PHYSICS

A Quantum Critical Route to Field-Induced Superconductivity

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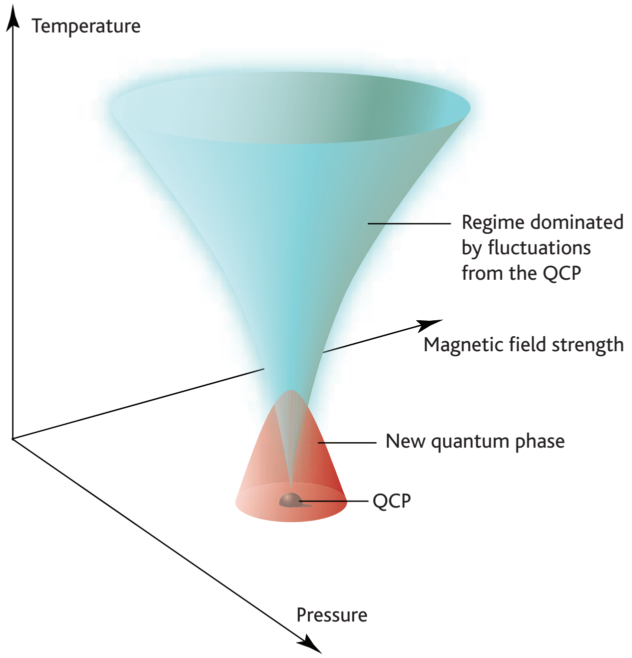
These are exciting times for superconductivity research and for studying the physics of materials with strongly interacting electrons. We are witnessing a revolution in our understanding of new and exotic forms of superconductivity, and novel behavior is being discovered every few months. The report by Lévy *et al.* on page 1343 of this issue (*1*) describes a particularly important development in a line of investigation focused on the concept of quantum criticality. At a typical thermal phase transition, such as the ferromagnetic transition of iron, thermal energy produces strong fluctuations that drive the phase change from ferromagnetism (when the material is spontaneously magnetized) to paramagnetism (when the individual magnetic dipoles only align in response to an external field). Over the past decade, we have realized that it is possible to use some external parameter such as high pressure to tune the critical temperature of a phase transition toward absolute zero, producing a quantum critical point (QCP). The idea of a fluctuation-driven transition remains, but the fluctuations become dominantly quantum mechanical rather than thermal. This has profound consequences for our theoretical understanding and has generated a mini-industry within the physics community (*2*).

The existence of a QCP also has striking effects on the observable physical properties of the system. It gives rise to previously unexpected behavior in the quantum critical region (see the figure), which, paradoxically, might even extend to room temperature and beyond. The consequences for the low-temperature properties can be more spectacular still. In 1998 the Cambridge group studied the formation of QCPs by tuning the antiferromagnetic transition in a series of specially chosen metals. Before the critical point was reached, the systems underwent a second phase change to a superconducting state (*3*). This was a real revelation, because the discovery of new superconductors has traditionally been an extremely subtle business. Although there was some guidance from empirical rules of thumb, notably those based on understanding of crystal structure, actual discoveries were more or less serendipitous. Now we had a new set of guidelines: Make QCPs and search for novel superconductivity in their vicinity.

The quantum critical approach has led to a number of important discoveries. Advances have been made concerning our understanding of the heavy fermion superconductor $CeCu_2Si_2$ (*4*), and new materials have been discovered in which superconductivity coexists with ferromagnetism (*5*). In each of these cases, QCPs were produced by the application of high hydrostatic pressure. A related question that several groups began to address was what would happen in special circumstances in which a magnetic field was used to tune the criticality. Would superconductivity or something else be the result? Superconductivity would certainly be disfavored in these circumstances, because superconductors screen out magnetic fields, and this costs energy. Indeed, the first evidence for phase formation in the vicinity of magnetically tuned QCPs involved novel nonsuperconducting behavior (*6*, *7*). Nothing in this work proved that field-induced superconductivity is impossible, but it seemed like quite a long shot, because even if there is a net energy gain from forming a superconducting state, it must compete with the net energy gain from forming other phases.

This, then, is the context in which Lévy *et al.*'s work is important. Soon after the discovery of pressure-induced superconductivity in UGe_2 (*5*), Aoki *et al.* discovered superconductivity at ambient pressure in the related material URhGe (*8*). When superconductivity was first discovered in UGe_2, it was assumed to be related to the ferromagnetic transition going quantum critical. Later, however, evidence began to emerge that the driving transition might be one between two subtly different forms of ferromagnetic order. Working with URhGe, Lévy *et al.* noticed signs of a magnetic transition at high fields and decided to investigate further (*1*). Using neutron scattering, they established that it involved a rotation of spin direction within the ferromagnet, and that this might be the source of a metamagnetic quantum critical endpoint (*9*). Low-temperature measurements on their best crystals then revealed that although the original superconductivity is suppressed by a magnetic field in the usual way and



Quantum criticality and phase formation. A schematic quantum critical phase diagram. The quantum critical point (QCP) is formed by tuning some combination of external parameters such as pressure and magnetic field. The presence of strong quantum fluctuations and the depressed energy scales increase the susceptibility of the system to entering a state with a class of order that did not form part of the original phase diagram (red cone). Empirically, the new phase is found surrounding the QCP, which is therefore not actually reached.

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disappears at 2 T, even stronger superconductivity reappears at the astonishingly large field of ~10 T.

Field-induced superconductivity had been seen before but could be explained in a rather conventional way, with the external field simply canceling the internal field that exists in a ferromagnet. Thanks to their neutron-scattering work, Lévy *et al.* can give convincing arguments for an entirely different, quantum critical origin for what they are seeing. A common feature of novel quantum order near QCPs is that the new states are fragile and are rapidly destroyed if the crystals are imperfect and contain disorder. This is also the case here, so in addition to performing difficult high-precision physical measurements, Lévy *et al.* had to use state-of-the-art crystal growth to obtain material of the requisite purity. Their work is an experimental tour de force.

In a more general sense, the importance of these advances is the construction—arguably for the first time in this field—of a framework for discovery. Careful work producing and then investigating QCPs is leading to a series of experimental breakthroughs. This does not, however, mean that we now understand everything. For example, it is widely assumed that quantum critical superconductivity is driven by magnetic fluctuations. Although this is very likely to be true, further work will be needed before the statement can be made with absolute certainty. Coupling between magnetic and structural properties ensures that phonons will also still play some role, and the strength of this coupling has not yet been determined in most cases.

A broader question is whether one needs a fluctuation-driven description at all. QCPs are indisputably accompanied by strong quantum fluctuations, but the mean-field free energy landscape also becomes very flat in their vicinity, increasing the susceptibility to phase changes in which the role of fluctuations is much less clear. The fact that these new phases need not always be superconducting gives promise for advances that will continue to surprise. Progress is rapid and exciting, but there is still much to be achieved.

References

1. F. Lévy *et al.*, *Science* **309**, 1343 (2005).
2. P. Coleman, A. J. Schofield, *Nature* **433**, 226 (2005).
3. N. D. Mathur *et al.*, *Nature* **394**, 39 (1998).
4. H. Q. Yuan *et al.*, *Science* **302**, 2104 (2003).
5. S. S. Saxena *et al.*, *Nature* **406**, 587 (2000).
6. S. A. Grigera *et al.*, *Science* **306**, 1154 (2004).
7. K. H. Kim *et al.*, *Phys. Rev. Lett.* **93**, 206402 (2004).
8. D. Aoki *et al.*, *Nature* **413**, 613 (2001).
9. S. A. Grigera *et al.*, *Science* **294**, 329 (2001).

10.1126/science.1117436

MICROBIOLOGY

Exploring Microbial Diversity—A Vast Below

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Exploring microbial diversity is becoming more like exploring outer space with soil representing a "final frontier" that harbors a largely unknown microbial universe. There are more than 10^{16} prokaryotes in a ton of soil compared to a mere 10^{11} stars in our galaxy. Astronomers have wisely inferred the population of celestial objects by mathematical inference. Now microbiologists are following suit, adopting a similar strategy to estimate the number of prokaryote taxa in soil. As shown by Gans *et al.* on page 1387 (*1*), the inferred diversity is staggering—higher than previously thought by almost three orders of magnitude.

The extent of prokaryote diversity has been hotly debated and rightly so. Microbial communities are central to health, sustainable cities, agriculture, and most of the planet's geochemical cycles. Prokaryote communities are also reservoirs for the discovery of new drugs and metabolic processes. As with any reservoir, its size is important.

Measuring the reservoir of prokaryotic diversity is not a trivial task. There is broad agreement that the key is to eschew the organisms themselves and to focus instead on their DNA. If DNA from a single organism is purified and heated, the strands of the double helix separate or "melt." If you then slowly cool the DNA, the strands will reassociate or reanneal, and the rate at which this happens is affected by the size and complexity of the DNA. Big and complex DNA reanneals slowly. This fact has been used for the past four decades to estimate the size and complexity of genomes from individual organisms. Around 15 years ago, Torsvik *et al.* (*2*) reasoned that pooled genomic DNA from a microbial community might reanneal like the DNA from a large genome. Indeed, they showed that DNA extracted from soil reassociated slowly—so slowly that it resembled a genome that was 7000 times as large as the genome of a single bacterium. It follows that there could have been at least 7000 different prokaryote taxa in the sample of soil that they analyzed. At the time, this was considered a mind-boggling number. Even ecologist E.O. Wilson speculated that "microbial diversity was beyond practical calculation" (*3*).

There is, however, another way to estimate prokaryotic diversity in the environment. A biological community has a characteristic abundance distribution of its member species. The observation and contemplation of these distributions have a rich literature in conventional ecology that is helping rescue microbial ecology from the conundrum of how to estimate diversity. In principle, if you know the shape of the taxa abundance distribution curve, you know the diversity. But there is a catch: Typically, for large organisms, species abundance distributions have been determined by assessing the abundance of almost all of the species in a sample, which means that you must already know the number of species. In the absence of such information, one still can draw upon certain theoretical considerations (*4*), assume that a particular species distribution pertains, and then make an estimate (*5*). Alternatively, you can fit a curve to the data you have to make an estimate (*6, 7*). The latter approach has great merit, but gathering enough data to make a sensible decision about the underlying species distribution pattern is problematic. At present, most microbiologists attempt to estimate diversity by looking at a gene that occurs in all cellular life forms. They infer diversity from the number of different variants that can be cloned from a sample of environmental DNA. Unfortunately, the number of clones analyzed is typically small (tens to hundreds) compared to the number of individual microbes being analyzed (billions or trillions). This is like randomly sampling a bus load of people and then trying to infer the diversity of all people in the world. You would not expect to find many Lithuanians.

Gans *et al.* (*1*) and others (*8*) realized that the pattern of DNA reassociation

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