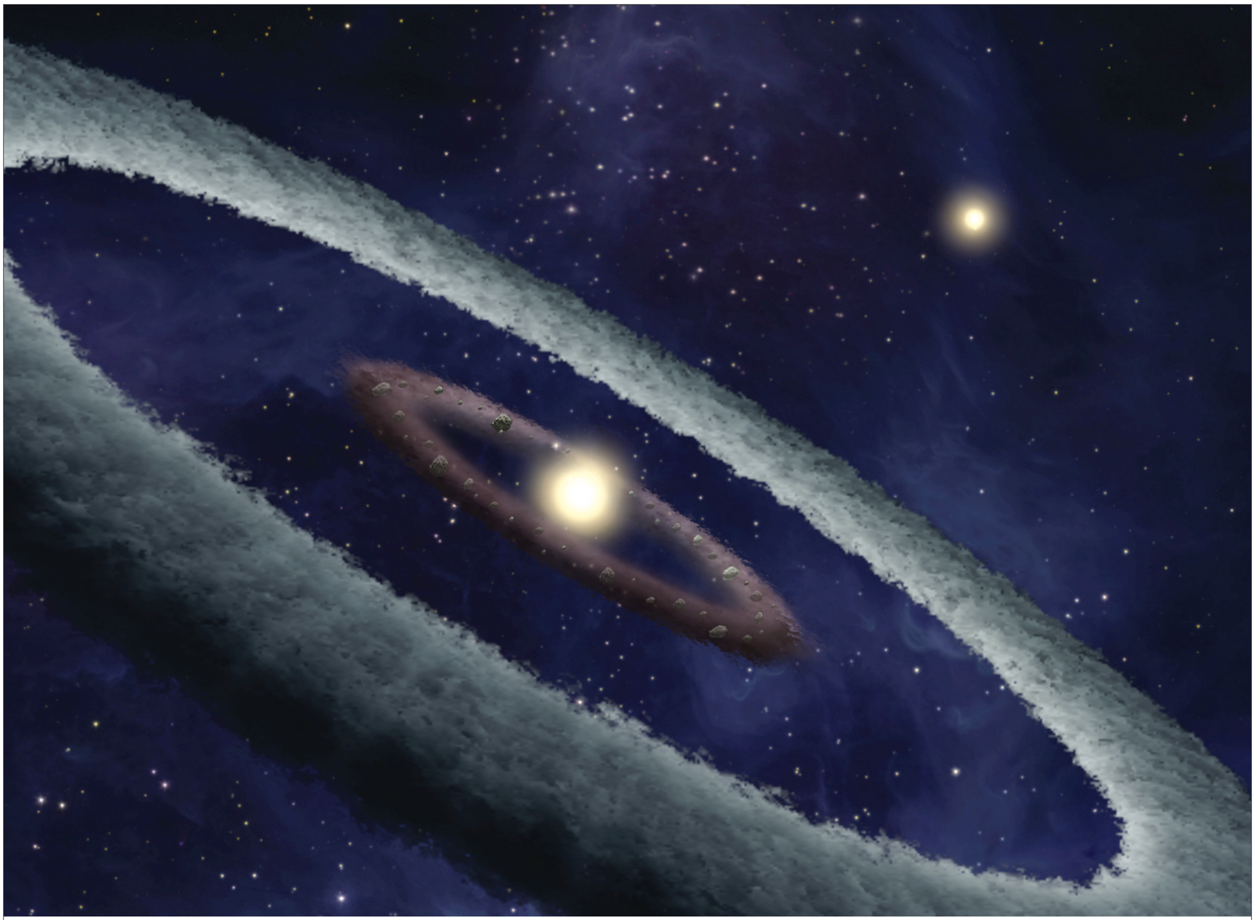

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New Evidence That Magnetism Is Driving Force Behind Superconductivity

European and U.S. physicists this week are offering up the strongest evidence yet that magnetism is the driving force behind unconventional superconductivity. The findings by researchers from Rice University, the Max Planck Institute for Chemical Physics of Solids (MPI-CPfS) in Dresden, Germany, and other institutions were published online December 13 in Nature Physics.

The findings follow more than three decades of research by the team that discovered unconventional superconductivity in 1979. That breakthrough, which was led by MPI-CPfS Director Frank Steglich, preceded by seven years the more widely publicized discovery of unconventional superconductivity at high temperatures. In the latest study, the team revisited the same heavy-fermion material -- a mix of cerium, copper and silicon -- that was used in 1979, applying new experimental techniques and theoretical knowledge unavailable 30 years ago.

"In 1979, there was not much understanding of quantum criticality or of the collective way that electrons behave at the border of magnetism," said Rice physicist Qimiao Si, the lead theorist and co-author of the new paper. "Today, we know a great deal about such collective behavior in the regime where materials transition to a superconducting state. The question we examined in this study is, How does all of that new knowledge translate into an understanding of the superconducting state itself?"

Magnetism -- the phenomenon that drives compass needles and keeps notes stuck to refrigerators the world over -- arises when the electrons in a material are oriented in a particular way. Every electron is imbued with a property called spin, and electron spins are oriented either up or down. In most materials, the arrangement of electron spins is haphazard, but in everyday refrigerator magnets -- which scientists call ferromagnets -- electron spins are oriented collectively, in the same direction.

Classical superconductors, which were discovered almost a century ago, were the first materials known to conduct electrons without losing energy due to resistance. Electrons typically bump and ricochet from atom to atom as they travel down a wire, and this jostling leads to a loss of energy in the form of electrical resistance. Resistance costs the energy industry billions of dollars per year in lost power, so scientists have been keen to put superconducting wires to widespread use, but it hasn't been easy.

It took physicists almost 50 years to explain classical superconductivity: At extremely low temperatures, electrons pair up and move in unison, thus avoiding the jostling they experience by themselves. These electron twosomes are called Cooper pairs, and physicists began trying to explain how they form in unconventional superconductors as soon as Steglich's findings were published in 1979. Si said theorists studying the question have increasingly been drawn to the collective behavior of electrons, particularly at the border of magnetism -- the critical point where a material changes from one magnetic state to another.

In the new experiments, Steglich, the lead experimentalist co-author, and his group collaborated with physicists at the Jülich Centre for Neutron Science at the Institut Laue-Langevin in Grenoble, France, to bombard heavy fermion samples with neutrons. Because neutrons also have spin, those experiments allowed the team to probe the spin states of the electrons in the heavy fermions.

"Our neutron-scattering data provide convincing evidence that the cerium-based heavy fermion compound is located near a quantum critical point," said Oliver Stockert, a study co-author and a neutron-scattering specialist from MPI-CPfS. "Moreover, the data revealed how the magnetic spectrum changes as the material turns into a superconductor."

From the data, Si and co-author Stefan Kirchner, a theorist from the Max Planck Institute for the Physics of Complex Systems and a former postdoctoral fellow at Rice, determined the amount of magnetic energy that was saved when the system entered the superconducting state.

"We have calculated that the saved magnetic energy is more than 10 times what is needed for the formation of the Cooper pairs," Kirchner said.

"Why the magnetic exchange in the superconductor yields such a large energy saving is a new and intriguing question," said Si, Rice's Harry C. and Olga K. Wiess Professor of Physics and Astronomy. He said one possible origin is the electronic phenomenon known as the "Kondo effect," which is involved in a class of unconventional quantum critical points advanced by Si and colleagues in a theoretical paper published in Nature in 2001. Regardless of the final answer, Si said the present study already constitutes a definitive proof that "collective fluctuations of the electrons at the border of magnetism are capable of driving superconductivity."

Si and Steglich found it remarkable that the notion of quantum criticality is providing fresh insights into the workings of the very first unconventional superconductor ever discovered. At the same time, both said more studies are needed to determine the precise way that quantum-critical fluctuations give rise to heavy-fermion superconductivity. And thanks to key differences between the heavy-fermion materials and high-temperature superconductors, additional work must be done to determine whether the same findings apply to both.

"We are certain that we are on the right track with our investigations, however," Steglich said.

The research was facilitated by the International Collaborative Center on Quantum Matter, a collaborative entity formed by Rice, MPI-CPfS, China's Zhejiang University and the London Centre for Nanotechnology. Research support was provided by the German Research Foundation, the National Science Foundation and the Welch Foundation.

Journal Reference: 1. O. Stockert, J. Arndt, E. Faulhaber, C. Geibel, H. S. Jeevan, S. Kirchner, M. Loewenhaupt, K. Schmalzl, W. Schmidt, Q. Si, F. Steglich. Magnetically driven superconductivity in $C_eCu_2Si_2$. Nature Physics, 2010; DOI: 10.1038/nphys1852