previously thought. That could happen if the core is rich in sulfur; just as salt water freezes at a lower temperature than fresh water, the melting point of an iron–sulfur mixture is lower than that of iron alone. But the material present at the time and place of Mercury's formation should not have contained much sulfur. If Mercury's core does contain sulfur, it's likely that the planet was formed from pieces of material in the solar nebula drawn in from farther afield than previously thought.

Mercury is an extreme planet in many ways. It's the closest to the Sun, it's the smallest of the planets in our solar system, and its core is, proportionally, the largest. For those reasons, any new information about Mercury's formation and interior properties will be particularly helpful for understanding planets under a wider range of conditions.

Instant messenger

Future work for Margot and his colleagues includes better characterization and understanding of the possible free libration. But the most anticipated development will come from the *MESSENGER* spacecraft. *MESSENGER*'s trajectory will provide better data on Mercury's gravity field, and thus a more precise measure of the asymmetry that underlies the solar torque. The first flyby, next January, will reduce the uncertainty considerably; once the craft starts to orbit Mercury in March 2011, it will allow a measurement of still greater precision. By then, the 90–95% confidence in Mercury's molten core could be improved to a virtual certainty.

Johanna Miller

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Whiskers of tantalum trisulfide twist in response to an electric field

A coherent electronic structure known as a charge-density wave is responsible for the twist. How the whiskers pick a rotation direction is a mystery.

One might expect a one-dimensional metal to be rather simple: a string of equally spaced atoms whose valence electrons occupy a flat, featureless band. But in 1930 Rudolf Peierls found an interesting theoretical wrinkle.

Below a critical temperature, Peierls argued, the atoms of a 1D metal spontaneously acquire a periodic distortion that nudges them together in groups of two, three, or more. The energy cost of reordering the atoms is met by the valence electrons, which assemble in a coherent state called a charge-density wave (CDW).[1]

For decades, Peierls's idea remained untested, not least because 1D arrays of mutually attracting atoms tend to be thermodynamically unstable. But in the 1970s chemists succeeded in making bulk materials from molecular chains whose mutual coupling is strong enough to forestall thermodynamic instability yet weak enough to let the chains distort unhindered.

Physicists soon observed a host of interesting electronic properties in niobium triselenide, tantalum trisulfide, and other CDW materials. The most remarkable properties, including nonlinear conductivity, occur when an applied electric field sets the entire CDW in motion. (See the article by Robert Thorne, PHYSICS TODAY, May 1996, page 42.)

CDW motion also changes elastic properties. In 1984 Joe Brill of the University of Kentucky and George Mozurkewich of UCLA found that TaS_3, $NbSe_3$, and $(TaSe_4)_2I$ become less stiff when a CDW flows through them. And in 1992 Alex Zettl of the University of California, Berkeley, and his collaborators found that CDW motion causes centimeter-long samples of TaS_3 to lengthen by a nanometer or so.

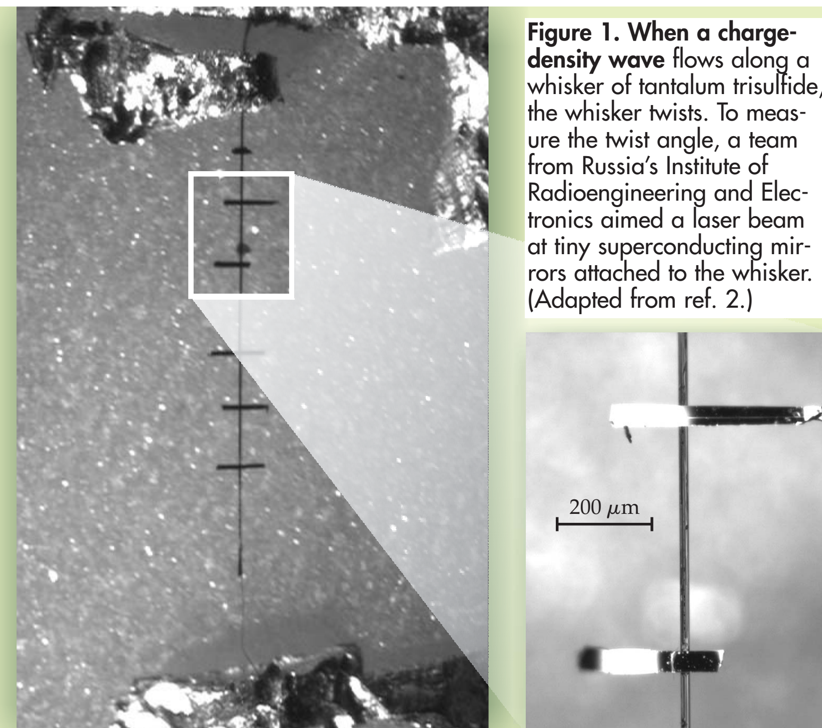

Figure 1. When a charge-density wave flows along a whisker of tantalum trisulfide, the whisker twists. To measure the twist angle, a team from Russia's Institute of Radioengineering and Electronics aimed a laser beam at tiny superconducting mirrors attached to the whisker. (Adapted from ref. 2.)

Now, Vadim Pokrovskii of the Institute of Radioengineering and Electronics in Moscow and his coworkers Sergei Zybtsev and Irina Gorlova have discovered another CDW-induced change: Freely suspended whiskers of TaS_3 twist.[2]

Finding one more manifestation of CDWs would not be remarkable, except for two things. First, it's quite baffling why a whisker would choose to rotate one way rather than the other. The structure of TaS_3 lacks the requisite symmetry-breaking features. Second, the twist is so large that Pokrovskii thinks his whiskers could find use as torsional actuators in micro- or nanoelectromechanical systems.

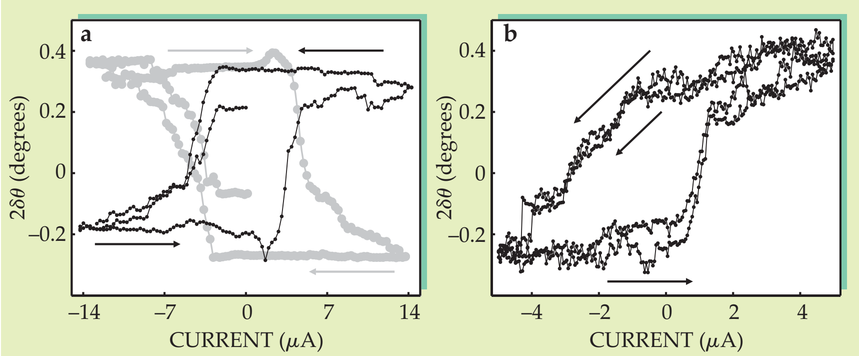

Figure 2. At the start of the experiment, the current and deflection are both zero. Once the threshold for charge-density wave motion is reached—a current of about 4 μA for sample **(a)** and 1 μA for sample **(b)**—the deflection rapidly climbs, then saturates. Reversing the current reveals considerable hysteresis. Turning sample **(a)** upside down (gray image) reverses the direction of the twist. (Adapted from ref. 2.)

Unpinning the wave

For TaS_3, $NbSe_3$, and other CDW materials, Peierls's critical temperature T_P is around 200 K. At and below T_P, the reduction in electron energy that accompanies the lattice distortion opens a narrow, semiconductor-like energy gap at the Fermi surface.

If CDW materials behaved like silicon, germanium, and other semiconductors, lowering the temperature would deprive the electrons of the thermal energy they need to hop across the gap. Electrical conduction would cease. But that doesn't happen. Thanks to the CDW's collective nature, its constituent electrons can move en masse—provided the electric field is above a threshold value E_t.

Below E_t, a few scattered impurities or defects suffice to pin the CDW to the lattice. Above E_t, a microscopic movie of the lattice—if one could be made—would show the electrons and atoms rocking back and forth like fluid elements in a wave while the electric field drives the crests of charge over the impurities and defects. That coordinated motion is what changes a CDW material's properties.

CDW materials derive their distinctive character from a 1D transition; yet they are fully 3D. Out of that mix of dimensions, Pokrovskii hopes to find interesting and novel properties using atomic force microscopy, scanning tunneling microscopy, and other techniques in the nanotech toolbox.

Setting up such experiments is time-consuming. Impatient to get started, Zybtsev decided to look for one kind of deformation—torsion—in a simpler, lower-tech way.

Of the CDW materials synthesized so far, orthorhombic TaS_3 shows the biggest CDW-induced change in stiffness. It's typically available in the form of thin whiskers. Zybtsev attached tiny mirrors to TaS_3 whiskers and suspended them vertically between two contacts (see figure 1). He then aimed a laser beam at the mirrors and positioned a detector to intercept the reflected beam. If the whiskers twisted, the beam would be deflected, and the detector would measure the deflection angle.

As the voltage along the whiskers approached the threshold for depinning the CDW, the whiskers began to twist, the angle increasing rapidly until it saturated at about 0.2 degrees. As figure 2 shows, reducing the voltage back to zero and then reversing it led to a hysteresis and a reversal of the twist direction.

The hysteresis is not unexpected and reflects the presence of domains. But the value of the deflection was surprisingly large. It corresponds to a surface strain of 10^{-4} and a piezoelectric coefficient of 10^{-4} cm/V, which is four orders of magnitude larger than that of PZT, a piezoelectric material used for high-precision alignment systems and scanning stages.

To convince themselves they'd seen a real, CDW-induced effect, Pokrovskii, Zybtsev, and Gorlova ran several tests. All 13 of their samples, whose cross-sectional areas ranged from 5 to 300 μm^2, showed the effect. They also attached a series of mirrors along the length of whiskers. As expected for an intrinsic material property, the deflection increased linearly along the sample length. The deflection was also larger overall at lower temperatures.

Although Pokrovskii, Zybtsev, and Gorlova haven't identified the twist's origin, their experiments limit the

possibilities. The shadow image in figure 2a shows what happened when a whisker was cut in half, turned upside down, and put back in the cryostat: The direction of the deflection reversed. In another test, the team warmed whiskers above T_P and recooled and remeasured them. The deflection's size and direction remained the same.

Both tests point to an intrinsic, structural origin for the twist, yet the structure of orthorhombic TaS_3, whose unit cell consists of 24 tantalum sulfide chains, has neither up–down nor left–right asymmetry. Because torsional strain deforms the surface of a whisker more than its interior, defects or impurities at the surface could be responsible. Angle-resolved photoemission studies could help reveal whether that's the case.

Even if the twist remains mysterious, it appears to be robust and repeatable. TaS_3 whiskers could serve as torsional actuators. All that's needed to generate twist is an electrical field and one moving part. No other actuator, microscopic or macroscopic, would be as simple.

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Quantum oscillations finally seen in high-temperature superconductors

The oscillations focus renewed attention on the nature of the Fermi surface near the onset of superconductivity.

In the 20 years since the discovery of high-temperature superconductivity in a class of copper-oxide materials, the search for the mechanism underlying this phenomenon has extended beyond the superconducting region itself. Before they are doped to become superconductors, the cuprates are antiferromagnetic insulators, as shown in the phase diagram of figure 1. Researchers have wondered how the material transitions to a robust superconductor as dopants are added and what type of state is reached when the material is overdoped.

A useful way to characterize the electronic states in the underdoped and overdoped regions surrounding the superconducting dome (yellow region in figure 1) is to map out their Fermi surfaces. As the boundary in momentum, or reciprocal (*k*), space between filled and empty energy levels, the Fermi surface is a key determinant of a material's physical behavior, such as the temperature dependence of the material's electrical resistivity. Alas, when experimenters in the 1990s tried to use two methods—the de Haas–van Alphen (dHvA) and Shubnikov–de Haas (SdH) effects—that had successfully probed the Fermi surfaces of numerous metals, they failed to get convincing results.

In the absence of the standard tools, practitioners of angle-resolved photoemission spectroscopy (ARPES) have stepped in to fill the vacuum. They have adapted ARPES to map the Fermi surface, and over the years they have progressively improved its resolution.

The ARPES studies have revealed the underdoped cuprates to be especially mysterious. Measurements have found that well-defined quasiparticles, or excitations, only seem to exist along disconnected arcs in two-dimensional *k* space, rather than on continuous Fermi surfaces.[1,2] (In the layered copper-oxide superconductors, most of the conduction occurs in the 2D planes of copper and oxygen atoms. Thus the most relevant part of the Fermi surface is the corresponding 2D plane in *k* space.) The observations of Fermi arcs have raised lots of questions about what they could mean.

New insight into this region has now come from a familiar tool: After five years of work, a group headed by Louis Taillefer of the University of Sherbrooke in Canada and Cyril Proust at the National Pulsed Magnetic Field Laboratory in Toulouse, France, has succeeded in seeing the signature characteristics of the SdH effect: quantum oscillations in the resistance as a function of an applied magnetic field.[3]

The measurements were made last March in Toulouse by Taillefer's postdoc Nicolas Doiron-Leyraud and graduate students David LeBoeuf and Jean-Baptiste Bonnemaison, working with Proust and his student Julien Levallois. The researchers needed the extremely high field available in Toulouse to suppress superconductivity and boost the oscillation amplitude. Equally essential were the exceptionally clean and ordered crystals provided by Ruixing Liang, Douglas Bonn, and Walter Hardy of the University of British Columbia. The crystal growth was an outcome of a long-term materials development program sponsored by the Canadian Institute for Advanced Research.

The experiment has created quite a buzz in the community of researchers studying the cuprates. At first glance, the data appear to conflict with the results from ARPES studies: Rather than finding disconnected Fermi-surface arcs, the observation of SdH oscillations clearly suggests that the Fermi surface consists of small closed areas, or pockets. Perhaps there are ways to reconcile the two results. But perhaps ARPES and the high-field oscillations are not measuring the same state: ARPES measurements probe the surface of a material

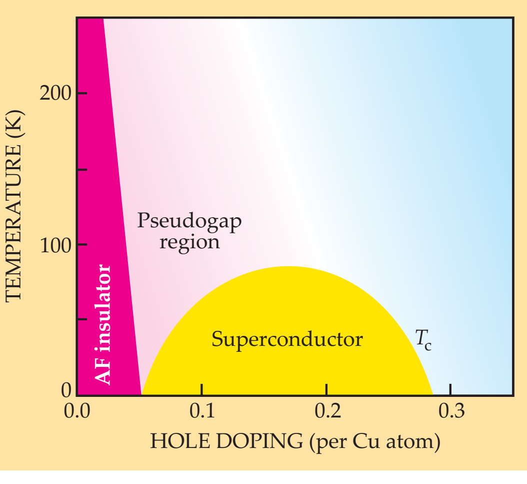

Figure 1. Phase diagram for high-temperature superconductors in the plane of temperature and doping level. The parent compound is an antiferromagnetic insulator (hot pink area). As doping and temperature increase, the material enters a "pseudogap" phase (light pink shading). At still higher doping, the material is superconducting below a temperature T_c (yellow). The overdoped region is shaded in blue. (Adapted from ref. 3.)