Nano-size loop current hunting in superconducting cuprates, using polarized neutrons

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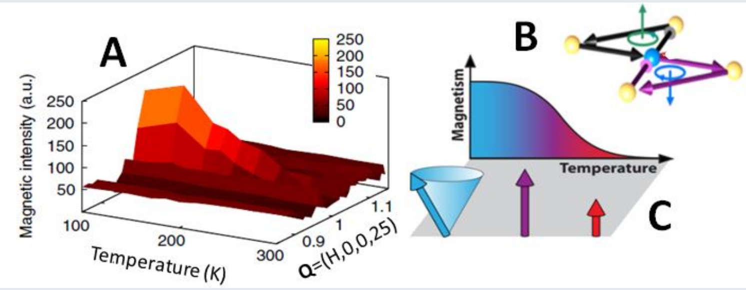
After 30 years of extensive research efforts, the origin of high-temperature superconductivity in cuprates remains one of the great challenges faced by condensed matter physicists. At room temperature, these materials do not behave as conventional metals. When cooled below a temperature T*, they enter the mysterious "pseudo-gap" phase, where portions of their Fermi surface are wiped out. When cooled further below the critical temperature T_c, the electrical resistivity in the whole material falls to zero and the material becomes a superconductor. Surprisingly, superconductivity seems to emerge out of the pseudo-gap phase. There is a general consensus that the essential keys to unraveling superconductivity may be found in the pseudo-gap phase. A recent idea was put forward suggesting that nano-size electrical loop currents, travelling around tiny circuits of only three atoms each, are formed in the pseudo-gap phase. These loop currents can be viewed as the hallmark of a ferro-toroidal order, breaking both time reversal and parity symmetries, while preserving the lattice translation invariance.



A/ temperature dependence of the polarized neutron magnetic scattering intensity. B/ staggered orbital moments induced by loop currents. C/ Schematic representation of the magnetic moment deduced from the polarized neutron experiment. At high temperature (starting from room temperature), the moment points perpendicular to the expected loop current whereas a tilt occurs at low temperature (down to 100 K) when the moment strengthens. All Measurements are done above the superconducting temperature (T_c=89 K)

The task for the experimentalist consists in tracking down features predicted by this intriguing model, such as the magnetic field that the loop currents must generate. Actually, one expects in each crystalline unit cell two loop currents flowing in opposite directions, producing two anti-parallel moments. The difficulty here is that the fields, and the size of the loops that generate them, are tiny. Measuring such fields is, however, exactly what neutrons are extremely good at. Like tiny compass needles, they explore the magnetic field on length scales going down to atomic dimensions. And indeed polarized neutron diffraction measurements could show the presence of magnetic moments within the pseudo-gap state, as predicted (B. Fauqué et al Physical Review Letters 2006). A recent polarized neutron study allows one to get a deeper insight of the intra-unit-cell magnetic moments and their connection with loop currents (Nature Communications 2015). Magnetic signals more than 3 orders of magnitude weaker than the dominant nuclear part could be measured on the instruments 4F1 (LLB) and D7 (ILL) using the method of polarized neutron diffraction. The measurements allowed not only to determine with precision the magnitude of the tiny moments but equally their direction and the extent to which they are correlated in space, and all of this could be followed as a function of temperature. These results form an eagerly awaited stringent set of conditions on any model that tries to describe the physics of the pseudo-gap phase. They provide us with a way better idea of the form that the postulated current loops may take. In particular, as a function of temperature, loop currents could evolve from a classical to a quantum regime, with a quantum superposition a several loop current patterns.

L. Mangin-Thro, Y. Sidis, A. Wildes & P. Bourges, *Intra-unit-cell magnetic correlations near optimal doping in* $YBa_2Cu_3O_{6.85}$, Nature Communications 6, 7705 (2015)

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