Quantum Criticality in a Clean Metal

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0.4

M (Jug/Ru)

2.8 K

20 K

n ordinary phase transitions, raising the temperature induces a transformation between ordered and disordered states. Examples are the freezing point of water, where the crystalline solid transforms into a liquid, and the Curie point of iron, where

the metal loses its spontaneous magnetization. Such transitions are driven by increasing thermal fluctuations that destabilize the low-temperature, ordered state.

Classical phase transitions in clean, defect-free materials are now well understood. Experiment and theory have converged on the concept of "universali-

ty": No matter how complex the system, its behavior near the phase transition should be largely [but not exclusively (1)] governed by its spatial dimensionality. Fluids confined to surfaces should thus have more in common with the magnetic layers in some transition metal salts than with ordinary three-dimensional fluids.

Does universality also exist for quantum phase transitions (2), where quantum rather than thermal fluctuations are responsible for a change of state? Because the probabilities of quantum fluctuations depend on their profiles as a function of both time and space, quantum transitions should be analogous to classical transitions in a system of higher dimensionality given by the sum of space and time dimensionalities (3). Thus, 25 years ago, the problem of quantum transitions in clean materials was reduced to the study of classical phase transitions in higher dimensional systems and regarded as essentially solved.

Because the underlying arguments seemed so solid and it is experimentally much more difficult to vary quantum fluctuations than to vary temperature, few quantum phase transitions have been examined with the same level of precision as classical transitions. Most quantum critical points accessed to date occur in systems in which static disorder plays a crucial role (4). One study (5) did examine a quantum phase transition in a clean material with the precision customary for classical transitions. The material, the insulating ferromagnet LiHoF₄, has a spontaneous magnetic moment along one crystal axis. A magnetic field applied perpendicular to this axis induces quantum fluctuations,

> which eventually destabilize the ferromagnetic order, in excellent agreement with theory.

The LiHoF₄ experiment is satisfying but does not resolve what happens in clean metals



Metamagnetic quantum transition. (Top) Magnetization of Sr₃Ru₂O₇ (*8*) as a function of applied magnetic field. As the temperature is lowered, a steplike feature appears at a critical field (B_c) of ~7.8 T. (**Bottom**) A simple origin for a metamagnetic transition. An ion with zero net magnetic moment (J = 0) in the ground state (such as free Ru⁴⁺) but with a J = 1 first excited state would switch between its zero-magnetization ground state and its fully magnetized excited state at a critical field B_c , where the Zeeman energy lowers the J = 1 state below the J = 0 state. The resulting magnetization step occurs at a critical field proportional to the zero-field level splitting Δ . On warming, the step is smoothed out by thermal fluctuations.

near magnetic quantum phase transitions. The latter are found in the vicinity of almost every interesting phenomenon such as high-temperature superconductivity—in metals.

Experiments on disordered alloys have yielded intriguing results, most notably electrical resistances that vanish linearly rather than quadratically with temperature, as expected for two- and three-dimensional metallic magnets at quantum criticality. Some researchers have asserted that disorder may be responsible for the deviations and that for truly clean materials, the data would agree with the conventional theory. Several recent papers (6-8), including one in this issue by Grigera on page 329 (9), clearly lay this controversy to rest.

The papers describe experiments that probe quantum phase transitions in clean metals, namely the intermetallic compounds CeRu₂Si₂ and UPt₃ and the oxide $Sr_3Ru_2O_7$ (10, 11). As in the case of Li-HoF₄, the control parameter is the external magnetic field. But unlike LiHoF₄, the transitions are not ordinary magnetic transitions where a spontaneous magnetic moment disappears. Rather, the materials are "metamagnetic"; that is, a sharp rise in magnetization occurs near a nonzero critical field. This rise becomes increasingly steplike for lower temperatures (see the top panel in the figure) and is superposed on the usual metallic magnetization. which varies linearly with field.

Magnetization steps at specific fields are expected for isolated ions in insulators

when the Zeeman energy associated with the external field matches a quantum mechanical level splitting (see the bottom panel of the figure). As the temperature is raised, they broaden and ultimately disappear. For example, ruthenium ions have partially filled d shells and might show such behavior in an insulator. High-temperature magnetometry (10, 11) indicates that a similar description may be a suitable starting point even for metallic Sr₃Ru₂O₇.

This simple rationalization can account for the presence of the metamagnetic step but explains neither its magnitude nor the electrical properties in its vicinity. Papers on both UPt₃ and $Sr_3Ru_2O_7$ show that near the step, the resistance behavior is unconventional, becoming large in the zero-temperature limit and displaying a temperature (*T*) dependence different from the conventional T^2 law.

Perry *et al.* (8) present a very simple picture [similar to fig. 1 in (9)] for the unconventional behavior. When the logarithmic derivative α of the resistance with respect to *T* is plotted versus temperature and field, α tends toward 1 (rather than the generic 2) in a funnel extending toward the T = 0 metamagnetic transition. This result is gratifying because it resembles what is found for very different materials also displaying quantum criticality, such as the layered copper oxides (12, 13) famous for high-temperature superconductivity and nearly antiferromagnetic Ce(Cu,Au)₆(14, 15).

The experiments on UPt_3 and $Sr_3Ru_2O_7$, together with those on other, more disor-

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dered materials, indicate that the universality associated with thermal phase transitions also emerges for quantum phase transitions in metals. To test this universality with greater rigor, Grigera et al. (9) have now measured the resistance at the bottom of the funnel, at temperatures an order of magnitude lower than were used before. They find that the metamagnetic transition appears to be split into two transitions, with α rising to an anomalous value of 3 between the two.

At first sight, those seeking simplicity in complex situations will be disappointed. However, classical first-order transitions, characterized by magnetization jumps, often appear split because of coexistence regimes intervening between high and low magnetization states. Metamagnetic transitions, when interpreted as the outcome of a quantum mechanical level crossing (see the bottom panel of the figure), are

quintessential first-order transitions. Grigera et al.'s experiment verifies another analogy between classical and quantum phase transitions: Coexistence regimes are possible in both cases.

The importance of such coexistence near many quantum critical points in solids is increasingly recognized (16). The highly quantum mechanical helium liquids and solids have long been known to coexist in certain pressure ranges near 0 kelvin (17). What is new and will require explanation is why the electrical resistance in the two-phase regime for metamagnetic $Sr_3Ru_2O_7$ varies as T^3 .

Researchers studying quantum phase transitions now face the same situation as for thermally driven phase transitions 35 years ago: Experiments on ever cleaner materials are revealing increasingly universal behavior independent of the materi-

PERSPECTIVES: STRUCTURE

An Anthropomorphic Integrin

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n multicellular organisms, adhesion receptors organize the molecular complexes that flank the plasma membrane. The extracellular face of the cell apposes extracellular matrix fibrils that are decorated with growth factors, whereas its cytoplasmic face teems with signaling complexes, compartmentalized by cytoskeletal polymers and lipid microdomains. It is the job of specialized plasma membrane adhesion receptors called integrins to bridge and conflate these two dynamic systems, a task that demands a structurally versatile molecule. Despite extensive investigation. it has not been clear exactly how integrins interact with their ligands, how ligand occupancy affects integrin conformation, and how receptor activation is coupled to bidirectional signal propagation. On page 339 of this issue, Xiong et al. (1) report the first crystal structure of the extracellular portion of an integrin and concomitantly advance the field one enormous stride toward achieving these goals.

The integrin selected by Xiong et al. is $\alpha V\beta 3$, a receptor expressed by many cells that recognizes a series of glycoprotein ligands, including vitronectin and fibronectin. This integrin appears to be important for the integrity and function of cardiovascular and bone tissues. The in-

vestigators expressed both subunits of the integrin heterodimer as full-length soluble constructs in insect cells, and crystallized this complex in the presence of calcium ions (Ca^{2+}). The overall shape of the crystallized conformer (resolved to 3.1 Å) is that of a large "head" on two "legs" (see the figure), similar to the images seen using electron microscopy (2, 3). The head contains a seven-bladed β -propeller structure contributed by the α subunit (corresponding to its seven amino-terminal repeats) and a von Willebrand factor A domain contributed by the β subunit (termed the βA domain). The β propeller (a toroidal arrangement of seven β sheets) is found in many other proteins, including the β subunit of heterotrimeric GTP-binding proteins (G proteins). The A domain (a central β sheet sandwiched by two sets of α helices) is also a common fold found, for example, in the α subunit of G proteins. In the integrin, the βA domain is positioned cheek-by-jowl with the upper face of the β propeller, with a helical region on top of the βA domain articulated to the β propeller's central shaft. The remainder of the head is a unique hybrid immunoglobulin fold, its two β sheets contributed by the polypeptide regions that flank the amino and carboxyl termini of the βA domain.

The α -subunit leg of the integrin contains three large β -sandwich domains. Between the "thigh" domain and the first of two "calf" domains is a highly flexible "knee" (or "genu"), which exhibits a al, even while no quantitative theory can explain the results.

References and Notes

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- C. M. Varma, and P. Coleman for helpful discussions.

cramping bend in the crystal structure. The β -subunit leg contains a PSI (plexins, semaphorins, and integrins) domain, four epidermal growth factor (EGF)-like repeats, and a cystatin-like fold. The B-subunit knee region, formed from the conjunction of the hybrid domain, two EGF repeats, and the PSI domain, in agreement with previous biochemical data (4), is also capable of extreme flexibility, suggesting that the integrin may pivot at this point.

The binding of an integrin to its ligand is known to be dependent on divalent cations, and six Ca²⁺-binding sites are seen in the structure. Four of these lie as previously predicted in β -loop- β structures (5) on the lower face of the β propeller, and another site is in the knee region of the α subunit. The top face of the βA domain contains a potential cation-binding site, known as the metal ion-dependent adhesion site, or MIDAS (6), although this is unoccupied in the crystal structure. However, a new site is seen adjacent to the MIDAS, to which the authors give the name ADMIDAS.

Some features of the integrin structure were widely anticipated from predictive studies [for example, the βA domain and propeller predictions of Tuckwell (7) and Springer (8)] and from the intense biochemical dissections of the past decade (9). Other features, however, were totally unexpected. The Xiong et al. structure advances our understanding of how integrins work in at least three ways. First, the means of intersubunit association was previously unknown. Now it can be seen at a glance how the two partners unite, together with the likely mechanism for selecting the α/β pairing. Second, the position of the ligand-binding pocket has been clarified

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