Quantum Hall Effect in Weyl-Hubbard System: Interplay Between Topology and Correlation

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Motivation

- Relevance of electronic correlations has been found in recent Weyl semimetal Materials ($Co_3Sn_2S_2$, $Pr_2Ir_2O_7$).
- Interplay between the topology and electronic correlations provides unique opportunity for the emergence of new states of the matter, which can be driven by the external control parameters such as high magnetic field.

Weyl Fermions and Topology

❖Weyl Fermion: Introduced in High Energy Physics in 1929.

❖Massless spin-1/2 particles (Massless solution to the Dirac equation :

$$(\gamma^\mu p_\mu - mc)\psi(\mathbf{p})=0$$

❖Appear as a low-energy quasiparticles near the linearly touching of a pair of bands.

❖Low-energy Hamiltonian: $H_{\mathbf{k}}=\sum_{i=1}^{3} v_i(\mathbf{k}_i)\sigma_i$

❖Weyl node act as the source and sink of the Abelian Berry curvature.

❖Topological invariant: Monopole Charge: $\frac{1}{2\pi}\int_\Sigma d\boldsymbol{S}\cdot\boldsymbol{\Omega}=\pm\mathcal{N},$

❖Weyl nodes come in pairs in WSM with opposite chiralities.

❖Example: TaAs, WTe_2, NbAs (uncorrelated), $Co_3Sn_2S_2$, $Pr_2Ir_2O_7$ (correlated)

Method of Solving

Model Hamiltonian + Orbital B + Hubbard U → (Gutzwiller Method) → Landau Level Dispersion → (Kubo Response) → 2D SHC+ 3D QHE

Weyl-Hubbard Hamiltonian

$$H=\sum_{i,ss'}[-t\sigma_{x,ss'}(c^\dagger_{js}c_{j+\hat{x},s'}+c^\dagger_{js}c_{j+\hat{y},s'}+c^\dagger_{js}c_{j+\hat{z},s'})$$
$$-it'(\sigma_{y,ss'}c^\dagger_{js}c_{j+\hat{y},s'}+\sigma_{z,ss'}c^\dagger_{js}c_{j+\hat{z},s'})+H.c.]+m\sum_{j,ss'}\sigma_{x,ss'}c^\dagger_{js}c_{js'}+U\sum_i n_{i\uparrow}n_{i\downarrow}$$

t, t' = hopping parameter ; m=site-dependent potential energy ; U=Onsite Hubbard interaction

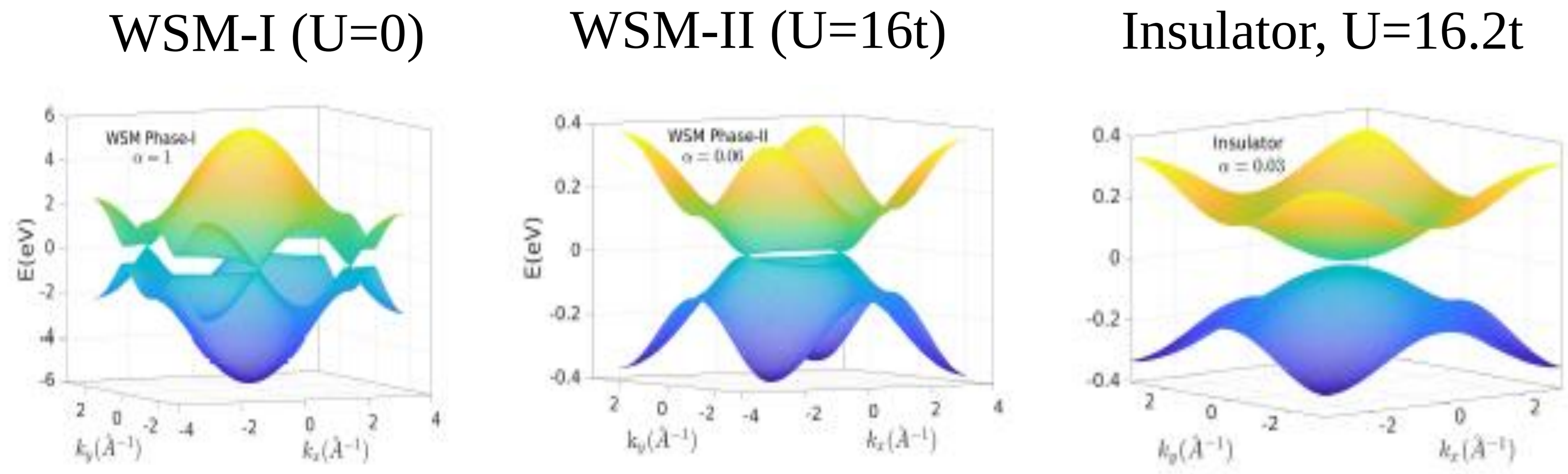
Gutzwiller Framework

Self-Consistency Condition: $\left.\begin{array}{l}\alpha=16(1/2-d)d\\ \frac{\partial\alpha}{\partial d}\langle H_{kin}\rangle+U=0\end{array}\right\}$ half-filling case

d=double occupancy; α=Renormalization factor

Tuning U ➡ t,t' → $t_{nor}=\alpha\, t$, $t'_{nor}=\alpha\, t'$

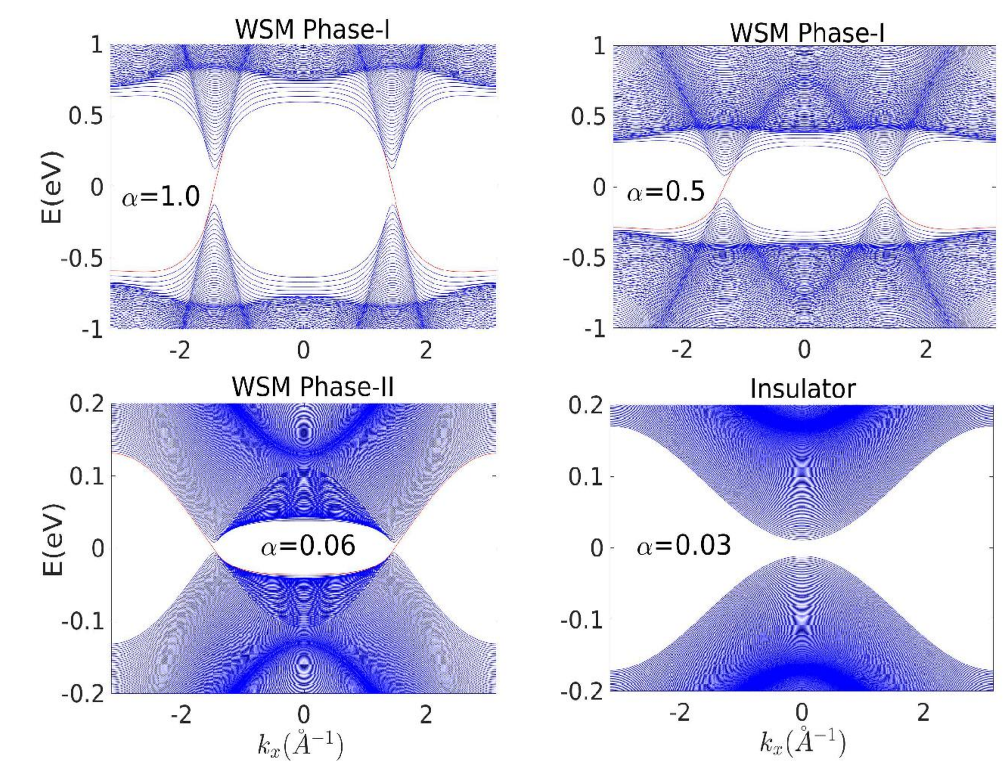
$m/2t_{nor}<1$ WSM-I (U=0)	$m/2t_{nor}>1$ WSM-II (U=16t)	Insulator, U=16.2t



4 WNs 2 WNs

With increasing U, following phase transition occurs:
Weyl phase-I ➡ Weyl phase-II ➡ Trivial insulator

Landau Level Spectrum



Magnetic Field $\mathbf{B}=(B_x,0,B_z)$

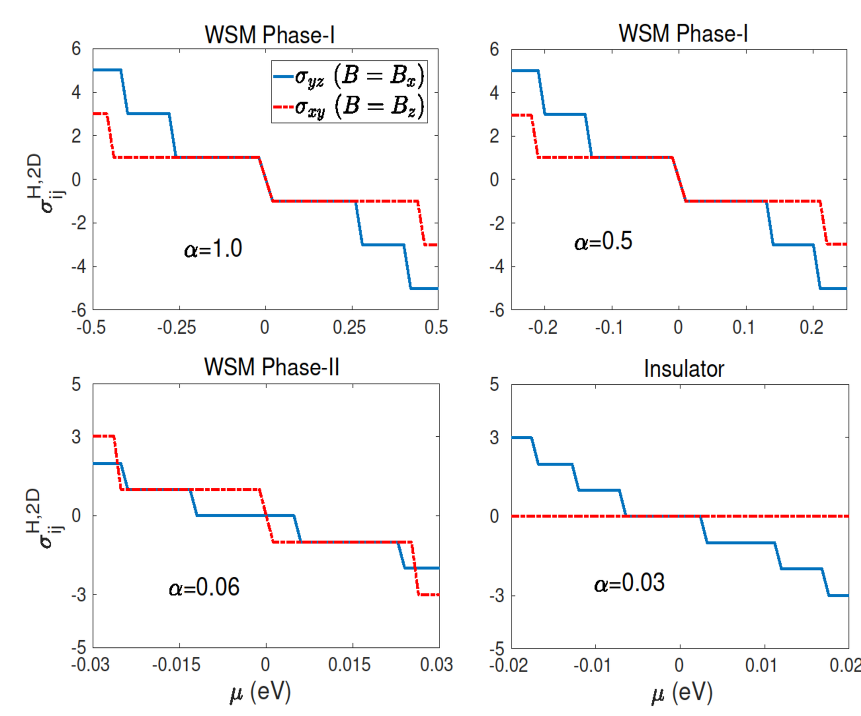
Landau Gauge $\mathbf{A}=(-yB_z,0,yB_x)$

$\mathbf{B}=\mathbf{B_x}$, $\mathbf{A}=(0,0,yB_x)$

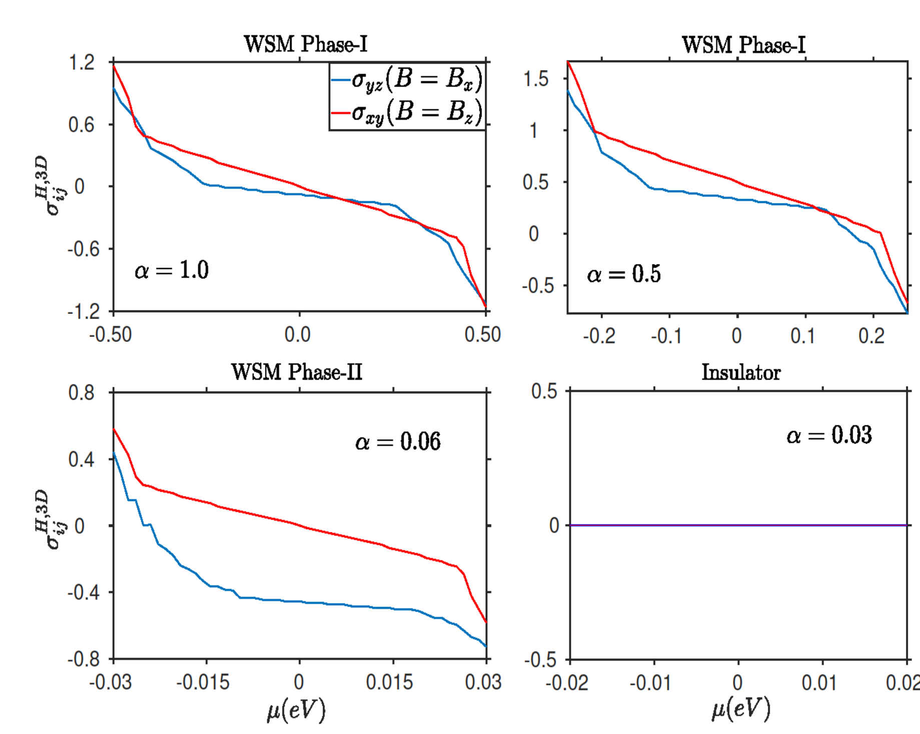
❖ Landau levels are doubly degenerate and nondegenerate in Weyl phase-I and Weyl phase-II respectively.

❖ Chiral Landau Levels change sign from WSM-I to WSM-II.

2D SHC



3D QHC



Results

➢ The Sheet Hall conductivity (SHC) in both Weyl phases depicts staircase profile whereas 3D quantum Hall conductivity (QHC) does not show any quantized profile.

➢ σ_{yz} (**B** ∥ **x**): In WSM phase-I, the quantization of SHC changes by ±2 whereas the SHC in WSM phase-II shows jump by ±1.

➢ σ_{xy} (**B** ∥ **z**): : In both WSM phase-I and II, the quantization of SHC changes by ±2.

➢ The qualitative difference of quantization in SHC can track the phase transition between two different Weyl phases.

➢ A linear-chemical potential behavior appears in QHC within the bulk gap of WSM phases due to chiral LLs.

Acknowledgements

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