Probing Ising Superconductivity in Atomically Thin NbSe₂ under High Magnetic Fields

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Introduction
Effects of spin-orbit interactions (SOIs) on superconductivity (SC), which can lead to unconventional pairing symmetries and topological SC, have attracted tremendous recent interests. Most of the recent studies have focused on inducing SC in non-superconducting materials with strong SOIs either through substitutional doping or proximity effects. Here we examine the effects of SOIs on SC in NbSe₂, a superconducting material with strong intrinsic SOIs, down to the monolayer limit.

Experimental
Devices of atomically thin NbSe₂ were obtained by mechanical exfoliation followed by direct transfer onto Si substrates with pre-patterned electrodes. The samples can be maintained very clean in this lithography-free fabrication method. The four-point resistance was measured as a function of temperature T, out-of-plane and in-plane magnetic fields H. Field dependence up to 31T was measured at Cell 9 in the NHMFL.

Results and Discussion
Fig. 1a shows the resistive transition of atomically thin NbSe₂ under different in-plane magnetic fields up to 31T. Fig. 1b summarizes the H-T phase diagram for samples with different thickness. The T-axis is normalized to the zero-field transition temperature Tc0 and the H-axis is normalized to the Pauli paramagnetic limit Hp = 1.84*Tc0, the highest possible upper critical field Hc2 for a conventional BCS superconductor. Surprisingly, Hc2 for atomically thin NbSe₂ far exceeds Hp (over 6 times in the monolayers). To understand the observation, we first note that the orbital effects responsible for vortex formation is absent in monolayer NbSe₂ under in-plane fields. Consideration of spin alignment by H is then needed. The strong SOIs in NbSe₂, which locks the spin to the out-of-plane direction (effective Ising spins), on the other hand, significantly reduce the spin Zeeman energy for destruction of SC. With effects of SOIs taken into account, Hc2 can be rewritten as Hc2 = √Hp*Hso, a geometric mean of Hp and Hso. The strong effective spin-orbit magnetic field Hso ≈ 1000T thus greatly stabilizes SC in atomically thin NbSe₂ under an in-plane magnetic field.

Conclusions
Extremely high Hc2, far above the conventional Pauli paramagnetic limit, is observed in atomically thin NbSe₂. The observation can be understood in terms of the strong intrinsic SOIs in this material. The study is important for experimental search of unconventional SC in the exact two-dimensional limit.

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References

Fig. 1a: The resistive transition of trilayer NbSe₂ under different in-plane magnetic fields. a The H-T phase diagram of atomically thin NbSe₂. The solid and empty data points correspond to in-plane and out-of-plane magnetic fields, respectively.