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MATERIALS RESEARCH HIGHLIGHT

Probing hidden magnetism and quantum criticality in unconventional superconductors

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An exotic form of superconductivity appears in classes of complex materials, such as the high-T_c cuprates and heavy-fermion compounds based on cerium, uranium and plutonium. Unlike conventional superconductivity in which electrons form pairs by an attraction provided by lattice vibrations, unconventional superconductivity in these complex materials develops near some form of magnetic order. The proximity of magnetism and unconventional superconductivity has led to speculation that fluctuations associated with magnetism may provide the glue that binds electrons into superconducting pairs, and, moreover, if a magnetic transition could be tuned toward absolute zero temperature, fluctuations associated with this magnetic quantum-critical point could be particularly effective in creating superconductivity[1]*. Several examples show that a maximum superconducting transition temperature T_c occurs near a value of some tuning parameter, such as chemical composition or pressure, where a quantum-critical point would be expected, but invariably, unconventional superconductivity intervenes to hide magnetism and prevent proof that a quantum-critical point exists. Using high pressures and high magnetic fields, we explicitly identify a quantum-critical point in the heavy-fermion compound $CeRhIn_5$ (Figure 1). This discovery suggests a common relationship among hidden magnetism, quantum criticality, and unconventional superconductivity in classes of strongly correlated electron materials.*

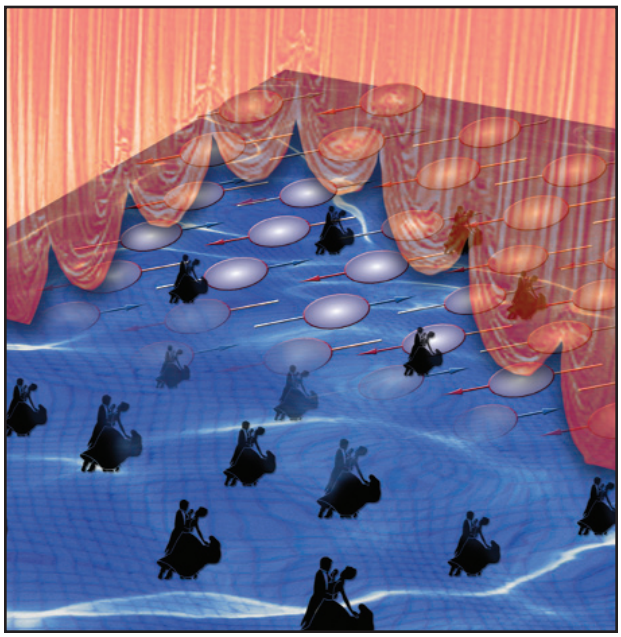

Figure 1. At absolute zero temperature, unconventional superconductivity, formed by electron pairs dancing at the surface of an electron sea, hides a background of antiferromagnetism. Opening the veil by applying a magnetic field reveals magnetism coexisting with superconducting electron partners. The boundary set by the curtain represents the quantum-phase transition.

The temperature-pressure (*T-P*) phase diagram of $CeRhIn_5$ is shown in Figure 2 (ref. 2) and is typical of other classes of unconventional superconductors: in high-T_c cuprates, the control parameter (*x*-axis) is chemical substitution. Above the superconducting dome, normal state properties are not at all typical of metals but are consistent with properties dominated by long-ranged, long-lived fluctuations that are expected if the magnetic phase boundary extended smoothly to absolute zero temperature, i.e., to a magnetic quantum critical point (P_2). Experimentally, however, magnetic order abruptly disappears at a finite temperature where the superconducting and magnetic phase boundaries meet. This first order or weakly first order boundary at P_1 provides no obvious connection between magnetism and the putative P_2. In such a case, it is difficult to reconcile the existence of an extended range of unconvention-

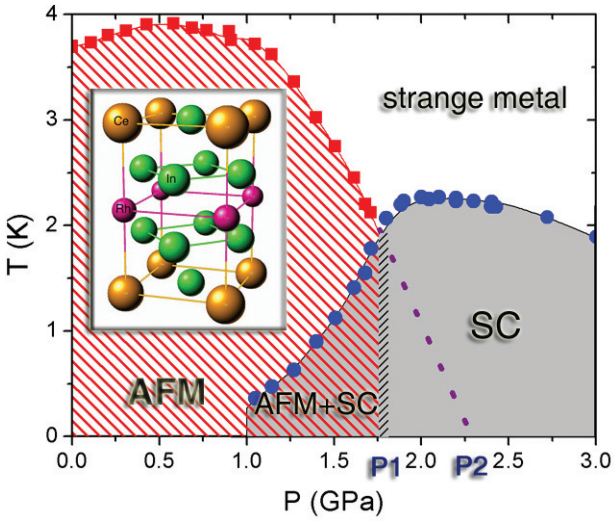

Figure 2. Temperature-pressure (*T-P*) phase diagram of $CeRhIn_5$. The tetragonal crystal structure of $CeRhIn_5$ is imbedded in the phase diagram. AFM and SC stand for antiferromagnetic and superconducting states, respectively.

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al superconductivity beyond P_1 and of an unusual normal state above T_C.

To resolve this dichotomy, we measured the specific heat and electrical resistivity of $CeRhIn_5$ as simultaneous functions of applied pressure and an additional control parameter, magnetic field. Figure 3a shows the specific heat divided by temperature as a function of temperature at 1.95 GPa ($P_{c1} < P < P_{c2}$) and at various applied fields. At magnetic fields to 22 kOe, there is only a pure unconventional superconducting state for temperatures below 2.15 K. At 33 kOe, a weak peak due to long-range magnetic order appears and grows in intensity with increasing magnetic field, which also induces units of quantized magnetic flux or vortices that penetrate into the superconductor. The anomaly in specific heat signifies a field-induced phase transition from a pure superconducting state to a phase of coexisting superconductivity and magnetism[3]. Subtracting a smoothly varying background makes the anomaly clearer, as plotted in Figure 3b. The temperature T_M , where the anomaly peaks, increases with increasing field and extrapolates to zero temperature at a non-zero magnetic field, indicating field-induced quantum-phase transition. The entropy involved in the transition is linearly proportional to magnetic field, a signature that the presence of vortices is crucial to the quantum effects. When superconducting (SC) and magnetic orders compete, magnetic order (MO) appears in the field-induced quantized vortices as their ground state and suppresses superconductivity around the vortices. Repulsive coupling between magnetic and SC orders can be tuned by chemical substitution, pressure, or magnetic field, which tips the balance between the two competing grounds states and leads to a quantum-phase transition among a pure MO phase, a MO+SC coexisting phase, and a pure SC phase[4]. The absence of magnetic order in zero field then may be explained by the presence of a superconducting gap that strongly inhibits a mechanism by which spins communicate, such as the Rudermann-Kittel-Kasuya-Yoshida (RRKY) interaction (Figure 1).

Similarities between the high-T_c cuprates[5] and $CeRhIn_5$ suggest that phenomena in them may be ubiquitous features among classes of unconventional superconductors. We note, however, that whereas magnetic order is due to localized 4f electrons and quantum criticality in the normal state is associated with a localized to delocalized transition in the 4f configuration of $CeRhIn_5$[6], this is not an appropriate description of cuprate physics nor possibly of all heavy-electron compounds. Exploiting both commonalities and differences will constrain refinement of theory and define additional experiments needed to fully understand relationships between unconventional superconductivity and magnetic quantum criticality.

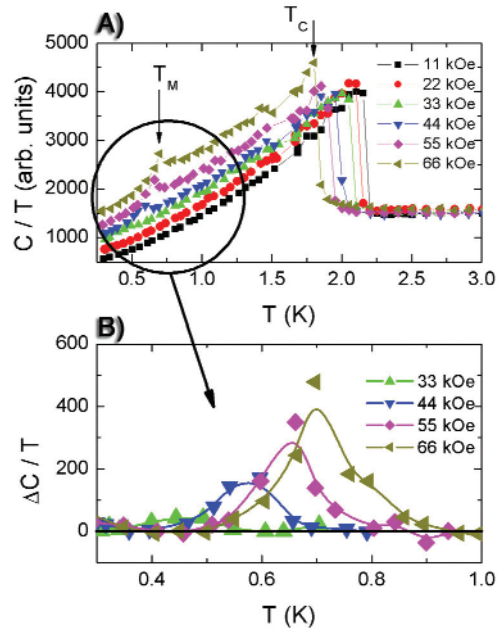

Figure 3a. Specific heat divided by temperature as a function of temperature. T_C and T_M represent superconducting and field (*H*)-induced phase transitions, respectively. Figure 3b. Evolution of the *H*-induced anomaly after subtracting a smoothly varying SC background. Solid lines are spline fits.

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