Co-existence of Antiferromagnetism and Superconductivity in a Heavy Fermion compound

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Recommended with a Commentary by Zachary Fisk, University of California, Davis

This paper presents a pressure/ac-specific heat study of the heavy Fermion superconductivity/antiferromagnetic phase boundary in $CeRhIn_5$, the ambient pressure antiferromagnet among the heavily studied 115 materials. These compounds are particularly useful for detailed measurements, given the ease of growth of high quality single crystals and relatively accessible phase transition temperatures.

The usual context for thinking about heavy Fermion superconductivity is within the picture of a competition between RKKY and Kondo scales. With Ce intermetallic antiferromagnets, increasing pressure eventually leads to reduction of the Neél temperature $T_N \rightarrow 0$, beyond which the Kondo lattice ground state emerges. A fairly extensive data set supports the idea that virtually all of the heavy Fermion superconductors are found near this magnetic quantum critical point (QCP). A fundamental issue is whether quantum criticality has in fact anything to do with heavy Fermion superconductivity or is the superconductivity more simply framed in classical terms.

The Ce-115 compounds can be pictured as sheets of CeIn3 interleaved with Co-, Rh- or Ir-In2 ones. The 10K antiferromagnet $CeIn_3$ was found by Mathur et al.[1] to become superconducting at pressures near 2.5 GPa below 200 mK, at which pressure $T_N \rightarrow 0$K. A subsequent study by Kawasaki et al.[2] found, however, that the phase diagram was considerably more complicated than that of a dome of superconductor spreading in a range of a few GPa below the $T_N \rightarrow 0$K phase transition line in the (T,P)-phase diagram. Rather, separate paramagnetic and antiferromagnetic phases coexist near T=5K, P=2.35K, extending to higher P and lower T; the dome of superconductivity involves a coexistence of superconducting and antiferromagnetic phases and a first order phase transition from this condition into a different superconducting phase with no coexisting antiferromagnetism.

The ac calorimetry in pressure clamps reported here for the 4K ambient pressure antiferromagnetic $CeRhIn_5$ finds a similarly rich phase diagram. Superconductivity emerges near $p_c^* = 1.8$GPa where $T_N = T_c = 2.0K$. At lower T and $p < p_c^*$, a narrow lens extends back to $1.5GPa, T = 0K$ within which superconductivity and antiferromagnetism coexist. Above p_c^* a pure superconducting phase exists which is separated from the lens of afm/sc by a first order line. The thermodynamic signatures for these conclusions give confidence that the phase diagram has the richness found although the details of the various phases need further investigation, particularly in view of recent results from Los Alamos[3].

Related to the occurrence of heavy Fermion superconductivity and more general issues connected with the QCP is the question of incorporation of 4f-electrons into the Fermi surface. In the case of CeRhIn5, dHvA experiments at high pressure[4] discovered that new frequencies appear quite abruptly near 2.5 GPa, and that above this pressure the Fermi surface resembles that of the ambient pressure heavy Fermion superconductor CeCoIn5. This is not where superconductivity first occurs with this compound but but rather this is the pressure one gets by extrapolation of dT_N/dP beyond p_c^* to T=0K.

However it seems important to consider that the dHvA experiments are performed in high magnetic fields, so we in fact do not know what that Fermi surface might be like at 1.8GPa and H=0. The 1st order phase line at p*c suggests the possibility that it corresponds to the new Fermi surface being established, and that this boundary has substantial field dependence. The richness of the phase diagram then might be thought of in terms of what is seen in many binary alloy systems. Think qualitatively of the effect of pressure as alloying non-magnetic $CeRhIn_5$ into $4f^1 - CeRhIn_5$. The 1st order phase boundary, adjacent to the two phase lens, then simply represents the insolubility of a solid solution of magnet/non-magnetic 115 in a purely non-magnetic 115. The superconductivity on the two sides of the 1st order boundary would in this view be of the same type, the lower pressure variant being adapted to a different boundary conditions coming from coexistence with an antiferromagnetic phase. But one sees the central issue as still that of understanding how and where in the experimental parameter space the new Fermi surface constructs itself.

1. N. D. Mathur et al., Nature 394 (1998) 39.
2. S. Kawasaki et al., J. Phys. Soc. Japan 73 (2004) 1647.
3. Joe D. Thompson, private communication (to appear in Nature).
4. H. Shishido et al., J. Phys. Soc. Japan 74 (2005) 1103.