THE PHYSICS OF VORTEX MATTER

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It is a great honor for me to be awarded the Latsis Prize. I would like to express my sincere gratitude to the Latsis family and their foundation. It is my pleasure to introduce my working field, the theory of Vortex Matter to you.

Vortices

The simple way to imagine Vortices in type II superconductors is to view them as a direct visualization of magnetic force lines. Magnetic field (for example the earth field that we identify by compass) is in every point of the space. If we insert the normal metal inside the magnet the field will freely penetrate it. However, if we cool this metal down into the superconducting state the magnetic field will penetrate through the superfluid via creation of topological defect lines: vortices. Then magnetic field lines will be confined in narrow tubes, with the diameter about few thousands Angstroms. These tubes are called vortices. They can be visualized. For example, if one puts some magnetic powder on the top of the sample, magnetic particles will be attracted to the magnetic field of vortices. In this way one can make pictures of them.

Vortex Motion

Vortices are topological defects. Each of them carries one magnetic flux quanta $\Phi_0=hc/2e \approx 2\ 10^{-7}$ G cm^2. They cost energy and since vortices are line objects their bending leads to an energy increase. They repel each other and in equilibrium at low temperatures form a triangular lattice. Vortices move under the action of the external current but can be also pinned by the inhomogeneities of the sample. The last property is very important. Current exerts the Lorentz force acting on vortices. In homogeneous superconductor this force leads to the vortex motion. The flux motion produces an electric field proportional to the driving current density and thus the flux flow resistivity appears. As a result the most valuable superconducting property of dissipation free current is lost. Fortunately, any defect in the sample interacts with the vortices. In this case the driving Lorentz force is counteracted by the pinning force and there is no vortex motion. As a result the technological usefulness of the type II superconductors is recovered.

Flux Creep

Strictly speaking, this is the situation at zero temperature. Then dissipation appears only when the external current is increased beyond its critical depinning value. The inclusion of thermal fluctuations changes the dynamical behaviour of the vortex system. Vortex lines can move then even at small currents due to thermally activated jumps over the pinning barriers, leading to the famous creep phenomenon in type II superconductors. Creep of vortex lines produces small but finite directed motion of vortices and thus reestablishes dissipation in the system. In conventional low temperature superconductors flux creep is not important. Activation energies there are much larger then temperature. Vortex motion is very slow and observable only for the current that is very close to the critical one. Situation is dramatically different in high temperature superconductors. The layered structure of the copper oxide compounds leads to the reduction of the effective barriers due to anisotropy of the material. Operational temperature is also considerably higher. As a result thermally activated vortex motion is very pronounced there. Due to this so called giant flux creep, supercurrents in the sample are decaying rather rapidly. Crucial question then is whether creep persists down to the limit of zero driving force. If activation barriers $U(j)$ saturate for currents j going to zero, then the thermally assisted flux flow will produce a finite resistivity at any nonzero temperature $\rho(j \rightarrow 0) > 0$. In this case the electromagnetic response of the system is not qualitatively different from the normal metal. If, however, barriers diverge with decrease of the current $U(j) \rightarrow \infty$ as $j \rightarrow 0$ then the linear resistivity vanishes $\rho(j \rightarrow 0) \rightarrow 0$. This corresponds to the `glassy' response of the true superconductor.

Collective Creep Theory

It is the collective creep theory that describes glassy motion of the vortex lines. The crucial ingredient there is the line nature of vortices. Whereas for point like objects in random potential activation energy barriers are finite, they are infinite for lines. To understand that let us note, that the creep like motion of an individual vortex line can be visualized as a thermal diffusion process where vortex segments move between metastable states. In the absence of an external current density j a vortex segment lowers its energy by finding the optimal low energy state. With an applied current density j a new metastable state becomes more favorable and the vortex moves. The new optimal states are determined by the condition that the energy gain due to the driving Lorentz force matches the energy of the new deformed vortex configuration. For a current density j near its critical value j_{ock} this condition is already fulfilled for the neighboring metastable state that is short distance away. However, upon decreasing the current density j the Lorentz force is reduced and the next metastable state is further away. As a consequence, the thermal motion of vortices will involve more extended segments hopping larger distances in order to reach the next optimal low energy state. With increase of the size of the moving vortex segment its energy is also increased. As a result creep energy grows algebraically with decreasing current density j

$$U(j) = U_c \left(\frac{j_c}{j} \right)^{\mu}$$

Correspondingly, the current-voltage characteristic exhibits highly non-linear glassy behaviour at low drive

$$V \propto \exp\left[\frac{U_c}{T} \left(\frac{j_c}{j} \right)^{\mu} \right]$$

This very nonlinear vortex diffusion leads to a vanishing resistance at low currents producing superconducting response.

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