

SUPERCONDUCTIVITY

Importance of fluctuations

Pioneering measurements of the superfluid density in ultrathin films of a high-temperature superconductor demonstrate the importance of phase fluctuations for the physics of these fascinating materials.

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The study of phase transitions focuses on understanding how a more ordered state of matter, such as crystalline ice, transforms into a less ordered state, such as liquid water. Among the best understood transitions are those occurring in conventional superconductors, such as lead or niobium, which turn into normal metals as the temperature is increased beyond a critical value T_c . In high- T_c superconductors, however, the transition into the 'normal' state remains poorly understood, because even after more than 20 years of research we still do not know for certain what state of matter lies on that other side. On page 700 of this issue, Hétel, Lemberger and Randeria¹ present some truly pioneering measurements of the superfluid density in copper oxide films as thin as two monolayers, which reveal the nature of the transition and indicate a direction in which we should search for the mysterious state of matter that exists on the normal side.

Transitions between different phases of matter are characterized by order parameters. The superconducting order parameter, conventionally denoted by Ψ , is a complex number whose amplitude and phase describe different aspects of the superconducting order. Its amplitude $|\Psi|$ is closely related to the energy gap in the excitation spectrum, and is responsible for the activated behaviour of thermodynamic quantities, such as the specific heat, as a function of temperature. The energy gap also prevents a superconductor from absorbing electromagnetic radiation at frequencies that lie inside the gap. The phase θ of the order parameter, on the other hand, relates to the ability of the superconductor to carry electrical current without resistance. In conventional superconductors the transition into the normal state occurs when the amplitude $|\Psi|$ vanishes; the

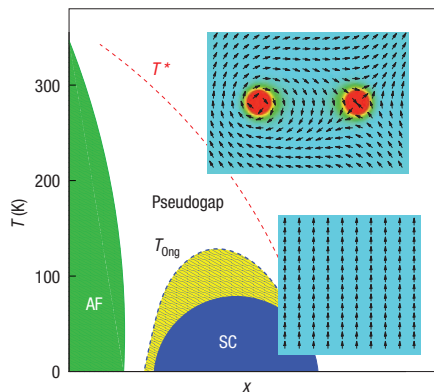


Figure 1 Schematic phase diagram of the copper oxide superconductors as a function of the doping concentration x of holes. Dominant phases are the antiferromagnetic insulator (AF), superconductor (SC) and mysterious pseudogap phase. T_{0ng} denotes the temperature below which solid experimental evidence exists for phase fluctuations. T^* is the pseudogap temperature. The insets illustrate possible configurations of θ : either completely ordered in a superconductor (lower) or disordered, containing vortices, in the pseudogap phase (upper).

energy gap collapses and, in the absence of an amplitude, the phase loses its meaning.

In the copper oxide superconductors, a leading school of thought^{2–5} holds that the transition over a large range of doping values (see Fig. 1) proceeds by a different route, namely through the disordering of the phase degrees of freedom. In essence, the state on the other side is thought to be a 'phase-disordered superconductor' characterized by a non-zero value of $|\Psi|$ but spatially fluctuating phase θ as illustrated pictorially in the insets to Fig. 1. This 'pseudogap' state indeed seems to possess an energy gap, presumably related to $|\Psi|$, but is normal in the sense that it exhibits non-zero electrical resistance.

The above point of view is supported by many tantalizing experiments^{6,7} but is not yet universally accepted. One significant issue has to do with certain

theoretical constraints placed on the behaviour of physical observables near a phase-disordering transition. Specifically, for a material comprising weakly coupled two-dimensional superconducting layers, the transition should be of the Kosterlitz–Thouless (KT) type, driven by unbinding vortex–antivortex pairs. The theory says that the superfluid density $n_s(T)$ must undergo a universal 'jump' at the KT transition — a discontinuous jump from a prescribed value (related to $n_s(0)$) just below T_c to zero just above T_c . But such a jump had not been seen in the cuprates until very recently.

In retrospect it is now clear that a number of obstacles have hidden the characteristic KT behaviour from experimentalists. First, it is very difficult to grow sufficiently clean samples, and disorder tends to wash out any signatures of a sharp KT transition. Second, $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, the one that can be grown clean enough, turns out to be in the regime where the coupling between the layers is not particularly weak. Under such conditions the transition in a bulk sample is not of the KT variety but becomes the so-called '3D-XY' transition driven by the unbinding of vortex loops. The loops are the three-dimensional cousins of ordinary vortices, similar to smoke rings. This 3D-XY transition does not have a universal jump. Instead, the theory predicts a smooth critical behaviour that has been observed in clean bulk crystals⁸.

It took great persistence and skill to unravel this particular conspiracy. By using ultrathin films of Ca-substituted $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ — in some cases only two monolayers thick — Hétel *et al.* finally nailed the elusive KT behaviour. Such ultrathin samples do indeed show an unambiguous jump in $n_s(T)$. Moreover, their experiments enable us to observe how, with increasing number of monolayers, the jump becomes rounded and eventually crosses over to the characteristic 3D-XY behaviour. Hétel *et al.*¹ also found another way to test the theory of phase-disordering transitions, which makes a specific prediction⁹ for the dependence of the critical temperature T_c on the zero-temperature superfluid

density $n_s(0)$. The new measurements, when combined with earlier work on bulk crystals¹⁰, confirm these predictions in a spectacular way.

Given these developments it will be very difficult from now on to argue that the transition in the underdoped high-temperature superconductors is not a phase-disordering transition. The unavoidable implication, then, is that the state of matter on the other side of the transition must be characterized as a phase-disordered superconductor. A question that remains open to discussion

is up to what temperature this interesting state persists. There exists compelling experimental evidence^{6,7} for phase fluctuations up to the ‘Ong’ temperature, marked as T_{Ong} in Fig. 1, which can be as high as 140 K in certain materials. Some believe, however, that T_{Ong} merely marks the point at which instruments lose sensitivity to detect phase fluctuations that remain important up to the much higher pseudogap temperature, T^* . A remarkable possibility then arises if we permit ourselves to imagine that a way could be found to suppress phase fluctuations

in these materials: they would turn into room-temperature superconductors.

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QUANTUM COMMUNICATION

Coherence by measurement

A global infrastructure for exchanging quantum information requires coherent communication over long distances. The demonstration of interference between photons from two unsynchronized sources could bring us a step closer to that goal.

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The ‘big goal’ in quantum information technology is to extend the distance over which information can be transmitted such that, eventually, a global quantum communication network can be established. Matthäus Halder and colleagues might have moved the dream of long-distance quantum communication just a bit closer. On page 692 of this issue¹ they report an experiment showing that certain long-distance operations that so far have required synchronization of light sources — a difficult task if these sources are far away from each other — can be also achieved with completely autonomous sources.

One of the incentives offered by encoding information not in bits, but in qubits (that is, using not only two states, such as zeros and ones, but also any coherent superposition of the two) is that messages can be transmitted, in principle, in an absolutely secure way. However, the probability that an error occurs during transmission grows exponentially as the length of the communication channel increases because all the losses along the way multiply. In classical communication, we can increase the signal strength and insert ‘repeaters’ that re-encode the information

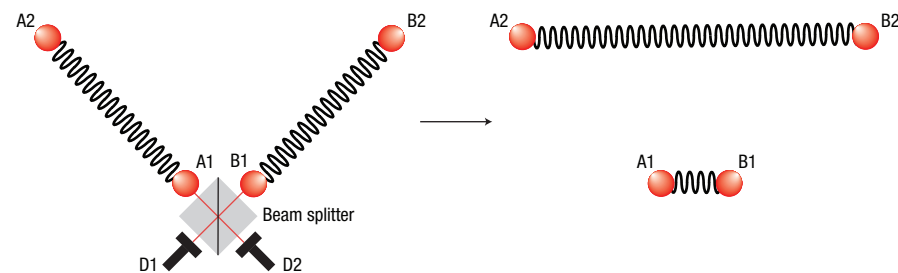


Figure 1 Knitting a quantum network. Two distant photons A2 and B2 can be entangled by combining two photon pairs (A1–A2 and B1–B2) that are entangled over shorter distances. This is done by passing photons A1 and B1 through a 50:50 beam splitter. Whenever the two detectors D1 and D2 see simultaneously one photon each, A2 and B2 are projected in an entangled state (see text for details).

after a channel. Any distance can then be covered by stringing enough of those channels together to form, for example, a transatlantic cable.

With the feeble qubits, the situation is more complicated, as measuring the quanta to obtain classical results (for re-encoding the qubits) destroys the quantum state. Perfect copying is forbidden by the no-cloning theorem², and signal amplification does not help, because any amplification by necessity adds at least almost as much noise as there is signal to begin with^{3,4}. Long-distance quantum communication, therefore, seemed pretty hopeless. That was until the conception of the quantum repeater⁵, an ingenious scheme that relies

on breaking down a desired long-distance link into a number of shorter links. A quantum repeater establishes entanglement across a long link (which can then be used for coherent quantum communication) by connecting a string of particle pairs that are each entangled over shorter distances. In this way, the exponential loss of information with increasing channel length can be, theoretically, circumvented because the entanglement can be used to teleport any quantum information that we may wish to communicate.

Building a full quantum repeater, however, is still a daunting task. The biggest challenges to be mastered on the way to a practical quantum repeater concern the