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Parity games and mystery order in a heavy-fermion superconductor

1. **Pressure-tuned quantum criticality in the locally non-centrosymmetric superconductor $\mathbf{CeRh_2As_2}$**
   Authors: Meike Pfeiffer, Konstantin Semeniuk, Javier F. Landaeta, Robert Borth, Christoph Geibel, Michael Nicklas, Manuel Brando, Seunghyun Khim, and Elena Hassinger
   arXiv:2312.09728
2. **Exposing the odd-parity superconductivity in $\mathbf{CeRh_2As_2}$ with hydrostatic pressure**
   Authors: Konstantin Semeniuk, Meike Pfeiffer, Javier F. Landaeta, Michael Nicklas, Christoph Geibel, Manuel Brando, Seunghyun Khim, and Elena Hassinger
   arXiv:2312.09729

Recommended with a Commentary by Daniel F. Agterberg,
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Heavy fermion superconductors are a fascinating class of materials. These unconventional superconductors form from heavy quasiparticles that originate from localized f-electrons liberated into a Fermi sea. Recently two new members of this materials class, UTe_2 and $CeRh_2As_2$, have generated tremendous interest. UTe_2 was the emphasis of a commentary by Piers Coleman and Tamaghna Hazra [1]. The interest in $CeRh_2As_2$ stems from its superconducting temperature-magnetic field phase diagram when a magnetic field is applied along the c-axis in this tetragonal material (see Fig. 1) [2]. This phase diagram has two notable features. The first is a field induced first order transition between two superconducting phases (called SC1 and SC2). The second is a record high value of H_{c2}/T_c, where H_{c2} is the upper critical field and T_c is the superconducting transition temperature. This record value suggests a natural protection of superconductivity against a c-axis field.

The observed behavior has been attributed to the crystal structure. There are two inequivalent Ce atoms per unit cell and there is no inversion symmetry at either Ce atom. However, the two inequivalent Ce atoms are inversion symmetry partners of each other, so there is a global inversion symmetry. The inequivalent Ce atoms each form a square lattice. The interpretation of the superconducting phase diagram is that in each Ce square lattice layer, there are local interactions that give rise to a spin-singlet superconducting state (for example *s*-wave or *d*-wave) [2, 3]. As shown in Fig. 2, the inversion center between the two Ce layers naturally allows for two superconducting states: an even parity state where the

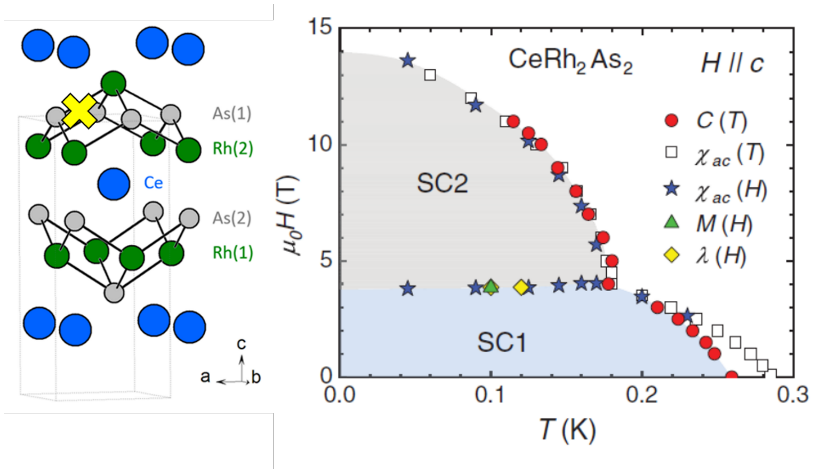

Figure 1: Structure and phase diagram of $CeRh_2As_2$ for a field along the c-axis [2]. The left panel shows the structure with the yellow cross denoting a center of inversion symmetry. The right panel shows the experimentally observed temperature (T)- magnetic-field (H) phase diagram revealing two superconducting states named SC1 and SC2 (from Ref. [2]).

two layers have the same order parameter and an odd-parity state, where the two layers have an order parameter with opposite signs. The observed field-induced transition is then from an even-parity to an odd-parity state. The even parity state is the ground state in zero-field but is suppressed by the application of field. The odd-parity superconductor is robust against a magnetic field. Such an experimental realization of an odd-parity state is important since such superconductors are rare and often topological. Furthermore, this odd-parity superconducting state differs from more usual odd-parity states in that it has its origin in spin-singlet interactions within a layer. The observation of such a state in $CeRh_2As_2$ points towards a new route towards stabilizing odd-parity superconductors.

While a field-induced odd-parity state provides an exciting explanation of the experimental results, the initial experimental report revealed an observation that caused doubt: at a temperature T_0 slightly above T_c (see Fig. 3) there is an additional weak anomaly seen in specific heat, pointing to a second order parameter of unknown origin [2]. Furthermore, under a c-axis field, this parameter order evolves in such a way that it may intersect the superconducting state at the same field as the observed SC1 to SC2 transition, pointing to a very different explanation for this phase transition. Initial experiments suggested this was not the case [2]. However, more recent experiments on samples that show sharper specific anoma-

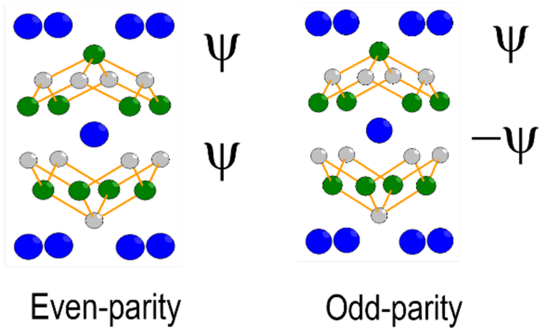

Figure 2: The global even-parity and odd-parity states formed by different phasing of spin-singlet order within the two inequivalent Ce square lattices layers.

lies have reopened the discussion of this possibility [4].

Confounding the phase diagram further is a nuclear quadrupole resonance observation of a magnetic order that onsets below T_c (this order has not been observed through thermodynamic probes) [5]. This magnetic order is itself unusual. It preserves the translation symmetry of the normal state but has opposite moments on the two inequivalent Ce atoms in the unit cell. Since these two Ce atoms are related by inversion symmetry, this is an odd-parity magnetic state. The possible coexistence of superconducting, unknown order, and odd-parity magnetic order provides a confusing wealth of orders in this material.

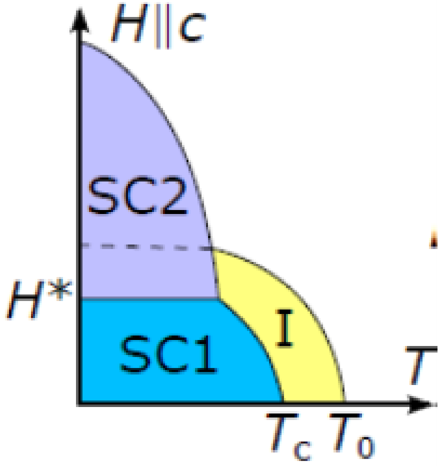

Figure 3: *T*-*H* phase diagram of $CeRh_2As_2$ including the unknown order that onsets at T_0 (from Ref. [6])

The experiments in Refs. [6, 7] provide clarity on the interplay of these different orders. Specifically, the evolution of the unknown T_0 under pressure was measured. This evolution leads to three key results. The first is that above a critical pressure of approximately 0.5 GPA, the unknown T_0 order disappears. Moreover, even though the unknown T_0 order has vanished, the field-induced transition between the two superconducting states SC1 and SC2 still exists at larger pressures, revealing that the unknown T_0 order does not drive this transition. The second result is that at the pressure that the unknown T_0 order vanishes, resistivity measurements reveal quantum critical behavior together with an enhancement of the superconducting T_c. This suggests that the unknown T_0 order plays a key role in stabilizing the superconducting state and is not a distraction as earlier thought. Finally, the third key result is that with increasing pressure, the putative odd-parity superconducting state becomes increasingly more stable relative to the even parity state. Indeed, it appears that if higher pressures were experimentally available, then the putative odd-parity state would even become stable at zero-field.

The authors of Refs. [6, 7] have suggested three possible scenarios to tame the many observed order parameters in $CeRh_2As_2$. The simplest of these scenarios is that the odd-magnetic order is the origin of the unknown T_0 order, and its fluctuations are responsible for the superconducting state. The interplay of odd-parity magnetic quantum fluctuations and superconductivity is not a well-studied problem. Indeed, there are reasons to question if such fluctuations serve as an effective mediator for superconductivity: a recent study of fluctuating loop current (another odd-parity magnetic order) suggests that they suppress superconductivity [8]. However, this theory applies in the single band limit which may not be sufficient for $CeRh_2As_2$. While the pressure measurements of Refs. [6, 7] have gone a far way towards addressing the interplay of the different orders in $CeRh_2As_2$, it is clear there remains much to be understood.

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