CORRELATED ELECTRONS IN A MILLION GAUSS

Researchers are planning experiments using million-gauss magnets to investigate many of the most intriguing phenomena in condensed matter physics.

Greg Boebinger

Because high-magnetic-field experiments have proved to be valuable tools for illuminating the physics of phenomena ranging from the quantum Hall effect to high-temperature superconductivity, magnet laboratories around the world are constantly striving to produce more intense magnetic fields, using both continuous- and pulsed-field magnets. To date, magnetic fields above 100 tesla have been achieved only by self-destructing (exploding or imploding) magnet technologies. These intense magnetic fields persist for only a few microseconds, and most of the destructive-magnet technologies also destroy the sample. However, the recent development of structurally stronger composite conductors has made feasible the design of pulsed magnets capable of nondestructively delivering 10-ms 100-T (that is, megagauss) pulses. (See the box on page 41.) During the past five years, researchers in both Europe and the US have proposed building such magnets,[1] along with experiments to exploit this new experimental regime.[1–4]

Because a complete review of interesting high-magnetic-field experiments is not possible in this limited space, I focus here on a few systems in which the electron interactions give rise to sufficiently strong correlations that the electrons cannot be treated individually. Such correlations give rise to fundamentally altered behaviors—from spin-density waves to the quantum Hall effect to heavy-fermion behavior to high-T_c superconductivity. More intense magnetic fields, with field energies comparable to the electron-correlation energies, can provide a new window through which to view correlated electron systems.

In condensed matter physics,[5] a wide range of phenomena can be explained within an approximation that treats electrons as individual particles. It is not obvious that such a simple approach would apply in a solid, in which electrons are degenerate and strongly interacting. In a solid, overlapping orbitals of neighboring atoms develop into energy bands, which can have quite complex dispersion relationships between the energies, E, and wavevectors, $\mathbf{k}$, of the electrons. In a noninteracting approximation, electrons fill the lowest energy states up to the Fermi energy, E_F. The surface in momentum space that encloses all occupied energy states at 0 K is called the Fermi surface. Because the electrons with energies near E_F are most energetically accessible, these electrons often govern the electronic properties of a material. The low-energy excitations in many materials can be treated as weakly interacting particles, called quasiparticles, with energies near E_F and an effective mass, m^*, which can be different from the free electron mass. This so-called Landau–Fermi liquid behavior persists in many materials despite the strength of the electron interactions. Researchers are now directing considerable attention toward phenomena that are difficult or impossible to understand in terms of such a Landau–Fermi liquid.[6]

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Fields, spins and energy levels

Because they can alter both the spin configuration and orbital motion of electrons in a material, magnetic fields have long been a conventional experimental tool in condensed matter physics.[5] A magnetic field, H, tends to align electron spin moments and induce a magnetization, M. The dependence of M on H and on the temperature, T, can reveal information about how the spins interact. If the spins are mobile (or itinerant) and form a degenerate electron system, the magnetic susceptibility, $\chi_m \equiv \partial M/\partial H$, will be temperature-independent, or Pauli-like. Such systems can form spin-density waves—modulations of the magnetization caused by spatial variation of the electron-spin orientation—which can be destroyed by high magnetic fields. On the other hand, if the spins are localized on given atomic sites, they will exhibit a Curie magnetic susceptibility, with $\chi_m \propto T^{-1}$. (Interactions between local moments give rise to a Curie–Weiss susceptibility, with $\chi_m \propto (T \pm T_0)^{-1}$, where the minus sign corresponds to ferromagnetic interactions and the plus sign to antiferromagnetic interactions, and T_0 is a constant characteristic of the material.) Magnetic fields can directly measure exchange energies in systems of local spins by inducing transitions between different spin configurations of the system. Because correlated-electron effects typically occur below a characteristic temperature, T^*, one often expresses their energy scales, E^*, in kelvin, with the implicit understanding that $E^* = k_B T^*$. Thus, the typical energy scale for spin-flip transitions is the Zeeman energy, $E_Z = g^* \mu_B H$, where g^* is the quasiparticle's spectroscopic g-factor and μ_B is the Bohr magneton. For $g^* = 2$, the free-electron value, this is roughly 1.34 K per tesla. Intense pulsed magnetic fields are a unique tool for probing many magnetic materials because the energy difference between two spin configurations is often comparable to thermal energies at room temperature.[1–4]

Magnetic fields also affect electrons' orbital motions. Lev Landau determined that a magnetic field acting on a free electron is equivalent to the harmonic oscillator problem. The resultant evenly spaced energy levels, called Landau levels, are separated by the cyclotron energy $E_c = \hbar\omega_c = eH/m^*$, which increases by 1.34 K/T for a quasiparticle with m^* equal to the free-electron mass, m_e. Each Landau level can be "spin-split" into two energy levels separated by E_Z, with one level occupied by electrons

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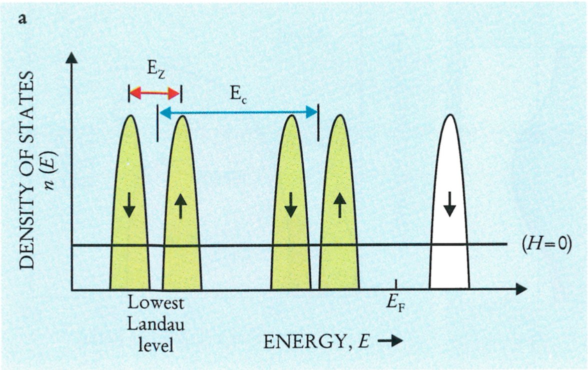
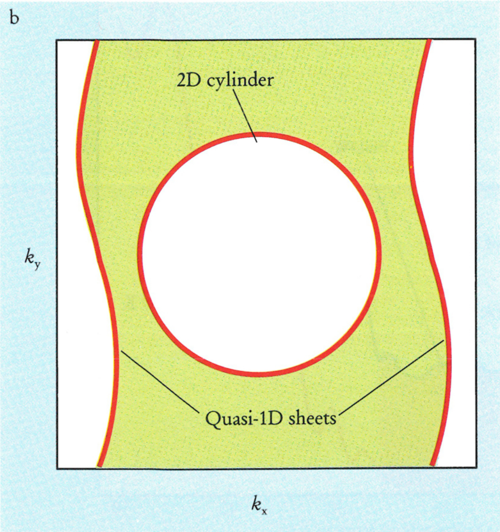
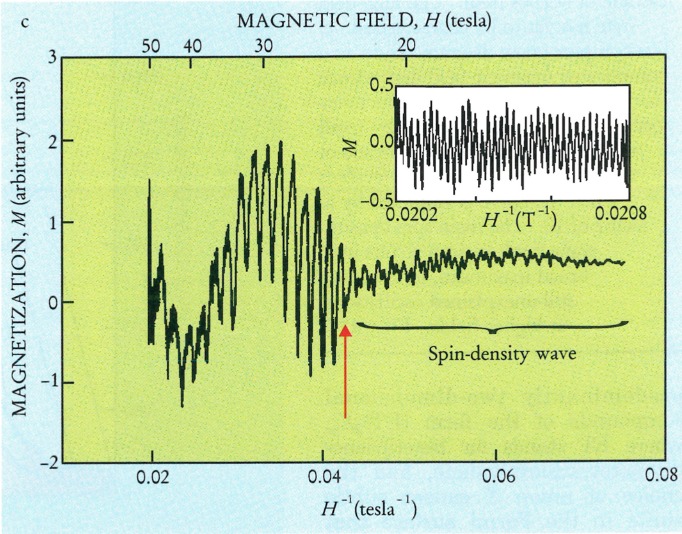


Magnetic fields and Fermi surfaces. **a:** In a two-dimensional electron system, a magnetic field, H, destroys the uniform density of states (indicated by $H = 0$), forcing electrons to occupy discrete energy levels (Landau levels), separated by the cyclotron energy, E_c, up to the Fermi energy, E_F. Each Landau level accommodates both spin-up and spin-down electrons, the energies of which differ by the Zeeman energy, E_Z. **b:** In wavevector (**k**) space, the Fermi surface of a two-dimensional electron system is a cylinder (red), and that of a quasi-one-dimensional compound comprises two slightly warped one-dimensional sheets (red). **c:** Experimentally, one determines the Fermi surface from quantum oscillations, periodic in $1/H$. Because the oscillation frequency depends on electron density, the magnetization of κ-$(ET)_2KHg(NCS)_4$ oscillates much more slowly than that of a metal such as copper (inset). The enhanced amplitude above about 23 T (red arrow) indicates the destruction of a spin-density wave.[8] **Figure 1**





with spins aligned along H and the other by electrons with spins anti-aligned. (See figure 1a.)

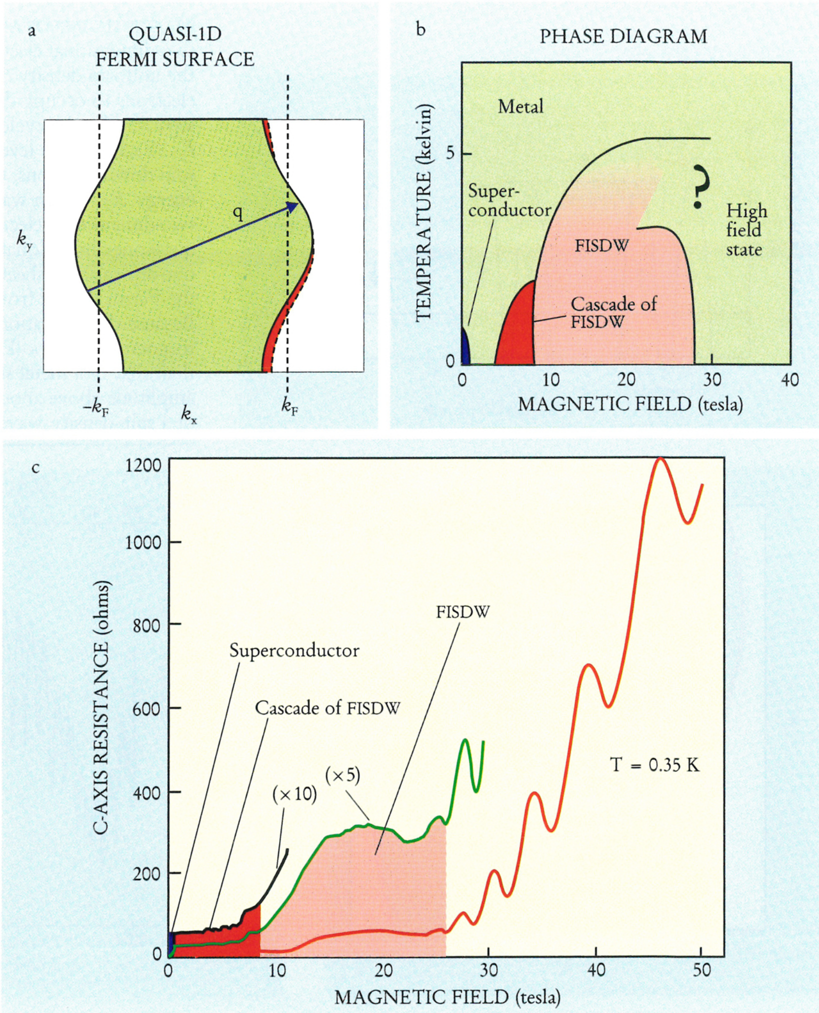
As an illustration designed to be be useful throughout this article, consider a single parabolic energy band, with $E = \hbar^2k^2/2m^*$. According to this equation, a band with a flat dispersion relation, $E(k) \approx$ constant, corresponds to a heavy effective mass, m^*. (Localized electrons correspond to infinite m^*.) If the electrons can move only in, say, the x direction, the Fermi surface consists of two planar sheets defined by $k_x = \pm k_F \equiv (2m^*E_F/\hbar^2)^{1/2}$. If the electrons are confined to the (x,y) plane, the Fermi surface is a cylinder defined by $k = (k_x{}^2 + k_y{}^2)^{1/2} = k_F$. (See figure 1b.) The cylinder's cross-sectional area, A_{FS}, determines the density of the two-dimensional electron system, $n = A_{FS}/(2\pi^2)$.

The cyclotron and Zeeman energies and the number of electron states, eH/h, in each Landau level all increase linearly with increasing magnetic field, H. Thus, as the magnetic field increases, the spin-split Landau levels move to higher energy, and fewer of them are occupied. The number of energy levels occupied—the "filling factor," $\nu = nh/eH$—is the ratio of the areal density of electrons, n, to the areal density of magnetic flux quanta, eH/h. In figure 1a, the position of E_F is shown for $\nu = 4$. As each energy level passes through E_F, it depopulates, causing the material's transport and thermodynamic properties to oscillate periodically in $1/H$. The quantum oscillations most often studied are those in resistivity (Shubnikov–de Haas oscillations) and magnetization (de Haas–van Alphen oscillations).[5,7]

Applying a magnetic field to a solid superimposes the Landau-level energy structure on the material's band structure. The frequency of the quantum oscillations is proportional to the cross-sectional area of the Fermi surface in the plane perpendicular to the applied magnetic field. The temperature and magnetic-field dependences of the quantum-oscillation amplitude reveal the quasiparticles' effective mass and scattering rate.

This article necessarily focuses on materials with particularly simple Fermi surfaces, for which a single frequency dominates the quantum oscillations. Materials with more complicated Fermi surfaces exhibit quantum oscillations at many frequencies. Thus, in principle, detailed studies of the angular dependence of these quantum oscillations can map the exact shape of the Fermi surface of any material. Historically, the determination of the Fermi surfaces in common metals, such as copper and gold, was one of the earliest triumphs of research using magnetic fields in condensed matter physics.[5,7]

For more than a decade, measurements at intense magnetic fields on organic charge-transfer salts have found that these compounds have remarkably complicated phase diagrams in spite of their relatively simple one-dimensional and two-dimensional Fermi surfaces.[1,3,4] The data[8] in figure 1c are for a compound in a family of



FERMI SURFACES AND PHASE DIAGRAMS. **a:** Compounds with one-dimensional Fermi surfaces can form spin-density waves when the electron-spin orientation distorts with a spatial periodicity corresponding to a wavevector, **q**, that would cause the two sheets (black lines) of the Fermi surface to overlap, or "nest." The distortion lowers the system's overall energy, particularly if the nesting is perfect. In some systems, imperfect nesting leaves a small two-dimensional pocket of charge carriers (red). **b:** Such interactions result in a very complex phase diagram, including a metallic phase, a superconducting phase (purple) and a cascade of FISDWs (red). The high-field state has yet to be characterized. **c:** The complex phase diagram results in a complicated magnetic field dependence for the resistance.[9] Superconductivity occurs at low fields, followed by small oscillations arising from a cascade of FISDWs (red region) that are evident when the curve is amplified by a factor of 10. The main spin-density wave (pink region) results in a broad maximum, followed by still-unexplained oscillations at higher fields. FIGURE 2

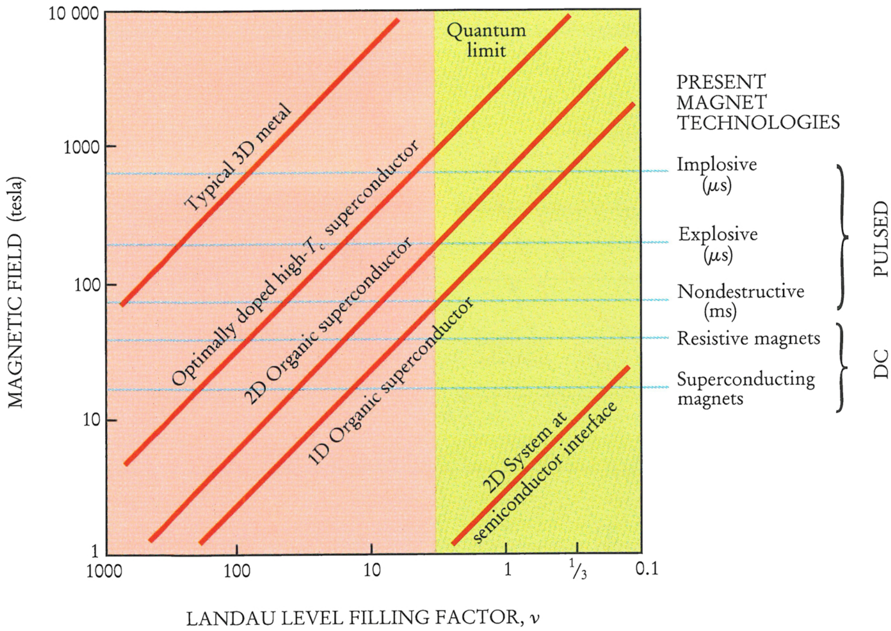
predominantly two-dimensional compounds of the form $(ET)_2X_n$, where ET stands for bis(ethylenedithio)tetrathiafulvalene, and the choice of anion X causes subtle shifts in the Fermi surface that determine whether the ground state is, for example, a spin-density wave as in figure 1 (with $X = KHg(NCS)_4$), or a superconductor with $T_c = 10$ K (with $X = Cu(NCS)_2$).

Organic compounds of the form $(TMTSF)_2X_n$ (where TMTSF is tetramethyl tetraselenofulvalene) exhibit deceptively simple quasi-one-dimensional Fermi surfaces.[1,3,4] Compounds with one-dimensional Fermi surfaces are especially prone to the formation of spin-density waves. This is because strong interactions between electrons of the two quasi-one-dimensional sheets make it energetically favorable for the electron spins to modulate with a spatial periodicity corresponding to the wavevector, **q**, with a magnitude of approximately $2k_F$. (See figure 2a.) A magnetic field can induce subtle shifts in the **q** corresponding to minimum energy, resulting in a field-induced spin-density wave (FISDW). As a result, compounds in this family have strikingly complicated phase diagrams. For $X = ClO_4$ in figure 2b, the diagram includes a superconducting phase ($T_c = 1$ K), a metallic phase, a cascade of at least seven FISDWs, and a high-field state, which has yet to be characterized and exhibits strong—and still unexplained—quantum oscillations at the highest fields probed.[9]

Quantum Limit

In the quantum limit, which occurs when the magnetic field is intense enough that the filling factor, ν, is near unity, strong interactions between magnetic flux quanta and electrons give rise to new phenomena,[6,10] one of the best known being the integer quantum Hall effect in two-dimensional metals formed at semiconductor interfaces. In the classical Hall effect, the Lorentz force exerted on the charge carriers induces a Hall voltage, V_{Hall}, transverse to the current, I. The Hall resistivity, $R_{Hall} \equiv V_{Hall}/I$ depends linearly on the magnetic field and inversely on the charge-carrier density. However, in the integer quantum Hall effect, R_{Hall} exhibits plateaus precisely quantized at $h/(\nu e^2)$ for integral values of ν. The plateaus are accompanied by a vanishing resistance parallel to the current, in part because E_F lies in an energy gap between Landau levels (as in figure 1a). At even higher magnetic fields, similar plateaus appear at fractional filling factors with odd denominators, despite the fact that there is no energy gap for individual electrons at such filling factors. This fractional quantum Hall effect can be understood in terms of new charge carriers—called composite fermions—each consisting of an electron bound to a pair of flux quanta. (See PHYSICS TODAY July 1993, page 17.) In effect, the fractional quantum Hall effect is the integer quantum Hall effect for these composite fermions.

Although, in principle, the quantum limit can be reached for all materials, given sufficiently high magnetic fields, the quantum limit in ordinary metals such as copper or gold occurs at fields on the order of 50 000 T.[5] Figure 3 shows the magnetic fields needed to reach the quantum limit in a number of the materials discussed in this article.



APPROACHING THE QUANTUM LIMIT. Electron systems exhibit interesting quantum effects as their filling factor, ν, approaches 1 (green region). In a given material, the filling factor depends linearly on the charge-carrier density and inversely on the magnetic field. The blue lines to the left of the listed technologies indicate the maximum fields they can currently achieve. FIGURE 3

Kondo interactions

The Kondo interaction is an antiferromagnetic interaction between a localized spin moment and mobile electrons that gives rise to the unusual behavior of "heavy-fermion" metals.[2,3,6,11] (See the article by Daniel Cox and Brian Maple, PHYSICS TODAY, February 1995, page 33.) At high temperatures, these materials behave like ordinary metals possessing localized spins: The charge carriers are itinerant electrons with effective masses near the free-electron mass, while the localized spins (usually from cerium or uranium atoms) give rise to a Curie–Weiss susceptibility—that is, $\chi_m \propto (T+T_0)^{-1}$. However, below a certain temperature T^* (typically 10–100 K), the charge carriers assume masses up to several orders of magnitude larger than those in ordinary metals, and the susceptibility becomes Pauli-like (that is, temperature independent), indicating the destruction of the localized spins. Some of the heavy-fermion metals, such as $CeRu_2Si_2$, are also superconductors. Specific heat measurements have shown that the quasiparticles that form the Cooper pairs in these superconductors are quite heavy, and, thus, that the heavy quasiparticles are itinerant at temperatures below T^*.[3] Although the nature of the heavy-fermion correlated ground state is still imperfectly understood, figure 4 depicts schematically how the behavior of heavy-fermion metals can be understood in terms of hybridization, or mixing, between bands of itinerant and localized electrons.

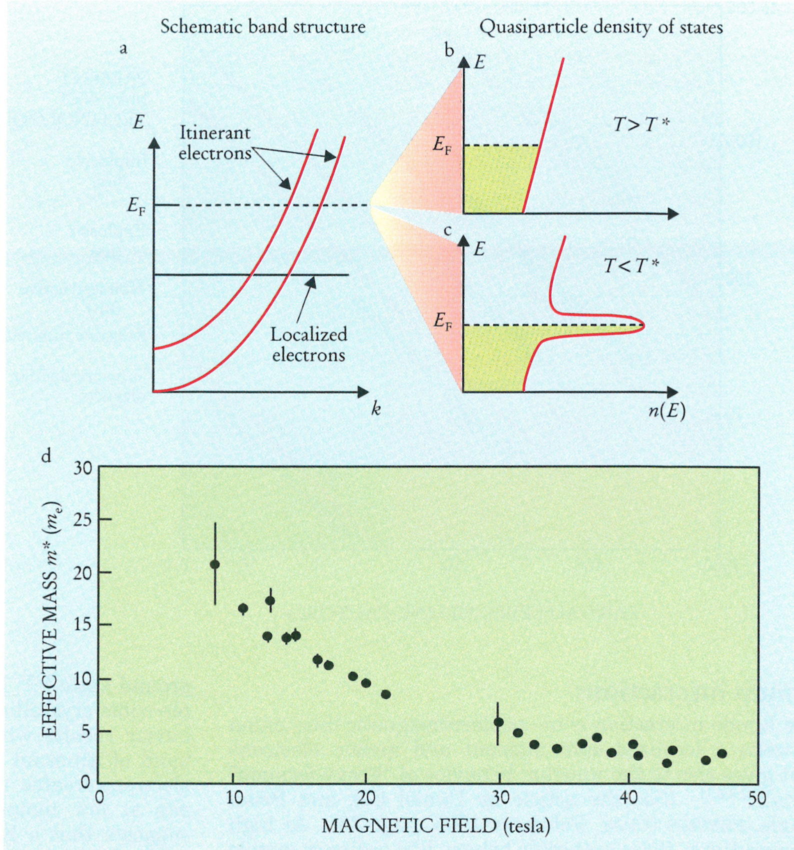
The energy scale, T^*, of the Kondo interaction suggests that magnetic fields of 10–100 T will suppress the low-temperature correlations arising from the Kondo interaction. Indeed, although each heavy-fermion metal behaves somewhat differently, high-magnetic-field experiments on heavy-fermion metals with small T^*s have successfully "undressed" the quasiparticles and recovered aspects of the uncorrelated behavior seen at high temperature.[4,12] Quantum oscillation experiments with CeB_6 have found that the quasiparticles' effective mass, m^*, decreases dramatically as the magnetic field increases up to 50 T. (See figure 4d.) In $CeRu_2Si_2$, not only does the effective mass decrease with increasing field, but the frequencies of the quantum oscillations shift in a manner that suggests the f-like electrons are disappearing from the Fermi surface.

Related compounds, the Kondo insulators, exhibit high-temperature behavior similar to that of the heavy-fermion metals; below T^*, however, the Kondo insulators simultaneously lose magnetic moments and charge carriers, resulting in a low-temperature insulating ground state.[2,13] Most of the Kondo insulators have simple-cubic crystalline structures, and, apparently their behavior results when the hybridization between a single band of itinerant electrons and a flat band of localized f electrons creates an energy gap, in which the Fermi energy sits at low temperature. (See figure 5.) This model suggests that a Kondo insulator will become metallic in magnetic fields high enough that the spin splitting of the two bands exceeds the size of the energy gap. Indeed, recent experiments in pulsed magnetic fields up to 60 T have discovered a metallic state above 50 T in the Kondo insulator, $Ce_3Bi_4Pt_3$. Higher magnetic fields would increase the number of heavy-fermion metals and Kondo insulators that could be investigated and thereby aid in the search for a systematic understanding of the electron correlations resulting from the Kondo interaction.

High-T_c superconductors

High-magnetic-field experiments offer many opportunities for investigating the properties of high-T_c superconductors and the unusual properties of the resistive state out of which the superconducting phase arises.[6,14,15] (See the story on page 17 of this issue.) These superconducting compounds are doped antiferromagnets. (See the inset in figure 6.) Without intense magnetic fields, the low-temperature transport properties of the resistive state can be measured only in extremely overdoped (metallic) or underdoped (insulating) samples. Just as the critical temperature, T_c, is unusually large in these superconductors, so is the upper critical field H_{c2}—which is the maximum magnetic field at which superconductivity can occur. High-magnetic-field experiments have found that, unlike the conventional superconductors, H_{c2} in at least two of the high-T_c compounds increases rapidly with decreasing temperature. (See figure 6.) For $Bi_2Sr_2CuO_{6-\delta}$ (where δ indicates the amount of doping), which has a T_c of only 20 K, a magnetic field of 30 T was required to suppress superconductivity at low temperatures. Recent experiments on $La_{2-x}Sr_xCuO_4$ (T_c = 40 K at optimal doping) required 60-T magnetic fields to suppress superconductivity sufficiently to reveal that the normal-state resistivity in underdoped samples diverges as the logarithm of the temperature. Studies of H_{c2} in other high-T_c

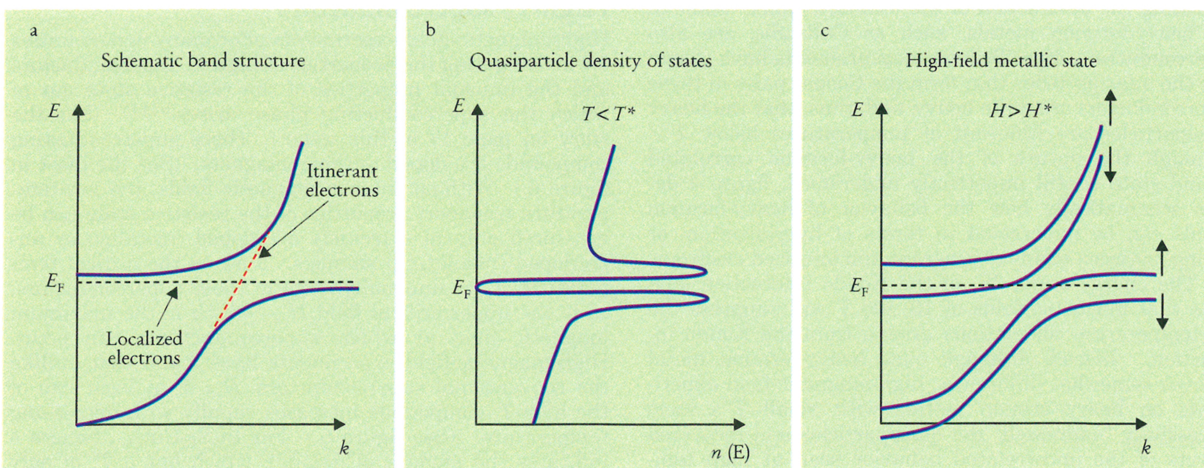
HEAVY-FERMION METALS. **a:** These materials exhibit unusual behaviors because of hybridization between a band of localized f electrons (black), and a number of conduction bands of itinerant electrons (red). **b:** Above the characteristic temperature, T^*, these compounds behave like ordinary metals, with a smooth quasiparticle density of states, $n(E)$. The quasiparticles have masses near the free-electron mass, m_e. **c:** Below T^*, hybridization of the localized and itinerant bands gives the electrons a very heavy effective mass, m^*, causing $n(E)$ to develop a narrow resonance near E_F. **d:** Many experiments have shown that high magnetic fields suppress heavy-fermion effects, as shown by the decrease of m^* in CeB_6 as a function of increasing magnetic field H.[12] FIGURE 4



compounds, as well as low-temperature studies of normal-state properties will clearly require the highest fields available.

Recent experiments have also investigated what happens when a superconductor approaches the quantum limit.[16] Once Landau levels were resolved, quantum oscillations were seen in the superconducting phase ($H < H_{c2}$) in a variety of superconductors, including $NbSe_2$, V_3Si and Nb_3Sn. Magnetization measurements on $YBa_2Cu_3O_{7-\delta}$ in destructive pulsed magnetic fields have also indicated quantum oscillations below H_{c2}, although additional experiments will be required to map the entire Fermi surface. Because quantum oscillations have smaller amplitudes below H_{c2}, higher magnetic fields will greatly assist efforts to determine how the Fermi surfaces of the high-T_c cuprates evolve as a function of charge-carrier concentration.

Almost 30 years ago, A. K. Rajagopal and R. Vasudevan first predicted that Landau-level quantization should give rise to oscillations in the upper critical magnetic field curve, $T_c(H)$. Such oscillations (shown schematically in figure 7) arise from the same oscillations in the density of states at the Fermi energy that give rise to quantum oscillations in the magnetization and resistivity.



KONDO INSULATORS behave like heavy-fermion metals at high temperature, but lose charge carriers and magnetic moments below a given temperature, T^*, becoming insulators. **a:** This behavior can be understood in terms of hybridization (solid purple lines) between a single conduction band of itinerant electrons (red dashed line) and a band of localized f electrons (black dashed line). **b:** The hybridization gives rise to an energy gap in the quasiparticle density of states, $n(E)$, centered around the Fermi energy, which makes the compound an insulator at low temperature. **c:** Turning on a magnetic field restores metallic behavior by spin-splitting the two energy bands and causing them to overlap. FIGURE 5

Superconductors in the quantum limit are receiving renewed interest because of the possibility that superconductivity may occur at fields well above the semiclassical H_{c2}.[2,17] Such re-entrant superconductivity may occur when Landau level quantization enhances the density of states at the Fermi energy (as shown in figure 1a for a two-dimensional material). In high magnetic fields, spin polarization should eventually suppress superconductivity (except, perhaps, in the case of a triplet superconductor, where the Cooper pairs are already spin polarized). An-

Generating High Magnetic Fields

The development of high-intensity magnets is in a state of constant flux.[1] The recent development of stronger permanent magnets, such as those made of Sm–Co and of Nd–Fe–B, has had tremendous technological impact, ranging from in-your-ear stereo speakers to the ubiquitous presence of small, high-torque motors in modern life. However, because the magnetization of permanent magnets results from electron-spin polarization, the field strength such magnets can achieve is limited. Even if nearly all the electron spins in a material were polarized—an admittedly unrealizable upper theoretical limit—the resulting magnetic field would be around 5 T.

Electromagnets generate magnetic fields from electric currents and face no such obvious limits. Their intensities are bounded instead by considerations of energy dissipation and material strengths. Each class of high-intensity electromagnets, from superconducting magnets to the explosive, destructive pulsed magnets, addresses (or ignores) these problems differently.

Superconducting materials conduct electricity without dissipation because electrons of opposite spin and momentum bind together to form charge carriers called Cooper pairs. Superconducting magnets using NbTi wire and Nb_3Sn wire have now exceeded 20 T. These compounds are examples of type II superconductors, which allow a magnetic field to penetrate the superconducting state in the form of thin filaments of flux. A vortex of circulating superconducting current surrounds each flux filament. A magnetic field that exceeds the upper critical field, H_{c2}, destroys superconductivity, either by spin-polarizing the electrons or by threading the superconducting state with so many flux filaments that the nonsuperconducting cores of these filaments begin to overlap.[5]

Electromagnets constructed from superconducting wire are limited not only by the intrinsic upper critical magnetic field, above which superconductivity is destroyed, but also by the mechanical properties of the wire itself. Historically, the evolution of highest-field superconducting magnets has focused on developing reliable, high-strength conductors from often-brittle superconducting compounds. As the problems associated with each new conductor have been solved, the peak achievable field has increased from 12 T with NbTi, to 20 T with Nb_3Sn, to almost 22 T at the National Research Institute of Metals (NRIM) in Tsukuba, Japan, using a solenoid of $(Nb,Ti,Ta)_3Sn$ with a small insert solenoid fabricated from $Bi_2Sr_2CaCu_2O_y$, a high-temperature superconductor. As for the future of superconducting magnets, although the high-temperature superconductors offer upper critical magnetic fields estimated to exceed 100 T, they also pose daunting technological challenges because they are very brittle and because magnetic flux motion causes dissipation even below the superconducting transition.

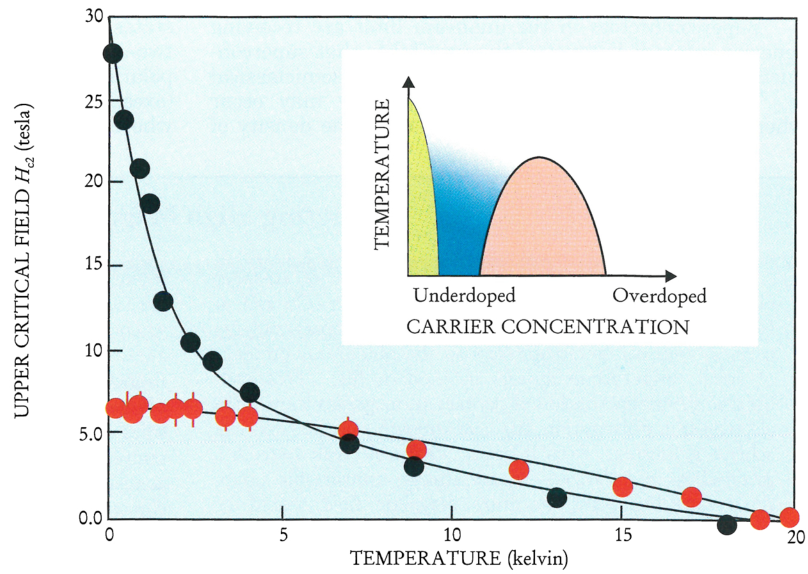
To generate magnetic fields much higher than 20 T, magnet designers have had to turn to resistive magnets. Successful designs not only must handle the exceedingly high stresses but also must accommodate the cooling water required to offset Joule heating in the conductor. Recently, the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida, successfully generated a continuous magnetic field of nearly 34 T in a resistive magnet. Resistive magnets of this intensity can dissipate up to 20 MW, consideration of which has led designers to look to hybrid resistive–superconducting solenoids to generate still higher magnetic fields. By nesting a resistive magnet inside a large superconducting solenoid, the Francis Bitter Magnet Laboratory (FBML) at MIT in Cambridge, Massachusetts, has exceeded 35 T. These peak intensities can be further enhanced by several tesla by placing the sample under study between holmium or dysprosium flux concentrators. New hybrid magnets are currently under construction: a 40-T hybrid at NRIM and a 45-T hybrid at NHMFL in Tallahassee.

One can generate still higher magnetic fields and sidestep cooling problems by using subsecond pulsed magnets. (The pulse duration is limited by the dissipated power, which would melt the conductor in about a second.) Currently, the peak achievable fields are above 72 T, even though such fields exert internal pressures on the magnet windings of 1.3 gigapascals (200 000 pounds per square inch)—stresses exceeding the tensile strengths of most materials.[18]

The use of exceptionally strong microcomposite wires has been one strategy for dealing with such stresses and increasing achievable magnetic fields. Ten years ago a magnet built at FBML achieved a pulsed field of 68 T. This magnet used a CuNb microcomposite wire developed by Harvard University (Cambridge, Massachusetts), Supercon (Shrewsbury, Massachusetts) and Ames Laboratory (Ames, Iowa). Two other strategies for handling the internal stresses on the conductors have been developed more recently. One, inspired by an original design from the Catholic University of Louvain in Belgium, reinforces each layer of magnet windings with a layer of fiberglass or some other strong fiber. The other strategy, pursued at Bell Laboratories, seeks to distribute the stress among the magnet windings by carefully choosing the conductor for each layer of windings according to its ductility, tensile strength and conductivity.

These pulsed magnets are often powered by a capacitor bank, where the shape, or time dependence, of the pulse is determined by the bank's capacitance and magnet's inductance. More complicated power supplies can "shape" the pulse by continuously varying the voltage applied to the solenoid. A 40-T shaped-pulse magnet has a long history of success in The Netherlands—at the University of Amsterdam—and 60-T designs are currently under construction both there and at NHMFL in Los Alamos, New Mexico. The proposed 100-T magnets would be of a "pulsed hybrid" design with a 10-ms, capacitor-driven magnet nested in the bore of a 100-ms shaped-pulse magnet.

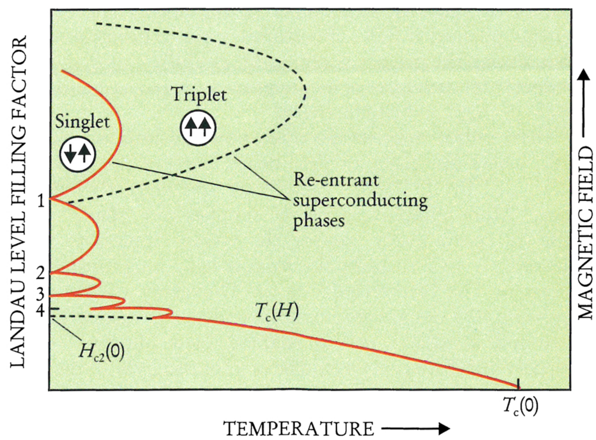
The highest experimental magnetic fields are generated in self-destructing magnets, in which the pulse duration is limited to the few microseconds between the triggering of the device and the arrival of the shockwave. An exploding technology used at the Institute for Solid State Physics in Tokyo and, more recently, at the Humboldt University of Berlin, generates magnetic fields of over 200 T by discharging a 40–60-kV capacitor bank across a single copper loop—typically 1 cm in diameter. Imploding pulsed magnets can achieve still higher fields, but they destroy the sample in the process.



SOME HIGH-T_c SUPERCONDUCTORS exhibit magnetic behaviors quite different from those of conventional superconductors. The upper critical field, H_{c2}, for $Bi_2Sr_2CuO_{6-\delta}$ (black circles) diverges as temperature goes to zero, in contrast to the conventional behavior of H_{c2} for $Nd_{2-x}Ce_xCuO_4$ (red circles), which is one of the few high-T_c compound with negative charge carriers. Large values of T_c mean that high magnetic fields are required to suppress superconductivity in optimally doped samples (pink) and study how the normal state moves from insulating (blue) to metallic (white) as doping increases. Undoped high-T_c compounds are antiferromagnets (green). (Courtesy of Michael Osofsky.) FIGURE 6

other prediction suggests that the one-dimensional superconductors, such as $(TMTSF)_2ClO_4$, might also exhibit re-entrant superconductivity if the magnetic field is perpendicular to the one-dimensional molecular chains and sufficiently strong that the electrons are confined to a single chain. Under such conditions, the electrons can not circulate current around the magnetic flux lines, and the ability of the magnetic field to suppress superconductivity would be inhibited.

Although this article has focused on correlated electron systems, hopefully it has given some indication of the wide variety of experiments that would benefit from the availability of nondestructive pulsed magnetic fields in the 100-T range. Because many experiments would benefit more from longer pulse durations than from higher peak-field intensities, advances in shaped-pulse magnets and continuous-field magnets, whether resistive, superconducting, or hybrid, are all important endeavors for progress in condensed matter physics.



RE-ENTRANT SUPERCONDUCTIVITY may occur at magnetic fields well above the classical upper critical field, $H_{c2}(0)$, because Landau-level quantization enhances the density of states at the Fermi energy and favors the formation of superconducting Cooper pairs. Such re-entrant superconductivity would reveal itself in oscillations in the critical temperature, T_c, as a function of the applied field. Above a certain field, all the electrons become spin-polarized, destroying the singlet Cooper pairs. However, triplet Cooper pairs might survive in still higher fields. FIGURE 7

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