# Eric Hudson

High Temperature Superconductivity, One Atom at a Time

For over twenty years high temperature superconductivity has defied explanation. Amazingly complex electronic interactions and resultant material properties have enticed many to try. Has this complexity masked a simpler picture? New experiments answer "perhaps."

DESPITE TWO DECADES OF INTENSE RESEARCH, high temperature superconductors still hold many mysteries. Although they share some properties with their well-understood "conventional" low-temperature cousins, in particular the ability to carry current without any resistance, the differences are plentiful. The most obvious difference is the transition temperature T_C, below which superconductivity turns on. This transition temperature tops out near 30 K for conventional superconductors, but is above the 77 K boiling point of liquid nitrogen for the most studied high temperature superconductors, and for others is as high as half way to room temperature. These high transition temperatures have driven much excitement in the field, with thoughts of myriad applications for hypothetical room temperature superconductors, including perfect energy storage and transmission systems
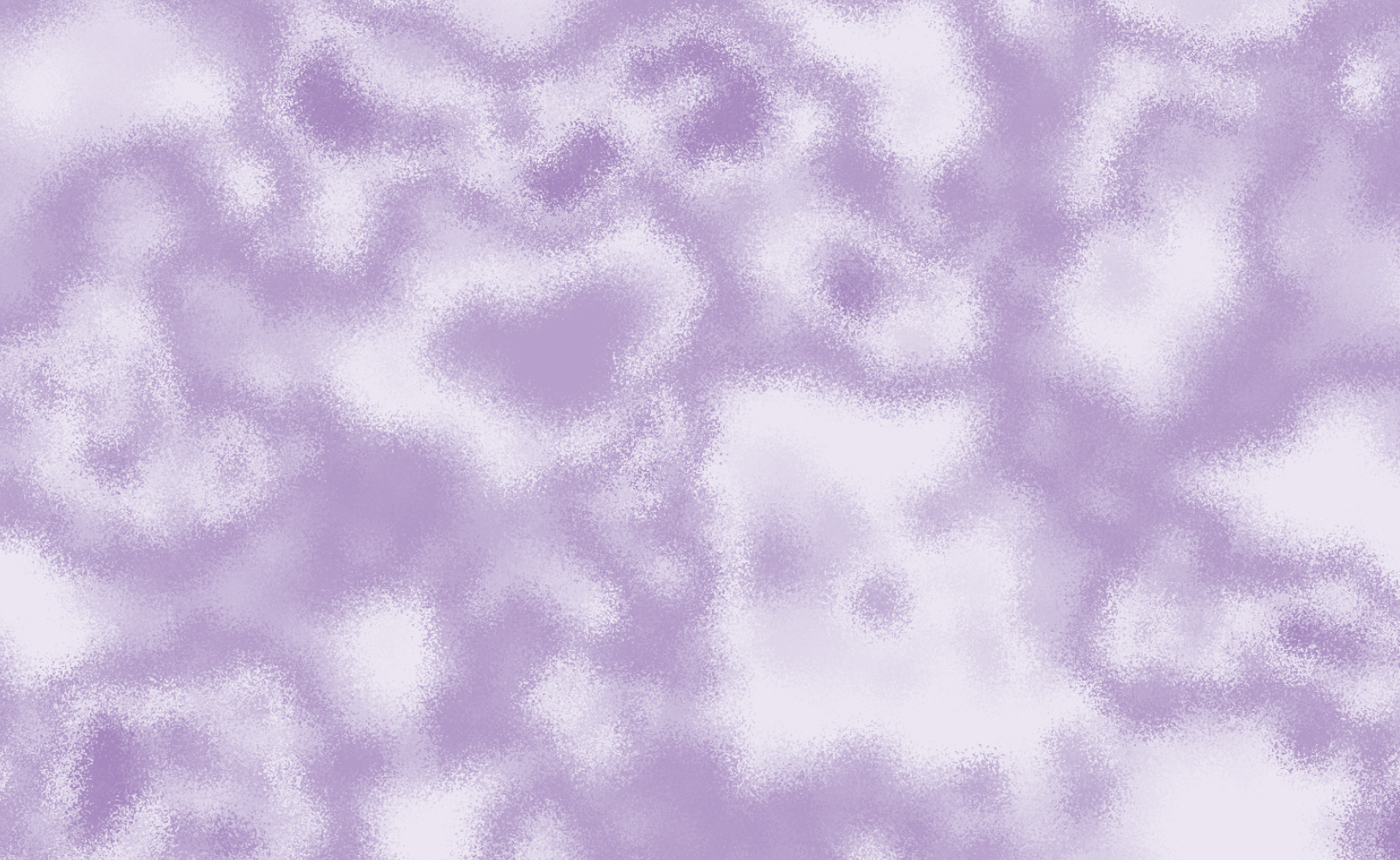
that will lead to evolution of the world's electrical grids and perfect diamagnetic levitation that could lead to a revolution in transportation.

Aside from the potential applications, physicists study high temperature super-conductivity to understand its basic science: how does it work? The theoretical framework for understanding more conventional materials, including conventional superconductors, appears to simply fail when applied to high temperature super-conductors. The prospect of developing a new framework for understanding this apparently new state of matter is seductive.

Understanding Conventional Superconductivity

Major theoretical advances were required to understand what is now referred to as conventional superconductivity. Its discovery in 1911 predated the development of quantum mechanics, which lies at the heart of its understanding. Experimentally, the discovery was driven by Kamerlingh Onnes's development of a technique for liquefying Helium, which happens at a chilly 4 K (4 °C above absolute zero). This led to a series of experiments involving low temperatures, including the measure-ment of the resistivity of mercury, which he found fell abruptly to zero when cooled to liquid Helium temperatures. Although the zero resistance state was a mystery, the search for other superconductors commenced, leading to the discovery of
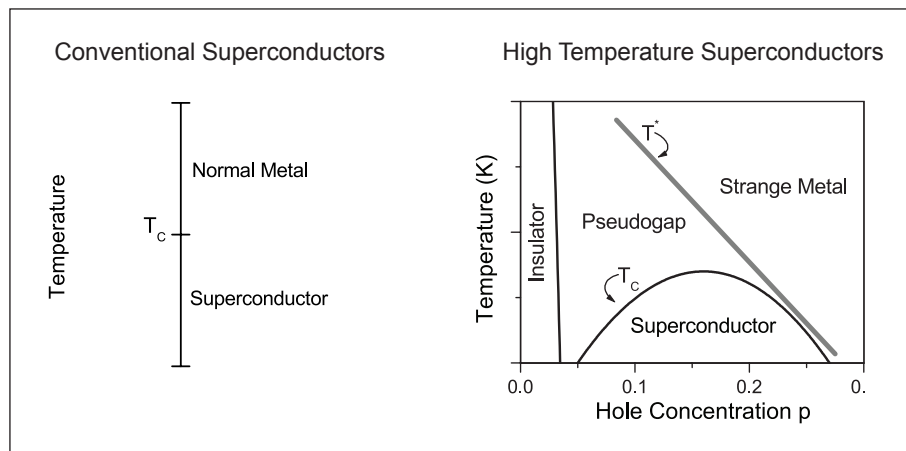
superconductivity in over thirty elements and numerous compounds. Along with materials advances, experimental research led to discoveries of new superconducting properties, most notably the Meissner effect, in which superconductors expel magnetic flux, becoming "magnetic mirrors" capable of levitating magnets on a cushion of their own reflected magnetic field lines.

It would take over forty years, until 1957, for theorists Bardeen, Cooper and Schrieffer to finally provide a microscopic picture of how materials superconduct. The key lies in electron interactions. In metals it is often reasonable to think of electrons as non-interacting, essentially oblivious to each other's presence. These electrons behave as a liquid, flowing in a container structured by the lattice of positively charged nuclei to which the electrons originally were bound. Although they essentially ignore each other, electrons do occasionally scatter from (bounce off of) the lattice, leading to electrical resistance.

In superconductors, when the temperature is lowered below the transition temperature T_C, electrons stop ignoring each other and instead bind to partners, forming Cooper pairs. Although one might imagine that Coulomb repulsion between electrons would prevent such pairing, the partners keep far enough apart so that mutual interactions with positively charged nuclei dominate and hold the pairs together. That is, phonons (motion in the lattice) provide the "glue" that hold Cooper pairs together, thus binding them so that a finite energy Δ is required to remove each electron from the pair.

How do these Cooper pairs of electrons lead to macroscopic properties like zero resistance? As mentioned above, resistance arises from scattering of electrons, mostly from the lattice. When bound together in pairs, electrons are prevented from scattering by their partners. So, without the energy to break their bonds, electrons are kept on the straight and narrow, flowing without resistance.
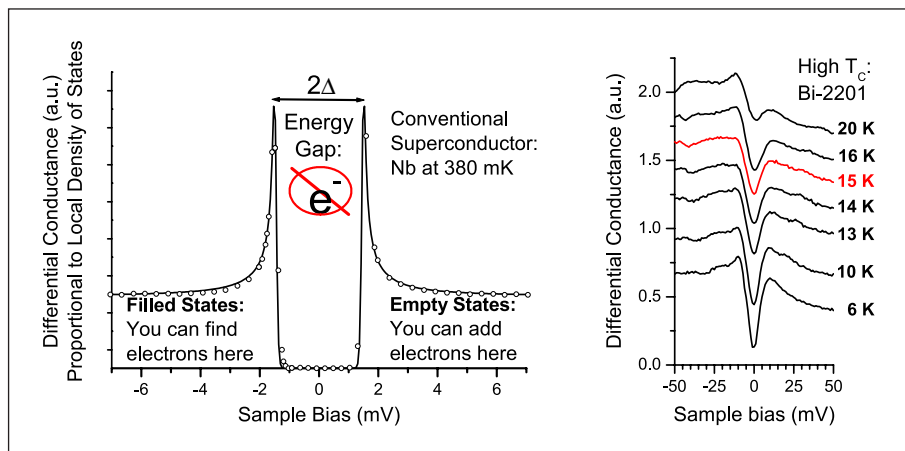
Turning Up the Temperature

The temperature T_C at which a material becomes superconducting is hence closely related to the binding energy Δ of the Cooper pairs. In fact, if thermal energy becomes comparable to the binding energy it can break pairs, leaving electrons free to scatter. Both depend on materials properties, such as how many electrons are available to pair and the strength of their connection to the phonons—essentially how well the glue works. Based on knowledge of these parameters it had widely been assumed that superconducting transition temperatures would never top 30 K. Thus physicists were excited when, in 1986, Bednorz and Müller announced the discovery of a new superconductor $La_{2-x}Ba_xCuO_4$, with transition temperatures near 35 K[1], and stunned when just months later Paul C.W. Chu and collaborators found $YBa_2Cu_3O_{6+x}$ with T_C = 92 K.[2]

What is responsible for the vastly higher transition temperatures in high temperature superconductors? This question remains unanswered today. High temperature superconductors still rely on Cooper pairs, just like their conventional counterparts. Phonons, however, appear not to be responsible for the pairing, and researchers identify possible alternatives. Some point to strong magnetic interactions in the materials. Others argue that the physics of high temperature superconductivity is so different that to think of "glue" at all is incorrect.

A mechanism for electron pairing is just one of many debates about the puzzling nature of these materials. The root cause of these debates is the incredible complexity of the cuprates (so called because all of the high T_C materials contain CuO_2 planes in which the Cooper pairs reside). While most conventional superconductors are simple metals before cooling into their superconducting state, high temperature superconductors are ceramic materials which exhibit a variety of phases depending on their exact chemical composition as well as their temperature. As depicted in a prototypical phase diagram *(Figure 1)*, they can be converted from magnetically ordered insulators to superconductors by doping (increasing by a few percent the

number of charge carriers by adding non-stoichiometric dopants like Oxygen in $YBa_2Cu_3O_{6+x}$). Even in the "normal" state, above the superconducting transition temperature, the cuprates are far from normal, with thermodynamic properties unlike any other materials we know.
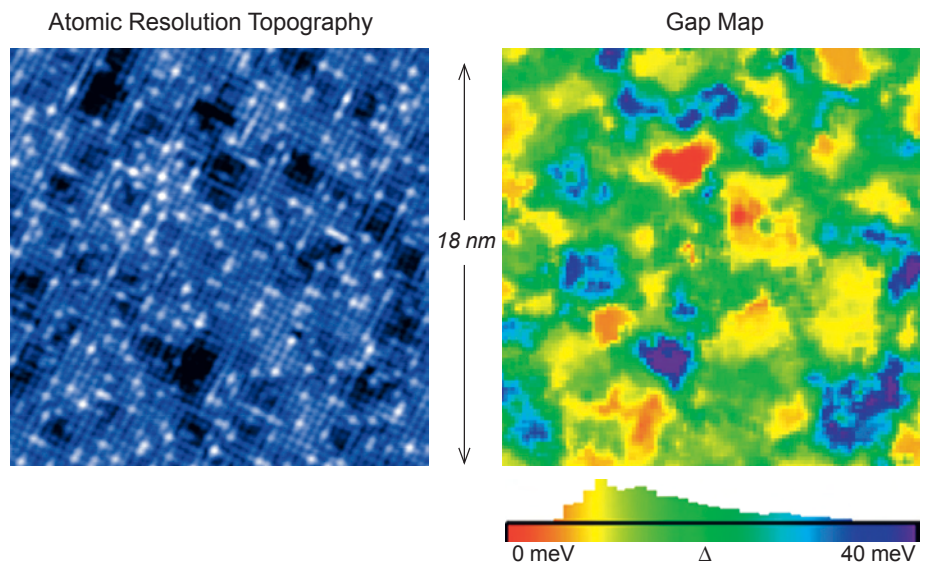
A Closer Look:
Electronic Behavior at the Atomic Scale

The attempt to clarify the nature of the superconducting and other phases of the cuprates has led to the development and improvement of an extraordinary array of experimental techniques. One which has seen significant improvement over the past two decades, scanning tunneling microscopy (STM), happened to earn its inventors Binnig and Rohrer the Nobel Prize in physics the same year Bednorz and Müller announced their discovery of high temperature superconductivity (and the year before they won the Nobel prize). At its heart, STM is simple. Similar to a record player, a sharp tip is brought close to a sample, and scanned across its surface. Remarkably, the technique allows imaging of atoms and even interaction with them, such that one can build nanoscale objects one atom at a time.

The key scientific capability of an STM, however, lies in its ability to measure atomic scale variations in the local density of states of the material—an essential measure of the spatial and energy dependent distribution of electronic excitations in the system. Understanding the excitations in a system is often a crucial step towards understanding the system as a whole. For example, in conventional superconductors the measurement of a gap in the excitation spectrum—a minimum energy below which no electronic excitations are created—confirmed the existence of Cooper pairs and allowed direct measurement of their binding energy Δ (*Figure 2*).

FIGURE 3

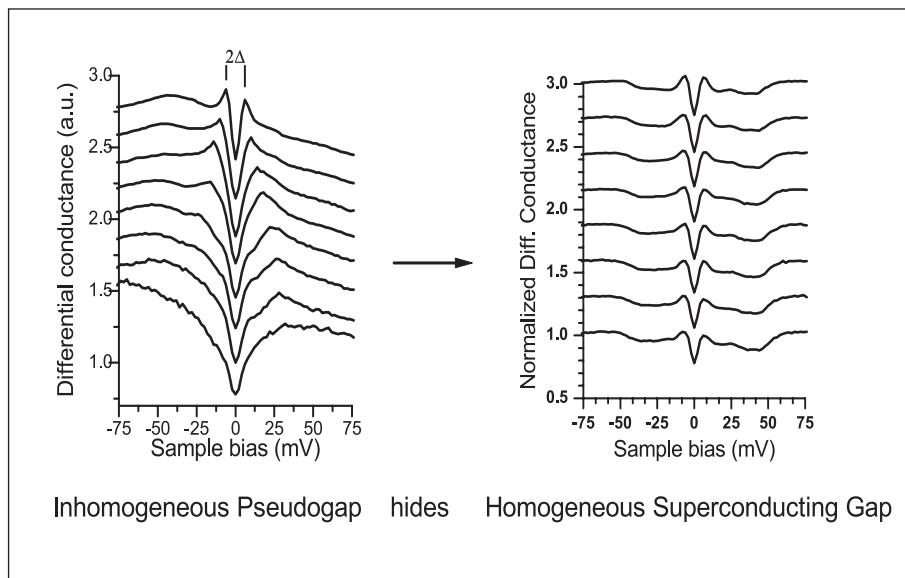*STM measurements of the gap reveal large inhomogeneity on nanometer length scales.*

Atomic Resolution Topography

Gap Map

18 nm

0 meV Δ 40 meV

Gap or Pseudogap?

In high temperature superconductors, however, even the gap is not straightforward. First of all, a gap appears at temperatures well above T_C. Although there are a variety of phenomena which can create gaps in the excitation spectrum, the gaps above and below T_C appear to be the same. By example, temperature dependent STM spectroscopy *(Figure 2)* of $Bi_2Sr_2CuO_{6+x}$ (Bi-2201) doped to $T_C = 15$ K shows no obvious transition at T_C, while in a conventional superconductor the gap is gone above T_C. The continued existence of the gap up to very high temperatures, even reaching room temperature in some systems, has led many to ask not why T_C is so high in the cuprates but why it is so low, given that the "glue" that leads to pairing seems to take affect at much higher temperatures.

The region of the phase diagram in which this gap continues to exist is called the "pseudogap" phase, and is entered into upon heating most high temperature superconductors through T_C. The pseudogap phase itself has a transition temperature T* that, as shown in *Figure 1*, increases as the sample is doped towards its insulating phase, while the superconducting transition temperature T_C falls to zero. This fact, along with the observation that gap magnitude Δ scales with T*, and not with T_C, are further complications in understanding superconductivity in the cuprates, as they appear to highlight the decoupling of pairing and superconductivity.

Scanning tunneling measurements of the gap reveal yet another troubling fact: vast inhomogeneity. As depicted in *Figure 3*, in Bi-2201 the gap size varies by over a factor of five on nanometer length scales (5-10 atoms distance). This then presents the dual challenge of understanding how and why superconductivity can vary so strongly on such short length scales, as well as why other experimental measurements don't see evidence of these variations.

New Experiments, New Insights

These and other issues have led some in the high T_C community to question the interpretation of the pseudogap as Cooper pairing gap without superconductivity. Instead, they contend, the pseudogap could be a competing phase, also characterized by a gap, which pervades the system at higher temperatures but which either loses out to or coexists with superconductivity below T_C. The idea of a competing phase is appealing for many reasons. It explains why "the gap" (really the pseudogap) is tied to T* and not T_C, and why as T* increases T_C decreases.

Until recently, however, there was little evidence for the existence of another phase, and the observation of a smooth evolution from the superconducting gap below T_C to the pseudogap above it has led others to suggest that their similarities would be too great a coincidence if not directly related. Recent STM measurements suggest that this argument is probably correct, although not as originally intended. As shown in *Figure 4*, spectra below T_C actually contain two gaps: a large, dominant one which is typically reported and which remains unchanged on warming through T_C (the pseudogap), and a smaller, previously hidden gap which opens at T_C (the superconducting gap). Careful temperature dependent measurements have allowed a normalization technique[3] to reveal the hidden gap. In addition to opening at T_C, this hidden gap is also significantly more homogeneous than the coexistent pseudogap. Other techniques, including angle resolved photoemission spectroscopy[4] and Raman spectroscopy,[5] point to the same conclusion that two distinct gaps coexist below T_C, indicative of another state coexisting with superconductivity below T_C.

Clearly these discoveries highlight another path forward for understanding the cuprates in which the superconducting state is more conventional and possibly easier to explain than originally imagined. Nonetheless, many questions remain unanswered. Chief among them: what is the pseudogap and why is it so unusual?

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Hudson joined the Department of Physics as an Assistant Professor in January 2002. He received a B.A. in Physics/Linguistics in 1992 from the University of Chicago, and completed his Ph.D. at the University of California, Berkeley, in 1999. After a brief postdoctoral tenure at UC-Berkeley, where he continued his research on scanning tunneling microscopy (STM) of impurities and disorder in superconductors, he became an NRC Postdoctoral Research Associate in the Electron Physics Group at the National Institute of Standards and Technology (NIST), studying spin polarized STM.