ELECTRONIC LIQUID CRYSTAL STATE IN HIGH TEMPERATURE SUPERCONDUCTOR $YBa_2Cu_3O_{6.45}$

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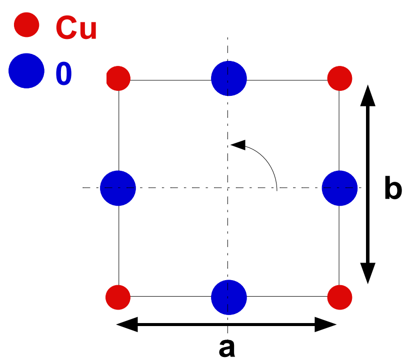
The strongly interacting conduction electrons can be accurately represented as a gas of weakly interacting electron-like excitations. This description, known as Fermi liquid theory, works for many metallic systems. However, over the past two decades, new types of metallic materials with strongly correlated electrons have been discovered that do not fit this standard description. The list includes the superconducting copper oxides and many other materials.

Fermi liquid behavior occurs where the kinetic energy of the electron fluid dominates the particle dynamics. In contrast, where the Coulomb interactions are dominant, electrons are known to form an insulating electron crystal. The electron fluids in strongly correlated metals lie in an intermediate range where neither of these energies is dominant. An analogy can be made with complex classical fluids. There is generally a gas phase at high temperatures, where entropy dominates, and a crystalline solid phase at low temperatures, where interaction energies dominate. In many cases there is an intermediate liquid phase in which interactions and entropic considerations must be treated on an equal footing. In some cases, there are additional "liquid crystalline" phases (e.g., nematic and smectic) that can flow like a liquid but exhibit patterns of broken symmetry that are somewhat like those of a solid. At the end of the 90's, it has been proposed that strong correlations can induce electronic liquid crystal phases. These phases are quantum fluid (conducting) states with a pattern of spontaneous symmetry breaking that is intermediate between those of the simple fluid and an electron crystal.

The nematic metal is named in analogy with a classical uniaxial nematic liquid crystal [1]. One can think of an electron nematic as a partially (quantum) melted version of an anisotropic electron crystal. For instance, correlated materials can exhibit "stripe order" in which the electrons form a striped pattern that breaks translational symmetry and chooses a preferred axis in the crystal. One can imagine a nearby phase in which quantum fluctuations melt the stripe order but the preferred direction of the stripes remains as a memory of the proximate ordered phase. An alternative approach to the metallic nematic phase considers the effect of increasingly strong interactions in Fermi liquids. It has long been known that a Fermi liquid becomes thermodynamically unstable if certain interactions are sufficiently strongly attractive. It was shown that in some cases, rotational invariance is spontaneously broken while translation symmetry is preserved.

High temperature copper oxide superconductors are quasi-two dimensional material, made of the stacking of CuO_2 planes. These planes can be described as the juxtaposition of squared CuO_2 plaquettes (see below). Physicals properties should therefore be invariant under a rotation of 90°.



In the high-transition-temperature superconductor $YBa_2Cu_3O_{6.45}$ [2], magnetic excitations, that develop around the antiferromagnetic wave vector (0.5,0.5), exhibit a net quasi-1D anisitropy at low energy and low temperature (Fig.A). The low magnetic excitation spectrum is characterized by a set of two incommensurate spin excitation along a* direction at wave vectors ($0.5\pm\delta$,0.5) (Fig.B-C). The one-dimensional, incommensurate modulation of the spin system appears spontaneously upon cooling below ~150 K (Fig. D), whereas static magnetic order is absent above 2 kelvin. The evolution of this modulation with temperature and doping parallels that of the in-plane anisotropy of the resistivity (see insert in Fig.D). Our observations highlight the existence of an electronic nematic phase that is stable over a wide temperature range. The results suggest that soft spin fluctuations are a microscopic route toward electronic liquid crystals and that nematic order can coexist with high-temperature superconductivity in underdoped copper oxides.

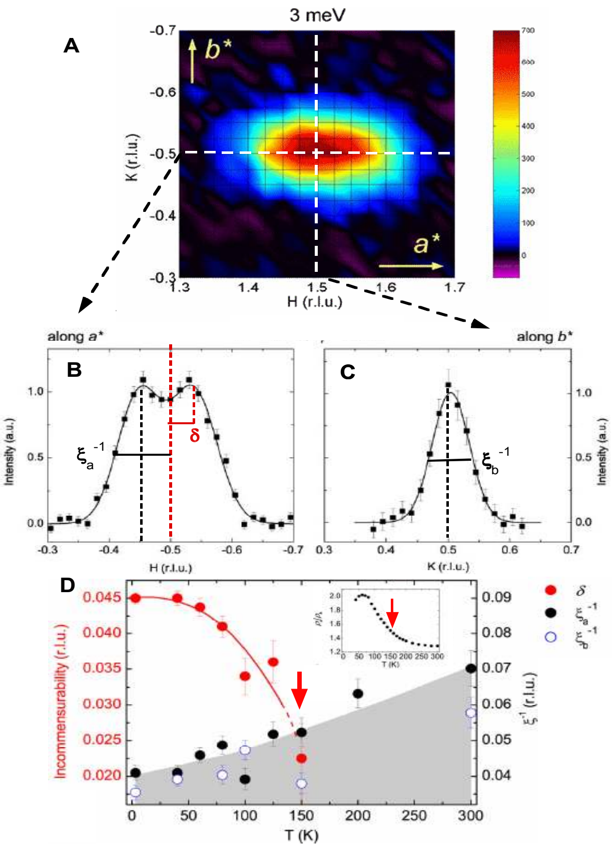


Fig.: A) Intensity map of the quasi-1D incommensurate at 3 meV and 5 K. B-C) Constant energy scans at 3 meV along directions a and b*. D) Temperature dependencies of the incommensurability parameter δ and of the magnetic peak widths along a* and b*. The insert shows the temperature dependence of the a-b anisotropy of resistivity ρ_a/ρ_b*

The energy and momentum dependence of the spin excitations we have observed helps to develop a microscopic description of the nematic state, and to discriminate between different theoretical descriptions of the coupling between spin and charge excitations in the cuprates. Incommensurate peaks in the magnetic neutron scattering pattern can arise either from a longitudinal modulation, where the magnetic moments are collinear but their amplitude is spatially modulated, or from a transverse modulation, where the moment direction varies but the amplitude remains constant. Our data are compatible with slow fluctuations characteristic of either type of modulation. Spin-amplitude modulated states naturally go along with a modulation of the charge carrier density, and the carrier mobilities along and perpendicular to the modulation axis are generally expected to be different [3]. It has also been shown that a transverse modulation with spiral spin correlations can lead to anisotropic hopping transport in weakly doped cuprates with diverging low-temperature resistivity [4]. Further work is required to assess whether this mechanism can be generalized to metallic electron systems such as the one in $YBa_2Cu_3O_{6.45}$.

References:

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