery is exciting in part because the phase transition is reminiscent of the change undergone by ferromagnetic superconductors. In that case electrons in the superconducting material pair off into Cooper pairs below a critical temperature, allowing the material to conduct electricity without loss.

"At this temperature, pairing was reintroduced," Nam said of neutrons in the germanium isotope. "It went through this phase transition. It's like superconducting, where you have to be a certain temperature for the Cooper pairs to form. And that results in the superconducting phenomenon."

The team simulated germanium-72 on Jaguar using a statistical technique called Shell Model Monte Carlo, pioneered at CalTech in the 1990s by a collaboration that included team members David Dean, now of ORNL, and Karlheinz Langanke, now of GSI. In the nuclear shell model, protons and neutrons occupy successively higher energy levels, with a limited number of nucleons able to occupy each level. So, for instance, two neutrons can sit in the lowest energy level, four in the one above that, two more in the one above that, and so on.

The computational technique looks at protons and neutrons in each of these energy levels. To avoid having to look at every possible configuration of the 72 nucleons—a trillion trillion configurations in all—the technique calculates properties of the nucleus using a quantum statistical average. This approach gives the team a highly accurate answer combined with a known uncertainty.

Even with this sampling technique, the calculation used 80,000 of Jaguar's 240,000 processor cores for four hours to study a single nucleus.

"Jaguar's impact in solving these calculations is tremendous," Nam said. "Finding this same amount of information used to take months to complete a decade ago. Now we are able to conduct the computational research on a supercomputer in a week."

The team plans to continue this research to see whether the effect is present in isotopes other than germanium-72. The researchers have also suggested a way to compare the theoretical results to experiment. Initial results indicate that the phase transition seen in germanium-72 may be unique.

"In continuing studies we will look at a dozen or more medium-mass nuclei within this range to see if we can get the same effect," Nam said. "Because Jaguar is such a formidable resource, we can delve in deeper and essentially perform more 'experiments' in a short period of time to gain a better understanding of the science. The speed at which we can look at a large range of nuclei would have been impossible when David first started this."

One advantage of the Shell Model Monte Carlo technique, she noted, is that it predicts consequences of the phase transition that can be experimentally verified. In this case the amount of energy needed to raise the temperature of the material—known as the specific heat—drops noticeably at the critical temperature.

Nam said the team has been contacted by experimentalists interested in verifying the result, a daunting but doable task. Researchers have been able to examine the specific heat of nuclei in the past, but so far no one has taken a close look at germanium-72.

So what does it mean that at least some nuclei go through this type of phase change? Nobody's sure. The result is very new, and the implications will take time to become clear.

"The competition between superconductivity, rapid rotation, and temperature is a fascinating topic that can be studied in diverse physical systems, including tiny atomic nuclei and macroscopic-scale ferromagnets," said team member Witold Nazarewicz, a physicist at the University of Tennessee-Knoxville and Poland's Warsaw University, as well as scientific director of ORNL's Holifield Radioactive Ion Beam Facility. "We were happy to find out that our theoretical model can offer the first realistic description of an elusive phenomenon of successive pairing phase transitions in nuclei."

"So what is the physical impact of learning that germanium has a phase change? Well, phase changes are certainly exploited in many engineering practices," said Nam. "For now, these results get us one step closer to understanding the atomic nucleus."

Provided by Oak Ridge National Laboratory

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