Quantum criticality, Antiferromagnetism and Superconductivity

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Usually small amounts of magnetic impurities lead to a suppression of the superconducting state in a conventional phonon-mediated superconductor. In contrast, in several heavy fermion superconductors it is found that superconductivity appears just at the border of a magnetically ordered state and that the attractive pairing interaction is due to critical magnetic fluctuations. For $CeRhIn_5$ we could show by performing specific heat, electrical transport, susceptibility, and neutron scattering experiments under high pressure and magnetic field that both states coexist close to the critical point where the antiferromagnetic order is suppressed.

The discovery of heavy fermion superconductivity in the Ce based heavy fermion family Ce*M*In_5 (M=Co, Ir, or Rh) opened a new route to investigate unconventional forms of superconductivity. While $CeCoIn_5$ and $CeIrIn_5$ are superconducting at ambient pressure,$CeRhIn_5$ is antiferromagnetically ordered below T_N = 3.8 K. Under application of pressure (see Fig. 1) T_N (p) reaches its maximum at 1 GPa and is monotonously suppressed for higher pressure. An extrapolation $T_N \rightarrow 0$ gives p_c = 2.5 GPa. However, $CeRhIn_5$ is also a superconductor in a wide pressure region from 1 to 5 GPa, and the superconducting transition temperature T_c is maximal at p_c. At the pressure p_c^* = 1.95 GPa the superconducting and magnetic transition temperatures fall together, $T_N = T_c$. Remarkably, no signature of a magnetic transition can be seen in the pressure window $p_c^*<p<p_c$. This indicates that the opening of a superconducting gap on large parts of the Fermi surface excludes the formation of a magnetic ordered state.

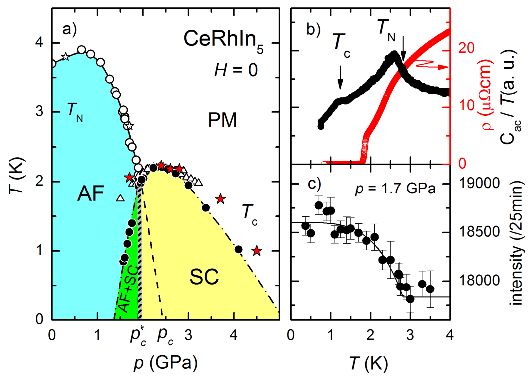

*Fig. 1: a) P-T phase diagram of $CeRhIn_5$ (H=0) from specific heat (circles), susceptibility (triangles) and resistivity measurements (stars). Above the pressure p_c^* the antiferromagnetic order is suppressed rapidly. The dashed line gives the extrapolation of T_N to zero at the critical pressure p_c. b) The specific heat and resistivity at p = 1.7 GPa where SC and AF coexist. c) Temperature variation of the peak intensity measured at the wave vector **Q** = (1/2, 1/2, 0.4) at 1.7 GPa on IN22 at ILL/CRG.*

Clear signatures of the quantum critical point p_c are the enhancement of the resistivity in the normal state and the strong enhancement of the inelastic scattering term in the resistivity, the maximum of the effective mass of the charge carriers derived from the slope of the upper critical field and also determined directly in dHvA experiments (performed at Osaka University). Furthermore, the electrical resistivity shows strong deviations from a T^2 temperature dependence due to critical quantum fluctuations in the spin and but also in the charge channel. The dHvA measurements show clearly that the Fermi surface changes abruptly under pressure at p_c from 4f localized to itinerant as function of pressures.

Spectacularly, the application of a magnetic field in the pressure window $p_c^*<p<p_c$ re-induces an antiferro-magnetic ordered state as can be seen in Fig. 2. This re-entrant phase does not exist only in the superconducting state, but persists deep inside the normal state. Detailed resistivity and specific heat experiments have shown that the re-entrant phase collapses for pressures above p_c when the Fermi surface has changed to 4f itinerant.

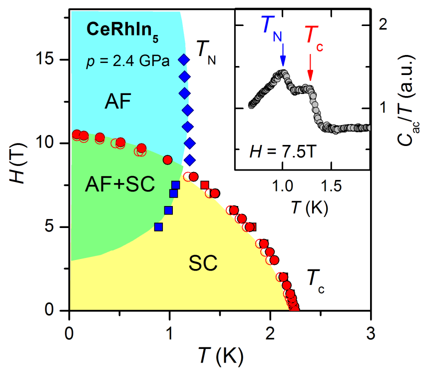

Fig. 2: H-T phase diagram of $CeRhIn_5$ at p = 2.4 GPa from specific heat (squares) and resisitivity (circles). The insert shows the specific heat measured at H = 7.5 T. Clearly a second anomaly appears inside the super-conducting state.

The microscopic nature of the AF+SC phases below p_c^* and the re-entrant AF+SC phase are not determined completely. Neutron scattering experiments under high pressure performed at the ILL/CRG spectrometers IN12 and IN22 have clearly shown the existence of magnetic order inside the AF+SC state at least up to 1.7 GPa (see Fig. 1c), however, the possibility of a spatial separation of AF and SC volumes can not be excluded by these experiments as well as a change in the magnetic structure from incommensurate to commensurate inside the AF+SC phase below T_c. These correlated phenomena may explain the non BCS like phase transition at T_c below p_c^* in contrast to the sharp anomaly of the specific heat above p_c^* as well as the double anomalies inside the reentrant AF+SC domain. To clarify the situation directly by neutron scattering is a future experimental challenge.

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