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Editorial: New heavy fermion superconductors

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Editorial on the Research Topic
New heavy fermion superconductors

Heavy fermion compounds host a lattice of localized spins that interact with a band of conduction electrons, resulting in a strongly correlated ground state and large effective mass of the charge carriers. The resulting flat bands are unstable to multiple competing states which leads to a complex phase diagram. In heavy fermion metals the rich array of nearby states can be readily accessed and tuned by modest changes in various experimental parameters such as temperature, magnetic field, pressure or concentration. Behaviors such as quantum criticality, strange metal conductivity, and unconventional superconductivity then readily emerge. Heavy fermion superconductors in particular—the subject of this Research Topic—provide an ideal platform for realizing unconventional superconductivity, and thus have been the focus of tremendous activity to understand their fundamental properties. Many open questions remain such as the origin of pairing, the symmetry of the superconducting order parameter, the nature of the spin correlations and how they may be related to pairing, and whether there are multiple superconducting regimes and/or superconducting order parameters. Interestingly, some heavy fermion superconductors are thought to be topologically non-trivial, and there are reports of possible Weyl topological superconductivity where the superconducting phase breaks time-reversal symmetry. A critical question here is whether Majorana fermions materialize. In addition to answering these fundamental questions, these materials hold the tantalizing prospect of being employed in applications in areas such as spintronics and quantum computation. The goal of this Focus Topic is to showcase recent exotic experimental and theoretical advances in heavy fermion superconductors.

The strongly correlated electron superconductor URu_2Si_2 exhibits a mysterious *Hidden Order* from which superconductivity emerges. Changing the crystal and electronic structure by chemical substitution elucidates how various phases evolve with doping. Pouse et al. show that the isoelectronic replacement of Ru with Fe transforms the hidden order phase into a large moment antiferromagnetic. The two phases can then be tuned by the application of a magnetic field to elucidate how they may be related, and these results show that the two phases in the T–H phase diagram only depend on the component of the magnetic field applied along the c-axis, H// c, and not on the in-plane components. Chappell et al. investigate the non-isoelectronic substitution of the Ru by Pt, which quickly extinguishes both the Hidden Order and the superconductivity, allowing the emergence of complex magnetism at larger Pt concentrations. The overall behavior is quite similar to that observed for other non-isoelectronic substitutions such as with Ir or Rh.

$CeRh_2As_2$ is a newly discovered Ce-based heavy fermion metal where unconventional superconductivity develops below 0.26 K. This compound may locate near a quantum critical point where superconductivity competes or coexists with antiferromagnetic order or quadrupolar order. Adding to this complexity is the appearance of a second type of superconducting phase with the application of a magnetic field, with the two phases presumably characterized by even-parity and odd-parity superconducting order parameters, as investigated by Onishi et al. $CeRh_2As_2$ thus provides a rare example in which the parity of the superconducting order parameters can be changed by an external magnetic field. Onishi et al. observed non-Fermi liquid behavior of $CeRh_2As_2$ at very low temperatures, but the Wiedemann-Franz law holds. Having multiple superconductors phases is then put into more general theoretical context by Nica et al. with comparisons of $CeRh_2As_2$ to $CeCu_2Si_2$ and UTe_2. The role of orbital selective (matrix) pairing is checked among these heavy fermion superconductors where intra- and inter-band pairing could manipulate the superconducting phase transitions in one compound. Nica et al. also discuss the role of quantum criticality and the associated strange metal behavior while pointing out that there is a much larger diversity of unconventional superconductors with novel pairing states.

One of the best examples of strange-metal behavior, where the resistivity is linear in temperature, is provided by $YbRh_2Si_2$. This behavior is realized over three orders-of-magnitude in T from just above T_C. Analyzing the resistivity behavior to achieve a quantitative understanding turns out to be problematic, and Li, et al. offer a different approach, analyzing the optical conductivity instead. In particular, the question is whether Energy/kT scaling seen in inelastic neutron scattering and the associated quantum criticality (Planckian behavior) is the origin of the strange metal behavior. They find that their Drude model-based analysis works for simple metals, but not for strange heavy fermion metals. On the other hand, the superconductivity in $YbRh_2Si_2$ only emerges at ultra-low temperatures, below Tc ≈ 2 mK (Schuberth et al.). This superconducting phase develops well below the temperature where long range antiferromagnetic order of the 4f moments develops at 70 mK. The interesting aspect is that emergence of superconductivity is proposed to be associated with the development of ordering of the nuclear spins, which apparently competes with the 4f-electronic order, resulting in a unique superconducting phase.

It is well known that uranium based heavy fermion superconductors could possess unconventional superconductivity, including topological superconductivity. The vortex lattice phase diagram of the potential topological superconductor UPt_3 is elucidated by Avers et al. The symmetry of the lattice is triangular throughout the regime, but its orientation with respect to the crystal as a function of temperature and magnetic field is complex and non-monotonic. This complexity originates from competition between the symmetry breaking field, the superconducting order parameter, and Fermi surface anisotropy.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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