when both phases can be thermally excited, neither quasiparticle description is appropriate. Instead, special scale-invariance properties of the critical point have to be used to develop a new framework for finite temperature dynamics.

The availability of a large number of 2D correlated electron systems (including the high-temperature superconductors), along with the highly nontrivial theoretical framework necessary to describe them, makes this one of the most exciting research areas in condensed matter physics. As I have already noted, the increased sensitivity of future experiments, including neutron scattering, tunneling, magnetic resonance, photoemission, and optics, along with better sample preparation techniques, will surely uncover much new physics. Many interesting theoretical questions, on the classification of ground states and quantum critical points, and on the description of dynamical crossovers in their vicinity, remain open. The interplay between theory and experiment promises to be mutually beneficial, in the best traditions of physics research.

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VIEWPOINT

Sources of Quantum Protection in High-T_c Superconductivity

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The layer-structure cuprates with high superconducting transition temperatures T_c exhibit a number of anomalous electronic properties in both superconducting and normal states. These anomalies are ascribed to the existence of independent spectra of excitations for charge and for spin, signaling a collective state, a "quantum protectorate."

Laughlin and Pines (*1*) recently introduced the term "quantum protectorate" to describe certain states of quantum many-body systems with properties that are unaffected by imperfections, impurities, and thermal fluctuations. Examples are the quantum Hall effect, which can be measured to extremely high accuracy on samples with very short mean free paths (comparable to the electron wavelength), and flux quantization in superconductors, which is independent of imperfections and scattering. A simpler example is the rigidity and dimensional stability of crystalline solids evinced by scanning tunneling microscopy. The source of quantum protection is likely to be a collective state of the quantum field, in which the individual particles are sufficiently tightly coupled that elementary excitations no longer involve just a few particles, but are collective excitations of the whole system. As a result, macroscopic behavior is mostly determined by overall conservation laws.

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Here, I discuss experimental evidence which shows that the metallic states of high–transition temperature (T_c) cuprate superconductors are a quantum protectorate. I propose that this collective state involves the phenomenon of charge-spin separation and give indications why such a state should be a quantum protectorate.

Experimental Evidence

We may define four regions of the generic cuprate phase diagram (Fig. 1): the "normal" metallic state near optimal doping, phase I, widely assumed to be a non-Fermi liquid; the pseudogap state, phase II, separated from phase I by the temperature T^*; the d-wave superconducting phase, phase III; and the Mott insulating antiferromagnet, phase IV. I will assume that the "stripe" phase, when encountered, is merely an inhomogeneous mixture of phases III and IV.

Phase IV, the Mott insulator, has a charge gap of ~2 eV, whereas the spin wave spectrum extends to zero energy. The spin waves, which are Goldstone bosons (collective waves of the order parameter), are weakly scattered by phonons and conventional impurities and are not scattered at all in the limit ω, $Q \rightarrow 0$, where ω is the angular frequency and Q is the wave number. They are in a quantum protectorate because the spin and charge dynamics are independent, and perturbations that interact primarily with charge do not much affect spin. I will argue here that phases I, II, and III also share this property and that it is responsible for the anomalous properties of the high-T_c cuprates compared with ordinary metals.

The transport properties of phase I have been well studied in $YBa_2Cu_3O_{(7-x)}$ (YBCO) and, to a lesser extent, in $Bi_2Sr_2Ca_2Cu_2O_8$ and $(La\text{-}Sr)_2CuO_4$. The energy distribution curves show no phonon contributions to the self-energy (the correction to the energy due to interaction effects) of the electrons. This behavior has been strikingly shown by comparing the phonon-dominated self-energy of a Mo surface state with that of a cuprate superconductor (*2*). Simply scaling the conductivity σ as a function of temperature T and ω

$$\sigma = \omega F(T/\omega) \quad (1)$$

gives the clearest indication that there is no extraneous energy scale that must be included to describe the normal state properties. Not even conventional electron-electron scattering would show the striking linear rise of scattering rate $1/\tau \propto \omega$ (where τ is the mean free time between scatterings) above the Debye frequency that is observed for phase I. Resistivity saturation, an effect associated with strong phonon scattering that is seen universally in conventional poor metals, is also absent near the Mott limit. I have shown previously (*3*) that these observations can be explained by charge-spin separation: if there was no spin-charge separation, the phonons should affect the conductivity and resistivity.

The knowledgeable reader may object that Zn and Ni impurities, which substitute for Cu in the CuO_2 planes, do in fact act as strong scatterers. But these impurities only act as Kondo scatterers for the spin degrees of freedom. They thus scatter spinons at the unitarity limit but do not show magnetism except at high temperature. The strict dichotomy between these two scatterers and most others is good evidence for the quantum protectorate and its explanation in terms of spin-charge separation.

In phase II, the pseudogap state, the most striking evidence for spin-charge separation is the pseudogap itself, which shows up as a gap in the one-electron spectrum along the "anti-nodal" directions in k space, whereas there is no evidence for a gap for charge excitations (except in systems with static stripes). The absence of a Luttinger-theorem Fermi surface excludes conventional theories in this region.

The superconductor phase, phase III, shows the clearest evidence of all for the quantum protectorate. Almost all cuprate superconductors are self-doped, presumably by nonstoichiometry at the level of 10 to 20%. I have demonstrated (*3*) that the doping centers should scatter quite efficiently. If so, they would be necessarily pair-breaking for conventional d-wave superconductors arising from conventional Fermi liquids. But there is no evidence that T_c is even affected by the degree of purity or by phonon scattering, which will also be pair-breaking for a d wave. The optimum T_c in YBCO is achieved not in $YBa_2Cu_3O_7$ (almost the only stoichiometric cuprate), but in $YBa_2Cu_3O_{6.93}$, which contains 7% charged impurities. The biggest mystery of high-T_c superconductivity is that T_c is so high. It seems likely, however, that high T_c's can be achieved in a quantum protectorate in which scattering does not affect the collective state.

The absence of pair-breaking effects is confirmed by analysis of the thermal conductivity of cuprate superconductors in a magnetic field (*4*). The field-sensitive thermal conductivity for temperatures well below T_c must be carried by quasiparticle excitations in the gap nodes. Several theorists have shown that the data can only be explained by the presence of true Dirac fermions with effectively zero mass at the gap nodes. The node is not smeared out by impurity scattering, as it would have to be in conventional d-wave superconductors. This, to me, is crucial evidence for a quantum protectorate.

Spin-Charge Separation

I have previously proposed (*3*) that some of the behavior described above results from charge-spin separation. The elementary excitations in phase I are not quasiparticles with the quantum numbers of electrons, but are solitons, that is, fractionalized electrons, one of which carries the spin quantum number and the other(s) the charge. The crucial component of this idea is the spinon, a neutral excitation carrying only the spin quantum number of an electron (*5*).

From a symmetry point of view, spin-charge separation is a very natural phenomenon in interacting Fermi systems (*6*). The Fermi liquid has an additional symmetry that is not contained in the underlying Hamiltonian because the two quasiparticles of opposite spins are exactly degenerate and have the same velocity at all points of the Fermi surface. As a result, charge and spin are interchangeable. But the interaction terms do not have this symmetry, and in the true symmetry of the interacting Hamiltonian, charge and spin are not interchangeable.

The reason why conventional Fermi liquid theory works is that U, the Hubbard interaction that describes a short-range repulsion, renormalizes away as $\Omega \rightarrow 0$ because of ladder diagrams that diverge in three or more dimensions. The resulting "effective range" theory contains only irrelevant symmetry-breaking terms. In one dimension, spin-charge separation always occurs (*6*); two is the critical dimension.

Spin-charge separation tells us that the spectrum of exact elementary excitations does not consist of quasiparticles, which carry both charge and spin. In the Mott insulator, phase IV, there is a large charge gap, and the Goldstone boson excitations are spin waves. In the other phases, there is neither a charge nor a spin gap; nonetheless, the spin spectrum remains distinct and reflects the symmetries of the spin system.

Unlike the Mott insulator, phases I and II are based on a ground state with no broken symmetry, presumably a singlet spin liquid. The spin excitations in such a fluid are spinons, that is weakly interacting fermion-like objects with linear spectra and finite momenta (*7*, *8*). In both of these phases, the charge spectrum remains without a gap. In ideal, weakly interacting, pure Fermi fluid, it consists of "holons," propagating, particle-like solitons that may have charge other than e and anyon statistics. But in the actual substance, the charge excitations are strongly scattered, and their low-frequency, long-range dynamics are diffusive.

Much effort has gone into describing

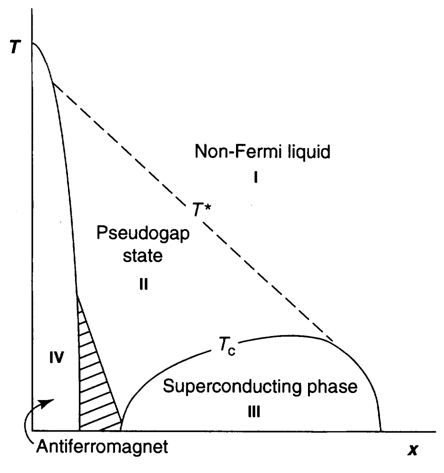

Fig. 1. Generalized phase diagram for high-T_c superconductors as a function of temperature T and doping x.

phase II and its spin excitations using gauge theory (*9, 10*). A fermionic field has indeed been found, which appears to be equivalent to spinons, providing another formal treatment of spin-charge separation. These groups seem, however, to have less to say about charge excitations (*9, 10*). Formal theory for a charge-spin separated superconductor is even more rudimentary.

A Quantum Protectorate

There are two sources for the quantum protectorate effect, which are not entirely independent but physically distinct. The first is that spinons are relatively weakly scattered because they are the "Goldstone fermions" that express fundamental symmetries of the spin system. The spinon dynamics in low-frequency states are averaged over all configurations of the holes. Thus, the effective Hamiltonian that controls their dynamics is a "squeezed," smoothed Heisenberg-like model with a number of sites equal to the number of electrons. Impurities will lead merely to local variations of the effective exchange integrals, which are inefficient in scattering long-wavelength, low-frequency spin fluctuations.

A second view is more direct. In the charge-spin separated state, the electron is a composite particle whose Green's function in space-time is the product of charge and spin factors. The resulting Fourier transform is the convolution of these and is in fact observed in angle-resolved photoemission spectroscopy (ARPES) measurements to have a broad, power-law shape with, at best, a cusplike feature at the (presumed) spinon frequency. By either this argument or the ARPES observations, one sees that the one-electron density of states vanishes at $\omega = 0$, as a power law

$$N(\omega) \propto \omega^p \text{ with } 1/2 < p < 1 \qquad (2)$$

Any perturbation that couples to electrons, in particular any time-reversal invariant perturbation other than substitution in the copper sites, thus renormalizes to zero at low frequencies.

The above discussion holds for phases I and II. For the superconducting phase, phase III, I will make the rather radical proposal that the charge excitations essentially remain separate and condense with "*s*-wave" symmetry, hence their insensitivity to scattering. The resulting condensate then automatically gives the spinons quasiparticle character. This hypothesis is speculative but is strongly supported by experimental observations.

Conclusion

The existence of quantum protectorate effects seems to me to be amply justified by the striking experimental anomalies I have listed: the absence of phonon scattering and of pair-breaking effects, and the unusual phenomenon of the spin gap. These anomalies are more generally characteristic than many of the peculiarities often considered crucial to understanding high-T_c superconductors. The rather old phenomenon of charge-spin separation seems the most plausible source. We propose a new vision of charge-spin separation arising not from the influence of a mysterious "quantum critical point," but as being a universal high-energy trait of electron systems, which is only renormalized away in low-temperature and high-dimensional systems.

The precise mechanism for the final superconducting transition is of course still in question. I suggest that its T_c is determined by the need to reduce the frustrated kinetic energy of the system, but do not here propose an explicit mechanism.

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