Beyond-Landau Quantum Critical Point in a Heavy-Fermion Ferromagnet

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Quantum critical points have been the subject of extensive studies in the recent past. In the vicinity of a quantum critical point, there is an enhanced entropy, which promotes the emergence of new states. Indeed, in metallic systems, quantum criticality is a viable mechanism for unconventional and even high temperature superconductivity, and provides an established route towards strange-metal, or non-Fermi liquid behavior. All these factors provide the motivation to study quantum criticality in a broad range of settings. In a recent work, Alexander Steppke and co-workers identified a new quantum critical point in a ferromagnetic heavy-fermion metal, $YbNi_4P_2$ under As doping. Their results came as a surprise, and call for new theoretical understandings.

To put the work in context, we recall some basics. Thermally driven critical points fall into universality classes, which rest upon the notion of symmetry breaking. According to Landau, an ordered state possesses a nonzero order parameter, a coarse-grained variable that characterizes the spontaneous breaking of a global symmetry. The critical point, where the order parameter is continuously suppressed, features collective excitations associated with the fluctuations of the order parameter. The critical component of the free energy is constructed from an effective theory of such order parameter fluctuations. It only depends on the internal symmetry of the order parameter and spatial dimensionality (d), thereby leading to university.

What happens at a quantum critical point? Within the Landau framework, the critical mode remains to be the order-parameter fluctuations, which however occur in both space and (imaginary) time. The effective theory has the same form as for the classical critical point, but the dimensionality of the fluctuations is enhanced to $d + z$, where z is the dynamic exponent.

Consider the case of a transition from a ferromagnetic metal to a paramagnetic metal. The ferromagnetic order breaks the global symmetry of spin rotations, and is characterized by a vector field $\vec{\phi}$, which physically corresponds to the magnetization. The Ginzburg-Landau theory for the thermally driven critical point is constructed in terms of the spatially fluctuating $\vec{\phi}$, written as a function of the wavevector $\mathbf{q}$. This is the $\vec{\phi}^4$ theory, containing invariants such as $\vec{\phi}^2$, $\vec{\phi}^4$, etc.. The theory contains various coupling constants, such as the spatial stiffness c in the quadratic term and nonlinear coupling u in the quartic term.

Generalizing to the quantum case, the theory contains the same invariants, but $\vec{\phi}$ is now a function of both $\mathbf{q}$ and the (Matsubara) frequency ω. Furthermore, taking the microscopic perspective that the order is Stoner magnetism of a band of itinerant electrons, the quadratic part also contains a Landau damping, which has the form $\gamma|\omega|/q$. Demanding that this new term has the same scaling dimension as the spatial stiffness term, cq^2, we end up with a dynamic exponent $z = 3$. The theory would then be in $d + 3$ dimensions. For $d \geq 2$, this is above the upper critical dimension so, according to Hertz [1], there is an itinerant quantum critical point described by a Gaussian fixed point.

There is however a catch. In deriving universality, it is standard to assume that the Ginzburg-Landau functional is analytic, and the parameters like c and u are just numbers. This assumption has been shown [2] to be invalid: because the gapless fermionic excitations are considered as non-critical variables and are integrated out in the process of constructing the critical theory, these parameters acquire non-analytic dependences on $\mathbf{q}$ and ω. From a theoretical perspective, the physical picture behind these non-analyticities is still somewhat opaque. For instance, it is not quite clear why the non-analyticities exist in generic cases but are absent in the purely Ising limit. Nonetheless, the practical consequence of the non-analyticities is to turn the zero-temperature transition first order. (Related mechanisms may lead to more than one first-order transitions [3].) This conclusion has been supported by experiments in weak ferromagnets, with a canonical example being the transition in $ZrZn_2$ induced by pressure [4].

The finding of Steppke *et al.* that the ferromagnetic $YbNi_4P_{2-x}As_x$ has a continuous quantum transition is, therefore, a surprise by itself. The conclusion is drawn not only by following the continuous thermal transition down to low temperatures, but also through the observation of a divergent Grüneisen ratio. The latter, corresponding to entropy accumulation, is an established means of identifying quantum criticality.

There is no indication that the system superconducts, but it does display very pronounced non-Fermi liquid behavior: the electrical resistivity shows a linear dependence on temperature (as opposed to the quadratic dependence in a Fermi liquid), and the specific heat coefficient diverges as temperature is lowered in a power-law fashion (as opposed to being a temperature-independent constant in a Fermi liquid).

One may suspect whether the order is actually antiferromagnetic, only with a very small ordering wavevector. To address such a concern, Steppke *et al.* carried out dissipative measurements, which establish magnetic hysteresis. There can hence be little doubt that the dominant order is ferromagnetic, although canting of the ordered moments is not ruled out.

It is also tempting to attribute the quantum transition's avoidance of the first-order fate to the effect of disorder, given that a small amount of As doping is used to reach the quantum critical point. However, already, in the stoichiometric material, the Curie temperature is 0.15 K, which is small not only in the absolute sense but also in comparison with the proper reference temperature scale (the bare Kondo temperature, about 8 K), and power-law behavior is observed for about a decade of temperature above the Curie temperature. The quantum critical behavior in the As-doped system appears to be the same as observed in the stoichiometric system, only extending to lower temperatures. It is therefore unlikely that disorder is playing a leading role for the quantum critical behavior.

With these considerations in mind, it is likely that the observation of Steppke *et al.* in $YbNi_4P_{2-x}As_x$ reflects a more dramatic form of beyond-Landau physics. The paramagnetic state here, unlike being featureless as assumed in the Landau framework, is a heavy-fermion metal, in which a thermodynamically finite number of local moments form a Kondo singlet with the spins of conduction electrons. While there is no broken symmetry, the Kondo singlet – a quantum-mechanically entangled state involving a macroscopic number of degrees of freedom – endows the paramagnetic ground state with the structure of a quantum order, and critically destroying the Kondo effect at the onset of magnetism would yield a new class of quantum transition. This type of physics has been extensively discussed in Kondo lattice models for antiferromagnetic heavy fermions. The ferromagnetic counterpart has so far been much less explored, but certainly ferromagnetism can also cause a Kondo destruction.

One may speculate that, because the fermions here are (via the Kondo effect) an active agent of the transition and are in particular not being integrated out, this type of ferromagnetic quantum transition can be continuous. Phenomenologically, the non-Fermi liquid behavior observed by Steppke *et al.* in the quantum critical regime has considerable similarities with those seen in the antiferromagnetic quantum critical heavy fermions. In particular, the amount of entropy in the quantum critical regime is a sizable fraction of $R\ln 2$, which implicates the involvement of Kondo physics in the quantum critical behavior. In any case, this work, together with several other recent experiments on ferromagnetic heavy fermion metals (*e.g.*, Refs. [5, 6]), provide new impetus for systematic studies of heavy-fermion quantum phases and their transitions in a ferromagnetic setting.

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