Magnetism and superconductivity of chromium trihalide heterostructures
MASCOTE

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Topological superconductors (TS) are the object of a quest for their predicted quantum properties such as robustness to decoherence (*1*). A two-dimensional TS with finite size should exhibit 1D dispersive Majorana states at its edge. This Majorana states are analogous to the Dirac states of graphene with in addition a particular quantum statistic: they are supposed to behave as non-abelian anyons, like the excitations in fractional quantum hall states. The case of one-dimensional TS is also interesting, these materials should exhibit zero-energy Majorana edge states (*2*) that may be used in new kind of qubits. Many controversial works have been done, in particular in Leiden and Copenhagen, with a strong financial support of Microsoft Station Q. From our point of view, the most appealing approach towards topological superconductivity seems to be the magnetic/superconducting heterostructures pathway.

Among the experiments that have shown some hint of one-dimensional topological superconductivity the very first one was performed by the Princeton group with magnetic Fe chains deposited on Pb(110). More recent work have confirmed the interest of this scheme with Mn chains deposited on Nb(110) (*3, 4*). Two-dimensional systems have also been explored, primarily in our team with the CoSi/Pb platform (*5*) and in the Hamburg group with Fe/O/Re (*6*). In these two works some evidences of dispersive Majorana modes have been observed. Among all the published works, the van der Waals heterostructure, $CrBr_3/NbSe_2$ appears to be the most attractive for its integration capability into nanoelectronic devices (*7, 8*). In this system, very clear edge states were observed at the edge of $CrBr_3$ island deposited on-top of $NbSe_2$, they were interpreted as dispersive Majorana edge states, a possible signature of topological superconductivity. The putative topological order observed in this heterojunction was recently related to the existence of a moiré pattern due to the mismatch between $CrBr_3$ and $NbSe_2$ lattices (*8*).

Motivated by the appealing discovery of topological superconductivity in magnetic Van der Waals / NbSe2 based heterostructures, we propose with this PhD project to explore this strategy. We aim at investigating 2D and 1D van der Waals magnetic systems deposited on metal and superconducting substrates. The final objective is to induce topological superconductivity in the van der Waals material NbSe2. We will seek for Majorana bound states either at the end of magnetic chains or close to dislocations of 2D magnetic layers.

The magnetic properties of many van der Waals magnetic materials have been extensively studied several decades ago (*9*). For instance, in the chromium trihalide family, $CrCl_3$, $CrBr_3$ and CrI_3 (CrX_3, X= I, Br, Cl), the emergence of a magnetic order results from super-exchange interactions within the layers (*10*). Interest in these supposed well known materials surged in 2017 when magnetic measurements performed on monoatomic-thick samples showed ferromagnetism in CrI_3, with a pretty high Curie temperature of 45K (*11*). More recently, experimental evidence of ferromagnetism in monolayers of $CrBr_3$ and $CrCl_3$ has been discovered(*12, 13*). Another fascinating observation concerns the influence of a moiré pattern on magnetic properties. In the CrX_3 family, magnetization has been predominantly found to be collinear. However, in the double bilayer CrI_3, a non-collinear magnetic order has been discovered and is believed to be linked to the moiré pattern, which leads to a significant spatial modulation of magnetic interactions (*14*).

With this project two routes will be explored with 2D and 1D systems:
2D magnetic layers: Our first objective is to conduct an in-depth investigation of the moiré pattern enabling topological superconductivity with van der Walls magnetic material based heterostructures strategy. According to the literature the moiré pattern in CrBr3 influence the magnetic order and this play a crucial role in inducing TS in the underneath $NbSe_2$ substrate. We will investigate the relationship between moiré and magnetism using spin resolved STM. We will examine how this influence the topological phase transition.
1D magnetic objects: Some recent STM experiments have shown the possibility to control the dimensionality of the magnetic CrX3 object when deposited on a substrate. For instance, $CrBr_3$ deposited on $NbSe_2$ forms 2D islands while, on the same substrate, $CrCl_3$ forms 1D nanostripes (*7, 15*). In the quest of topological superconducting materials, 1D systems are particularly appealing due to their Majorana end states.

We are already involved in the exploration of 1D and 2D CrX_3 assemblies on various substrates, principally Au(111) and $NbSe_2$. In the case of 2D $CrCl_3$ islands on Au(111), we were lucky to discover topological defects in a moiré lattice due to the presence of edge dislocations in the $CrCl_3$ layer (Figure 1a). One question arising is whether these topological defects would stabilize 0D Majorana modes, since punctual topological defect such as vortices can host Majorana bound states.

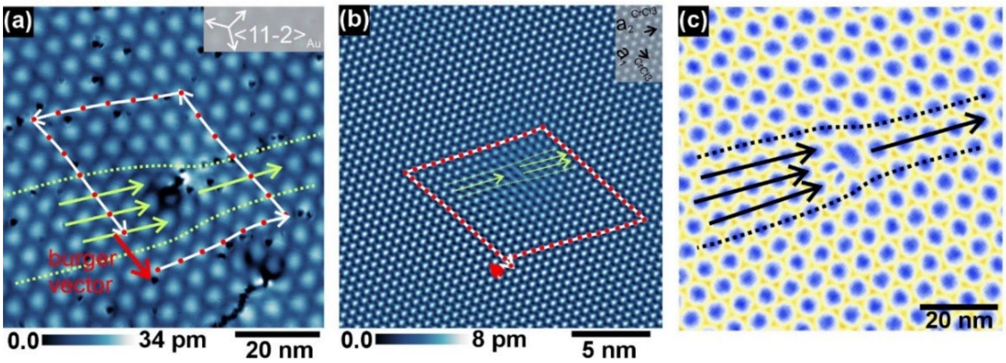

Figure 1: (a) STM topography of CrCl3/Au(111) evidencing a moiré pattern with an edge dislocation. To highlight the dislocation, green dashed lines are employed as visual guides. The dislocation is characterized by a burger vector (red arrow) with twice the period of the moiré pattern. (b) Magnified view around the dislocation in the moiré pattern showing the corresponding edge dislocation in the atomic structure of $CrCl_3$, see green arrows. The dislocation at the atomic level is characterized by a Burger vector equal to the vector unit of the atomic lattice of CrCl3. (c) Numerical simulation showing a quantitative agreement with the experimental observations.

This experimental project will be carried out at INSP. The SNEQ team has a unique instrumentation in France composed of scanning probe microscopes working under UHV at very-low temperature and in high-magnetic. The PhD candidate will work under the supervision of Tristan Cren and Marie Hervé. Tristan Cren, is specialist of scanning tunneling spectroscopy on superconducting systems. He carried out some of the pioneering works on topological superconductivity in magnetic/superconducting heterostructures. Marie Hervé is specialist of spin polarized STM, low dimensional magnetism and molecular beam epitaxy. She is a pioneer of radio-frequency STM that could be used to do some coherent control of Qubit down to the atomic scale, but this is beyond the scope of this project.

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