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, Hetel, Lemberger and Randieri 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 \( \Psi \), 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 \( \theta \) 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 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\(^6,7\) 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 \( \theta \) 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\(^8,9\) 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 crystals\(^6\).

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 — Hetel 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. Hetel et al.\(^1\) also found another way to test the theory of phase-disordering transitions, which makes a specific prediction\(^8\) for the dependence of the critical temperature \( T_c \) on the zero-temperature superfluid...
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. Matthias 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 achieved with completely autonomous sources.

The news item ‘quantum repeaters’ that re-encode the information multiply. In classical communication, we know that the length of the communication channel transmission grows exponentially as the probability that an error occurs during transmission increases. Hence, if we wish to communicate messages can be transmitted, in principle, over long distances. The demonstration of interference between photons from two unsynchronized sources could bring us a step closer to that goal.

References