

These collective behaviors, or quasi-localizations, have been linked to high-temperature superconductivity in both pnictides and other high-temperature superconductors.

“We found that ordered vacancies enhance the tendency of the electrons to lock themselves some distance away from their neighbors in a pattern that physicists call ‘Mott localization,’ which gives rise to an insulating state,” Yu said. “This is an entirely new route toward Mott localization.”

By showing that merely creating ordered vacancies can prevent the mate-

rial from being electrical conductors like their relatives, the researchers concluded that even the metallic parents of the iron pnictides are close to Mott localization.

“What we are learning by comparing the new materials with the older ones is that these quasi-localized spins and the interactions among them are crucial for superconductivity, and that’s a lesson that can be potentially applied to tell experimentalists what is good for raising the transition temperature in new families of compounds,” Zhu said.

One impediment to the broader use of high-temperature superconductors has

been the struggle to precisely explain what causes them to become superconductors in the first place. The race to find that has been called the biggest mystery in modern physics.

“The new superconductors are arguably the most important iron-based materials that have been discovered since the initial discovery of iron pnictide high-temperature superconductors in 2008,” Si said. “Our theoretical results provide a natural link between the new and old iron-based superconductors, thereby suggesting a universal origin of the superconductivity in these materials.”

### Quantum phase transition revealed in ultrathin films

Like atomic-level bricklayers, I. Božović from Brookhaven National Laboratory, G. Dubuis from Ecole Polytechnique Federale de Lausanne, and their colleagues are using a precise atom-by-atom layering technique to fabricate an ultrathin transistor-like field effect device to study the conditions that turn insulating materials into high-temperature superconductors. The technical break-through, which is described in the April 28th issue of *Nature* (DOI: 10.1038/nature09998; p. 458), could lead to advances in understanding high-temperature superconductivity.

“Understanding exactly what happens when a normally insulating copper-oxide material transitions from the insulating to the superconducting state is one of the great mysteries of modern physics,” said Božović, lead author on the study.

One way to explore the transition is to apply an external electric field to increase or decrease the level of doping and see how this affects the ability of the material to carry current. But to do this in copper-oxide (cuprate) superconductors, one needs extremely thin films of perfectly uniform composition—and electric fields measuring more than  $10^9 \text{ V m}^{-1}$ .

Božović’s group has employed molecular beam epitaxy (MBE) to uniquely

create such perfect superconducting thin films one atomic layer at a time, with precise control of each layer’s thickness. Recently, they have shown that in such MBE-created films, even a single cuprate layer can exhibit undiminished high-temperature superconductivity.

Now, the researchers have applied the same technique to build ultrathin superconducting field effect devices that allow them to achieve charge separation, and thus electric field strength, for these critical studies.

These devices are similar to the field-effect transistors (FETs) that are the basis of modern electronics, in which a semiconducting material transports electrical current from the source to a drain electrode. FETs are controlled by a gate, positioned above the source–drain channel—separated by a thin insulator—which switches the device on or off when a particular gate voltage is applied to it.

But because no known insulator can withstand the high fields required to induce superconductivity in the cuprates, the standard FET scheme does not work for high-temperature superconductor FETs. Instead, the researchers used electrolytes to separate the charges.

In this setup, when an external voltage is applied, the electrolyte’s positively charged ions travel to the negative electrode and the negatively charged ions travel to the positive electrode. But when the ions reach the electrodes, they abruptly stop, as though they have hit a

brick wall. The electrode “walls” carry an equal amount of opposite charge, and the electric field between these two oppositely charged layers can exceed the  $10^9 \text{ V m}^{-1}$  goal.

The result is a field effect device in which the critical temperature of a prototype high-temperature superconductor compound (lanthanum-strontium-copper-oxide) can be tuned by as much as 30 K, which is about 80% percent of its maximal value—almost 10 times more than the previous record.

The researchers have now used this enhanced device to study some of the basic physics of high-temperature superconductivity.

One key finding is that as the density of mobile charge carriers is increased, their cuprate film transitions from insulating to superconducting behavior when the film sheet resistance reaches 6.45 k $\Omega$ . This is exactly equal to the Planck quantum constant divided by twice the electron charge squared. Both the Planck constant and electron charge are atomic units—the minimum possible quantum of action and of electric charge, respectively, established after the advent of quantum mechanics early in the last century.

“It is striking to see a signature of clearly quantum-mechanical behavior in a macroscopic sample (up to millimeter scale) and at a relatively high temperature,” Božović said. Most people associate quantum mechanics with character-

istic behavior of atoms and molecules.

This result also carries another surprising message. While it has been known for many years that electrons are paired in the superconducting state, the findings imply that they also form pairs (although localized and immobile) in the insulating state, unlike in any other

known material. That sets the researchers on a more focused search for what gets these immobilized pairs moving when the transition to superconductivity occurs.

Superconducting FETs might also have direct practical applications. Semiconductor-based FETs are power-

hungry, particularly when packed very densely to increase their speed. In contrast, superconductors operate with no resistance or energy loss. Here, the atomically thin layer construction is in fact advantageous—it enhances the ability to control superconductivity using an external electric field.

### Energy Focus

#### Conjugated microporous polymer networks chemically tuned for CO<sub>2</sub> adsorption

The capture and storage of CO<sub>2</sub> produced by the combustion of fossil fuels is a technical challenge with great impact to the environment. CO<sub>2</sub> uptake in metal-organic frameworks (MOFs) has been investigated, although under conditions—high pressure and low water vapor content—more relevant to pre-combustion CO<sub>2</sub> capture from syngas (a mixture of H<sub>2</sub>, CO<sub>2</sub>, and CO) or natural gas reserves. In a recent investigation of nanoporous organic polymers for CO<sub>2</sub> capture at ambient pressure, A.I. Cooper and co-researchers at the University of Liverpool postulated that rather than materials with very high surface areas, the introduction of tailored binding functionalities, and thereby increasing a material's heat of adsorption, would increase the amount of CO<sub>2</sub> adsorbed.

Cooper and co-researchers synthesized two conjugated microporous polymer (CMP) networks that incorporate primary amine and carboxylic groups, respectively. They found that the CO<sub>2</sub> uptakes and isosteric heats of adsorption of these CMPs are consistent with previously published computations showing that incorporation of carboxylic acid groups in MOFs, rather than amine groups, leads to the highest isosteric heat of adsorption, suggesting to the researchers a common design principle that spans the two materials classes.

As reported in the May 6th online edition of *Chemical Science* (DOI: 10.1039/c1sc00100k), Cooper and co-researchers synthesized, isolated, and analyzed by Fourier transform infra-

red spectroscopy carboxylic acid and amine-functionalized CMP networks designated CMP-1-COOH and CMP-1-NH<sub>2</sub>, respectively. Insensitive to water, the CMP networks were also shown with thermal gravimetric analysis to be stable up to about 300°C. Scanning electron microscopy showed that the CMP network morphologies are similar to previous CMP networks. N<sub>2</sub> adsorption/desorption isotherms, measured at 77 K for CMP-1-COOH and CMP-1-NH<sub>2</sub> as well as for previously synthesized CMPs (see figure) are mainly Type I, that is, they show high gas uptake at low pressures (CMP-1-CH<sub>3</sub> and CMP-1-OH<sub>2</sub> are Type IV). From these isotherms the

researchers calculated surface areas and micropore volumes.

The researchers noted that CO<sub>2</sub> uptake, measured at low pressure for the entire series of CMP networks, does not correlate solely with surface area or pore volume. However, the researchers found that the isosteric heats of adsorption depended on the functional group, increasing as: COOH > (OH)<sub>2</sub> > NH<sub>2</sub> > H > (CH<sub>3</sub>)<sub>2</sub>, with the heat of adsorption for CMP-1-COOH being substantially higher than all other CMP networks in this series, higher than activated carbon, but lower than for some MOF networks.

The researchers said that their data corroborates the fundamental compu-

