"Cloud" Chaser

BY SAREN JOHNSTON

IN THE ATOMIC WORLD, IT'S ALWAYS "CLOUDY." THE NUCLEUS OF EVERY ATOM EXISTS IN A CLOUD OF ELECTRONS.

When atoms are brought together to form a solid, some of these electron clouds "spread" throughout its whole volume. Investigating those clouds and probing the electrons that create them is Adam Kaminski's business. To do so, the Ames Laboratory physicist uses a technique called angle-resolved photoelectron spectroscopy, ARPES, to learn more about the interactions of electrons because the manner in which they relate to one another determines most properties of solid materials. And Kaminski is fascinated by metallic solids, especially high-temperature superconductors and the challenge of discovering how they work.

Electrons are very picky. They inhabit only particular energy levels and never more than two electrons share the same one. In solid materials at low temperatures, electrons will fill all of the energy states up to the Fermi level, the highest occupied state. Electrons occupying the high energy levels are Kaminski's favorites because they can respond to external stimuli, such as electric field and temperature gradient.

To better study electrons, Kaminski developed and set up Ames Lab's high-precision, laboratory-based ARPES system that provides energy resolution on the order of one millielectron volt, or 1meV. "There is only one place in the world that has better resolution than we do with this machine, and that's in Tokyo," says Kaminski. "So, our system is the second-best in the world.

"In the photoemission angle-resolved machine, we can map the band structure exactly to study the electrons that control most properties of conductors," Kaminski explains. By shining an ultraviolet light of much higher energy than visible light on the sample, Kaminski can cause some of the electrons to escape the sample. When electrons are ejected from the sample, the principle of conservation of energy of momentum can be applied to find the initial state of an electron before it escaped.

To help clarify the ARPES method, Kaminski compares it to the medical technique of magnetic resonance imaging. "With an MRI machine, physicians can use X-rays or gamma rays to image the inside of the body and see organs such as the heart and kidneys. With ARPES, we can see 3-D images of the bands of electrons directly," he says.

Kaminski continues, explaining that the important aspect of the MRI technique for medical diagnostics is spatial resolution. "Electrons don't have a well-defined spatial position," he notes, "but they do have very well-defined momentum. So instead of working in real space like physicians do, we're working in momentum space with ARPES. But we can still see what the bands look like, the states that are occupied and how electrons interact with each other and the rest of the solid."

Kaminski notes that the ARPES technique has evolved tremendously over the last few years. "With the new types of analyzers, we are able to 'see' electronic bands in explicit detail," he says. The ARPES analyzer sorts electrons according to their angles of ejection, which, in turn, provides momentum information. "Now we can get the data in a matter of five minutes with ARPES, where it previously took months," he says. Using ARPES, Kaminski can analyze many kinds of samples to address different types of problems in which electrons play a critical role, the most demanding of which is the effort to explain high-temperature superconductivity.

"Superconductivity is caused by just a very few electrons at the Fermi level – the highest occupied state," says Kaminski. "It's a very rare phase of matter where you have exactly zero electrical resistance" he explains. "In nature, very few things are perfect, but this particular phenomenon is absolutely perfect. The resistivity is exactly zero."

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Cuprate compounds are the most prominent high-temperature superconducting materials, and, although

the materials were discovered in 1986, no one has yet been able to explain why they superconduct. "We can easily make high-temperature superconductors in the lab, but we still don't know the mechanism of how they work," says Kaminski.

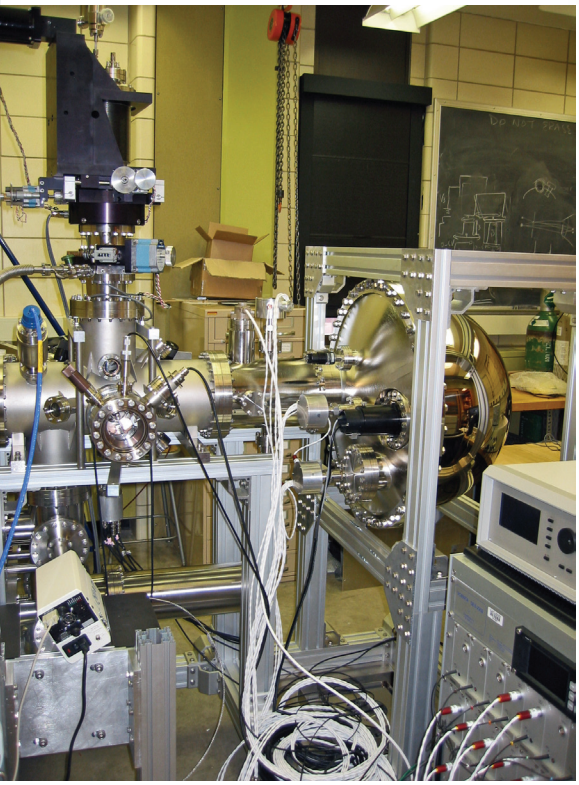
However, scientists do know some of the things that separate these materials from conventional superconductors. Every superconductor has a superconducting gap, an energy gap that appears at the superconducting transition temperature where resistance also disappears. But the superconducting gap in a high-temperature superconductor is very unusual – instead of being the same in all directions, it has a particular direction where the gap appears to go to sleep. "It's very different from conventional materials," says Kaminski. "Using the ARPES system in our lab, we can measure the superconducting gap with enormous precision."

Kaminski also uses ARPES to study the pseudogap in cuprates. "In these materials, the properties can be varied, for example, by adding a fraction of oxygen – 10 to 15 percent," he says. "That changes the properties dramatically." At very low oxygen content, the materials display a phenomenon called the pseudogap. It looks almost like the superconducting gap, and it persists to very high temperatures – well above room temperature.

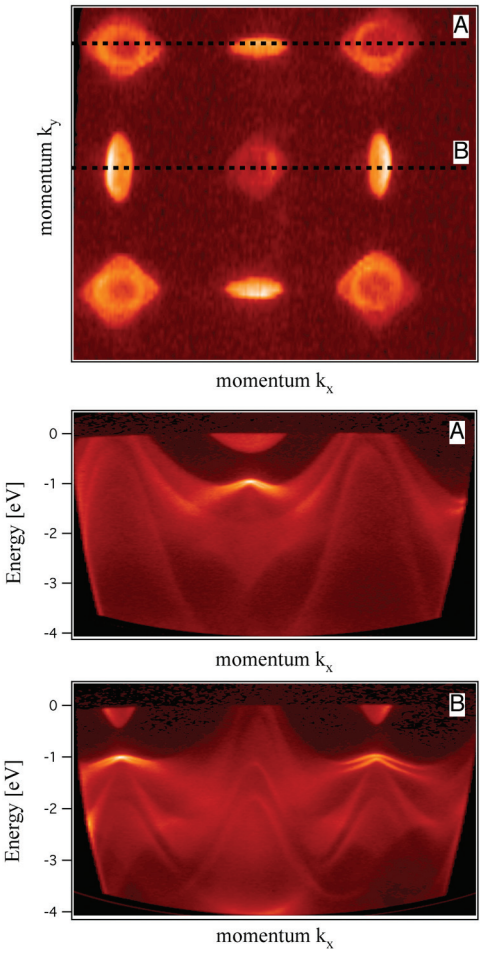
Kaminski notes that there was a lot of excitement surrounding the discovery of the pseudogap in cuprates. "People thought that with this sort of gap you could easily make cuprate samples superconducting at high temperatures," he says. "But what we found is that the pseudogap is actually not related to the superconducting gap. Instead of being a friend, it's actually a foe."

Kaminski says the pseudogap is just one example of the unusual behavior of these materials. "Nobody knows what this pseudogap phase is," he notes. "We've been studying the properties of this phase in relation to superconductivity with our ARPES system. Hopefully the information we get will provide clues to the origin of this phenomenon.

"These materials are the reason I started studying condensed matter physics," Kaminski admits. "They're so different from anything we've known so far. No classical theory can explain their behavior. We understand them a lot better now, but that's not to say we know how they work. It's probably one of the most complex problems in physics."



Ames Laboratory's lab-based ARPES system has a high-precision XYZ manipulator with closed-cycle refrigerator that cools a sample to 10 Kelvin (minus 441.67 degrees Fahrenheit). The system's lens (long horizontal tube) guides electrons into the ARPES analyzer (shiny, hemispherical piece).



The top panel is an image of Fermi surfaces in LuSb (lutetium antimony) samples grown by Ames Lab senior physicist Paul Canfield. The bright intense lines represent states that form Fermi surfaces. These are the electrons that control most of the properties of conducting solids. Below are images of electron bands along two cuts (indicated by lines A and B in the upper panel).

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