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zon synchronized in-phase across the sky in a series of acoustic oscillations of the temperature anisotropy. Clear evidence of this is seen in the peaks and troughs of the temperature power spectrum and in the superhorizon temperature-polarization cross-correlation; (v) there should be statistical isotropy with fluctuations having Gaussian-distributed random phases. Although some small exceptions have been claimed, observations to date match this prediction; and (vi) the generation of gravitational waves will imprint a polarization pattern on the large and intermediate-scale CMB. The amplitude of the curl pattern, when detected, will reveal the energy scale at which inflation took place.

The interim report card on inflation is excellent, but a specific inflation model is not yet uniquely preferred and other theories are not yet ruled out (14). Fortunately,

substantial advances are coming. Much of what we know today has come from combining WMAP's CMB measurements with the Sloan Digital Sky Survey's galaxy redshift survey. The recently launched Planck satellite will map the full sky with greater angular resolution and sensitivity. More than a dozen ground and balloon-borne measurements are also in various stages of development and/or observations (15). These experiments cover a wide range of frequencies, vary in angular resolution and sky coverage, and take diverse approaches to systematic error mitigation.

New CMB data will improve inflation constraints and possibly detect the key gravitational wave signature. With new spectroscopic redshift surveys of a quarter of a billion galaxies, the new combined data will help elucidate the reason for the accelerated expansion, characterize dark matter, probe

galaxy evolution, determine the mass of the light neutrinos, and test the Gaussianity and power spectrum of inflation.

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15. Ground CMB experiments include ABS, ACT, BRAIN, BICEP2, Keck Array, MBI, Poincare, PolarBear, QUIET, QUIOTE, and SPT. Balloon-borne experiments include EBEX, SPIDER, and PIPER.

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PHYSICS

The Thermodynamics of Quantum Critical Points

Zachary Fisk

A thermodynamic state, such as a gas or liquid, is usually characterized by well-defined properties such as density, but at high temperatures and pressures, a critical point can be reached suddenly where properties such as density fluctuate wildly. Quantum fluctuations that arise through the Heisenberg uncertainty principle can also lead to critical behavior but do so in the limit of low temperatures. Quantum critical points are often seen as fluctuations in electronic ordering driven by an external magnetic field. Because a quantum critical point can affect the properties of a material well above absolute zero, the search for unusual electronic phases of matter can be aided by their presence. However, it has proven difficult to see the changes in thermodynamic properties that must occur near quantum critical points. On page 1360 of this issue, Rost *et al.* (1) characterize the entropy changes of an unusual electronic phase that was observed in highly pure $\text{Sr}_3\text{Ru}_2\text{O}_7$ single crystals (2). These results show that the spin nematic state, an analog of the molecular ordering that occurs in nematic liquid crystals, is a true thermodynamic phase.

The study of new phase behavior at temperatures near absolute zero began after the successful liquefaction of helium in 1908 and the discovery by Kamerlingh Onnes of superconductivity in mercury just above 4 K (3). An apparent problem in defining a unique

Thermodynamic signatures have been obtained for phase transitions that occur as temperatures approach absolute zero.

thermodynamic superconducting state arose; the formation of this state in the presence of an applied magnetic field seemed to depend on whether the field was applied before or after the material became superconducting. In 1933, it was discovered that superconductors expelled a magnetic field, which fixed their thermodynamic state (4).

Accounting for infinite conductivity proved more challenging. In the 1930s, Sommerfeld and Bethe (5) described ordinary electrical conductivity by applying their treatment of the quantum mechanics of free-electron gases to metals, which worked surprisingly well despite its simplicity. However, understanding the origin of superconductivity, a macroscopic quantum phenomenon, did not follow trivially,

A cold critical jump. A jump in the magnitude of a thermodynamic variable, such as entropy ΔS or specific heat ΔC , across a gas-to-liquid phase transition as temperature T changes is called a first-order phase transition. Rost *et al.* examined electron-spin transitions of $\text{Sr}_3\text{Ru}_2\text{O}_7$ in the limit of zero temperature using the apparatus shown in (A). They observed jumps in $\Delta S/T$ and $\Delta C/T$ as the magnetic field H was varied (B). Both diverge with the functional form $(H - H_c)^{-1}$ at a fixed low temperature; the critical magnetic field H_c is 7.8 T, and the red line illustrates this dependence.

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and only in recent years has a broader range of possible low-temperature phases of metallic electrons been discovered (6). The quantum wave-particle strangeness of matter often emerges at very low temperatures, where quantum fluctuations can dominate thermal fluctuations. For example, the failure of liquid helium to solidify at atmospheric pressure arises from large quantum-mechanical fluctuations in atomic motion, the so-called zero-point motion.

Until recently, the experimental search for new superconductors has been largely empirical, but a guiding principle that has emerged in the last decade is that an interesting set of superconductors (including the cuprate and heavy fermion superconductors) can reside near a quantum critical point. In the case of the so-called heavy fermions, fluctuations occur between one state in which the magnetic moments reside on the atoms and another state in which these moments are screened by itinerant delocalized electrons.

Among the unusual electronic phases driven by quantum fluctuations near a quantum critical point is the spin nematic phase in $\text{Sr}_3\text{Ru}_2\text{O}_7$, whose presence was inferred on the basis of large, anisotropic magnetoresistance effects. The layers within $\text{Sr}_3\text{Ru}_2\text{O}_7$ support a quasi-two-dimensional electron gas whose spins have a net magnetization. This magnetization is characterized by a spin texture—the ordering of the orientation of the electron spins that are still freely moving as a fluid—and resembles the ordering of molecules in nematic liquid crystals.

Experiments have revealed that metals in the vicinity of a quantum critical point have temperature dependences in their physical properties unlike those normally exhibited by metals as they approach absolute zero (7). For example, the electrical resistivity of a metal at low temperatures should be the sum of a T^2 electron scattering term plus a T^5 lattice vibration scattering term. In the cuprates, an anomalous linear temperature dependence is seen near the quantum critical point, as well as the divergence of various properties.

In looking at changes in thermodynamic properties such as entropy around a quantum critical point, it is useful to see if they are first order (the property itself diverges) or second order (the property does not diverge but one of its derivatives does). Rost *et al.* found that the change in entropy divided by temperature ($\Delta S/T$) of the almost defect-free $\text{Sr}_3\text{Ru}_2\text{O}_7$ sample diverges on approaching the first-order phase boundaries from both the low- and high-magnetic field sides at fixed temperature (see the figure). These first-order phase boundaries are connected by an upper

boundary in temperature, and a second-order transition is seen when the magnetic field is fixed. The unusual new phase can be thought of as the material's solution to the problem of lowering its entropy in accord with the third law of thermodynamics, which demands that the entropy of a phase at equilibrium goes to zero as temperature goes to zero.

What do we learn from these new results? First, the putative spin nematic state is a true macroscopic phase for $\text{Sr}_3\text{Ru}_2\text{O}_7$. Such characterization is not yet possible for similar phases that occur in two-dimensional electron gases created in atomic-layer heterostructures. Second, the symmetric divergence in $\Delta S/T$ (also seen in the change in specific heat ΔC divided by T) around the critical magnetic field is strong evidence that spin nematic phase arises from proximity to an underlying quantum critical point. Third, the magnetocaloric effect used to map out the first-order boundaries could be applied to other exotic phase transitions driven by magnetic fields.

Finally, these studies reinforce the importance of creating almost defect-free samples for experimental searches for new phases. In $\text{Sr}_3\text{Ru}_2\text{O}_7$, observing this new phase requires increasing the distance an electron traveled in the solid before scattering from 300 to 3000 Å. The exotic superconductivity found in the closely related material Sr_2RuO_4 was also observed only when high-quality single crystals were grown (8).

Many quantum critical points occur for transition-metal compounds near a magnetic/nonmagnetic boundary where electronic charge and spin degrees of freedom are strongly coupled and bonding and magnetism interfere. Defects in such materials stabilize less interesting noncritical behavior. Defects can also distort the crystal lattice so that it nucleates a stable phase that does not support the divergences characterizing a quantum critical point, or cause the loss of the phase coherence needed for collective macroscopic electronic phases. The interesting and unusual physics seen in the study of Rost *et al.* arises because their clean material must find a way to avoid the quantum critical point and its associated divergences.

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NEUROSCIENCE

Low-Cost Travel in Neurons

Pierre J. Magistretti

More precise measurements are now available for energy budgets in the brain.

About 20% of the energy consumed by the body sustains brain function (1), yet the brain represents only 2% of human body mass. This consumption, reflected by the use of glucose and oxygen delivered by blood flow, provides signals that can be detected in real time with imaging techniques such as positron emission tomography and functional magnetic resonance imaging (2). On page 1405 of this issue, Alle *et al.* (3) weigh in on the ongoing debate about how energy utilization by brain neurons contributes to the signals detected by these techniques.

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Information processing consumes much of the energy used by the brain. The neuronal signaling involved is based on the rapid flow of electrical charges—carried by ions such as sodium (Na^+), potassium (K^+), and calcium (Ca^{2+})—across neuronal membranes. This is not expected to consume much energy because the flow of ions follows favorable electrochemical gradients. However, reestablishing these gradients through ionic pumps, such as the Na^+/K^+ -ATPase (adenosine triphosphatase), does indeed cost energy (4).

Two processes mediate signaling between neurons: action potentials that carry electrical signals along the axon (and dendrites), and postsynaptic potentials, which are generated by neurotransmitters that are released

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