Correlation-driven electronic states in low-dimensional nanoscale systems (research overview)

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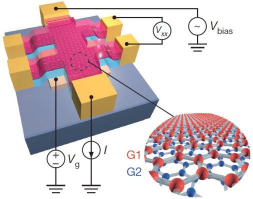
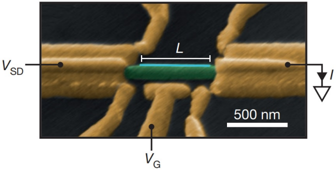
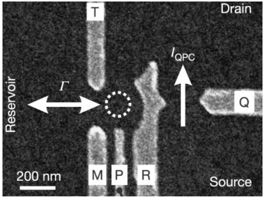
Nanoscale systems in low dimensions

- Target systems:
  quantum wires, nanotubes, quantum point contacts, quantum dots,
  topological superconductors, topological insulators, two-dimensional materials ...

- Low-dimensional nanoscale systems:
  - two dimension (2D)
  - one dimension (1D)
  - zero dimension (0D)





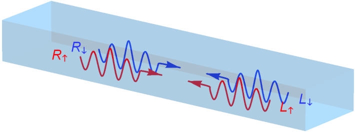


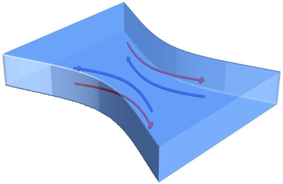
Cao et al., Nature 556, 43 (2018); Albrecht et al., Nature 531, 206 (2016); Elzerman et al., Nature 430, 431 (2004)

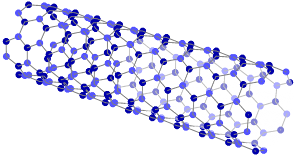
- Controllable ingredients in nanoscale systems:
  confinement potential, carrier density, spin-orbit coupling, micromagnets, superconductivity ...
  $\Rightarrow$ platform for quantum matter and quantum phenomena

Correlated 1D channels in nanoscale systems

- 1D channels formed due to electric potential or band structures
- Interacting systems in 1D: no well-defined quasiparticle excitations
- Power-law suppression of density of states at the Fermi level: $\rho(\epsilon_F) \to 0$
  $\Rightarrow$ power-law behavior of correlation functions (observable features)
- Correlation effects in any interacting 1D systems
- Tomonaga-Luttinger liquid (TLL): excitations with bosonic nature
  ex: nanowires, quantum point contact, nanotubes ...





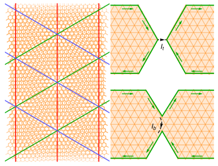


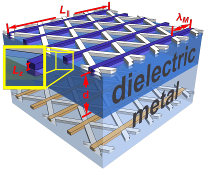
- Research at IoP: generalizations to other platforms

Correlated electron systems in low-dimensional nanoscale systems

- Generalization of the usual Tomonaga-Luttinger liquid (TLL)

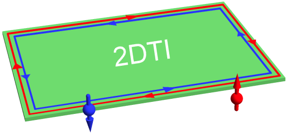
  - *Coupled TLL* beyond 1D:
    a network of domain wall modes in
    twisted bilayer graphene (TBG)

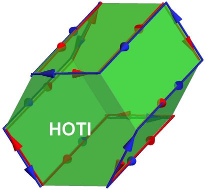




Quantum anomalous Hall states in TBG network
  CHH et al., PRB 108, L121409 (2023)
Superconductivity in TBG network
  Wang & CHH, 2D Mater. 11, 035007 (2024)
2D helix in TBG network
  Chang & CHH, arXiv:2412.14065 (2024)

  - *TLL* beyond spin-degenerate systems:
    spin-momentum-locked boundary states
    ⇒ helical liquids

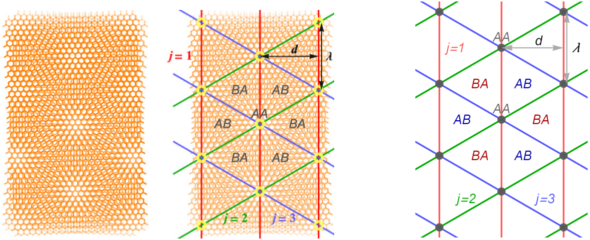




Topological superconductivity in double helical liquids
  CHH, Nanoscale Horiz. 9, 1725 (2024)
Time-reversal soliton corner modes in HOTI
  Hung, Wang, CHH et al., PRB 110, 035125 (2024)
Majorana zero modes in high spin Chern insulators
  Hung, CHH et al., arXiv:2412.08632 (2024)

Domain wall network in twisted bilayer graphene

- Moiré pattern from twisted structure + interlayer bias
  ⇒ local spectral gap with alternating signs between AB- and BA-stacking areas



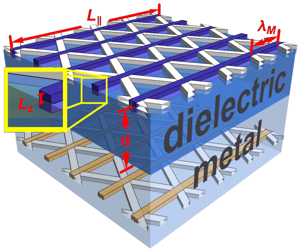
- Domain wall network with general quadratic interaction terms:

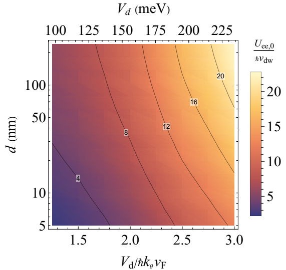
$$H_{0,c}^{(j)} = \sum_{mm'} \int \frac{dx}{2\pi} \left[V_{\phi,mm'}^{j} \partial_x \phi_{c,m}^{j} \partial_x \phi_{c,m'}^{j} + V_{\theta,mm'}^{j} \partial_x \theta_{c,m}^{j} \partial_x \theta_{c,m'}^{j} \right]$$

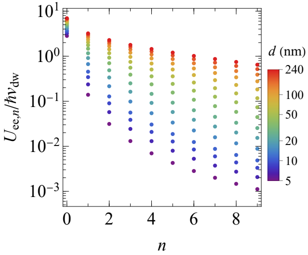
$$H_{0,s}^{(j)} = \sum_{m} \int \frac{\hbar dx}{2\pi} \left[\frac{u_s}{K_s} (\partial_x \phi_{s,m}^{j})^2 + u_s K_s (\partial_x \theta_{s,m}^{j})^2 \right]$$

  - $V_{\phi,mm'}^{j}$, $V_{\theta,mm'}^{j}$, K_s: forward-scattering terms ($R \leftrightarrow R$ & $L \leftrightarrow L$)
  - $\phi_{c,m}^{j}$, $\theta_{c,m}^{j}$, $\phi_{s,m}^{j}$, $\theta_{s,m}^{j}$: boson fields in the charge/spin sector

Electrically tunable correlated domain wall network





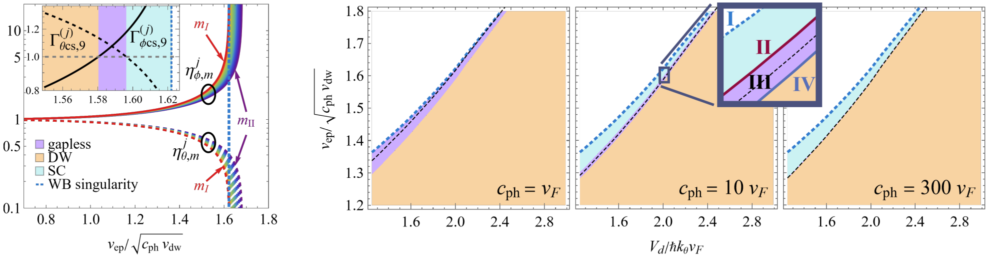


- Spatial profile of the charge density $\rho(\vec{r})$ of the domain wall modes
- Electrically tunable interaction strength in the domain wall network

$$U_{\mathrm{ee},n} = \frac{e^2 L_y}{4\pi\epsilon_0} \int d^3\mathbf{x} \int d^3\mathbf{x}' \left[\frac{\rho_m^{\mathrm{dw}}(x)\rho_{m+n}^{\mathrm{dw}}(x')}{|\mathbf{x}-\mathbf{x}'|} + \frac{\rho_m^{\mathrm{dw}}(x)\rho_{m+n}^{\mathrm{image}}(x')}{|\mathbf{x}-\mathbf{x}'|} \right]$$

- Interaction strength tunable through device design and interlayer bias
  $\Rightarrow$ input for bosonized model of the correlated domain wall network

Electrically tunable correlated domain wall network

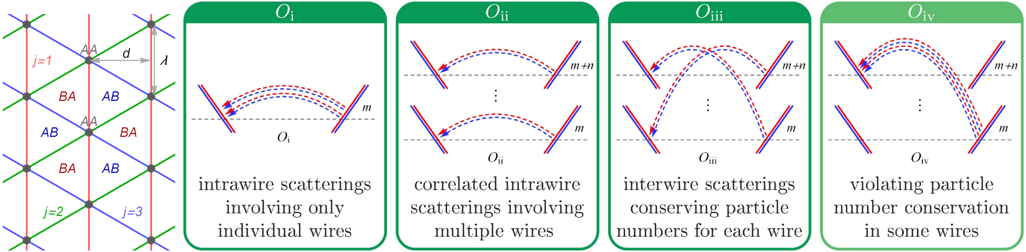


Wang & CHH, 2D Mater. 11, 035007 (2024)

- Various phases: correlated network, density wave, superconductivity, e-ph-coupled liquid
- Distinct behavior upon for different phonon velocity:
  - low-velocity regime: no pairing instability
  - higher-velocity regime: pairing instability for sufficiently large electron-phonon coupling
- Even larger e-ph coupling destabilizes the network: Wentzel-Bardeen (WB) singularity

General scatterings in the domain wall network

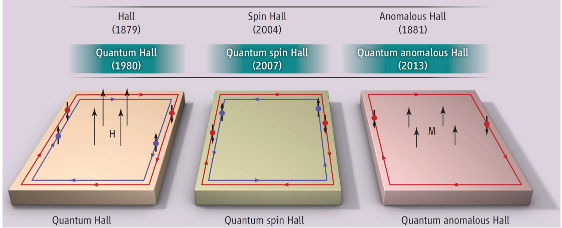
- We consider general scatterings in the domain wall network of twisted bilayer graphene
- We systematically construct scattering operators allowed by the conservation laws
- Moiré pattern allows for novel correlated states and fractional excitations
  $\Rightarrow$ moiré umklapp scatterings



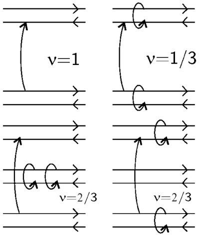
- $O_{\rm iv}$: correlated states hosting a gapped bulk and gapless edge modes at fractional fillings
  $\Rightarrow$ integer and fractional quantum anomalous Hall effects

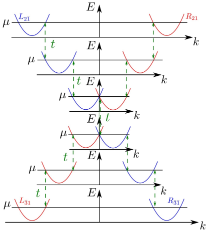
Trio of quantum Hall-related phenomena

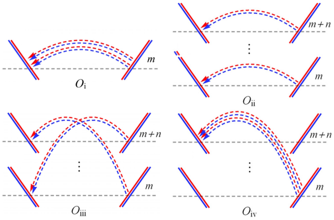
- coupled-wire or network construction



Oh, Science 2013



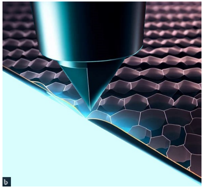


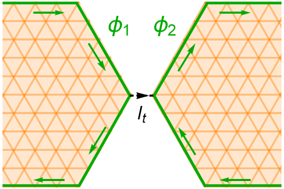


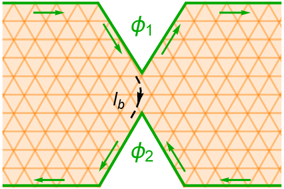
Kane et al., PRL 2002; Klinovaja and Tserkovnyak, PRB 2014; CHH et al., PRB 108, L121409 (2023)

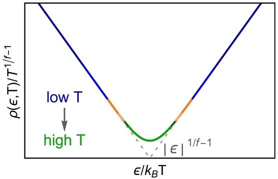
Moiré correlated states at fractional fillings

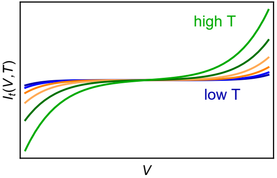
- We proposed spectroscopic and transport setups for experimental verification

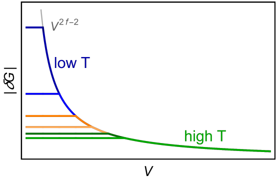








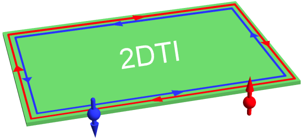


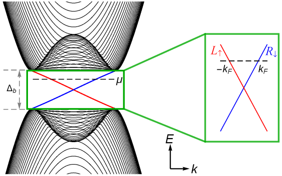


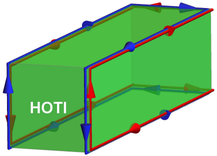
- Universal scaling curve for current-bias (I_t-V) curve at temperature T:

$$I_t \quad \propto \quad T^{\frac{2}{f}-1} \sinh\left(\frac{eV}{2k_B T}\right) \left|\Gamma\left(\frac{1}{f} + i\frac{eV}{2\pi k_B T}\right)\right|^2$$

Helical liquids formed by interacting electrons in helical channels







- Electrons in 2DTI edges or HOTI hinges: $H_{\rm hl} = H_{\rm kin} + H_{\rm ee}$
- Kinetic energy:

$$H_{\rm kin} = -i\hbar v_F \int dr \left(R_\downarrow^\dagger \partial_r R_\downarrow - L_\uparrow^\dagger \partial_r L_\uparrow \right)$$

- e-e interaction (g_2, g_4: interaction strength):

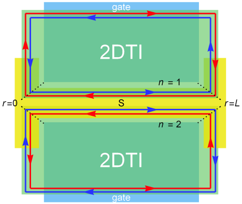
$$H_{\rm ee} = g_2 \int dr\, R_\downarrow^\dagger R_\downarrow L_\uparrow^\dagger L_\uparrow + \frac{g_4}{2} \int dr \left[\left(R_\downarrow^\dagger R_\downarrow \right)^2 + \left(L_\uparrow^\dagger L_\uparrow \right)^2 \right]$$

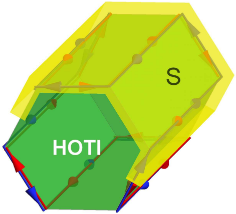
- Spin-momentum locking nature + correlation effects in 1D confinement
  $\Rightarrow$ helical liquids

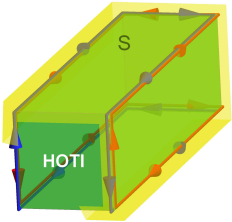
  Review article: CHH et al., SST 36, 123003 (2021)

Nanoscale platforms for topological superconductivity and zero modes

- Synthesizing nanoscale systems with nontrivial topology + superconductivity
- Intensively investigated setup in proximitized 1D nanowires with strong spin-orbit coupling
  $\Rightarrow$ fine-tuning μ and external B field are needed
  Sato PLB 2003; Sato et al., PRL 2009; Sato & Fujimoto, PRB 2009; Lutchyn et al., PRL 2010; Oreg et al., PRL 2010 ...
- Alternative setups proposed to avoid external B fields or fine-tuning μ
- Proposals based on double helical liquids with proximity-induced pairing
  $\Rightarrow$ dominant nonlocal pairing over local pairing

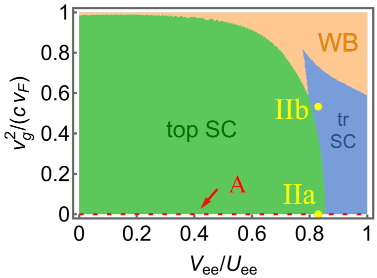


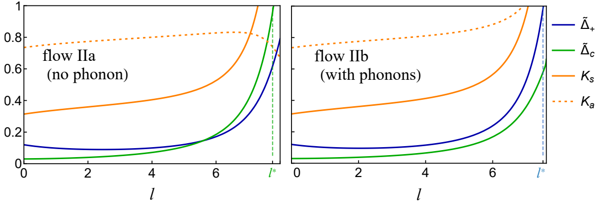




CHH et al., Semicond. Sci. Technol. 36, 123003 (2021); CHH et al., Phys. Rev. Lett. 121, 196801 (2018)

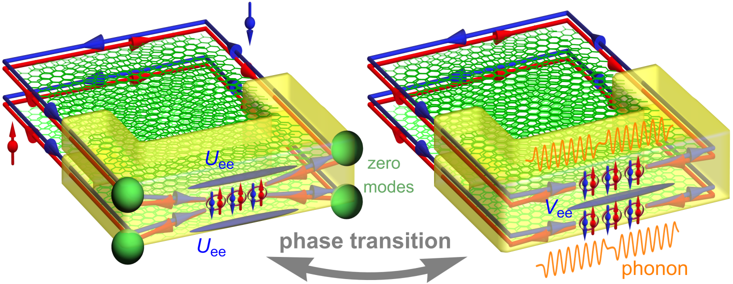
Interaction and phonon effects on pairing in double helical liquids





- e-ph coupling $g \propto v_g^2/(cv_F)$ vs inter-channel to intra-channel interaction ratio V_{ee}/U_{ee}
- Phonons: effectively mediate attractive interactions within each channel
  $\Rightarrow$ enhancing local pairing Δ_n more significantly (compared to Δ_c)
- Electron-phonon coupling can push the system from topological SC to trivial SC phase
  $\Rightarrow$ phonon-induced topological phase transitions
- Reaching the Wentzel-Bardeen (WB) singularity in a non-monotonic way

Interaction- and phonon-induced topological phase transitions



- Electrically tunable topological phase transitions through the ratio V_{ee}/U_{ee} of the inter-channel to intra-channel interaction strength
- Omnipresence of e-e interactions and phonons
  ⇒ practical constraints in utilizing helical channels to realize topological zero modes

CHH, Nanoscale Horiz. 9, 1725 (2024); CHH et al., Phys. Rev. Lett. 121, 196801 (2018);
topical review: CHH et al., SST 36, 123003 (2021)

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- Correlation effects in any interacting 1D systems
  - *Coupled TLL* beyond 1D:
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  - *TLL* beyond spin-degenerate systems:
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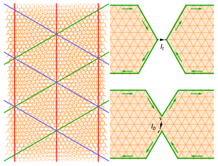
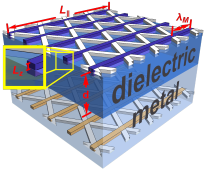
    ⇒ helical liquids





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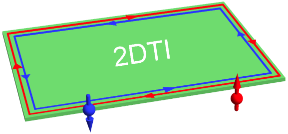

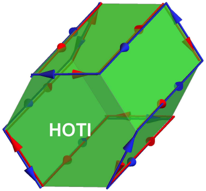

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Topical review on helical liquids
CHH et al., SST 36, 123003 (2021)

Collaboration and recruitment

- Research interests:
  Quantum matter and quantum phenomena in nanoscale systems

- Research positions at IoP, AS
  - Postdoctoral Researcher
  - Graduate Student
  - Research Assistant
- Webpage: https://sites.google.com/view/qmtheory
- Contact: chenhsuan@gate.sinica.edu.tw

- We welcome highly motivated people to join us
- Welcome to share the information!

- Twitter (or X) @hbar_FanClub