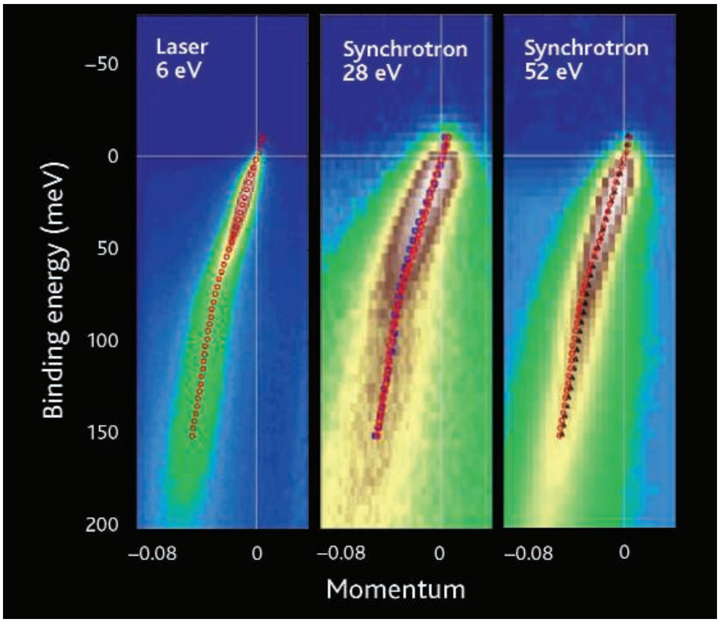
Researchers Turn Up the Heat In Superconductivity Hunt

Physicists still can't explain why some ceramic materials lose electrical resistance at relatively balmy temperatures, but they think they're on the right track

When Peter Johnson and colleagues set out to study the behavior of electrons in high-temperature superconductors, their experiments raised more than a few eyebrows. In 1999, Johnson, a physicist at Brookhaven National Laboratory in Upton, New York, systematically blasted electrons out of a superconductor with bursts of photons. The technique, called angle-resolved photoemission (ARPES), can reveal intricate details about how electrons behave inside a material. The Brookhaven team's results, however, flew in the face of other ARPES results as well as other types of electron-tracking experiments.

Today, things are falling into line. Armed with more-precise electron detectors, Johnson and his colleagues say the bumps and wiggles in their data better match other experimental results. Other photoemission experimenters, such as Z. X. Shen's group at Stanford University in Palo Alto, California, report a similar swerve toward consensus. "We are correcting ourselves, and Z. X. is happy to correct us as well," Johnson quips.



Signpost? "Kinks" in photoemission data may show that electrons interact with vibrations of the crystalline lattice—a possible clue to high-T_c superconductivity.

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That turnabout and others have convinced a number of researchers that they are closing in on what many view as the biggest mystery in condensed-matter physics: the mechanism that causes certain ceramics to superconduct at unusually high critical temperatures (T_c). But as experimental results grow ever more precise and convincing, just what they all mean remains highly contested. "There has been a tremendous amount of progress in the experiments," says Mike Norman, a high-T_c theorist at Argonne National Laboratory in Illinois. "The data are pretty clear. But there is a lot of controversy about the interpretation."

Controversy has been in steady supply since 1986, when Swiss physicists Georg Bednorz and Alex Müller discovered a class of copper-and-oxygen–containing ceramics called cuprates. The materials have since been shown to conduct electricity without resistance at temperatures as high as 138 kelvin—more than three times the temperature of the best metallic superconductors. As in those conventional superconductors, electrons in the cuprates pair up into "Cooper pairs" and surf through the material without the electrical friction typical of electrons traveling through other materials. Because all electrons carry a negative charge, they usually repel one another and don't want to pair up. But the rules change for superconductors. In the low-temperature metallic variety, a moving electron creates vibrations in the material's atomic lattice that pull another electron in its wake. It's these lattice vibrations, also known as phonons, that glue Cooper pairs together.

So what glues Cooper pairs together in high-temperature superconductors? After nearly 20 years of searching, physicists continue to battle over the answer. Perhaps the most prevalent view is that this pairing is driven by the magnetic behavior of the copper atoms in the atomic lattice of the cuprates: The presence of an electron on one copper atom causes nearby magnetic "spins" to align in a way that attracts another electron to sit nearby. Plenty of other researchers, however, argue in favor of phonons or some still more exotic mechanism.

Sorting out what is going on has been a headache in part because of the odd way in which the cuprates superconduct. In traditional superconductors, Cooper pairs surf through the material with the same ease in all directions. That's not the case with the cuprates. These materials have a complex layered structure that forces Cooper pairs to travel in the flat planes that contain copper and oxygen atoms. And even within these planes, they travel only along the two axes of the crystal, not along the 45° angles. When researchers map out the energy that binds Cooper pairs together versus their momentum (a product of their mass and velocity), they see a cloverleaf pattern, very different from what is seen in metallic superconductors.

Researchers initially turned to ARPES because it can track both the energy level of liberated electrons—which is determined in part by what other players the electrons are interacting with—and how this behavior changes with the electron's momentum. Other techniques reveal only the energy. But although early ARPES experiments did a fair job of nailing down the momentum, they couldn't come close to the energy resolution of other types of experiments. Over the past several years, the ability of the detectors to gauge the particular track of the electrons has improved 40-fold, and the energy resolution has skyrocketed as well. "The measurements are vastly superior to 10 years ago," which has made ARPES an essential tool for investigating high-T_c materials, Norman says.

In Johnson's early photoemission experiments, he and his colleagues found that the electrons evicted from the cuprates had a broad range of energies. As they lowered the temperature of their sample from above the superconducting temperature to below it, the spread stayed about the same. That stability muddied the waters by suggesting that the researchers weren't seeing excited electrons interacting with any specific player in the material, such as a lattice vibration or type of magnetic fluctuation. In the parlance of physicists, they didn't see any "quasiparticles" in the superconducting state, which are essentially the combination of excited electrons together with the forces exciting them. Superconductivity in cuprates, it seemed, was due to a jumble of influences instead of a specific one.

That picture soon began to change when a company called Scienta came out with new, more-sensitive electron detectors, and it has been growing sharper ever since. Researchers led by Juan Campuzano at Argonne National Lab, for example, reported evidence in 2000 that quasi-particles were in fact present below the material's superconducting temperature. And this summer, after a series of very precise measurements, Johnson's team reported at a meeting that it largely agrees. Still, Johnson and others say that just what influences those quasi-particles represent remains unclear. But they're offering new hope that experimenters and theorists will soon pin them down. "It offers a signpost that we might be seeing something important," says Daniel Dessau, a photoemission expert at the University of Colorado, Boulder, and the National Institute of Standards and Technology.

Another set of key signposts gives added reason for cheer. When researchers plot the energy of electrons liberated by a photoemission experiment against their momentum, they now regularly see what looks like a straight line with a kink in it, reminiscent of the bend in a flexible drinking straw. "The kink is an indication of a sudden change in the electron's velocity at a particular energy," Shen explains. "There must be something making that change." And the energy signature of that something is conspicuously close to the amount of energy that binds Cooper pairs together—suggesting that whatever gives rise to the kinks also acts as the mysterious glue for Cooper pairs.

In results reported at an American Physical Society meeting in March, for example, Dessau's team, working with photons from a high-power laser, sees a crystal-clear kink at 70 milli–electron volts (meV), an energy level that is most commonly associated with a phonon (see figure, p. 1271). Shen and colleagues working at the Hiroshima Synchrotron Radiation Center in Japan see a similar kink as well, which these and other groups had spotted with less resolution before. The catch is these electrons are traveling at a 45° angle to the crystal lattice—a direction, called the "node," in which Cooper pairs can't travel. Because the electrons couldn't have been paired before being blasted out of the material, many researchers question how relevant this phonon is to the glue that holds Cooper pairs together. "This is not the node to study pairing," Shen says.

Along the "antinode," the 0° and 90° axes of the crystalline lattice, the picture is more confusing. Several groups, including Dessau's, see a kink there as well, at 40 meV. That suggests a different influence is acting on the electron. Shen and colleagues argue that their data point to a separate phonon from the 70-meV version present along the node. But for now, many other researchers don't agree. "The other groups are fairly insistent that it is not a phonon effect along the antinode," Norman says. Most of these teams suggest that the kink is caused by a collective magnetic behavior of the electrons. The wrinkle, Johnson says, is that both the phonons and the magnetic excitations would likely have about the same energy signature, so it is hard to tell which one is playing the key role. But the recent progress in ARPES and other experiments has many high-T_c researchers feeling more confident than ever that they will find the answer soon. Says Norman: "I think it will be sorted out in the next couple of years."

–ROBERT F. SERVICE

Space Science

The Question on the Table: Will Europe Go to Mars?

At a meeting in Berlin next month, members of the European Space Agency will be asked to invest in Aurora, a still-evolving scheme to explore the solar system

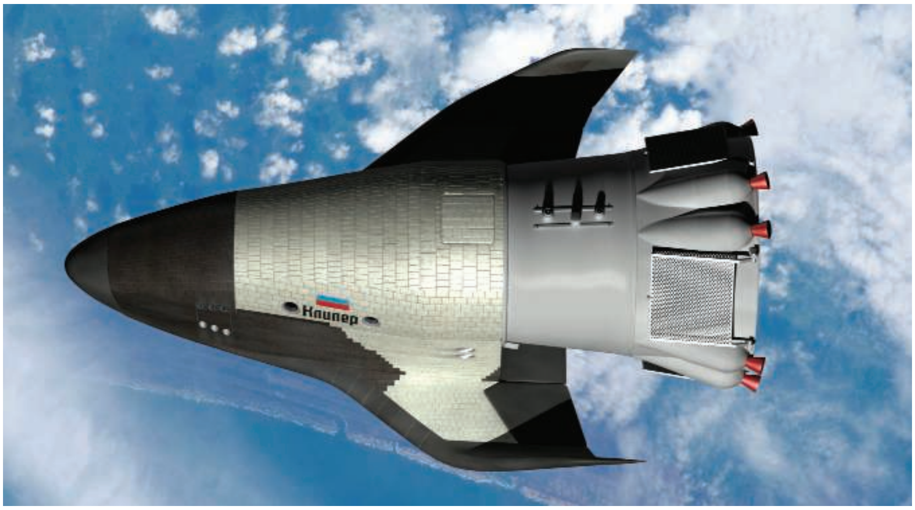
CAMBRIDGE, U.K.—Next month, when ministers from the 15 member states in the European Space Agency (ESA) meet in Berlin to discuss the next 5-year chunk of funding, they will face an important question: Is it time for Europe to forge its own path among the planets? European governments made a tentative move in this direction in 2000—several years before President George W. Bush committed the United States to going to the moon and Mars—by asking ESA to lay the groundwork for human exploration of the solar system. In 2001, this program got a name—Aurora—and some seed money. Now it is time to write a big check.

Aurora, if it goes, will be small by NASA's standards. In its first decade, it will consist principally of a single robotic mission, known as ExoMars, and technology development for a future Mars sample-return mission and human exploration. ESA next month will request a budget in the region of $800 million to $950 million for Aurora over the next 5 years.

Although the program is beginning modestly, it is symbolic of the agency's burgeoning ambitions and Europe's desire to assert its independence in space. "Europe now has greater confidence and capability in planetary exploration," says astrophysicist Ken Pounds of the University of Leicester, a former chief executive of the United Kingdom's Particle Physics and Astronomy Research Council. And to underline this new spirit of bravado, ESA also wants to collaborate with Russia to build a minishuttle called Clipper that would carry up to six astronauts into space.

As a rule, space agencies' plans tend to outrun their available budgets. Whereas NASA must go to Congress every year to get its budget approved and make good the cost overruns, ESA walks a different financial tightrope: It must persuade 15 governments to agree on its funding once every 5 years or so—as it hopes to do in Berlin on 5 to 6 December.

ESA's science missions often fare badly in this process because science is one of the



Shuttle-lite. ESA is interested in Russia's design for a six-person exploration vehicle.

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