**Project Title:** *Engineering Quantum Spin Hall Effect in Graphene*

**Principal Investigator:** *Long Ju, Physics Department and Research Lab of Electronics, Assistant Professor*

**Co-investigators:** Joaquín Fernández-Rossier, International Iberian Nanotechnology Laboratory, group leader of Theory of Quantum Nanostructures and tenured staff researcher, Portugal

Sascha Sadewasser, International Iberian Nanotechnology Laboratory, Leader of the Laboratory for Nanostructured Solar Cells

**Proposal Research Area:** *Other research area(s) of benefit to the Portuguese people Quantum and Nano sciences*

**Layperson's Description:** *Conventional semiconductor-based electronic devices suffer from energy dissipation that can be described by classical physic pictures. Two-dimensional (2D) materials are a promising platform for realizing topological electron physics, based on which novel quantum devices can be engineered for low-power electronic and quantum computation applications. We aim to explore such opportunities by combining experimental efforts at MIT and contributions from two groups at INL, doing theory and experiments, and explore a specific Quantum Spin Hall Effect in this project.*

**Aims of the project:**

In this project, we will attempt to realize QSHE in heterostructures formed by atomically thin 2D materials. We will employ electron transport measurements at cryogenic temperatures and search for the quantized conductance as evidence of QSHE. We will get theory support from Dr. Joaquín Fernández-Rossier at the International Iberian Nanotechnology Laboratory (INL), Portugal, to design experiments and understand the data obtained. In addition, the experimental group of Sascha Sadewasser will contribute with the growth of as a substrate materials using molecular beam epitaxy. We will arrange exchanges of staff and students to facilitate realizing the goal of this project.

Beginning with this seed project, we expect to establish a long-term collaboration to generate impacts in higher-education, fundamental physic research, and industrial application in MIT and in Portugal.

**Summary of research activities so far:**

1. **We have built several devices** of trilayer, tetralayer and pentalayer rhombohedral graphene proximitized by WS2 and WSe2 layers. The latter introduces spin-orbit coupling (SOC) to electrons in graphene. Some devices are made to just test the effect of SOC on the ground states in graphene in general, such as the breaking of spin-valley-degeneracy of electronic

bands, while others are made to engineer the QSHE. Specifically, devices in the latter category have two WS2 layers rotated by 180 degrees, to created the inversion symmetric configuration that is required for the QSHE.

2. **We have built a new dilution refrigerator** for milli-Kelvin electron transport measurement of the graphene devices. The major component of this setup is a new Bluefors dilution refrigerator, which we purchased partially using the MPP grant. This is a critical step since most of federal grants have very strict policy on the purchase of major equipment. **The flexibility of the MPP grant makes it possible for us to orient the fund towards the most urgent need of a research project.**

   In addition, we have fabricated home-built electronic filters, sample holders, break-out boxes etc. for electrical measurement inside the dilution refrigerator. This setup has been functioning since Feb 2025, and can reach an extremely low electron temperature of < 20mK for our graphene devices.

3. Combining the devices and measurement setup, **we have performed milli-Kelvin magneto-electrical measurements** to search for QSHE and other interesting properties.

   On the end of the QSHE, we have observed some vague experimental signatures, but the data so far is not good enough to support the conclusion of QSHE. We are making more efforts on improving the device quality and optimizing the twist angle between graphene and WS2/WSe2 to strengthen the effect. We are also thinking of alternative solutions of enhancing the SOC, possibly by using other materials to proximitize graphene.

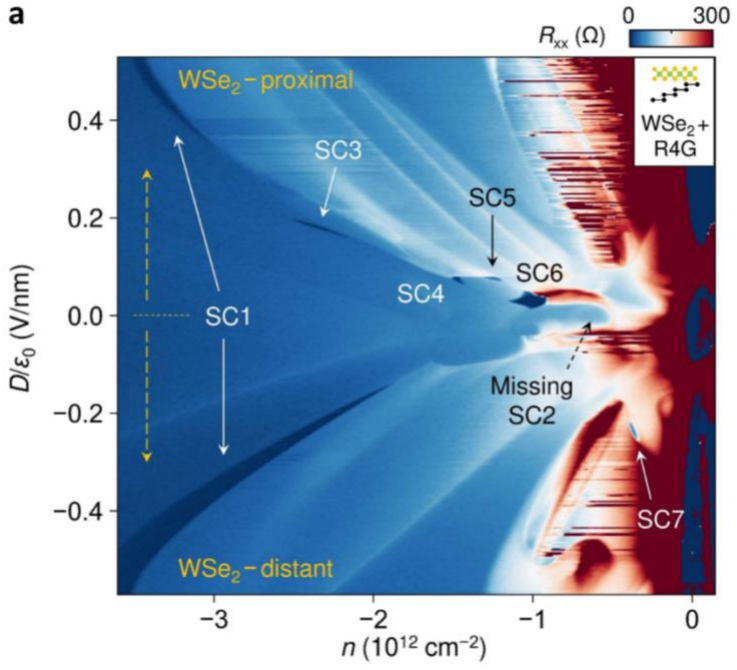


***Figure 1. Superconducting states in rhombohedral tetrlayer graphene proximitized by $WSe_2$.*** *A total of 7 different superconducting states are observed, with a clear difference induced by the WSe2 and the associated SOC effect.*

To our surprise, the same devices we made for exploring QSHE showed superconductivity instead. We have observed several new superconducting states, in WS2- and WSe2-proximitized 3-5 layer rhombohedral graphene. These superconducting states have a transition temperature on the order of 100 mK, but they exhibit highly unusual properties against magnetic field: when applying magnetic field along the in-plane direction, the superconducting state does not show any sign of being weakened up to 8.8 Tesla, which is the limit of our magnet. Such high critical magnetic fields break the so-called Pauli-Limit of conventional s-wave superconductivity, and suggest a kind

of unconventional superconductivity known as spin-polarized superconductivity. We have summarized part of the findings into two manuscripts, which are currently under review at ***Nature*** and ***Science***, respectively. Figure 1 shows an example of the superconducting states we observed, adapted from the paper under review at ***Nature***.

**Summary of interactions, efforts to secure additional funding, and personnel exchange with Portugal collaborators:**

We have had several remote discussions with our INL collaborators. We are planning on sending one graduate student, Joao Carlos Henriques, from INL to MIT for a short visit. Long Ju will attend a conference organized by Joaquín Fernández-Rossier in Portugal in Nov 2025, and meet the student to finalize the details of the logistics.

We have also applied to the MIT MISTI Global Seed Fund based on this MPP collaboration in Dec 2024, aiming for securing traveling fund to facilitate the personnel exchange between the MIT team and the INL team. Especially, we were hoping to support graduate student exchange for better communication and collaboration. Unfortunately, our proposal was not chosen for funding. We will try again in Dec 2025.

**Summary of research outcomes so far, with MPP explicitly acknowledged:**

1. Seo, J., Cotten, A. A., Xu, M., Sedeh, O. S., Weldeyesus, H., Han, T., ... & Ju, L. (2025). Family of Unconventional Superconductivities in Crystalline Graphene. Under review at ***Nature***. *arXiv preprint arXiv:2509.03295*.
2. Yang, J., Sedeh, O.S., Yoon, C., Ye, S., Weldeyesus, H., Cotten, A., Han, T., Lu, Z., Hadjri, Z., Seo, J., Shi, L., Aitken, E., Liong, P., Wu, Z., Xu, M., Scheller, C., Zheng, M., Gazizulin, R., Watanabe, K., Taniguchi, T., Laroque, D., Li, M., Zhang, F., Zumbühl, D.M. & Ju, L. Magnetic Field-Enhanced Graphene Superconductivity with Record Pauli-Limit Violation. Under review at ***Science***. (2025)
3. Cao, T., Fu, L., Ju, L., Xiao, D. & Xu, X.D. Fractional Quantum Anomalous Hall Effect in 2D Materials, in Press at ***Annual Review of Condensed Matter Physics***. (2025)

**Plan of activities in year 2:**

In year 2, we plan to continue the engineering and search of QSHE based on rhombohedral graphene. We will fabricate devices with different twist angle between graphene and WSe2/WS2 to strengthen the SOC effect. We will collaborate with INL partners to theoretically investigate the angle-dependence of SOC effect, and search for other materials that might introduce even stronger SOC to graphene.

On the other hand, we plan to continue our research on the superconductivity discovered in these materials, and how SOC modulate the superconducting states. We will fabricate more complicated devices such as Josephson Junctions and ring-shaped devices to search for the signature of quantum coherence in these states. We will initiate discussions with INL on superconductivity for better understandings.

On the personnel exchange end, Ju will attend a conference organized by by Joaquín Fernández-Rossier in Portugal in Nov 2025. Ju will visit INL and discuss with INL team members

and any other local researchers who might be interested in collaboration on the current and other topics. Ju and one of his students plan to pay a visit to INL in the summer of 2026 to communicate with local researchers. A graduate student from INL will visit Ju's lab at MIT in early 2026, as the start of more incoming activities involving other students and researchers from INL to MIT.