Mesoscopic spin glasses

A glass is arguably the strangest phase of ordinary matter; it is neither a liquid nor a crystalline solid, but it has aspects of both. One of the simplest glass structures is the spin-glass. We have started a project aiming at elucidating the physics governing these strange systems using tools coming from another domain of condensed matter physics, namely mesoscopic physics. This problem illustrates how a given field of research can benefit from other fields developed separately, or even from fundamental mathematics.

In the late 60s, a new phase of matter, called a "spin glass", was discovered in non-magnetic compounds doped with magnetic impurities. The problem is actually very simple: because the impurities are randomly distributed, their mutual magnetic interactions (the "RKKY interactions") will also have a random distribution, especially because the sign of these interactions depends on the distance between impurities. So interactions between two impurities will force the impurities' spins to be aligned parallel or anti-parallel randomly, depending on the distance between them. It is easy to understand that it will be impossible to satisfy all the constraints of the system: it is said to be "frustrated", the system cannot choose between multiple possible spin configurations. The nature of the ground state of a spin glass is still mysterious and a heavily debated subject; the most intriguing property is that this state consists of a large (possibly infinite) number of degenerate states. This can be described by a very fancy mathematical formalism: by defining the "distance" between two states by the number of spins which are flipped between the two configurations, it can be shown that the phase space is "ultrametric". This is one striking example of the intimate relation between Nature and a fundamental mathematical concept such as topology.

However, so far, no experiment had been able to probe the ground state of a spin glass and exhibit the ultrametric nature of its phase space. The problem is that almost all the experiments have concerned magnetization measurements, which yield only an *average* quantity over the whole sample. We need to probe the *microscopic* configuration of the spins. Here, the techniques of mesoscopic physics, a field that studies quantum coherent conductors, can help. Since the 1990's and the emergence of this domain, it has been known that electronic transport in a quantum system is directly related to the transmission of the quantum waves associated with the conduction electrons. Diffusion of electrons over a magnetic impurity leads to a dephasing, and thus modifies the transmission; the conductance thus reflects exactly the spin configuration of the spin glass.

This is the subject of our experiment. We measure the conductance of mesoscopic-scale spin glasses (small wires of a conducting metal containing some magnetic impurities) at very low temperature, as a function of an external parameter such as magnetic field. As can be seen in Fig. 1, the conductance exhibits oscillations as a function of a magnetic field. These fluctuations are not noise : they are the so-called "Universal Conductance Fluctuations" (UCF's). The fluctuations are resolved because there is only a relatively small number of channels of conduction in the mesoscopic sample. They are a true "magneto-fingerprint" of the sample; any change in the spin configuration will change this fingerprint. Such measurements are a powerful tool for probing the nature of the phase space of a spin glass.

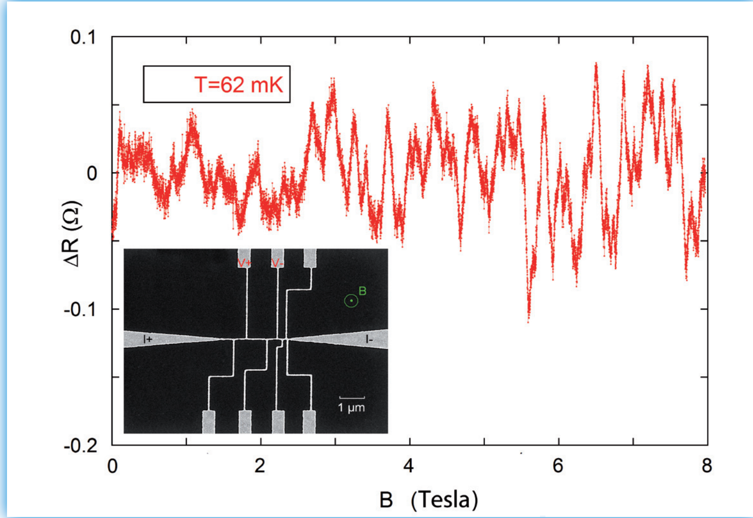

Fig. 1: Magneto-fingerprint of the spin glass Mn-doped silver measured at very low temperature (0.06 K). The conductance of the short (≈1 micron) wire section shown in the inset image fluctuates with magnetic field B. The fluctuations are perfectly reproducible and their precise shape corresponds to the configuration of the spins in the sample.

In recent work, we have made the first step in this direction by showing that these UCF's can tell us the number of free spins, i.e. spins that are not frozen, in the sample. This is actually a very old and recurrent question in the domain of spin glass physics: At the freezing temperature, do all the impurity spins freeze at the same time, as in a standard phase transition, or are things more complicated? We can answer this question because the Universal Conductance Fluctuations provide a direct measurement of the phase-coherence time of the electrons, which is directly related to the number of free spins (because spin-flips cause loss of coherence of the electrons).

We found that the glassy transition is more complicated than usual phase transitions: The transition does not appear at a precise temperature, but spreads over an extremely large temperature range. At the freezing temperature T (typically 700 mK in our case), only a fraction of the spins actually start to freeze, and freezing of the other spins occurs progressively down to very low temperature. At temperature T/10, almost 10% of the spins are still free.

This observation sheds new light on this very peculiar phase transition, and may help explain other strange experimental facts observed only for spin glasses. Finally, we have also found that spin glass systems are surprisingly robust against a very strong magnetic field : after a magnetic field cycling of magnitude several Teslas, the system ends up in *exactly the same microscopic spin configuration*. This unexpected observation could be related to the existence, in the glassy phase, of spin configurations much more "rigid" than the others, configurations the system will fall into after applying the strong magnetic field.

Mesoscopic physics is now a mature science, and it may lead to new dynamism in the field of the physics of complex systems. Our experiments give only a foretaste of the possibilities of this approach.

CONTACT

Laurent SAMINADAYAR
laurent.saminadayar@neel.cnrs.fr

Ph.D students
Thibaut CAPRON
Guillaume FORESTIER

FURTHER READING

Remanence effects in the electrical resistivity of spin glasses
T. Capron, A. Perrat-Mabilon, C. Peaucelle, T. Meunier, D. Carpentier, L. P. Lévy, C. Bäuerle and L. Saminadayar
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