

Magnetism's subatomic roots: Study of high-tech materials helps explain everyday phenomenon

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(PhysOrg.com) -- The modern world -- with its ubiquitous electronic devices and electrical power -- can trace its lineage directly to the discovery, less than two centuries ago, of the link between electricity and magnetism. But while engineers have harnessed electromagnetic forces on a global scale, physicists still struggle to describe the dance between electrons that creates magnetic fields.

Two theoretical physicists from Rice University are reporting initial success in that area in a [new paper](#) in the *Proceedings of the National Academy of Science*. Their new conceptual model, which was created to learn more about the quantum quirks of high-temperature superconductors and other high-tech [materials](#), has also proven useful in describing the origins of ferromagnetism -- the everyday "magnetism" of compass needles and refrigerator magnets.

"As a theorist, you strive to have exact solutions, and even though our new model is purely theoretical, it does produce results that match what's observed in the real world," said Rice physicist Qimiao Si, the lead author of the paper. "In that sense, it is reassuring to have designed a [model system](#) in which ferromagnetism is allowed."

Ferromagnets are what most people think of as magnets. They're the permanently [magnetic](#) materials that keep notes stuck to refrigerators the world over. Scientists have long understood the large-scale workings of

ferromagnets, which can be described theoretically from a coarse-grained perspective. But at a deeper, fine-grained level -- down at the scale of atoms and electrons -- the origins of ferromagnetism remain fuzzy.

"When we started on this project, we were aware of the surprising lack of theoretical progress that had been made on metallic ferromagnetism," Si said. "Even a seemingly simple question, like why an everyday refrigerator magnet forms out of electrons that interact with each other, has no rigorous answer."

Si and graduate student Seiji Yamamoto's interest in the foundations of ferromagnetism stemmed from the study of materials that were far from ordinary.

Si's specialty is an area of condensed matter physics that grew out of the discovery more than 20 years ago of high-temperature superconductivity. In 2001, Si [offered a new theory](#) to explain the behavior of the class of materials that includes high-temperature superconductors. This class of materials -- known as "quantum correlated matter" -- also includes more than 10 known types of ferromagnetic composites.

Si's 2001 theory and his subsequent work have aimed to explain the experimentally observed behavior of quantum-correlated materials based upon the strangely correlated interplay between electrons that goes on inside them. In particular, he focuses on the correlated electron effect that occur as the materials approach a "quantum critical point," a tipping point that's the quantum equivalent of the abrupt solid-to-liquid change that occurs when ice melts.

The quantum critical point that plays a key role in high-temperature superconductivity is the tipping point that marks a shift to

antiferromagnetism, a magnetic state that has markedly different subatomic characteristics from ferromagnetism. Because of the key role in high-temperature superconductivity, most studies in the field have focused on antiferromagnetism. In contrast, ferromagnetism -- the more familiar, everyday form of magnetism -- has received much less attention theoretically in quantum-correlated materials.

"So our initial theoretical question was, 'What would happen, in terms of correlated electron effects, when a ferromagnetic material moves through one of these quantum tipping points?" said Yamamoto, who is now a postdoctoral researcher at the National High Magnetic Field Laboratory in Tallahassee, Fla..

To carry out this thought experiment, Si and Yamamoto created a model system that idealizes what exists in nature. Their jumping off point was a well-studied phenomenon known as the [Kondo effect](#) -- which also has its roots in quantum [magnetic](#) effects. Based on what they knew of this effect, they created a model of a "Kondo lattice," a fine-grained mesh of electrons that behaved like those that had been observed in Kondo studies of real-world materials.

Si and Yamamoto were able to use the model to provide a rigorous answer about the fine-grained origins of metallic ferromagnetism. Furthermore, the ferromagnetic state that was predicted by the model turned out to have quantum properties that closely resemble those observed experimentally in heavy fermion ferromagnets.

"The model is useful because it allows us to predict how real-world materials might behave under a specific set of circumstances," Yamamoto said. "And, in fact, we have been able to use it to explain experimental observations on heavy fermion metals, including both the antiferromagnets as well as the less well understood ferromagnetic materials."

Provided by Rice University

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