# Probing mixed spin singlet-triplet Cooper pairs in 2D $NbSe_2$ under high magnetic fields

Sohn E., Xi, X., Wang, Z., Jiang, S., Shan, J., Mak, K.F. (Cornell, Physics and PSU, Physics); Park, J.-H. (NHMFL); Law, K.T. (HKUST, Physics); Berger, H., Forro, L. (EPFL, Physics)

## Introduction

Superconductivity in two-dimensional (2D) materials has recently received much interest due to the unusually large in-plane upper critical field ($H_{c2}$). In atomically thin superconductors, the orbital limit is quenched and $H_{c2}$ is paramagnetic-limited. The exceptionally large $H_{c2}$ in 2D-$NbSe_2$ originates from the broken inversion symmetry and strong spin-orbit interaction (SOI). Such non-centrosymmetric superconductors are particularly interesting for the predicted mixed-parity Cooper pairs and for the realization of 2D topological superconductivity.

## Experimental

We have prepared 2D $NbSe_2$ tunnel devices with two different tunneling barriers, $AlO_x$ and few layer $MoS_2$. Depending on the type of device, we have transferred the mechanically exfoliated 2-3 layer $NbSe_2$ upon pre-patterned electrodes so that the final stacking would be Pt/$AlO_x$/$NbSe_2$ or Pt/$NbSe_2$/$MoS_2$/Au. Compared to our previous studies, we were able to achieve improved tunneling devices that provided cleaner spectral information under high in-plane magnetic field. The differential conductance of the tunneling device was measured under in-plane magnetic field up to 45 T at low temperature down to 300 mK at Cell 15 at the NHMFL.

## Results and Discussion

Figure 1(a) and (b) shows the normalized differential conductance of $NbSe_2$/$AlO_x$/Pt and $NbSe_2$/$MoS_2$/Au, respectively, at 300 mK under in-plane magnetic field. The acquired superconducting gap(Δ(H)) through fitting is summarized in Figure 1(c). In both type of devices, we observe a continuous decrease of Δ(H) under in-plane magnetic field, an indication of a second-order phase transition. This is in contrast to the well-known first-order transition in paramagnetic-limited BCS superconductors. The strong SOI in 2D-$NbSe_2$ results in an upper critical field limited by van Vleck paramagnetism, and the spin susceptibility remains largely unchanged from that in the normal state, unlike the case in conventional BCS superconductors. This gives rise to a second order paramagnetic-limited phase transition. The large spin susceptibility thus provides evidence of mixed-parity Cooper pairs in 2D-$NbSe_2$.

## Conclusions

We have observed a paramagnetic-limited second-order phase transition under high in-plane magnetic field. This is a unique feature that strongly suggests the existence of mixed spin singlet-triplet Cooper pairs in 2D $NbSe_2$. This work will pave the way to study unconventional superconductivity, such as 2D topological superconductivity.

## Acknowledgements

A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by National Science Foundation Cooperative Agreement No. DMR-1157490 and the State of Florida. In addition, KFM is supported by DOE BES (DESC0013883) and NSF (DMR-1645901); JS is supported by DOE BES (DESC0012635) and NSF (DMR-1410407); ZW is supported by NSF MRSEC (DMR-1420451); KTL is supported by HKUST3/CRF/13G and the Croucher Innovation Grant; and HB and LF are supported by the Swiss NSF.

## References

[1] Sohn, E., *et al.*, submitted (2017).

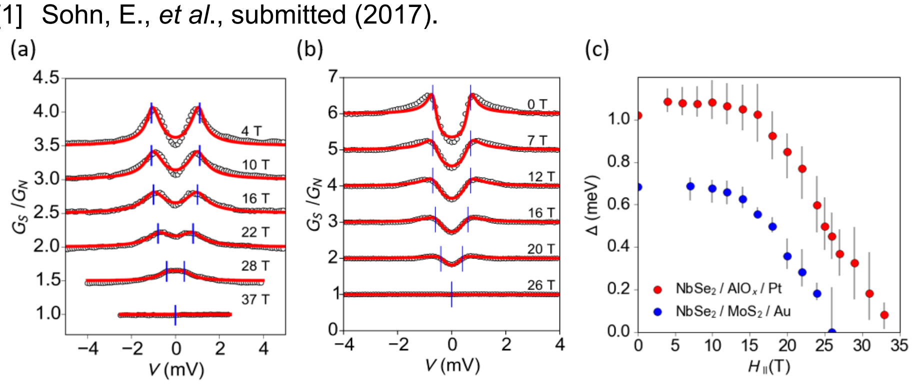


**Fig.1** Normalized differential conductance of (a) $NbSe_2$/$AlO_x$/Pt and (b) $NbSe_2$/$MoS_2$/Au tunnel junction under in-plane magnetic field at 300 mK. The superconducting gap from the BTK fit (red solid line) is summarized in (c). A continuous second-order transition is seen in both devices.