Interplay of Pair-Density Wave & Charge-Density Wave States with d-wave Superconductivity in Underdoped Cuprates

J.C. Séamus Davis. Cornell University/ Brookhaven NL / St Andrews University

A central issue of copper-oxide high temperature superconductivity research is to understand the nature of the pseudogap phase and its relationship to both the superconductivity and the charge order. Our sub-lattice phase-resolved electronic structure visualization within each CuO_2 unit-cell [1] revealed that the cuprate charge density wave state exhibits a *d*-symmetry form factor throughout the whole pseudogap region [2,3], and that the characteristic energy gap of this state is actually the pseudogap energy [4].

The existence and symmetry of this exotic charge density wave state has motivated contemporary microscopic theories in which the pseudogap phase must also contain a spatially modulating Cooper-pair density wave (PDW) state. In theory, the PDW state is akin to the famous FFLO state of spatially modulated superconductivity, but generated by strong correlations instead of high magnetic fields. However, since its first theoretical proposal in 1964, the FFLO state (or a PDW state) has never been observed.

To search for a cuprate PDW, we use scanned Josephson tunneling microscopy (SJTM) to image Cooper-pair tunneling from a d-wave superconducting STM tip at millikelvin temperatures to the Cooper-pair condensate of underdoped $Bi_2Sr_2CaCu_2O_8$. The resulting images of the Cooper-pair condensate show clear pair density modulations oriented along the Cu-O bond directions. Fourier analysis reveals the direct signature of a Cooper-pair density wave at wavevectors $Q_P \approx (0.25,0)2\pi/a_0;(0,0.25)2\pi/a_0$; the amplitude of these modulations is ~ 5% of the homogeneous condensate density and their form factor exhibits primarily s/s'-symmetry [5].

We review the implications from the discovery of a PDW state, and the observed interplay of CDW, PDW and dSC, for the microscopic theory of the cuprate pseudogap phase.

References

[1] ***Nature 466***, 347 (2010)
[2] ***PNAS 111***, E3026 (2014)
[3] ***Science 344***, 612 (2014)
[4] ***Nat. Phys.*** doi:10.1038/nphys3519 (2015)
[5] ***Nature*** *in press;* **arXiv:1511.08124** (2016)