PERSPECTIVES: SUPERCONDUCTIVITY

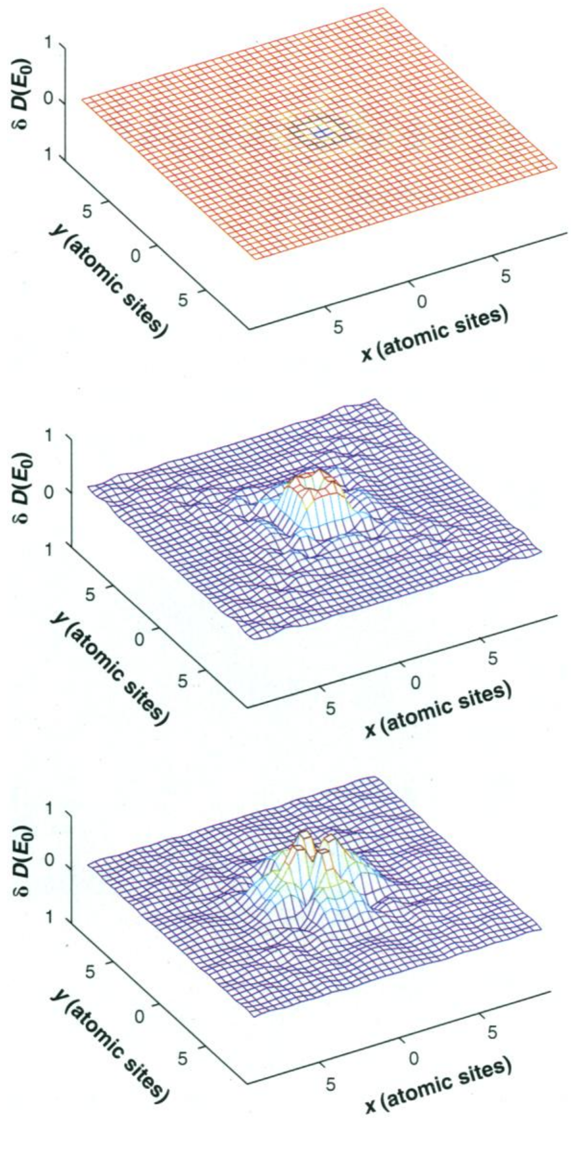
Visualizing Quasi-Particle Scattering Resonances

W. A. Atkinson and A. H. MacDonald

The quantum mechanics of electrons in a solid are relatively simple when imperfections in the crystal such as interstitials, vacancies, and substitutions are neglected and electrons are treated as independent particles. Each electron then sees a perfectly periodic mean-field potential from the positively charged nuclei and the negatively charged electron cloud of the crystal. The quantum mechanics of an independent electron, a "quasi-particle," moving in such a perfectly periodic potential are readily solved on modern computers even for quite complex crystals. In these solutions, the quasi-particles occupy intricate bands of quantum-mechanical states labeled by their momentum $\boldsymbol{k}$, with well-defined energies ε_k. Only states with energies less than the Fermi energy are occupied, and the electronic properties of the crystal are almost entirely determined by the quasi-particles that reside near the Fermi energy. Much of modern condensed matter physics concerns phenomena engendered by the breakdown of this idealized band picture.

The quasi-particles in the Bardeen-Cooper-Schrieffer (BCS) theory (*1*) of the superconducting state are much like the quasi-particles of electron band theory, although there are some important differences. Although BCS theory was originally developed to explain conventional superconductors like aluminum or mercury, experiments suggest that it is applicable as a phenomenological model for high–transition temperature (T_c) superconductors as well. The BCS quasi-particles of high-T_c superconductors are quite different from their counterparts in conventional materials, however, owing to different underlying superconducting mechanisms. Although the mechanism in conventional materials is well known, it remains elusive in high-T_c materials. Experiments that probe the quasi-particle states could shed new light on this fundamental aspect of high-T_c superconductivity. The scanning tunneling spectroscopy observations of single-crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) cuprate samples by Hudson *et al.* reported in this issue (page 88) (*2*) look at the quasi-particles directly by measuring their position-dependent density of states, that is, the quantum mechanical probability of finding quasi-particles with particular energies at particular positions. This work focuses on changes to the density of states produced by an impurity. In addition to providing detailed and previously unavailable information on the nature of the quasi-particle scattering centers in this important material, this kind of investigation may shed light on the nature of the quasi-particles and the origin of their interactions. One satisfying aspect of the observations is their confirmation of earlier theoretical predictions based on BCS theory (*3–5*) for the influence of an isolated scatterer on the quasi-particles of high-temperature superconductors.

In BCS theory, superconductors are characterized by a gap, Δ_k, which is a measure of the condensation energy gained when electrons form superconducting Cooper pairs. In conventional superconductors, Δ_k is only weakly dependent on the wave vector $\boldsymbol{k}$, and a gap of energy Δ appears in the density of states at the Fermi energy. When an energy gap is present in a quasi-particle band, an impurity usually creates a new quantum state bound to that impurity, with an en-



Response to disorder. Scanning tunneling microscopy studies can be used to distinguish different types of superconductors. To illustrate, the change in the position-dependent density of states (DOS) induced by an impurity, situated at $(x,y) = (0,0)$, is compared for three models of BCS superconductors. **(Top)** In a conventional superconductor, the DOS (shown at an energy $E < \Delta$, where Δ is the superconducting gap) is unchanged by an impurity, in accordance with Anderson's theorem. **(Middle)** In a *d*-wave superconductor, a single impurity produces a resonance at an energy $-\Delta < E_0 < \Delta$ (here $E_0/\Delta = -0.09$), and the spatial dependence of the DOS is shown at the resonant energy. The extended arms protruding along the diagonals of the lattice are a signature of *d*-wave superconductivity (*3–5*). **(Bottom)** Changing the band structure also affects predictions for the DOS. In the top and middle panels, a "nearest neighbor" band model, commonly taken as a generic model for high-temperature superconductors, is chosen. In the bottom panel, a realistic band structure for BSSCO is used, based on fits to angle-resolved photoemission experiments (*8*). Although the fourfold structure is still evident, it is suppressed relative to the more naïve predictions shown in the middle panel. In all three panels, results are based on exact T-matrix solutions of the mean-field BCS equations (*9*).

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ergy in the gap. These occur, for example, in the band gaps of semiconductors like silicon and are at the heart of semiconductor electronic technology. It turns out, however, that in superconductors, nonmagnetic impurities do not normally lead to states in the gap (see top panel in the figure). The crucial difference is that in semiconductors, the gap results from the crystal structure, which is altered by disorder, whereas the gap in superconductors results from the pairing of electrons by some attractive interaction. This pairing survives disorder and bound states do not occur, a property closely connected with Anderson's famous theorem (*6*) concerning the influence of disorder on superconductivity.

The situation changes in the case of high-T_c materials such as BSCCO, which are believed to be unconventional "*d*-wave" superconductors (*7*). The term "*d*-wave" refers to the gap Δ_k, which depends strongly on the wave vector $\boldsymbol{k}$ of the electrons in the Cooper pairs. In *d*-wave supercondutors, impurities do create states in the energy gap, much like in semiconductors and quite unlike in conventional superconductors (middle and bottom panels in the figure). One difference between semiconductors and *d*-wave superconductors is that in the superconductors, the new states (called "resonances") are not bound to the impurity but are actually predicted to have extended "tails" away from the impurity (middle panel of the figure). It is these resonances that have been seen by Hudson *et al.* (*2*).

Studies of the detailed structure of the resonances are likely to lead to an improved understanding of the superconducting state. Even within BCS theory, the dependence of the density of states on the underlying band structure (bottom panel of the figure) and the local structure of the impurities has not been fully explored. The possibility that BCS theory might break down is also an exciting prospect. The experiments reported in (*2*) are for "optimally doped" BSCCO, for which the notion of quasi-particle bands still appears to hold. By reducing the oxygen content, BSCCO can be shifted into the "underdoped" regime in which the quasi-particle band picture becomes questionable. Detailed studies of the quasi-particles in this regime have the potential to illuminate new physics relating to strongly interacting quasi-particles.

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PERSPECTIVES: GEOLOGY

Sediments Reveal Their Age

Martin J. Whitehouse

Sedimentary rocks made up of coarse crystals or rock fragments (siliciclastic rocks, such as sandstones) are ubiquitous throughout the geological record, often forming spectacular sequences many thousands of meters thick that may be the sole remaining record of long since eroded mountain belts (see the figure). Determining when these rocks were deposited remains one of the most challenging problems for geologists. As reported in this issue on page 78, McNaughton *et al.* (*1*) used a large ion microprobe to measure lead isotopes in microscopic crystals of a rare-earth element phosphate mineral, xenotime, which commonly grows during diagenesis (the modification of sedimented material shortly after sedimentation). Its lead content is entirely determined by the decay of uranium incorporated into the mineral at the time of its crystallization, and the lead isotopic composition is thus a direct chronometer for the diagenetic process.

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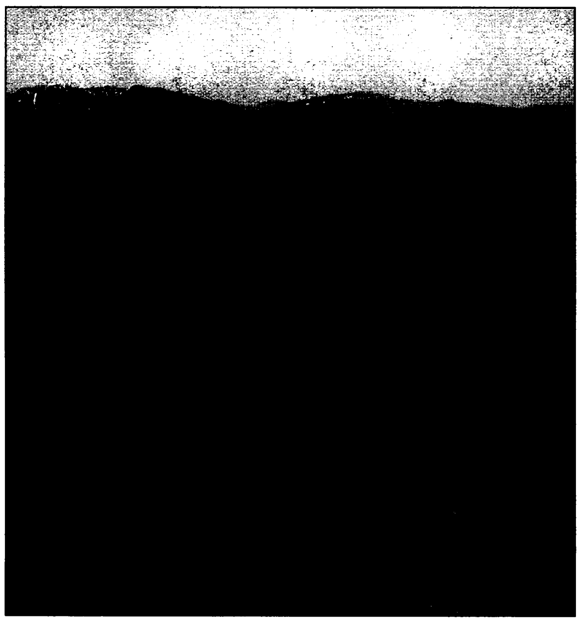
Since the discovery of radioactivity in the late 19th century and the development of modern mass spectrometers in the early 1950s, geologists have increasingly used radioactive decay sequences of elements as natural clocks to refine our understanding of the evolution of Earth. Much of this development has taken place against the backdrop of plate tectonics, the revolution in geological thinking in the 1960s that explains how continents have formed, amalgamated, and broken apart. Reconstructing plate movements through time requires correlation of the ages of rock units across both present and ancient oceans, formed when continents break apart. Such correlations clearly require accurate geochronology. Isotopic dating provides an increasingly precise, and largely unambiguous, way to date events such as the crystallization of a granite, the metamorphism of a gneiss or schist, or the eruption of an ancient volcano, ages that provide invaluable constraints. However, much of the exposed geology of the continents is made up of sediments, some of which—particularly siliciclastic rocks—are notoriously difficult to date. In the Phanerozoic era (that is, the past 540 million years), fine-grained sediments and limestones have preserved body fossils that can be used to erect a detailed "biostratigraphy." When this is calibrated by isotopic dating of, for example, interbedded volcanic rocks, it is precise and accurate. In contrast, in



A record of times past. The Torridonian sandstones in northwest Scotland were deposited after about 1.2 Ga, but accurate dating is difficult.

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