PERSPECTIVES: PHYSICS

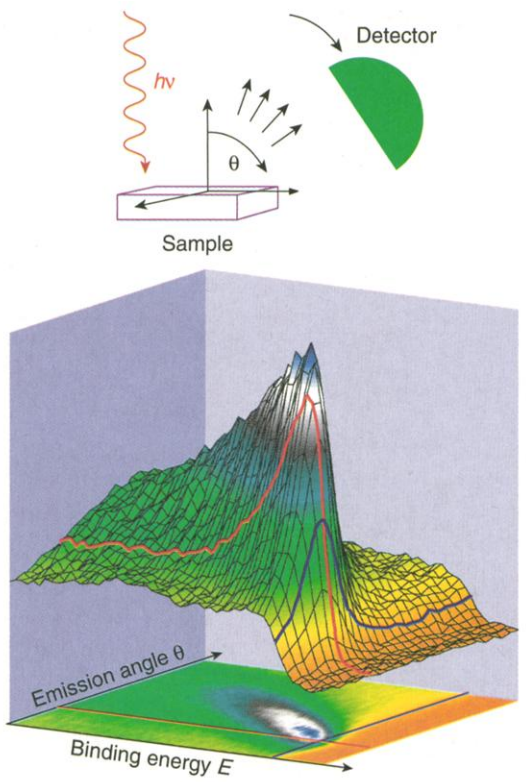
Quasi-Particles Survive—for Now

Bernhard Keimer

A typical centimeter-sized piece of solid contains on the order of 10^{23} electrons, each of which interacts with ($10^{23} - 1$) other electrons and a comparable number of positively charged nuclei through long-range Coulomb forces. An exact solution of the resulting many-body problem is hopeless even with the most advanced computing techniques. Nonetheless, thanks to ingenious concepts developed by solid-state physicists during the past century, our understanding of ordinary solids has reached a remarkable degree of sophistication. As long as some very general conditions are satisfied, the complex system of interacting electrons can be mapped one-to-one onto a system of noninteracting fictitious particles, termed "quasi-electrons." This reduces the initial 10^{23}-body problem to 10^{23} much more tractable one-body problems.

Like free electrons, quasi-electrons carry a spin of 1/2 and an elementary charge e. However, because the quasi-particles drag along the polarization cloud of displaced electrons and nuclei as they move through the solid, their "effective mass" can be much larger than the free electron mass. Furthermore, quasi-electrons away from the Fermi level (the highest occupied energy level in the solid) are not infinitely long-lived but decay after a finite period of time.

The quasi-particle concept has been extremely successful as a basis for describing the bulk properties of solids. For instance, the electrical and thermal conductivities of simple metals calculated with this concept are in near-perfect agreement with measurements (*1*). At the microscopic level, theory and experiment can be compared with the help of angle-resolved photoemission spectroscopy (ARPES), which is in essence a highly accurate measurement of the photoelectric effect (see the figure). For layered compounds whose electronic states near the Fermi level are effectively two dimensional (2D), ARPES allows one to obtain the full energy spectrum of quasi-electrons at a fixed wave vector $\boldsymbol{k}$. The energy, E, and lifetime, τ, of the quasi-electron can be directly extracted from the position and width of the photoemission peak, respectively.



Detection of quasi-electrons. Illustration of the principle of ARPES (**top**). Electrons are emitted from the surface of the sample by photons of energy $h\nu$ and detected as a function of the emission angle θ. For layered materials with quasi-2D electronic structure, the 2D wave vector $\boldsymbol{k}$ of a quasi-electron in the solid is proportional to sin θ. Traces of the intensity of the emitted electron beam as functions of θ (**bottom**, blue curve) and binding energy E (red curve) provide detailed information about the E-versus-$\boldsymbol{k}$ relation and the lifetime of the quasi-electron.

ARPES data on simple 2D systems have revealed well-defined E-versus-$\boldsymbol{k}$ relations in quantitative agreement with quasi-particle models (*2*). In contrast, the photoemission spectra of layered copper oxides—quasi-2D materials that exhibit high-temperature superconductivity—are generally very broad in the normal state. Moreover, in many of these materials, a gap (termed "pseudogap" because of its soft edge) is present on some portions of the Fermi surface (*3, 4*). Taken at face value, these observations are incompatible with the quasi-particle concept, which is only valid as long as the inverse lifetime τ^{-1} of the quasi-electron is much smaller than its energy E. They have thus inspired theories of "spin-charge separation," according to which the true "elementary particles" of the solid are characterized by spin and charge quantum numbers that differ from those of the electron (*5*). Do we have to abandon the quasi-electron concept, one of the pillars of our understanding of solids, in order to describe the copper oxides? And if so, is the breakup of the quasi-particle a necessary or sufficient condition for high-temperature superconductivity? These questions have been vigorously debated for the past 15 years.

Some manganese oxide compounds—which are not superconductors but are famous for the colossal magnetoresistance effect—are well suited to test these ideas because their chemical composition and layered crystal structure are similar to the copper oxides. The physical properties of these materials are in many ways more conventional than those of their copper-based analogs, but their ARPES spectra have proved even more mysterious. For example, the spectra for the metallic manganite $La_{1.2}Sr_{1.8}Mn_2O_7$ are very broad in energy, and a "pseudogap" extends isotropically over the entire Fermi surface (*6*). Many physicists have been skeptical because ARPES is a surface-sensitive technique that probes only the top few atomic layers, and there is no guarantee that these are identical to the bulk. Among the possible explanations that have to be considered for the observed spectral broadening and the pseudogap in the manganites are an insulating surface layer, a surface reconstruction, and other extrinsic effects (*7*).

In one stroke, Chuang *et al.* (*8*) now demonstrate the power of ARPES to reveal the intrinsic electronic structure of the layered manganites and go a long way toward solving the mystery of the pseudogap. In a report on page 1509 of this issue, they report sharp E-versus-$\boldsymbol{k}$ relations near the Fermi level of $La_{1.2}Sr_{1.8}Mn_2O_7$. These observations save the quasi-particle concept for the manganites and allow for the first time a detailed comparison with electronic structure calculations and transport measurements. The spectra are so sharp and the effective mass so small that one might expect a much larger bulk electrical conduc-

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tivity than is actually measured. However, the spectral weight of the quasi-particle features in the ARPES data is very small, suggesting that only a small fraction of the sample is metallic whereas the remainder is insulating. Complementary x-ray and neutron diffraction experiments (*9*) on the same material have provided clues to the nature of these insulating regions by revealing microscopic patches in which charge carriers are localized and form ordered arrays. The periodicity of the charge order within the arrays matches the wave vector connecting nearly flat segments of the Fermi surface determined by Chuang *et al*. It is thus plausible that the metallic and insulating states are on either side of a zero-temperature Peierls-type (*10*) phase transition and that $La_{1.2}Sr_{1.8}Mn_2O_7$ is in the middle of a two-phase coexistence region. The unusual line shape of the ARPES spectra [which are broad in energy but sharp in momentum space (*8*)], as well as some aspects of the x-ray and neutron diffraction data (*9*), suggest that the coexistence may not be static and that fluctuations between nanoscale domains may persist down to 0 K. This remains a topic for future investigation.

The detailed microscopic picture obtained by Chuang *et al.* is new, but extended two-phase coexistence regimes have also been reported for a wide variety of other manganites (*11*). The pronounced propensity toward phase separation is at least partly due to the fact that different *d*-orbitals, with their associated lattice distortions, are available to conduction electrons in the manganites (*12*). This makes these materials highly susceptible to lattice strain. In the copper oxides, where these orbital degrees of freedom are largely quenched, phase separation has also been reported (*13*) but appears to be relatively rare. Certainly, the extremely broad ARPES spectra in the normal state of underdoped and optimally doped high-temperature superconductors cannot be attributed to phase separation. Having barely survived in the manganese oxides, the quasi-electron is still in mortal danger in their copper-based sister materials.

References and Notes

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Published online 26 April 2001;
10.1126/science.1061205
Include this information when citing this paper.

PERSPECTIVES: POPULATION ECOLOGY

Not All Sheep Are Equal

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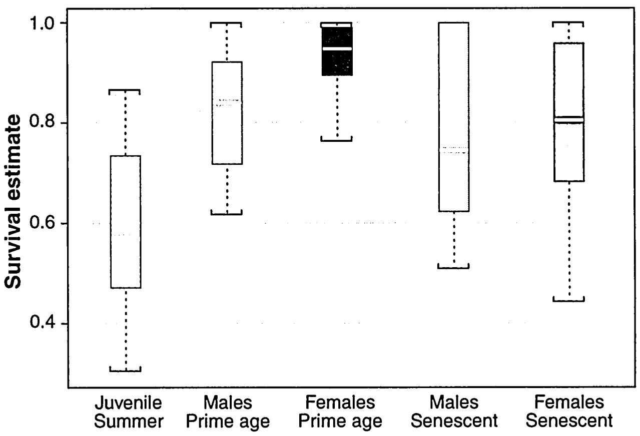
Our lives and those of large mammals are inextricably intertwined: We hunt them and spend time in zoos and wildlife parks viewing them; they feed on domestic animals, damage crops, cause traffic accidents, and may even eat the "produce" of local fisheries. Given this, it is not surprising that we are interested in the ecological factors that govern the dynamics of large mammal populations (*1*). Whereas some large mammals are very abundant (*2*), others are endangered (*3*), spurring the need to identify the ecological factors that maintain, increase, or reduce abundance. Although many studies have tested the accuracy and precision of census methods (*4*), it has proved difficult to test whether yearly field counts of wild mammal populations can accurately determine the factors causing variations in population numbers (*5*).

Enhanced online at www.sciencemag.org/cgi/content/full/292/5521/1499

Such difficulties, however, have not deterred Coulson and colleagues (*6*). On page 1528 of this issue, they report their 11-year field study of a Soay sheep (*Ovis aries*) population on a remote island off the coast of northwest Scotland. The merit of their study resides in the fact that they marked individual Soay sheep and tracked the dramatic annual fluctuations in the sheep population by monitoring the survival and reproduction of individuals of known age and sex. The authors found that age-structured models—which take into account the different ages and numbers of males and females in the sheep population—provided the most accurate predictions of population fluctuations in response to ecological stresses such as adverse weather patterns or increasing population density. Their study is the first to show that large mammal populations of equal size can have markedly different dynamics depending on their sex and age structure. This is not surprising—individual susceptibility to changing environmental conditions is known to differ between males and females and young and old animals—but has been difficult to demonstrate unequivocally.



The rise and fall of large mammals. Variations over 15 years (1985 to 1999) in the age- and sex-dependent survival (box-plot of yearly estimates) of a roe deer population (*Capreolus capreolus*) in eastern France. As with the Scottish island population of Soay sheep (*6*), females of prime reproductive age had the best survival rates and juveniles (during their first summer) the worst.

In feral sheep and in other ungulates, young and old individuals are affected more severely by adverse weather conditions and increases in population density than are adults of prime reproductive age (*7*), and males often tend to be more affected than females (*8*). Similar sex and age differences exist for susceptibility to parasites and disease, the probability of dispersal, and vulnerability to predation or harvesting

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