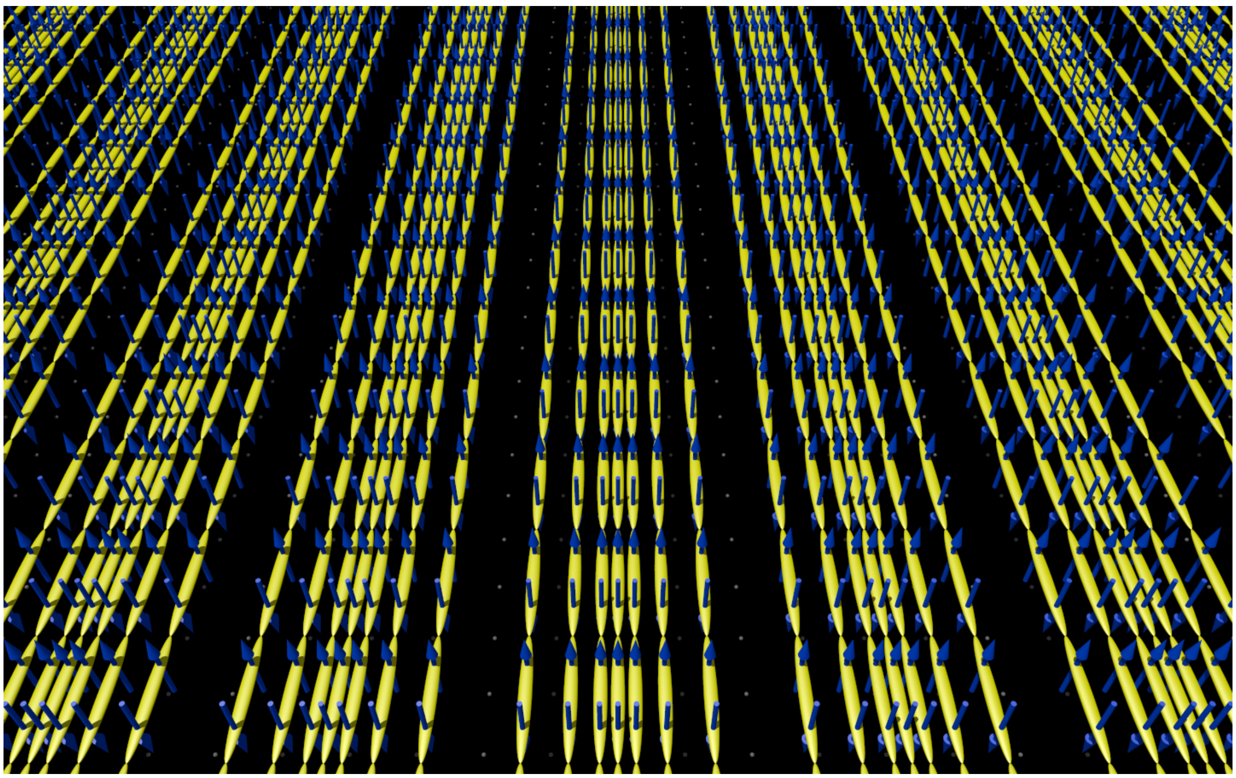
Elusive state of superconducting matter discovered after 50 years

April 13 2016



A schematic image representing a periodic variation in the density of Cooper pairs (pairs of blue arrows pointing in opposite directions) within a cuprate superconductor. Densely packed rows of Cooper pairs alternate with regions having lower pair density and no pairs at all. Such a "Cooper pair density wave" was predicted 50 years ago but was just discovered using a unique "scanning Josephson tunneling microscope. Credit: Brookhaven National Laboratory

Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, Cornell University, and collaborators have produced the first direct evidence of a state of electronic matter first predicted by theorists in 1964. The discovery, described in a paper published online April 13, 2016, in *Nature*, may provide key insights into the workings of high-temperature superconductors.

The prediction was that "Cooper pairs" of electrons in a superconductor could exist in two possible states. They could form a "superfluid" where all the particles are in the same quantum state and all move as a single entity, carrying current with zero resistance—what we usually call a superconductor. Or the Cooper pairs could periodically vary in density across space, a so-called "Cooper pair density wave." For decades, this novel state has been elusive, possibly because no instrument capable of observing it existed.

Now a research team led by J.C. Séamus Davis, a physicist at Brookhaven Lab and the James Gilbert White Distinguished Professor in the Physical Sciences at Cornell, and Andrew P. Mackenzie, Director of the Max-Planck Institute CPMS in Dresden, Germany, has developed a new way to use a scanning tunneling microscope (STM) to image Cooper pairs directly.

The studies were carried out by research associate Mohammed Hamidian (now at Harvard) and graduate student Stephen Edkins (St. Andrews University in Scotland), working as members of Davis' research group at Cornell and with Kazuhiro Fujita, a physicist in Brookhaven Lab's Condensed Matter Physics and Materials Science Department.

Superconductivity was first discovered in metals cooled almost to absolute zero (-273.15 degrees Celsius or -459.67 Fahrenheit). Recently developed materials called cuprates - copper oxides laced with other atoms - superconduct at temperatures as "high" as 148 degrees above absolute zero (-125 Celsius). In superconductors, electrons join in pairs that are magnetically neutral so they do not interact with atoms and can move without resistance.

Hamidian and Edkins studied a cuprate incorporating bismuth, strontium, and calcium ($Bi_2Sr_2CaCu_2O_8$) using an incredibly sensitive STM that scans a surface with sub-nanometer resolution, on a sample that is refrigerated to within a few thousandths of a degree above absolute zero.

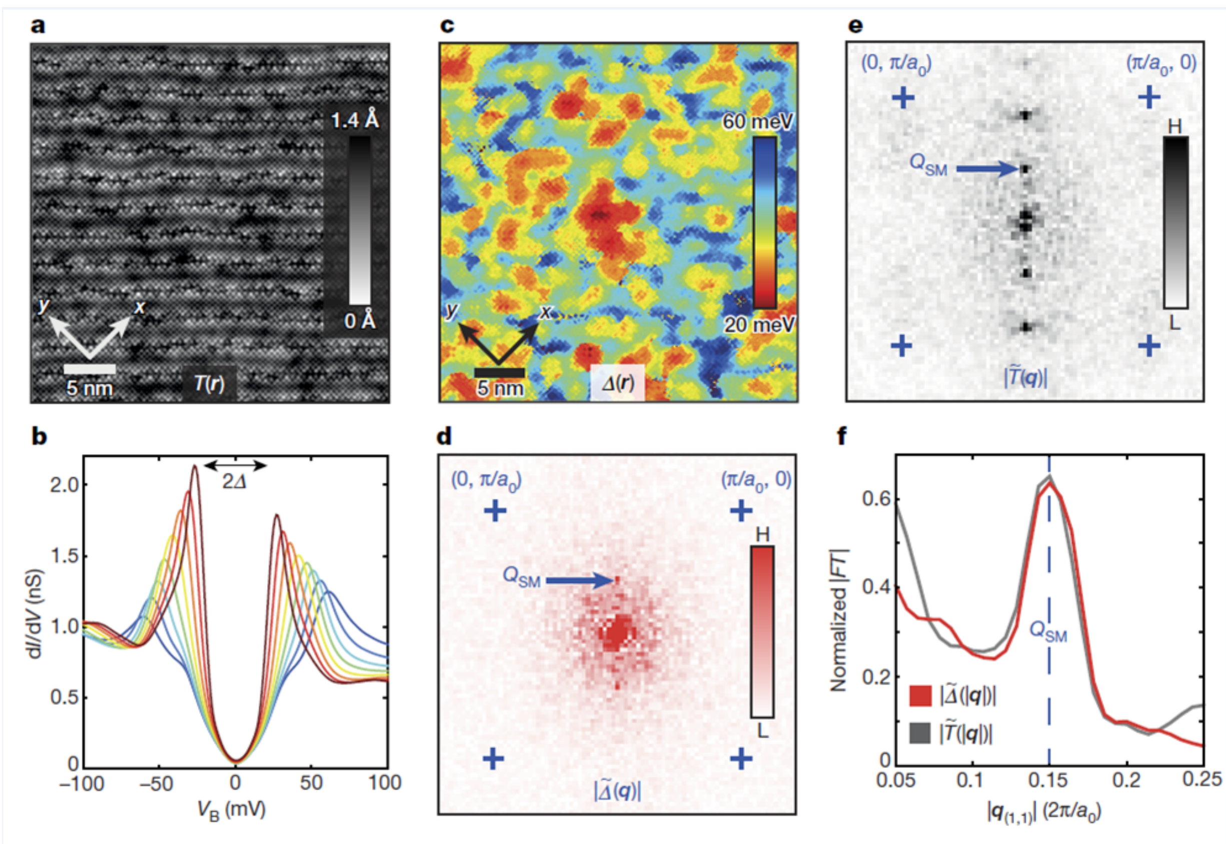


Figure 1.A: Typical 35 nm X 35 nm topographic image T(r) at BiO termination layer of BSCCO (crystal "supermodulation" runs vertically). B: Typical g(E)=dI/dV(E=eV) differential tunnel conductance spectra of superconducting

Bi2Sr2CaCu2O8. The maximum energy gap is determined from half the distance between peaks in each spectrum. C: Spatial arrangement of ƒ´(r) (gapmap) for p~17% Bi2Sr2CaCu2O8 samples studied here in same 35 nm X 35 nm FOV as A. D: Magnitude of Fourier transform of c, (crosses are at q=(π/a0,0);(0,π /a0)) E: As typical26, a single in equivalent peak due to the crystal "supermodulation" is observed (blue arrow). F: Simultaneously measured magnitude of Δ(q) and t (q) from d,e along the (1,1) direction. Their primary peaks coincide exactly. Credit: IBS

At these temperatures, Cooper pairs can hop across short distances from one superconductor to another, a phenomenon known as Josephson tunneling. To observe Cooper pairs, the researchers briefly lowered the tip of the probe to touch the surface and pick up a flake of the cuprate material. Cooper pairs could then tunnel between the superconductor surface and the superconducting tip. The instrument became, Davis said, "the world's first scanning Josephson tunneling microscope."

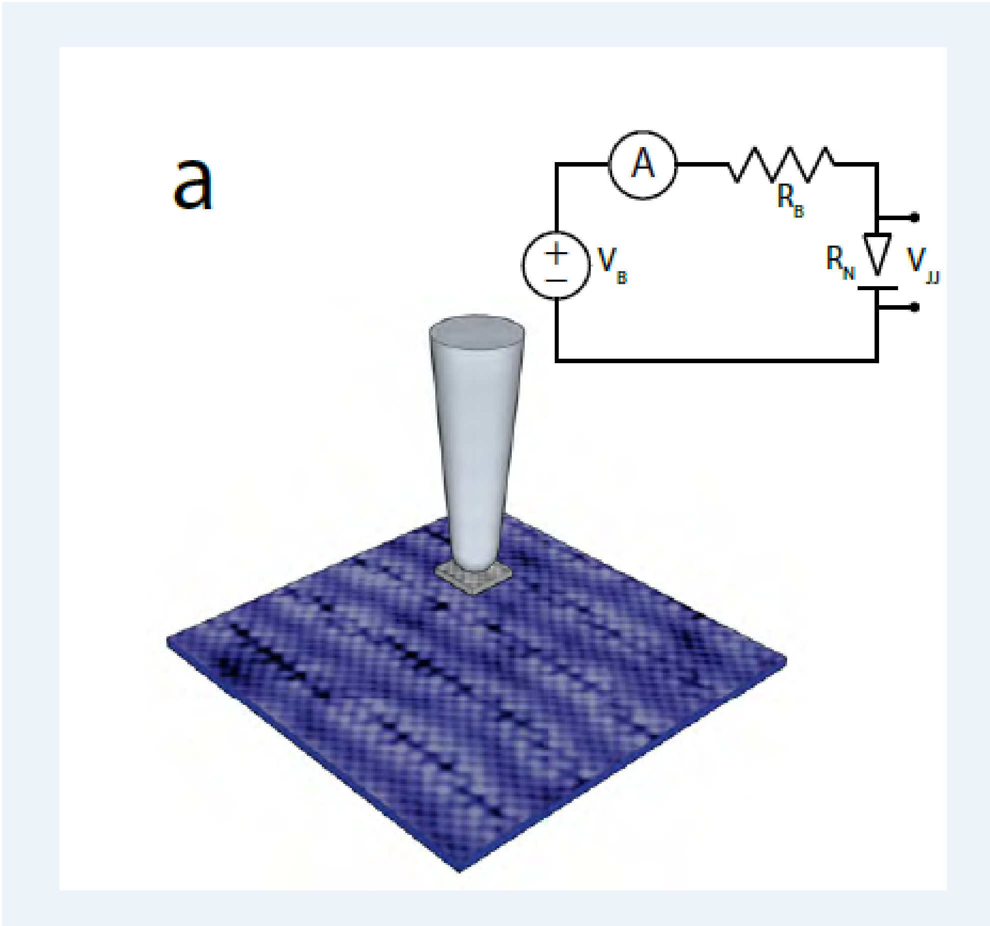


Figure 2: Schematic of tungsten STM tip with nanometer Bi2Sr2CaCu2O8 flake adhering. Inset: SI-STM and Josephson circuitry used where RB =10 M?. Credit: IBS

Flow of current made of Cooper pairs between the sample and the tip reveals the density of Cooper pairs at any point, and it showed periodic variations across the sample, with a wavelength of four crystal unit cells. The team had found a Cooper pair density wave state in a high-temperature superconductor, confirming the 50-year-old prediction.

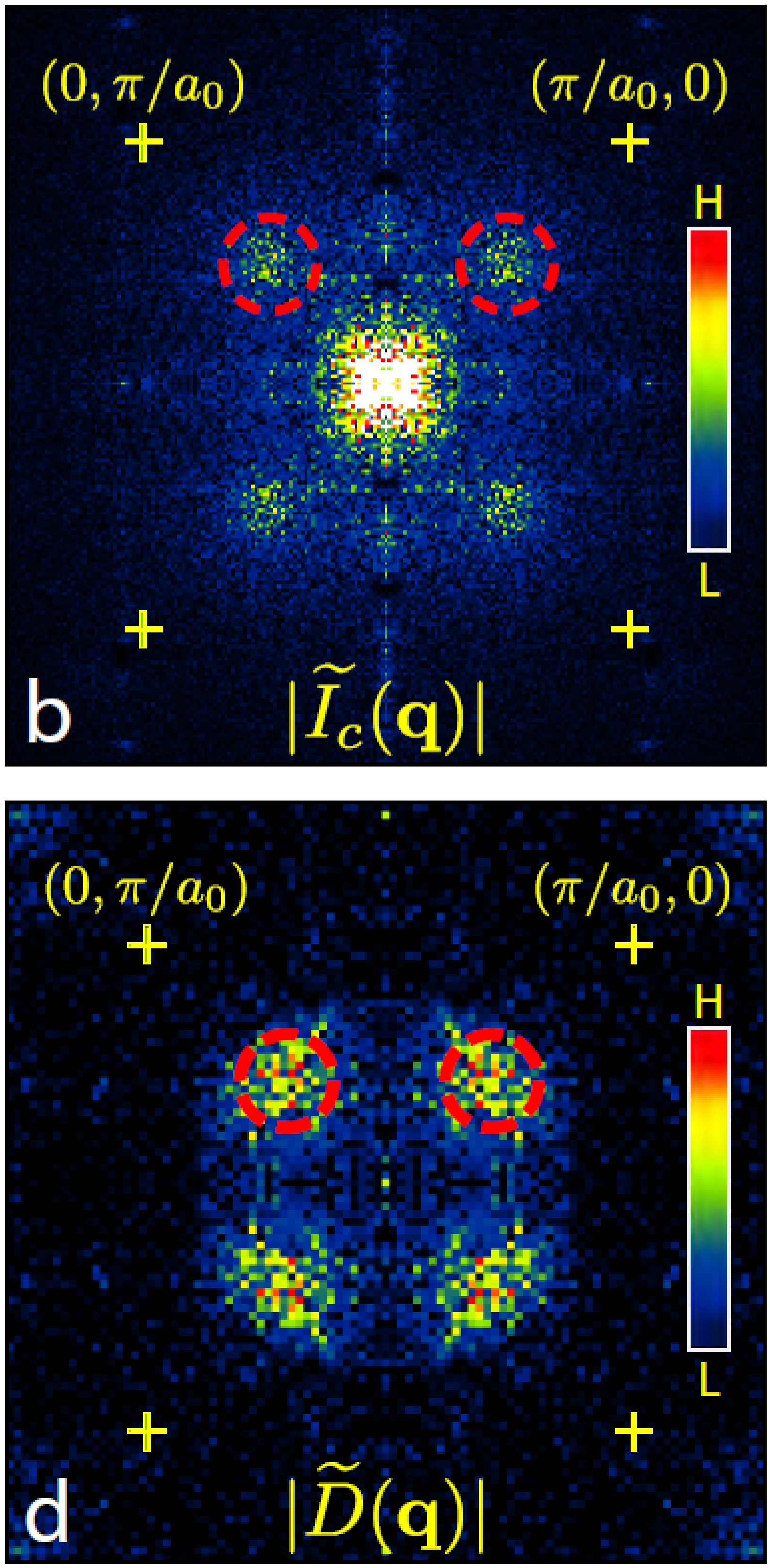

$(0, \pi/a_0)$
$(\pi/a_0, 0)$
H
L
b
$|\widetilde{I}_c(\mathbf{q})|$
$(0, \pi/a_0)$
$(\pi/a_0, 0)$
H
L
d
$|\widetilde{D}(\mathbf{q})|$

Figure 3. B: Magnitude of Fourier transform of Ic(r) in a, |Íc (q)| (crosses at q=(π /a0,0);(0,../a0)). Maxima due to modulations in Ic(r) (dashed red circles) occur at QP=(0.25,0)2 π./a0;(0,0.25)2 π /a0. No significant modulations occur in RN)Qp) (Methods V).

Figure 3.D: Magnitude of Fourier transform of D(q) = OX(q) -- Oy(q) revealing the d-symmetry form factor density wave measure at the same hole-density as b (crosses at q=(π/ao,0);(0 π/ao). Density wave modulations in |D(q)| (dashed red circles) occur at QC=(0.22,0) 2 π /a0;(0,0.22)2 π/a0. Credit: IBS

A collateral finding was that Cooper pairs were not seen in the vicinity of a few zinc atoms that had been introduced as impurities, making the overall map of Cooper pairs into "Swiss cheese."

The researchers noted that their technique could be used to search for Cooper-pair density waves in other cuprates as well as more recently discovered iron-based superconductors.

More information: M. H. Hamidian et al. Detection of a Cooper-pair density wave in Bi2Sr2CaCu2O8+x, *Nature* (2016). DOI: 10.1038/nature17411

Provided by Brookhaven National Laboratory