High Magnetic Fields Reveal Evidence for a Quantum Critical Point in Iron Pnictides

"Transport near a Quantum Critical Point in $BaFe_2(As_{1-x}P_x)_2$", Nature Physics **10**, 194 (2014)
by James G. Analytis, H-H. Kuo, Ross D. McDonald, Mark Wartenbe, P.M.C. Rourke, N. E. Hussey, and I. R. Fisher

Recommended and a Commentary by Qimiao Si, Rice University

In the iron pnictides, superconductivity occurs at the border of an antiferromagnetic (AF) order. A natural question, then, is whether quantum criticality plays a role in the phase diagram. At the beginning stage of this six-year-old field, it was proposed that a quantum critical point (QCP) can be realized upon an isoelectronic P- for As substitution of the AF parent iron arsenides. This has turned out to be a fruitful direction, and the latest work of James Analytis and co-workers has provided the strongest evidence yet that a QCP does exist.

In ordinary metals, conventional (BCS) superconductivity arises out of a Fermi liquid normal state. The nature of the normal state was easy to establish. The degeneracy temperature for the electrons in such metals is very high, on the order of tens of thousands of Kelvin. At the same time, the superconducting transition temperature, T_c, is typically only a few degrees Kelvin. In other words, there is a large dynamical range in the normal state, from T_c to an upper cut-off temperature that is practically the crystal's melting temperature, over which one can show that physical properties display Fermi liquid characteristics. The latter include, for instance, linear temperature dependences in both the specific heat and NMR relaxation rate.

In high temperature superconductors, the upper cut-off temperature scale for universal normal-state behavior may be reduced by electron correlations. Combined with the much higher T_c, this implies a more limited dynamical range of temperatures over which the nature of the normal state can be probed. It is then desirable to enhance the temperature range by suppressing superconductivity, which can be achieved by applying a magnetic field larger than the upper critical field, H_{c2}. This type of efforts on transport and thermodynamic measurements at high magnetic fields were pioneered in the context of the high T_c cuprates [1, 2].

For the isoelectronically substituted iron pnictides, experimental indications for a QCP existed in both P-doped CeFeAsO [3] and P-doped $BaFe_2As_2$ [4]. However, there had been limitations to the efforts.

In $CeFeAs_{1-x}P_xO$, where the phase diagram was determined by neutron scattering studies, some of the 3d-electronic properties at low temperatures are masked by contributions from 4f electrons of the Ce-ions. In $BaFe_2(As_{1-x}P_x)_2$, the low-temperature normal-state properties are hidden by superconductivity, with a maximal T_c of over 30 K.

To make progress, Analytis *et al.* eliminated superconductivity by applying a high magnetic field, up to 45 T (static field) or 65 T (pulsed). At substitution levels above the optimal P-concentration, *i.e.* when the ground state is non-magnetic, they showed that the resistivity at low temperatures follows a Fermi liquid $\rho_0 + AT^2$ form. The temperature range of the Fermi liquid regime narrows as x decreases towards $x_c \approx 0.32$. Simultaneously, the A coefficient increases as x is decreased, by a respectable factor of about a decade. Extrapolating the x-dependence of the A coefficient towards x_c reveals a tendency of divergence.

A quadratic temperature dependence of the electrical resistivity is customarily associated with the scattering amplitudes between the Landau quasiparticles of a Fermi liquid. When this scattering amplitude has only a smooth dependence on momentum, the coefficient A is proportional to the square of the quasiparticle mass, m^*. Analytis *et al.* showed the validity of this Kadowaki-Woods law in the low-temperature Fermi liquid regime. Moreover, they found that the Kadowaki-Woods ratio, $A/(m^*)^2$, has a value similar to what has been observed in many other strongly correlated metals.

Divergences in the A coefficient and m^* are similar to what has been observed on the paramagnetic side of an AF QCP in other strongly correlated systems, such as heavy fermion metals. In this sense, the experiments add considerably to the evidence for a QCP in the isoelectronically substituted iron pnictides.

The work of Analytis *et al.* opens up a number of new questions:

- To fully establish the existence of a QCP, several issues need to be clarified. In particular, it will be important to study the evolution of the system as a function of x on the ordered side, $x < x_c$. The question there is whether the ordered moment and ordering temperature go to zero continuously as x approaches x_c. In addition, a tetragonal-to-orthorhombic structural transition is known to occur in the pure As limit ($x = 0$), and there is an on-going debate as to whether magnetic or orbital degrees of freedom underlie this effect. Regardless, it will be important to establish how this structural transition evolves as $x \to x_c$ from below in the normal ground state.

- The accumulated evidence for the QCP should encourage studies of dynamics in the likely quantum critical regime. Unlike classical criticality, scaling in the quantum critical regime is manifested not only in the spatial fluctuations but also in the temporal ones. Would inelastic neutron scattering measurements identify ω/T scaling in the dynamical spin susceptibility?

- The evidence from Analytis *et al.* for a QCP in the underlying normal state encourages the exploration of its counterpart in the cases of electron and hole dopings. At the present time, whether a QCP exists in the carried-doped iron pnictides is still open. Similar transport studies under a high magnetic field for the carried doped cases would surely be illuminating.

These issues notwithstanding, the work of Analytis et al. is already significant in several regards:

1) It adds to the evidence that quantum criticality is pertinent to the superconductivity of the iron pnictides. For the isoelectronically P-doped iron arsenides, it suggests that T_c of the superconducting state is indeed maximized near an underlying QCP. Even for the carrier-doped iron arsenides, the case for the relevance of quantum criticality is made stronger by the evidence of a QCP in the underlying normal state of the overall phase diagram.

2) It opens up a new setting to study non-Fermi liquid behavior near a QCP. Their data suggest a (nearly) T-linear electrical resistivity at the QCP. This is a canonical signature of the breakdown of the Fermi liquid. This type of non-Fermi liquid behavior is often seen in the vicinity of AF QCP of heavy-fermion metals. It also appears in the normal state of the optimally doped cuprates. (Although, for the cuprates, the magnetic-field-induced normal state at low temperatures may contain a range of hole-doping concentrations with a $\rho_0 + aT + bT^2$ resistivity [2].)

   The usual spin-density-wave (SDW) QCP in the Landau framework leads to the so-called "hot spots" and "cold regions" of the Fermi surface; these respectively correspond to the parts of the Fermi surfaces that are/are not connected by the AF wave vector [5]. The cold regions short-circuit the electrical conduction, and the electrical resistivity will tend to have a Fermi liquid form. For the iron pnictides, one could envision two ways out. It is possible that the small sizes of the Fermi pockets imply that essentially the entire Fermi surfaces are connected by the AF wave vectors. More radically, the entire Fermi surfaces are hot because the quantum criticality is beyond the conventional SDW type, as has been discussed in quantum critical heavy fermions. Further studies are surely needed to clarify the interplay between the electronic excitations and quantum criticality in the present context.

3) One central issue about the iron pnictides and chalcogenides is the degree to which electrons are correlated. The Kadowaki-Woods phenomenology observed here is typical of strongly correlated metals, and is very different from the behavior seen in weakly correlated SDW systems such as Cr (under pressure or with V-doping). This adds to the evidence that the iron pnictides are bad metals with strong electron correlations.

[1] G. S. Boebinger *et al.*, Phys. Rev. Lett. **77**, 5417 (1996).

[2] R. A. Cooper *et al.*, Science **323**, 603607 (2009).

[3] C. de la Cruz *et al.*, Phys. Rev. Lett. **104**, 017204 (2010).

[4] S. Kasahara *et al.*, Phys. Rev. B**81**, 184519 (2010).

[5] R. Hlubina and T. M. Rice, Phys. Rev. B **51**, 9253 (1995).