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Title: Solving quantum riddles with neutron scattering

Author(s): Fobes, David M.
Janoschek, Marc

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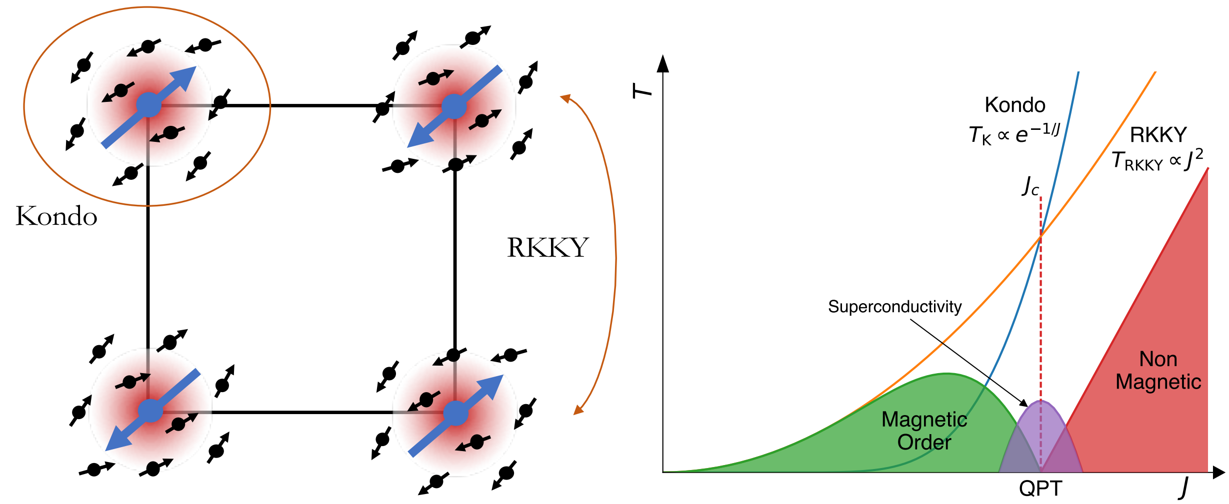
[headline] Solving quantum riddles with neutron scattering

[strap] Employing state-of-the-art neutron scattering techniques, we quantify the atomic-scale interactions responsible for the emergence of quantum matter.

[content]
Quantum materials exhibit a rich landscape of highly-degenerate quantum states that are widely regarded to hold vast potential for future applications, ranging from power management and transmission, to platforms for quantum computation, to novel versatile sensors and electronics. A key to realizing the promise of future applications is to identify the fundamental energy scales that control the emergence of such quantum states and their properties. An example of prototypical quantum matter that we study extensively in our group are heavy *f*-electron metals containing rare-earths or actinide ions. In these materials, the Coulomb interaction is large, localizing *f*-electrons into valence orbitals on rare-earth or actinide sites. These localized *f*-electrons form local magnetic moments, which interact with conduction electron spins in two ways (see figure): (i) conduction electrons mediate the coupling between neighboring *f*-electron moments, via the so-called Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction, resulting in long-range magnetic order; (ii) below a so-called Kondo temperature the conduction electrons typically screen *f*-electron moments by anti-aligning their moments. The Kondo interaction favors a non-magnetic state. As first pointed out by Doniach, the competition between these two interactions thus controls the emergence of quantum matter at temperatures near absolute zero; although the RKKY interaction results in magnetic order, external control parameters, such as pressure, can enhance the Kondo interaction by increasing the overlap of neighboring valence orbitals, and eventually lead to complete suppression of the magnetic order when the RKKY and Kondo interactions are equal. The strong quantum fluctuations that arise at this magnetic instability—a quantum phase transition (QPT)—are believed to result in the emergence of quantum matter states, like unconventional superconductivity, and alter material properties at much higher temperatures. This not only showcases the relevance of quantum matter for future applications but also explains why QPTs are one of the most important fundamental issues in solid-state physics. One of the major challenges in solving this quantum riddle, is that little quantitative information on the RKKY and Kondo interactions is available. Our group recently made meaningful progress by quantifying the RKKY interaction in a prototypical *f*-electron material, $CeRhIn_5$, which orders antiferromagnetically, and is thus RKKY dominated. Applying external pressure increases the Kondo interaction and accesses a QPT, around which unconventional superconductivity emerges. $CeRhIn_5$ is an ideal system to study this competition due to our ability to synthesize ultra-high-quality single crystals. In our latest study, we used neutron diffraction to precisely measure the size of the ordered magnetic moment, finding it to be suppressed by nearly half, suggesting that even in the magnetically ordered state, the strength of the Kondo interaction is a substantial fraction of the RKKY interaction. Because there are currently no theories to calculate the magnetic properties in the regime where Kondo and RKKY interaction are of similar size, our work highlights that new theoretical developments are desperately required to understand the emergence of quantum matter. These results have relevance beyond *f*-electron materials; although the interactions in other classes of quantum materials may differ, the theme of competition between localized and itinerant electronic degrees of freedom is universally thought to drive the emergence of quantum matter.



[bio(s)]

David M Fobes is a postdoctoral researcher working with staff scientist Marc Janoschek within the Condensed Matter and Magnet Science (MPA-CMMS) group at Los Alamos National Laboratory (LANL). David obtained his PhD in 2010 at Tulane University in New Orleans. His research is focused on exploring the emergent states of strongly correlated quantum matter using a combination of synthesis and state-of-the-art neutron scattering techniques. He also is the author of NeutronPy, a Python framework for neutron scattering data analysis (https://github.com/neutronpy).

Marc Janoschek is currently the capability leader for neutron scattering at MPA at LANL and a Hans Fischer fellow at the Institute for Advanced Study at Technische Universität München, where he leads the focus group "Quantum Matter". He received a PhD degree in physics from Technische Universität München in 2008. During this time, he also held joint appointments at three European neutron sources (ILL, PSI, MLZ), where he developed a neutron polarimeter ("MuPAD") for the unambiguous determination of complex magnetic structures. Before joining LANL in 2011 he was a Feodor Lynen fellow of the Alexander von Humboldt Foundation at the University of California, San Diego, where he acquired further expertise in the synthesis of high-quality single-crystals. Marc's research explores the emergent properties of quantum matter via x-ray and neutron scattering, with an emphasis on quantum criticality, unconventional superconductivity and novel types of magnetism such as skyrmions. For his pioneering research on helical magnets and plutonium metal, he has been awarded the Wolfgang Prandl price (2014) and the LANL Fellows Prize for Research (2016), respectively.