Theory

An analogy with water comes to the rescue of superconductors

Understanding often proceeds through unexpected analogies. Such an analogy has arisen between the properties of water and those of electrons in high-temperature superconductors, materials that conduct electricity without resistance at unusually high temperatures. More precisely, at high-temperature the difference between liquid water and water vapor gradually disappears, but not completely. Similarly, the electrons in a high-temperature superconductor can form a liquid-like phase and a vapor-like phase whose difference is apparent even at temperatures above those where one expects no difference.

It is a common experience that liquid water is denser than its vapor. However, at sufficiently high pressure, liquid water and vapor cannot be distinguished by their density and there is no boiling point. Yet, there is a narrow temperature-pressure range where viscosity changes rapidly from water-like to vapor-like upon heating. The temperature pressure range where this rapid change occurs is called a Widom line.

Our work unveils an unexpected analogy with electrons in materials that become high-temperature superconductors. In these materials, it is known that there is a density-dependent temperature, the pseudogap temperature, where the electronic properties change rapidly.

The temperature-density line where electronic properties change rapidly, T* in **figure 1**, can be understood as the Widom line that emanates from two distinct metallic phases with different densities at low temperature, one of which is the pseudogap phase that has been puzzling physicists for a long time.

In liquid water, molecules tend to stay close to their neighbours that attract them. In vapor a more disordered state is favored by thermal motion. Similarly, in high-temperature superconductors, the strong repulsion between electrons somewhat prohibits

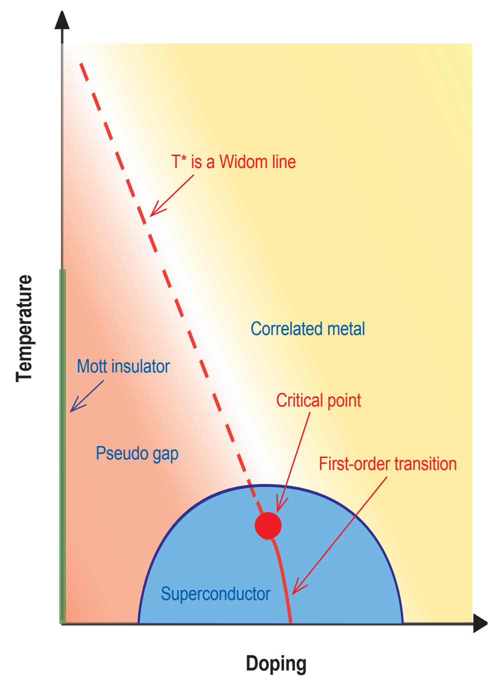

Figure 1:
Schematic temperature versus hole doping phase diagram based on the cellular dynamical mean-field solution of the two-dimensional Hubbard model. The pseudogap characteristic temperature T* corresponds to the Widom line arising above a first-order transition. (Image credit: Virginie Guérard, ILL).

their motion in the pseudogap phase. A more disordered state, akin to ordinary metals, is favored by thermal motion and can also exist at higher-temperature.

Previous theories envisioned that the pseudogap needed to be a manifestation of a new ordered state. Such ordered states are called broken-symmetry states.

Contrary to common theories, this work shows that the pseudogap can occur solely because of strong electronic repulsion and short nonlocal correlations.

No additional broken symmetry is necessary to explain the phenomenon. Broken symmetry states, such as superconductivity, appear in the pseudogap and not the other way around.

Since the superconducting state is born out of the pseudogap over much of the phase diagram, the nature of the pseudogap is a fundamental issue in the field and it is under intense theoretical and experimental scrutiny.

These results were obtained by solving the archetypal model of interacting electron systems with state of the art numerical methods using the most powerful computers available.

The Widom line emerges from a first-order transition that arises in the presence of strong interactions when there is less than one conduction electron per copper atom, providing a new and generic mechanism for the pseudogap (see **figure 2**).

The interrelation between the pseudogap temperature T* and the Widom line is the main finding.
Thus T* appears in a new light: it is an unexpected example of a phenomenon observed in fluids, namely a sharp crossover between different dynamical regimes along a line of thermodynamic anomalies that appears above a first-order phase transition, the Widom line.

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References

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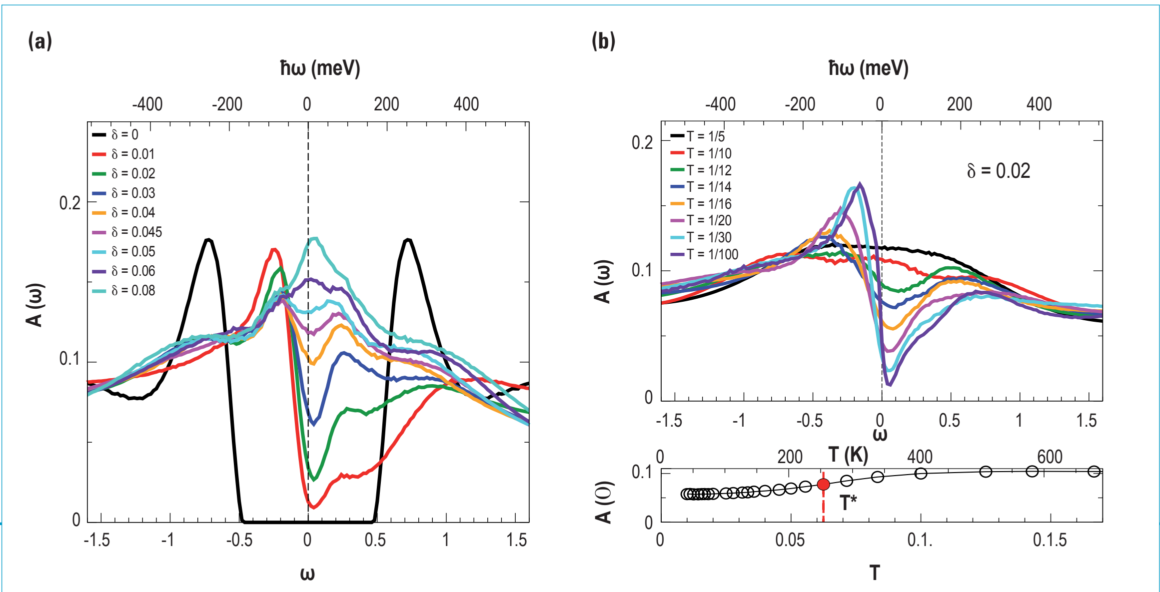

Figure 2: (a) Evolution of the electronic density of states with hole doping at a fixed temperature above the first-order transition. One can distinguish 3 phases: Mott insulator (δ = 0), pseudogap metal (0.01 ⩽ δ ⩽ 0.05), and ordinary metal (δ ⩾ 0.06).
(b) Temperature evolution of the density of states at constant doping. The inflection point in the density of state at the Fermi level, indicated by a red circle, is our estimate of T*.