Vortex creep in type II superconductors: when vortices cross walls

Perhaps the most striking property of superconductors, after the absence of electrical resistance, is their ability to expel a magnetic field. However, in the so-called “Type II” superconductors, the expulsion is incomplete: the magnetic field can penetrate to a certain extent into the superconductor forming quantized flux lines, called vortices. This “vortex matter” constitutes a very useful system to probe the physics of elastic systems in the presence of disorder, including the quantum creep of lines through a random pinning landscape.

Vortices are field lines spreading through the sample. They are constituted of a non-superconducting core surrounded by permanent electric currents. When the magnetic field applied to a Type II superconductor is increased progressively, vortices form at the edges of the sample and penetrate laterally into it, finally reaching the sample’s centre for high enough magnetic fields. The vortices are then expected to move back out of the sample as the field is reduced back to zero. However, some of them remain trapped inside the sample, as their non-superconducting core gets pinned by defects naturally present in all samples. A remnant magnetic field \( B \) then remains present even for zero applied field.

Since the magnetic flux carried by vortices is quantized, \( B \) is directly proportional to the vortex density and is hence much larger in the centre of the sample than at its periphery due to the larger number of vortices remaining pinned in the centre of the sample, see Fig. 1. The corresponding magnetic field distribution is then characteristic of this out-of-equilibrium vortex state (called the “Bean state”), which can be measured by scanning a miniature Hall probe over the sample surface.

This flux distribution is however only metastable, and the vortices try to creep towards the sample edges to disappear from the sample. At finite temperature, they can jump over the barriers constituted by the pinning potential but this so-called thermal creep is expected to vanish when the thermal energy \( (k_B T) \) drops well below the pinning energy \( (U_0) \). However, vortices can also pass through the (barrier) walls (see Fig. 2(a)), even at vanishing temperature.

The creep rate can be quantified by measuring the decay of the remnant magnetic field \( B \) at the centre of the sample. In the case of thermal creep, the decay rate \( S \) is expected to decrease with temperature as \( k_B T/\mu \), whereas, for quantum creep, \( S \) would remain finite down to zero temperature, being of the order of \( \hbar/\tau_c \), where \( \tau_c \) is the time spent by the vortex under the barrier. This time scale is inversely proportional to the size of the creeping object i.e. in our case the vortex radius \( R \), which is given by the coherence length. This quantum creep is similar to the quantum tunnelling of a single particle through any energy barrier but now concerns a vortex line (of radius \( R \)) spreading all the way through the sample.

So quantum creep is expected to be observed in systems where this radius (i.e. the coherence length) is particularly small. Iron Selenium Telluride belongs to the family of the iron-based superconductors discovered in 2009. This family has attracted much interest due to the presence of a magnetic element (Fe) and because the superconducting critical temperature can be as high as 55K (bettered only by the cuprates family). Our previous study of the \( H-T \) phase diagram has shown that the superconducting coherence length is indeed very small (~0.3 nm) in Fe(S,Te) which is therefore a very good candidate to look for quantum creep in vortex matter.

Using a Helium 3 cryostat built by the NEEL Institute’s cryogenics service, we have been able to measure the relaxation rate \( S \) down to 0.3 K, see Fig. 2(b). We found that \( S \) remains finite down to the lowest temperatures (with \( S(0) \sim 2\% \)). This shows clearly that quantum creep is the dominant relaxation mechanism at low temperature and that the vortex lines can, indeed, pass through the pinning-potential walls to reach the sample edges, and thus disappear.

**Fig. 1**: Profile of remnant magnetic field \( B \) across the Fe(Se0.5Te0.5) sample, measured by scanning a miniature Hall probe sensor over the sample surface. The wavy lines (and dots on the surface) represent pinned vortices traversing the sample.

**Fig. 2**: (a) Vortex pinning potential. Vortex creep can be either thermally activated or due to quantum tunnelling through the barriers. (b): Decay of magnetic field (measured at sample centre) showing that creep remains present down to the lowest temperatures.

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FURTHER READING

Vortex creep down to 0.3 K in superconducting Fe(Te,Se) single crystals
T. Klein, H. Grasland, H. Cercellier, P. Toulemonde, and C. Marcenat

Thermodynamic phase diagram of Fe(Se\(_{1-x}\)Te\(_x\)) single crystals in fields up to 28 tesla