Spontaneous Hall effect in superconducting materials

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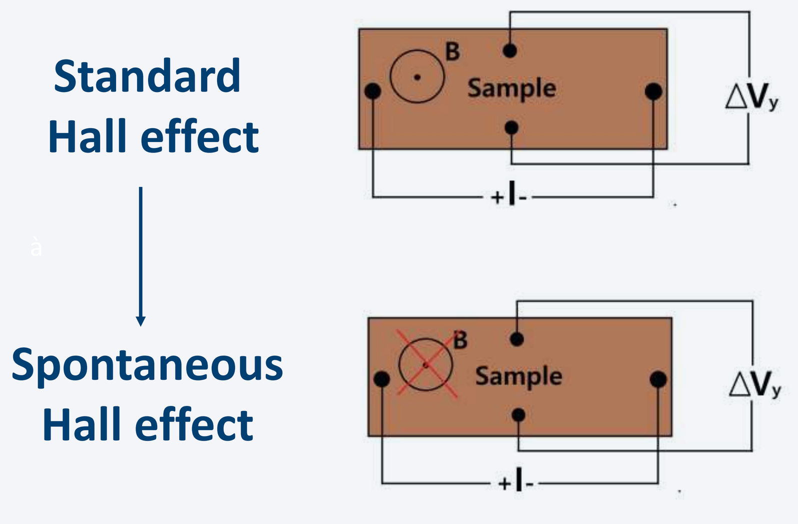
Spontaneous Hall effect

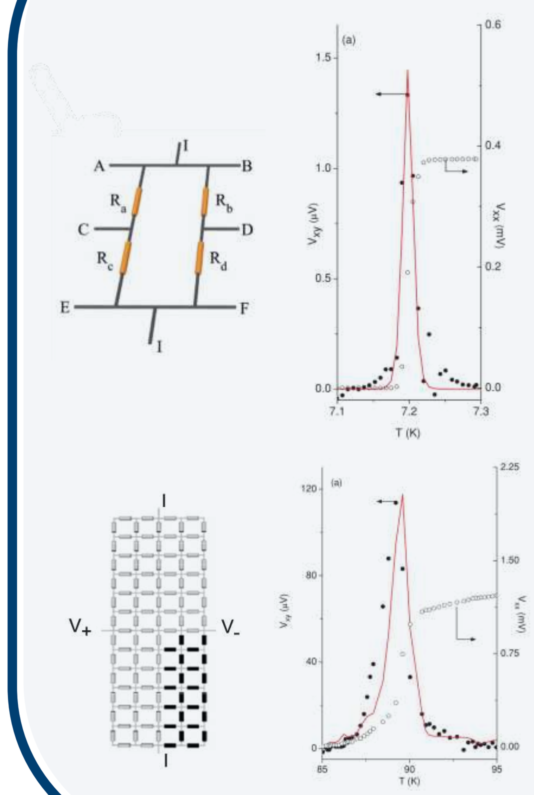
The standard Hall effect consists in the appearance of a transverse voltage in a conducting material when a longitudinal electrical current is combined with a perpendicular magnetic field, as result of the Lorentz force acting on the charge carriers.

The spontaneous Hall effect consists in the appearance of a finite transverse voltage, even in the absence of an applied magnetic field, when in principle there should not be any transverse force acting on the charge carriers.

In a superconducting material the spontaneous Hall effect appears in the form of a peak across the superconducting transition. The origin of this peak is still strongly debated



The inhomogeneities explanation: our starting point



The origin of the spontaneous Hall effect in superconductors is still strongly debated and many exotic explanation have been proposed during the years.
The appearance of a transverse voltage at zero magnetic field has been explained within the framework of Abrikosov vortices and anti-vortices motion [1]; an alternative interpretation to justify the spontaneous Hall effect has been suggested in the context of the breaking of time-reversal symmetry in two-dimensional high-temperature superconductors [2]. However, both explanations cannot justify the appearance of this effect in a very wide range of superconductors, spacing between type I and type II superconductors, BCS and unconventional superconductors, but also between thin films and bulk samples.
In this context a very interesting explanation has been proposed in [3]: the anomalous transverse voltage can be justified by the presence of an asymmetric spatial inhomogeneity in the material. Indeed, a distribution of inhomogeneities inside a sample, could prevent the current from moving in the longitudinal direction as expected, but force it to find percolative paths deviating in different directions. Therefore, the presence of local transverse current component leads to the appearing of a transverse voltage. Segal, Karpovski and Gerber [3], performed numerical calculations of current flow in inhomogeneous sample, depicted as a resistor grid in which a quarter of the resistors represent a quarter of a superconducting sample, which passes to the superconducting state with a small delay in temperature ΔT_t with respect to the other three-quarters of the material, thus representing an inhomogeneous portion of the sample.

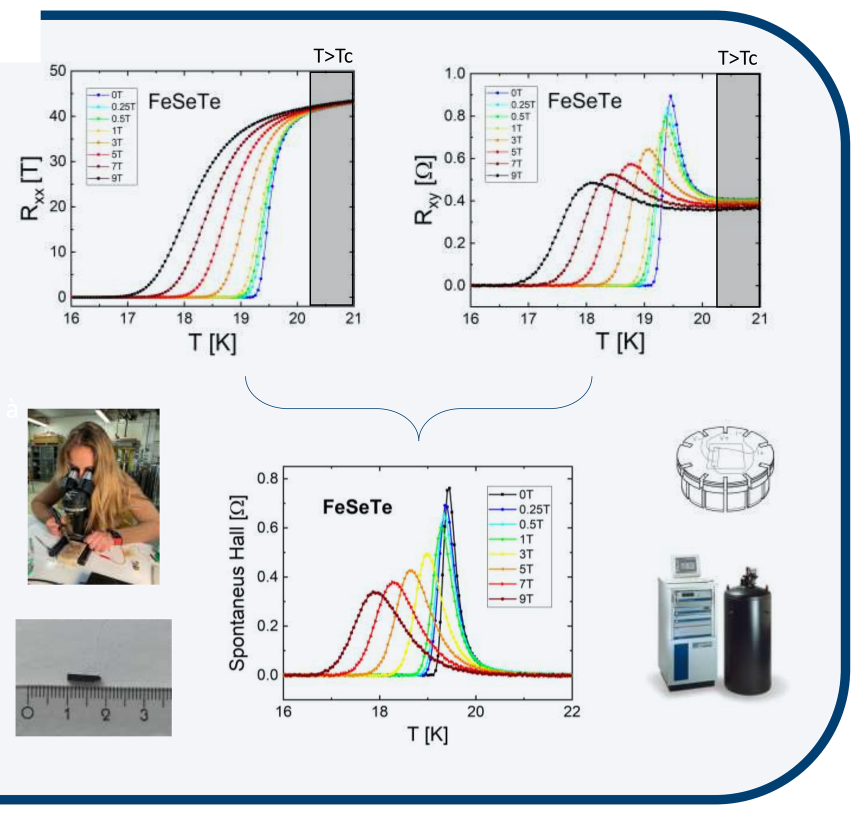
Experimetal details

To obtain the spontaneous Hall effect peak, we simultaneously measured the longitudinal resistance Rxx(T) and the transverse resistance Rxy(T), by means of contact pads placed over the surface.
The Spontaneous Hall effect is obtained as:

$$Spontaneous\ Hall = R_{xy}(T) - \alpha R_{xx}(T)$$

$$\alpha = \frac{R_{xy}(T > Tc)}{R_{xx}(T > Tc)}$$

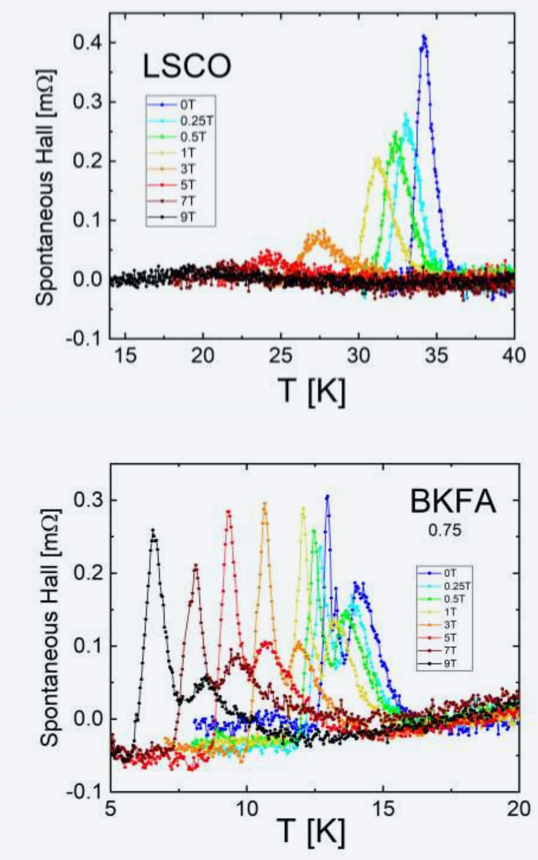
To study the in-field behaviour of the spontaneous Hall effect, we also performed the same measurements in an applied magnetic field up to 9T. In this case Rxy(T) is the magnetic field-symmetric component of the Hall signal.



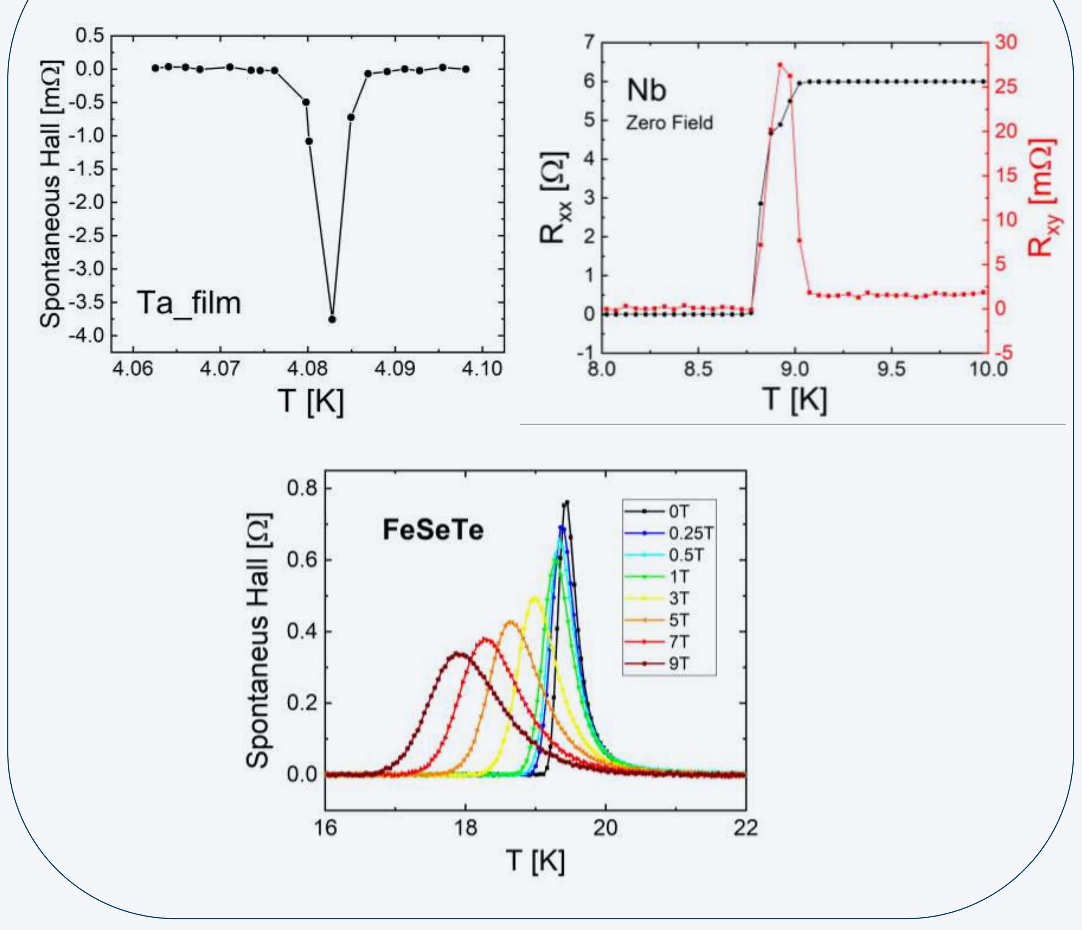
Compound	Type	BCS?	Spontaneous Hall effect?
$La_{2-x}Sr_xCuO_4$	Type-II	✗	✓
Nd	Type-II	✓	✓
Ta	Type-I	✓	✓
$FeSe_{0.5}Te_{0.5}$	Type-II	✗	✓
$Ba_{1-x}K_xFeAs$	Type-II	✗	✓

Results

Bulk samples

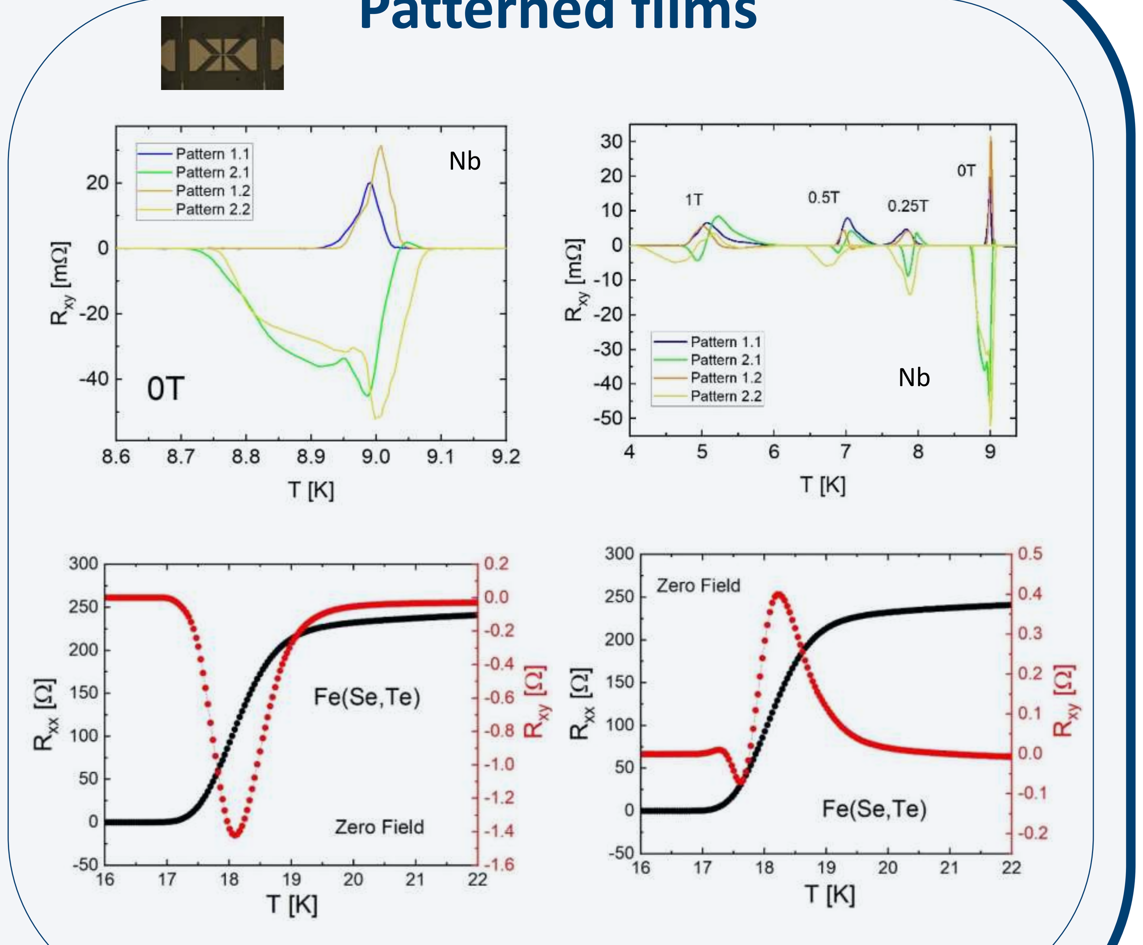


Thin films



The sign and the shape of the peak vary a lot. Could it maybe depend on the contact pads location over the sample?

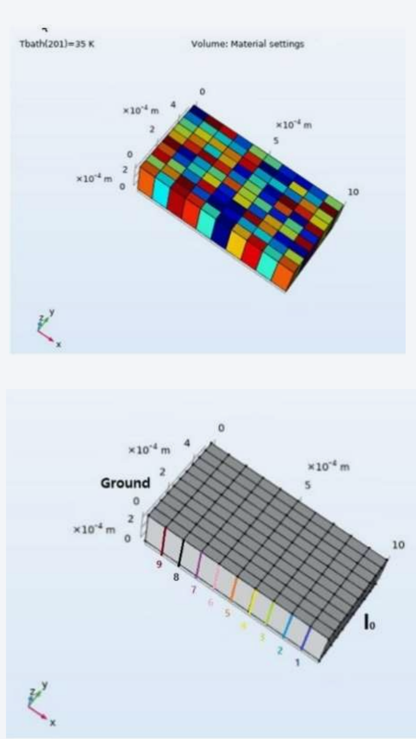
Patterned films



Simulations

In order to test if the Spontaneous Hall peak appearance can be ascribed to inhomogeneities in the sample composition even if they are ***randomly distributed*** we performed simulations with the software Comsol

Boundary conditions



The sample has been split into a 10x10 grid, and to each part a different ρ(T) has been assigned. 20 different ρ(T) have been created, differing from each other for their different Tc.

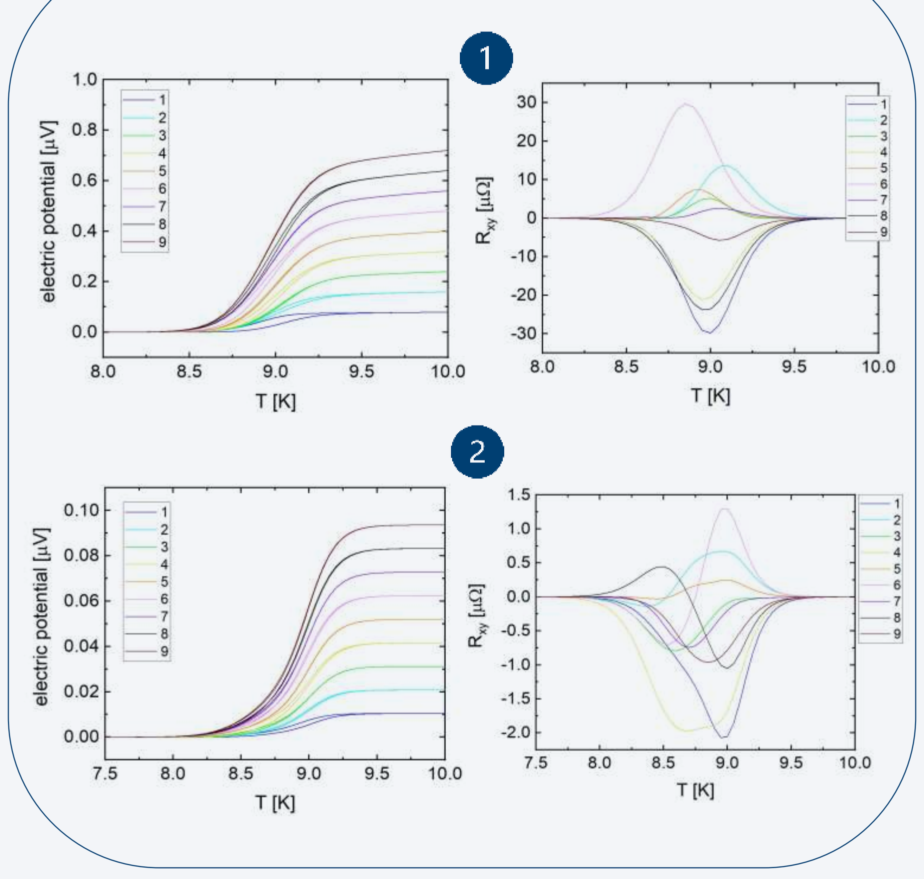
Two different simulation conditions:

1. $$\rho_0 \frac{1}{1+e^{-\frac{1}{\Delta T_c}(T-T_c)}}$$

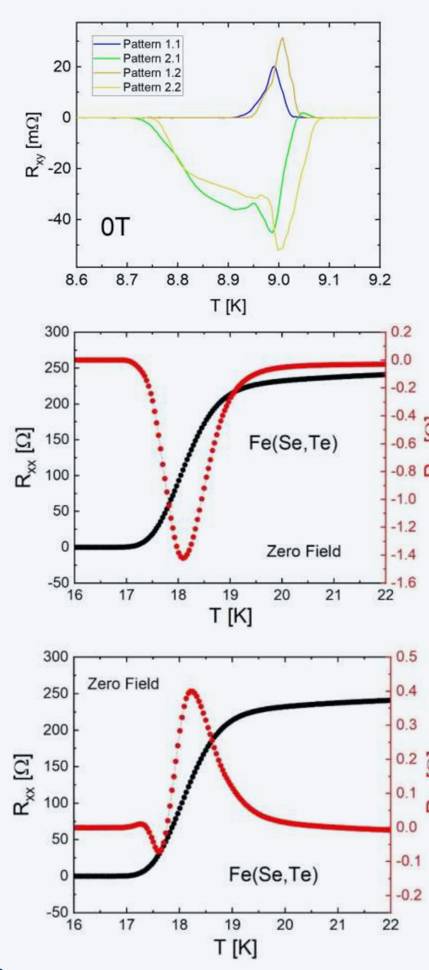
2. $$\rho_1 \frac{1}{1+e^{-\frac{1}{\Delta T_{c1}}(T-T_c)}} + \rho_2 \frac{1}{1+e^{-\frac{1}{\Delta T_{c2}}(T-T_c)}}$$

Along the sample 9 voltage probes have been setted, to verify to the Spontaneous Hall signal varies spatially.

Results



Comparison



Conclusions

We performed a comparative study of the appearance of the Spontaneous Hall effect in a wide range of materials, spacing between very different families of superconductors, which manifests itself as a pronounced peak in the transverse resistance in correspondence with the superconducting transition. Considering that this effect is transversal over different families of superconductors, we invoke the presence of inhomogeneities inside the material as explanation for the phenomenon, as already suggested in [3]. In addition, we found out that the Spontaneous Hall effect appears even in presence of a random distribution of inhomogeneities in the sample. Our hypothesis is corroborated by our Comsol simulations, thanks to which we demonstrated that the sign and the shape of the peak depend on the contact pads location over the sample, and therefore on the local distribution of inhomogeneities.
In conclusion we believe that the Spontaneous Hall effect measurement can be a sensitive probe to evaluate the level of inhomogeneity inside a superconducting material.

References

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[3] A. Segal, M. Karpovski, and A. Gerber Physical Review B, 83, 094531 (2011)