chain crystallites. The T-ULEED experiment revealed that ultrafast melting of the PMMA follows a hierarchy of events. The graphene substrate absorbing the laser pump energy increased its temperature to 540 K within the pump-pulse duration of 80 fs. Energy transfer to the PMMA bilayer led to an elevated temperature equilibration with a characteristic time of 43 ps. When the magnitude of transferred energy (heat) was sufficient, a loss of PMMA crystallinity, a change in PMMA chain spacing, and structural relaxation to the amorphous phase occurred on characteristic times of hundreds of picoseconds.

The innovative part of the T-ULEED experiment is the short-pulse illumination of a tungsten nanotip to produce the electron pulses. In recent years, it has been shown that few-cycle laser pulses focused to the apex of metal tips can induce field-driven photoemission of ultrashort electron pulses (*3*, *4*). This phenomenon has now been explored in cases ranging from multiphoton ionization to above threshold ionization and strong-field tunneling emission, including carrier-envelope phase effects (*5*).

Exploiting strong-field emission from a metal nanotip opens up the new frontier of ultrafast LEED techniques by substantially miniaturizing the electron diffraction apparatus compared with the high-energy diffraction methods that have recently come to fruition (*6*–*8*). Ultrafast electron or x-ray diffraction (*9*) techniques have provided insight into the structural dynamical events underlying processes as diverse as photoinduced chemical reactions in the gas phase, charge transfer in bulk systems, and melting of metal or semiconductor superstructures.

The T-ULEED method of Gulde *et al.* widens the field of ultrafast structural dynamics to surface science. Previous ultrafast electron diffraction methods relied on sophisticated experimental set-ups to produce the intense, short electron pulses needed to probe irreversible structural changes or to achieve femtosecond time resolution. Achieving similar time resolution with the T-ULEED experiment will be the next challenge. ■

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PHYSICS

An optical twist for triplet superconductors

Optical measurements may help reveal the secrets of exotic superconductivity and manipulate the pair condensate

By **Dirk van der Marel**[1] *and* **George Albert Sawatzky**[2]

The discovery of superconductivity in UPt_3 (*1*, *2*) immediately led to ideas and speculations about how the electrons pair up and condense into a superconducting state. Specifically, questions have surrounded the symmetry of the order parameter in these materials (a measure of the density of the condensed electron pairs, and of their phase). From the outset, it was suspected that these so-called heavy-fermion systems were "odd-parity" or "p-wave" superconductors (*3*); that is, instead of the electrons pairing up into spin-singlet states with opposite spins as in conventional superconductors, they would form spin-triplet states where the spins of the paired electrons point in the same direction. To date, consensus concerning the microscopic pairing mechanism applicable to these heavy-fermion systems has been lacking. On page 190 of this issue, Schemm *et al.* (*4*) report results of magneto-optical experiments that define the nature of the superconducting pairing in these compounds. The Kerr-rotation experiments provide compelling evidence in favor of the odd-parity mechanism, and show that UPt_3 belongs to the same universality class as superfluid ^{3}He and the ruthenates.

Various mechanisms favoring odd-parity superconductivity have been presented, either mediated by ferromagnetic spin-fluctuations (*5*) or by Hund's rule coupling (*6*–*9*). Other models have favored singlet superconductivity (*10*). Historically, the observation of strong mass renormalization in UPt_3 and other heavy-fermion metals suggested a close analogy with ^{3}He, which is also a Fermi liquid characterized by strong mass renormalization. Taken together with the high-spin susceptibility, the possibility was explored that the pairing symmetry in UPt_3 would also have similarities with ^{3}He, which is of the triplet variety.

Before the unique playground offered by these unconventional superconductors can be exploited, several questions must be answered. One concerns the interactions responsible for selecting the p-wave (triplet) pairing with a pair spin, $S = 1$, rather than the more conventional s-wave (singlet) pairing in which the pairs have zero spin. It could be that p-wave pairing occurs much more often than was generally assumed, but has gone unnoticed because the experiments were unable to detect the p-wave pairing aspects. In this regard, one of the first indicators of unconventional pairing was the extreme sensitivity to impurities. So what other tests, if any, of p-wave superconductivity are possible beyond the existing ones, including the extremely high-sensitivity magneto-optical measurements that Schemm *et al.* report?

> ***"... finding the correct balance between these interaction channels may be sufficient to form an exotic superconductor with a desired set of properties."***

It is also desirable to distinguish between the various proposed mechanisms for the pairing. Recently, Hund's rule coupling has become popular in the description of correlated electron systems such as the iron-based pnictide superconductors as so-called Hund's rule metals. In Hund's metals, the mass of the electrons is enhanced because of the Hund's rule interaction, J, that tends to align the spin of electrons when they occupy the same uranium atom.

Another question is whether the $S = 1$ character of the paired electrons can be exploited in potential spintronics applications that would use the flow of a supercurrent carried by condensed pairs and carrying with it a magnetic moment.

Most superconducting materials are of the conventional $S = 0$ variety in which

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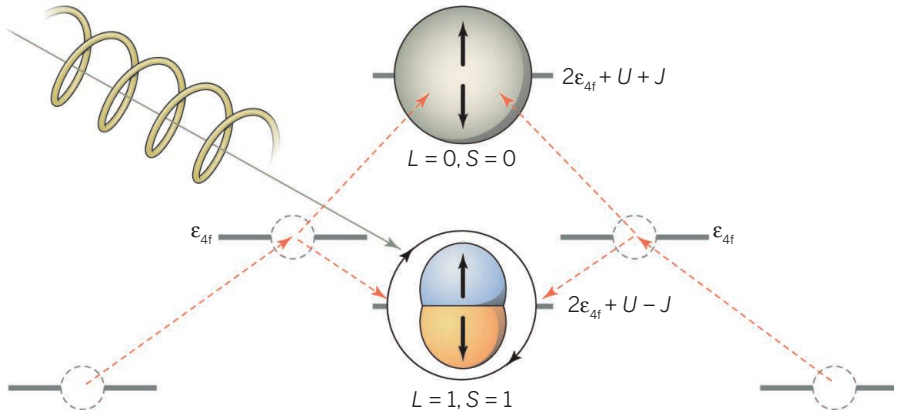

Upon reflection. Image showing how circularly polarized light interacts with superconducting Cooper pairs bound by Hund's rule coupling. Two electrons that move into the 5f shell of the same uranium atom have an interaction energy $U + J$ if they form a singlet spin = 0 state, and $U - J$ if they form a triplet spin = 1 state. Here, U represents the average Coulomb interaction between two electrons occupying the same 5f shell, and J is the Hund's rule exchange interaction. U is much more strongly screened than J. For $U < J$, an attractive interaction results between two conduction electrons hybridizing with the same uranium atom, but only if their spins are parallel. The antiparallel spin state would result in a repulsive interaction with this mechanism. Because of the angular momentum of the pair, left-handed and right-handed photons do not have the same absorption coefficient, and, because linear polarized light is a superposition of left- and right-handed light, the handedness of the absorption causes a finite rotation of the polarization angle.

magnetism was thought to be incompatible with the superconducting state. This view, however, has changed with the advent of the high-temperature superconducting cuprates and, more recently, by the iron pnictides and chalcogenides, both of which are fundamentally magnetic. The possibility of mixed singlet-triplet character has been proposed, because the low symmetry of the underlying crystal lattice allows for such a mixture to exist. If the interactions present that give rise to this type of pairing can be identified, finding the correct balance between these interaction channels may be sufficient to form an exotic superconductor with a desired set of properties.

Recently, superconducting two-dimensional electron gases have been generated by molecular beam epitaxy methods to physically grow dissimilar materials in layered structures, creating entirely new properties at the interfaces. Controlling the nature of the pairing interaction for triplet superconductors could lead to ways of creating new triplet superconductors based on the interface properties. The road of materials engineering combining ferromagnetism and superconductivity in a single material has been paved by the discovery of magnetic field–induced superconductivity in the pseudoternary europium-tin-molybdenum chalcogenides (*11*), and the demonstration of spin triplet supercurrent through the half-metallic ferromagnet CrO_2 (*12*). Because of the nature of the pairing type, p-wave superconductors are more compatible with ferromagnetism than conventional s-wave superconductors. Further improvement of these materials may be possible if they can be based on triplet (instead of singlet) superconductivity.

In the experiments reported by Schemm *et al.*, the sensitivity to time-reversal symmetry breaking relies on the chiral nature of the photon. Left-handed and right-handed photons will have different absorption coefficients if the state of matter of the material to which they couple has itself a certain handedness (see the figure). However, as the energy of the two states is independent of the handedness, textures (in ^{3}He, for example, textures are observed in the form of lines, planes, and points) involving these two degenerate states can in principle exist. And because each circularly polarized photon transfers a quantum of angular momentum, one may speculate on future spintronic devices in which the spin state of the pair-condensate is manipulated by the transfer of photon angular momentum. ■

ILLUSTRATION: P. HUEY/*SCIENCE*

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MICROBIOLOGY

A flipping cell wall ferry

How bacteria "flip" carbohydrate precursors across the cytoplasmic membrane

By **Kevin D. Young**

Most bacteria surround themselves with a tough, highly interconnected polymer called peptidoglycan. To create this wall, bacteria synthesize precursors in the cytoplasm, attach them to a lipid carrier (lipid II), transport ("flip") this compound across the cytoplasmic membrane, and then polymerize and cross-link the monomers to the existing cell wall (*1*). The enzymes responsible for the cytoplasmic and extracytoplasmic steps are well known. However, hydrophilic precursors must cross the hydrophobic membrane, and the protein that conducts this critical transfer has stubbornly resisted identification. On page 220 of this issue, Sham *et al.* (*2*) present evidence that the MurJ protein of *Escherichia coli* performs this "flippase" function in vivo, thus solving a major puzzle in the basic pathway that synthesizes the bacterial cell wall. The new data are somewhat disconcerting, though, because in vitro experiments identified another candidate, FtsW, as the relevant flippase, with MurJ being inactive (*3*). We are left with the tantalizing question of how these results are to be reconciled and which protein fills this fundamental biochemical role.

At issue is how hydrophilic compounds traverse a highly hydrophobic and nearly impenetrable lipid bilayer. Numerous receptors, transporters, pores, pumps, and transducers help transform lipid bilayers into the semipermeable membranes required for cellular life, but it is unclear how several important carbohydrates cross bacterial and eukaryotic membranes (*1*, *4*). There are a limited number of ways to export polysaccharides, so studying the mechanisms used by *E. coli* has the potential to shed light on other transport systems (*5*). The issue has practical import, as well, since the cell wall allows bacteria to exist in the osmotically inhospitable environments that cover most of Earth and oceans, and removing the wall or inhibiting its synthesis is one of the most frequently used means of controlling bacterial infection.

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Editor's Summary