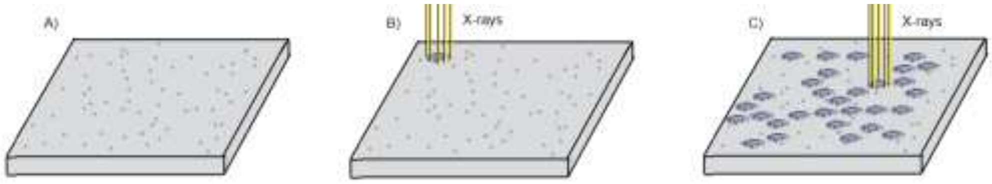
The outcome of the IMAX project are mainly three discoveries in the nanoscale superconductivity, far-from equilibrium phenomena and critical transitions.



IMAX

Intra-European Fellowships (IEF)

Superconducting materials show zero resistance to the passage of electric current below a specific low temperature and they expel the magnetic fields present within them. However, superconductors must be cooled down to temperatures close to the absolute zero to operate. A couple of decades ago it was discovered that ceramic materials can become superconductors at higher temperatures. But nowadays there is not yet a recognized microscopic theory able to describe what happens in this fourth state of matter, explaining the mechanism of this quantum phenomenon at the macroscopic scale.

1.st discovery

Solid state system shows usually a cubic symmetry. Using advanced X-ray microscopies at the synchrotron radiation facilities in Europe, we were able to investigate however the subtle variation point by point of the structure. In particular, we were able to probe the nanoscale and mesoscale ordering of electrons. In a superconducting cuprate material at high temperature (Tc = 95 K), we found that the electrons get aggregated and form puddles of different shapes. These electronic crystals are called technically charge density waves (CDW).

A detailed inspection of the order distribution showed us that the system of electronic crystals is highly inhomogeneous, forming clumps of very different shape and sizes. Indeed, the CDW order extends from many small puddles like the small ice crystals, to very large one (like an iceberg). We discovered that the distribution of the puddles size and puddle density follows a power-law distribution over more than one order of magnitude. This distribution that is quite know in the theory of network (it describes the connectivity distribution of the world-wide-web), can also describe a complex fractal-like self-organization. This fractal order is surprisingly showing the same statistical spatial inhomogeneity of another cuprate material with Tc=40K, although a different critical exponent. The recurrence of this mesoscale pattern made by the same competing nanostructures in the cuprates is a fact already surprising in its own right, suggesting a subtle trick found by nature in the organization of matter in order to sustain the condensation of quantum matter at high temperature and at ambient pressure.

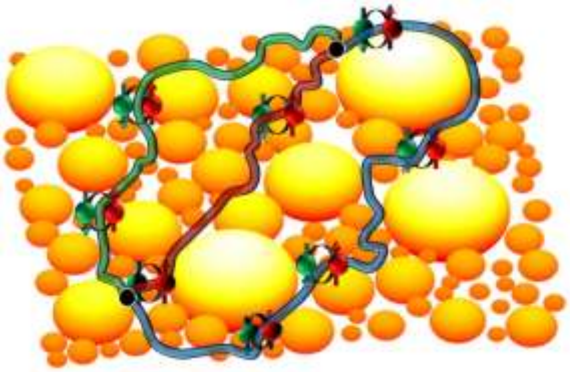


Figure 1. The picture shows the pathways of superconducting pairs running around the CDW puddles. The puddle size distribution is a power law. Between two points (black dots) there are an infinite number of pathways not only distinguished by the number of times a path goes around a single puddle, but also distinguished by the way the path is passing though the pattern of CDW puddles. This space can be mapped into a hyperbolic space.

However, not all electrons form electronic crystal puddles, other electrons remain in the liquid phase. In this space the superconducting electrons, which move in pairs like hydrogen molecules, do not move in an uniform three dimensional world as we are used in our everyday life, but they run only along pathways in the interstitial space left open by CDW puddles. Different paths connecting two points are not topological equivalent as shown by Figure 1. Between two points (black dots) there are an infinite number of pathways not only distinguished by the number of times a path goes around a single puddle, but also distinguished by the way the path is passing though the pattern of the CDW puddles. We argue that this emergent spatial interstitial space can be mapped into a non-euclidean geometry. These results finally open new venues in the field for the design of new superconducting metamaterials taking advances of the atomic organization in the mesoscopic world.

Reference: G. Campi, et al., Inhomogeneity of charge-density-wave order and quenched disorder in a high-Tc superconductor. Nature **525**, 359 (2015),

2nd discovery

Equilibrium systems -- where there is no energy moving around--are now understood quite well. However, nearly everything in our lives involves energy flow, from photosynthesis to digestion to tropical cyclones, and we do not yet have the physics to describe it well. A better understanding of far-from equilibrium physical phenomena could lead to huge improvements in energy capture, batteries and energy storage, electronics and more.

The realization of new superconducting metamaterials, driven far-from equilibrium, has been done at the University of Twente. We built a system containing 90,000 superconducting niobium nano-sized islands on top of a gold film. By applying magnetic fields on this system, they penetrate the superconducting material in the form of tiny filaments called vortices, which control the electronic and magnetic properties of the materials. In this configuration, the vortices find it energetically easiest to settle into energy dimples in an arrangement like an egg crate—and make the material act as a Mott insulator, since the vortices won’t move if the applied electric current is small.

The Mott transition occurs in certain materials that according to textbook quantum mechanics should be metals, but in reality turn insulators. A complex phenomenon controlled by the interactions of many quantum particles, the Mott transition remains mysterious--even whether or not it is a classical or quantum phenomenon is not quite clear. Moreover, scientists have never directly observed a dynamic Mott transition, in which a phase transition from an insulating to a metallic state is induced by driving an electrical current through the system; the disorder inherent in real systems disguises Mott properties.

The vortices display both classical and quantum properties, which led us to study them for access to one of the most enigmatic phenomena of modern condensed matter physics: the Mott insulator-to-metal transition. When we applied a large enough electric current, however, we saw a dynamic Mott transition as the system flipped to become a conducting metal; the properties of the material had changed as the current pushed it out of equilibrium. The vortex system behaved exactly like an electronic Mott transition driven by temperature.

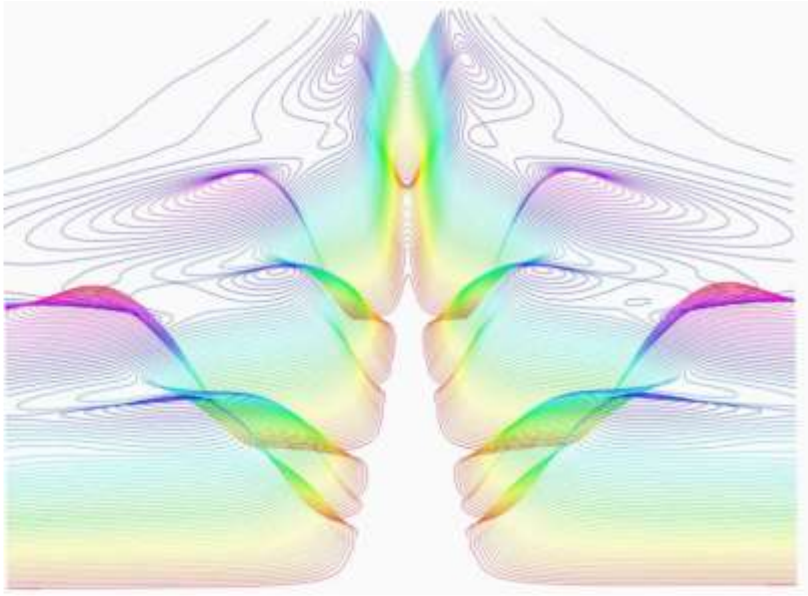


Figure 2. It shows the dynamic vortex Mott transition, which experimentally connects the worlds of quantum mechanics and classical physics and could shed light on the poorly understood world of non-equilibrium physics.

As we seek to make electronics faster and smaller, Mott systems also offer a possible alternative to the silicon transistor. Since they can be flipped between conducting and insulating with small changes in voltage, they may be able to encode 1s and 0s at smaller scales and higher accuracy than silicon transistors.

Reference: N. Poccia, et al**.** Critical behavior at a dynamic vortex insulator-to-metal transition. *Science* **349**, 1202-1205 (2015).

3rd discovery

Materials with exceptional electronic and magnetic properties are of great importance for many applications and are often are in the phase diagram proximity of a Mott state. A particularly versatile class of materials are the ‘perovskite oxides’.

Here, we have discovered a special effect relating to the magnetism of one of such perovskite-oxides; lanthanum-manganese-oxide. This material consists of stackings of $LaMnO_3$ unit cells, quite comparable to stacking blocks of LEGO. In this case, the individual building blocks are only 0.4 nanometer in size though (1 nanometer is 1 millionths of a millimeter).

The new discovery is that the magnetism in these layers is switched on abruptly when the number of $LaMnO_3$ building blocks changes from 5 to 6. Thin films of the oxide were grown on a perfectly flat crystal of nonmagnetic $SrTiO_3$, using a technique called pulsed laser deposition. By adding a sixth layer of $LaMnO_3$, the material switches from antiferromagnetic (antiferromagnets produce no magnetic field) to ferromagnetic. Such an abrupt transition has never been seen before. Using a Scanning SQUID Microscope, an instrument that uses superconducting electronics to measure magnetic fields with exquisite sensitivity, a direct image of the change in magnetic properties was obtained.

The discovery of such a sharp critical thickness for the appearance of ferromagnetism makes it possible to define magnetic structures on a nanoscale and implies that a very sensitive new functionality is present, in which a slight alteration or addition can alter the magnetic properties of the structure. We expect this to be not only limited to adding new layers, but possibly also to other manipulations such as applying electric fields or adsorbing specific molecules. Further study will be conducted, aimed at the use of the effect in information technology and sensors.

Reference: X. R. Wang, et al. Imaging and control of ferromagnetism in a polar antiferromagnet. Science **349**, 716 (2015).