QUANTUM PHASE TRANSITIONS

Frustration can be critical

An unusual flavour of critical phenomena with a stable quantum critical phase of matter is observed in a strongly correlated material and linked to the underlying lattice structure.

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One common example of a phase transition in condensed-matter physics is a transition between a magnetically ordered phase characterized by a finite magnetization and a well-behaved metallic state with zero magnetization. As temperature increases, the magnetization can be continuously suppressed such that the system is taken through what is called a critical point. In the quantum realm, tuning a material with pressure or magnetic field at zero temperature can also take the system through a quantum critical point. In the standard theories, this is a single point in the phase diagram, and is associated with the presence of strong quantum fluctuations that can destabilize the conventional metallic state. Against this standard picture, quantum critical phases, with associated strange metallic behaviour, have been observed over extended regions of the phase diagrams of heavy-fermion materials (Fig. 1). Now, Hengcan Zhao and collaborators perform a comprehensive set of measurements on CePdAl, showing that this geometrically frustrated material hosts a stable critical phase[1]. This work poses an interesting question: what is the role of frustration in the stabilization of critical phases of matter?

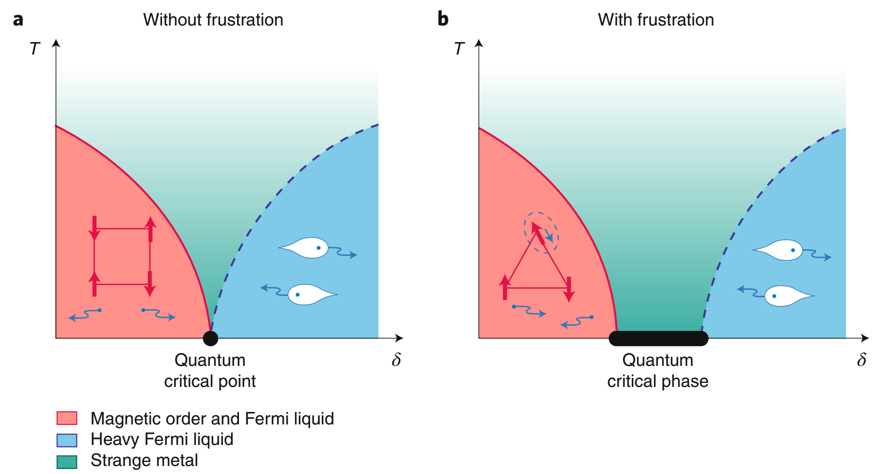

Fig. 1 | Quantum critical points and phases. a, Sketch of a phase diagram that contains a quantum critical point between an antiferromagnetic phase (red) and a heavy Fermi liquid (blue). The intervening regime shows strange metal behaviour (green) at finite temperatures. The solid red line indicates the second-order magnetic phase transition and the dashed blue line is the delocalization crossover of the *f* electrons. *T* is the temperature and *δ* is the external tuning parameter, which can represent pressure or magnetic field. The left inset depicts the antiferromagnetic arrangement of the localized spins (red) and the light delocalized electrons (blue). The right inset depicts the heavy electrons. **b**, When frustration is added, a quantum critical phase develops between the antiferromagnet and heavy Fermi liquid. The left inset shows how CePdAl releases its frustration and is able to order even in the presence of a frustrated lattice geometry by screening one of the spins in the triangular unit. As in **a**, the right inset depicts the heavy electrons.

Within strongly correlated materials, heavy-fermion systems are particularly attractive because of their high tunability by external magnetic fields or pressure. These systems are composed of two main ingredients: electrons that sit in *f* orbitals that usually give rise to local magnetic moments, and electrons from delocalized orbitals that form a conduction sea background. In this context, two types of interaction are relevant: the Kondo interaction between the spins of the local moments and the spins of the conduction electrons, and the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction, which is an effective spin–spin interaction between the local moments mediated by the conduction electrons. These two interactions compete with each other and favour very different ground states. The Kondo coupling tends to screen the local moments, which leads to the development of a heavy Fermi liquid, namely, a renormalized metallic state that incorporates the *f* electrons into the delocalized conduction sea. In contrast, the RKKY interaction tends to take the system towards a magnetically ordered state, but when the local moments are placed in a geometrically frustrated lattice, this tendency can be hindered.

CePdAl is a prototypical heavy-fermion system, with a phase diagram displaying both magnetic order and a heavy Fermi liquid state. One aspect that makes this material distinct from others in this family is the fact that the Ce atoms, the hosts of the local moments, are placed on a geometrically frustrated kagome lattice. The triangular motifs found in this lattice structure are the quintessential elements for the development of exotic states of matter such as spin liquids, in which the spins keep fluctuating down to the lowest temperatures due to quantum effects.

The quantum criticality in CePdAl has already been approached using an external magnetic field[2]. Now, Zhao and collaborators also explore the pressure axis so that they can cover a two-dimensional phase diagram at zero temperature in the search for critical points and exotic phases of matter. Pressure is known to increase the Kondo coupling in Ce-based compounds and this suppresses the magnetic order and drives the material in the direction of quantum criticality. The authors find that, at high pressures, a quantum critical phase with strange metallic behaviour is observed over an extended region of parameter space. This phase is contained within two important boundaries: the line marking the continuous transition between the magnetic and non-magnetic phases, and the localization–delocalization crossover line of the *f* electrons, which seems to coincide with the onset of short-range spin fluctuations. This finding suggests that the presence of the critical phase is directly related to geometric frustration.

It is important to emphasize that the suggestion that the critical phase comes purely from geometrical frustration in CePdAl might limit the broader picture in which this experiment is actually found. Other heavy-fermion materials — such as $YbRh_2Si_2$ (ref. [3]) and β-$YbAlB_4$ (ref. [4]) — are not geometrically frustrated but are also known to display similar quantum critical phases. If the mechanism for the stable critical behaviour in all these materials is the same, purely geometrical frustration might not be the key. Another interesting aspect observed in β-$YbAlB_4$ is the recovery of conventional metallic behaviour at very low temperatures[4]. In this context, measurements at even lower temperatures will be important to verify whether the strange metallic behaviour in CePdAl should be given the status of a new phase of matter.

Nevertheless, frustration does not have to originate from the lattice geometry, but can also stem from interactions in non-frustrated lattices. Another source of frustration concerns the nature of the *f* electrons, which can change from localized to delocalized, or when they are found in a mixed-valent state. A more general concept of frustration might reveal the solution to the conundrum of universal critical phenomena in strongly correlated systems, including not only $YbRh_2Si_2$ and β-$YbAlB_4$, but also potentially organic compounds[5] and spin liquids[6]. Theoretical descriptions based on fractionalization[7], local criticality[8] and supersymmetry[9] give us good hints, but a complete account of these phenomena is still lacking.

Quantum critical points in strongly correlated systems, and the associated strange metallic behaviour, have been a long-standing puzzle in condensed-matter physics. Now we find an even greater challenge in front of us, which is to describe not only critical points, but stable critical phases of matter. In this context, the results of Zhao and collaborators are of great importance to uncover the key ingredients necessary to sustain new flavours of critical phenomena. ❐

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