dation of its amalgamation, continental makeup, and fragmentation is hampered by the fact that at any given time, the latitudes for only a few continents are known.

To overcome these problems, we must tie paleomagnetic information to geologic matching of rock units with the same age between various continents. Doing so requires more precise dating of mobile belts and rift sequences associated with Rodinia's breakup. New paleomagnetic studies conducted in close conjunction with radiometric age studies are urgently needed to shed new light on the supercontinent's evolution. Until then, our efforts resemble a jigsaw puzzle where we must contend with missing and faulty pieces and have misplaced the picture on the box.

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PHYSICS

# Broken Cooper Pairs Caught Bouncing Around

**Bernhard Keimer**

The explosion of research activity after the discovery of high-temperature superconductivity in 1986 is the stuff of legends. But while the "Woodstock of Physics" has long subsided, research on the superconducting copper oxides ("cuprates") has remained steady. The field may even be experiencing a second, more measured boom.

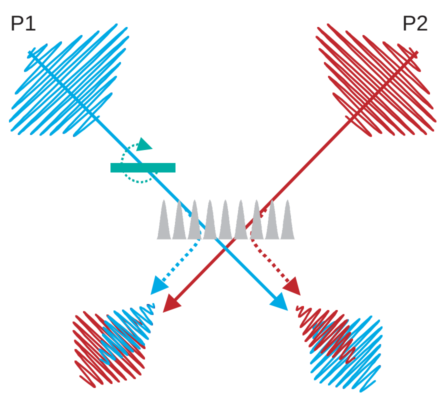
It took years to perfect the synthesis of cuprate compounds with optimal purity and minimal defect concentration. Today, excellent single-crystal samples are widely available. Meanwhile, advances in measurement techniques have made it possible to obtain scanning tunneling spectroscopy images of electronic states on cuprate surfaces (*1*), resolve minute (~0.1%) changes in the optical absorption spectrum at the superconducting transition temperature (*2*), and detect magnetic excitations by neutron scattering in millimeter-sized crystals (*3*).

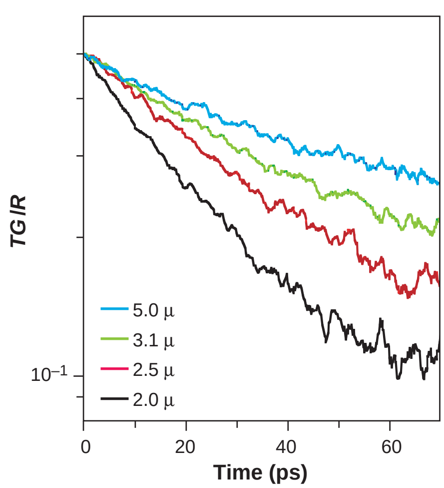
On page 1410 of this issue, Gedik *et al.* add a new experimental method to our arsenal (*4*). They use laser pulses to temporarily degrade the superconductivity in a cuprate by breaking up the "Cooper pairs" of electrons and holes that carry electrical currents without resistive losses. They then track the erstwhile partners while they are bouncing off the remains of other broken Cooper pairs and other obstacles in their way. The experiment provides new insights into the forces responsible for the formation of Cooper pairs.

To appreciate the contribution of Gedik *et al.*, it helps to recall that most experiments on cuprates have been carried out in thermal equilibrium. In a measurement of the electrical conductivity, for instance, an external electric field promotes electrons into current-carrying excited states, and the response of the material (the electric current) is measured after the electrons have come into equilibrium with the surrounding lattice. The conductivity is the response function linking current and field. Other common equilibrium measurements yield functions describing the response of the material to time-dependent and spatially nonuniform electric (*1*, *2*) and magnetic (*3*) fields. Theorists have recently found that calculations based on coupling of electrons to spin excitations agree well with several independently measured response functions (*5*). However, it remains controversial whether the electron-electron interactions mediated by spin fluctuations are strong enough to explain the formation of Cooper pairs at high temperatures (*6*).

The report by Gedik *et al.* is based on an entirely different experimental approach that is widely used in chemistry and physics: A non-equilibrium population of "hot" electrons is generated by an intense "pump" beam from a pulsed laser, and the response of the material is monitored by a weaker "probe" beam at regular time intervals following the pump pulse. The subpicosecond time resolution required to monitor electronic relaxation processes can be routinely achieved in this way.

When the pump-probe approach is applied to high-temperature superconductors, hot "quasi-particles" (both electrons and holes) are generated by the laser pulse. These quasi-particles affect the complex index of refraction of the superconductor and hence the intensity of the reflected probe beam. The reflected beam thus yields information about the interaction of the hot quasi-particles with their environment (*7*–*9*). Some of these data have been interpreted as evidence of strong coupling between charge and spin excitations (*8*), providing qualitative support for the models developed on the basis of equilibrium experiments (*5*). However, the data themselves have barely made it onto the radar screens of theorists looking for experi-




**A new tool.** **(Left)** Quasi-particle grating detection by coherent laser pulses. Each of the two probe beams (P1 and P2) is split at the grating into transmitted and diffracted beams. The transmitted P1 and diffracted P2 are collinear. Each pair of pulses is directed to a photodetector (not shown). Measuring the detector current as a function of the time delay between the two probes yields the average quasi-particle density *R* and the peak-to-trough variation *TG*. **(Right)** Dynamics of the quasi-particle density grating as a function of the grating period λ. *TG*/*R* decays with time as quasi-particle diffusion depletes the grating crests and fills the troughs. Analyzing the decay rate of *TG*/*R* as a function of λ yields the quasi-particle diffusion coefficient with high precision.

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mental signatures of possible microscopic mechanisms of superconductivity.

The lack of enthusiasm on the part of theorists is rooted in the complexity of the chain of events that unfolds after the Cooper pairs have been broken up by the initial laser pulse. The hot quasi-particles relax back into thermal equilibrium through a multitude of microscopic processes, including recombination into Cooper pairs with their former partners or other quasi-particles, inelastic scattering from lattice or spin excitations, and elastic scattering from defects and impurities.

The relative contributions of these processes to the time-dependent reflectivity are difficult to disentangle. A full theoretical description of hot quasi-particle relaxation requires solving a complicated set of nonlinear differential equations. Approximate solutions of these equations (*10*) have been difficult to test even for conventional superconductors where electron-electron interactions are weak. Theorists have shied away from repeating this exercise for the strongly interacting electrons in cuprates, opting instead to use their models to compute the well-defined linear response functions determined by equilibrium experiments.

By cleanly separating the effects of recombination and diffusion (which encompasses both elastic and inelastic scattering), Gedik *et al.* now go a long way toward establishing nonequilibrium transport as a quantitative probe of the superconducting state in cuprates. They do so through a clever manipulation of several phase-coherent laser beams (see the figure).

First, they interfere two pump beams at the sample to generate a spatially periodic population of hot quasi-particles. The intensity of a probe beam diffracted from this "transient grating" is recorded along with that of a second probe beam reflected from the surface. Both are then used to reconstruct the decay of the density modulation as a function of time. Because the decay rate depends on the periodicity of the transient grating, the contributions of diffusion and recombination can be distinguished: The larger the periodicity, the longer it takes the hot quasi-particles to diffuse from the peaks to the valleys of the density distribution, and the slower the decay. Recombination, on the other hand, gives a periodicity-independent contribution to the decay rate.

Like the response functions measured in equilibrium experiments (*1–3*), the diffusion constant determined by Gedik *et al.* imposes a hard constraint on models of the cuprate superconductors. As further measurements of its dependence on temperature and doping become available, hot quasi-particle diffusion could develop into a major new source of information about the microscopic interactions responsible for Cooper pair formation.

This is not the first time that electron diffusion has been observed in the superconducting state of the cuprates. Unlike conventional superconductors, where the paired electrons form an isotropic bound state, Cooper pairs condense into a highly anisotropic state, and quasi-particles with momenta in certain directions can be generated with almost no expenditure of energy. Equilibrium measurements with such low-energy (cool) quasi-particles (*11*, *12*) have contributed much to our understanding of the cuprates. However, these quasi-particles do not experience the pairing interaction strongly, which is why they can be created so easily.

The hot quasi-particles produced in the pump-probe experiment are expected to be much more strongly affected by the interactions that drive Cooper pair formation. In line with these expectations, Gedik *et al.* estimate a hot quasi-particle scattering rate that is more than two orders of magnitude larger than that inferred from microwave studies on the same samples. They also find that the quasi-particles are scattered many times before they recombine to form a Cooper pair. While surprising at first sight, it may be possible to understand this finding as a consequence of kinematic restrictions. In conventional superconductors (*13*), most direct encounters between hot quasi-particles do not lead to recombination, because energy and momentum conservation cannot be satisfied. Working out the corresponding kinematics for cuprate superconductors is the first task for theorists interested in exploiting this new source of information.

Time- and space-resolved experiments of the type reported by Gedik *et al*. (*4*) are a promising new testing ground for microscopic models of the superconducting cuprates. Theoretical concepts developed to describe these experiments could also help to explain some of the dramatic nonequilibrium effects recently observed in other correlated electron materials, such as ferromagnetic (*14*) and ferroelectric (*15*) phase transitions induced by hot electrons.


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MICROBIOLOGY AND EVOLUTION

# Modulating Mutation Rates in the Wild

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In evolution, the environment selects the fittest genetic variants, but does it also provoke the generation of genetic variants? And if it does, can this speed up the rate of evolution? Both of these ideas have been supported by work on laboratory strains of bacteria and yeast over the past 15 years. Bacterial cultures exposed to growth-limiting stress, such as starvation, sometimes produce mutants, apparently in response to stress (*1*). This process has been variously termed adaptive, stationary-phase, or stress-inducible mutation. In the best documented examples, both useful and deleterious mutations may arise. There seem to be multiple molecular mechanisms underlying stress-inducible mutagenesis, and some of these differ demonstrably from those causing spontaneous mutations in rapidly growing cells. Controversy surrounds whether any of these mechanisms was itself selected for its ability to produce genetic diversity, or whether all are by-products of error-prone DNA repair processes selected for their immediate survival value (or both). In addition, whether any of the assays using laboratory strains of bacteria reflect the biology of organisms in the real world has been a controversial subject. Some of these debates should be resolved with the report by Bjedov *et al.* (*2*) on page 1404 of this issue. These investigators provide support for stress-inducible mutagenesis in stationary-phase bacterial colonies grown from strains culled from the real world. They provide evidence that most natural isolates of *Escherichia coli* bacteria, from diverse habitats worldwide, increase their mutation rates in response to the stress of starvation.

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