Partially polarized chiral spin liquids induced by magnetic fields: application to transition metal dichalcogenide moiré systems

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Abstract: The search for chiral spin liquids (CSLs) under a magnetic field in normal triangular compounds has challenges in realizing the relavent model parameters. Twisted transition-metal dichalcogenide (TMD) bilayers, on the other hand, have significantly large length scales with tunability through the twisted angle. We focus on the heterobilayer $WSe_2/MoSe_2$ where the *SU(2)* symmetry is retained in the valley (spin) space and investigate the Mott insulating phase at half filling which is subject to an out-of-plane magnetic field. Tuning the magnetic field for different twisted angles we identify three conventionally ordered phase including a 120^oNeel phase, a stripe phase and an up-up-down phase. For intermediate fields an emergent topological quantum spin liquid phase is identified with partial spin polarization because of the competition between the effective spin interactions and the Zeeman interactions that are induced by the magnetic field. We further characterize the topological nature of the quantum spin liquid as the $\nu = 1/2$ Laughlin CSL through disorder-averaged spin flux insertion simulations and topological entanglement spectrum. In addition, we map out the quantum phase diagram expanded by different twisted angles and magnetic fields.

Challenges in Triangular CSL

It is hard to generate the required spin interactions in normal crystalline solid.

Crystalline solid has a small lattice constant around a few angstrom, thus about 2000T magnetic field is needed to reach large enough chiral interactions for the CSL.

$$J_\chi = \frac{24t_1^3}{U^2}\sin\left(\frac{e}{\hbar}2\pi B\frac{\sqrt{3}}{4}a_m^2\right)$$

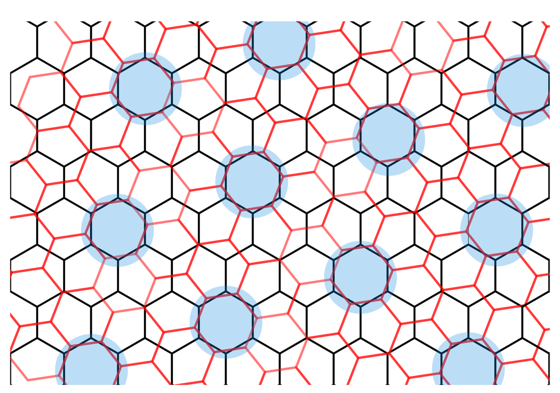
"TMD Moiré superlattices provide tunable strongly correlated systems with large length scales and new opportunity.

The Moiré superlattices offer a great platform to play with the twisted angles, and the tremendously large unit cell significantly reduces the strength of magnetic field for the required chiral interactions.

Proliferation of flat bands in TMD moiré systems leads to correlated insulating states at commensurate fillings.

For a heterobilayer with two similar lattice constants like $WSe_2/MoSe_2$ or WS_2/WSe_2, the moiré pattern can be formed with a large moiré lattice constant.

$$a_m \approx a_0/\theta$$



Because of the relatively large spin-orbit-coupling in the valence band, the top two valence bands can be isolated with only valley degeneracy. In the moiré or mini Brillouin zone the band folding gives an overlap between the two valleys. Due to spin-valley locking, the resulting two degenerate bands can be approximated by a single band Hubbard model on the moiré superlattice.

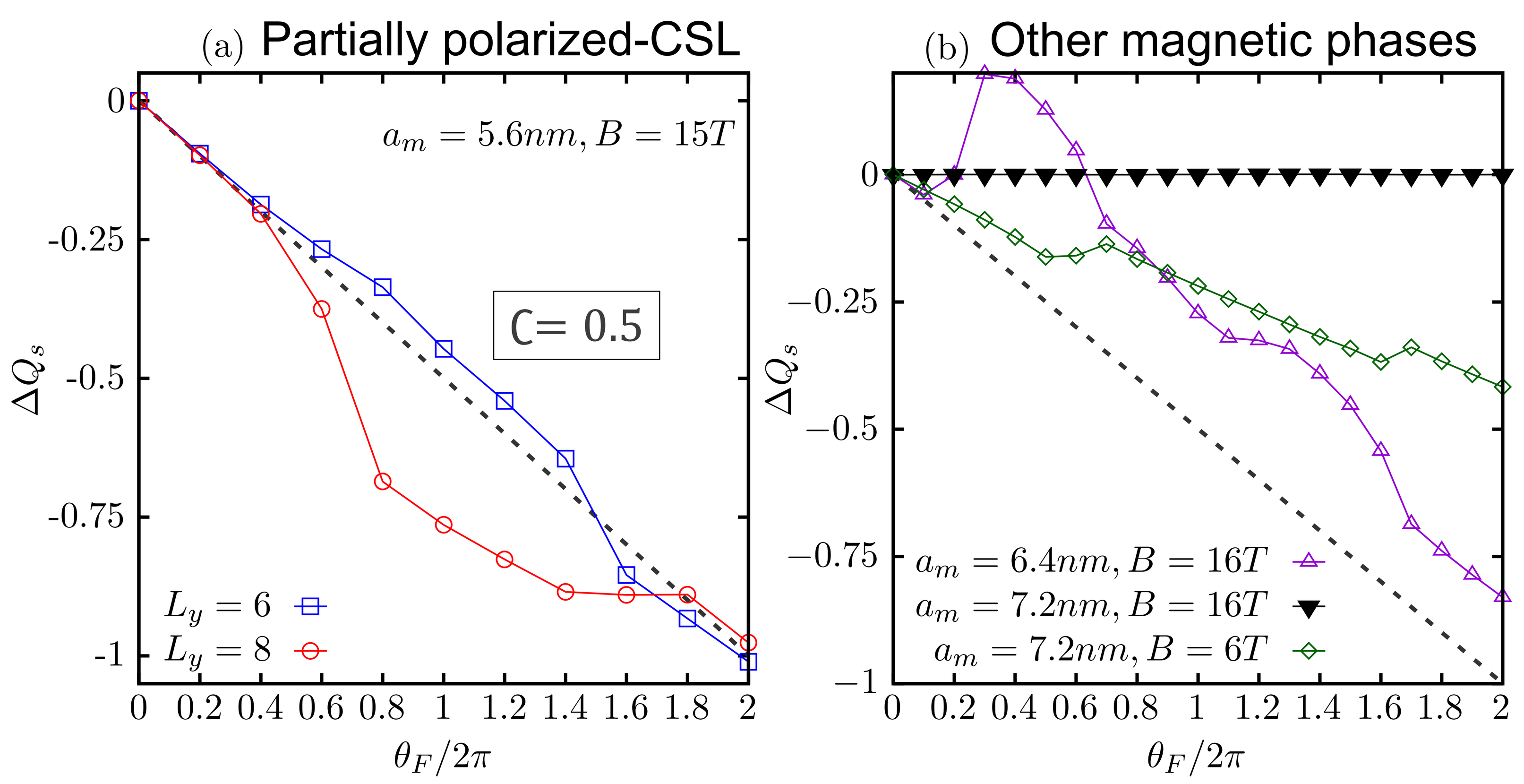
$$\mathcal{H}_{Hubbard} = \sum_{\{i,j\}} -t_{ij}e^{i\frac{2\pi e}{h}\vec{A}\cdot(\vec{r}_i-\vec{r}_j)}c_{i\sigma}^\dagger c_{j\sigma} + h.c. + U\sum_i n_{i\uparrow}n_{i\downarrow} + h_z\sum_i(c_{i\uparrow}^\dagger c_{i\uparrow} - c_{i\downarrow}^\dagger c_{i\downarrow})$$

Following *Wu, F. et. al. PRL 121(2), 026402*, the the nearest-neighbor hopping t_1 and next-nearest-neighbor hopping t_2 are obtained by fitting the moiré flat bands. The onsite Hubbard U is obtained by integrating the Wannier function localized near the moiré superlattice position. At half filling of the moiré bands, because $U \gg t_1, t_2$ the ground state is a Mott insulator, the effective spin model can be derived from the perturbation expansion of $\frac{t}{U}$ as

$$\mathcal{H}_{Heisenberg} = J_1\sum_{<ij>}\vec{S}_i\cdot\vec{S}_j + J_2\sum_{\ll ij\gg}\vec{S}_i\cdot\vec{S}_j + J_\chi\sum_{\{ijk\}\in\Delta/\nabla}\vec{S}_i\cdot(\vec{S}_j\times\vec{S}_k) + 2h_z\sum_i S_i^z$$

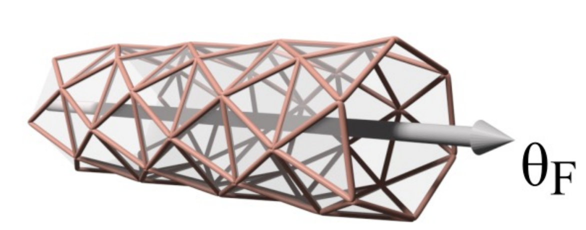
Magnetic field-induced CSL

Disorder-averaged spin flux insertion simulations can characterize the Chern number.



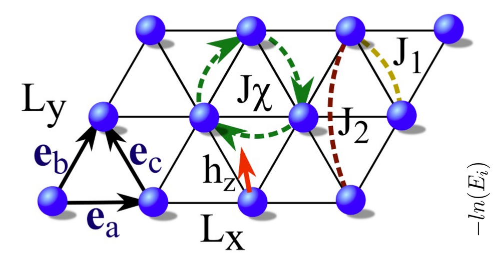
A spin flux θ_F is adiabatically inserted into the cylinder. As the ground state evolves with θ_F net spins will accumulate on the edges as phase response.

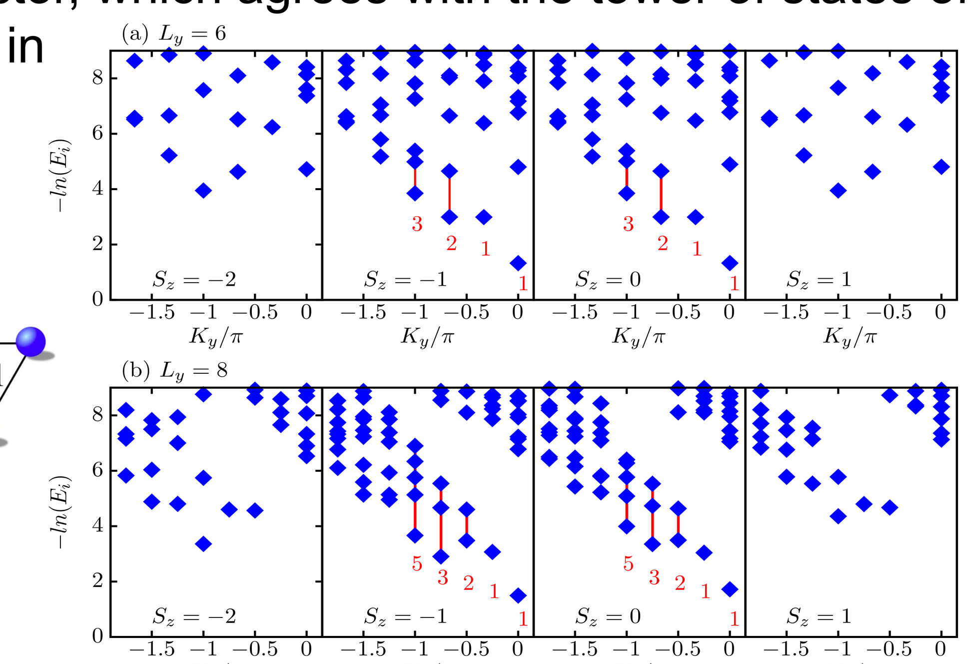
Because the CSL has partial spin polarization, we introduce a weak local disorder to create spin mobility gap and average over different disorder configurations to obtain a quantized spin pumping.



Topological entanglement spectrum

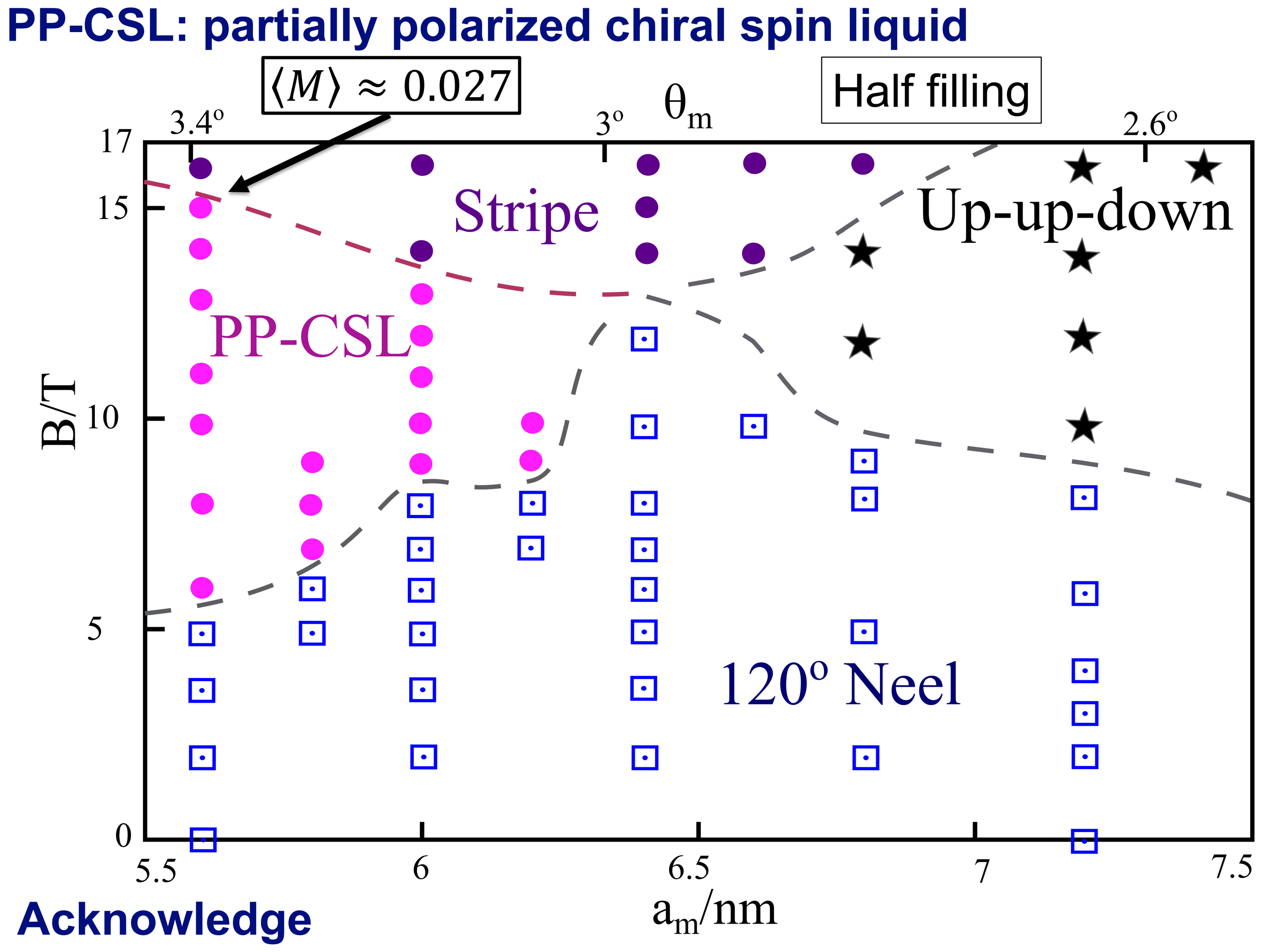
The quasi-degenerate eigenvalues form a pattern of {1, 1, 2, 3, ...} in every S_z sector, which agrees with the tower of states of the spinon sector in the $SU(2)_1$ Wess-Zumino-Witten theory.





Quantum phase diagram

PP-CSL: partially polarized chiral spin liquid



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