Unveiling topological hinge states in Bi$_4$Br$_4$ with quantum interferences

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Bi$_4$Br$_4$ crystals from M. Kobayashi and T. Sasagawa, Tokyo Institute of Technology
I) Topological Insulators (TIs)

**Topological insulator:**
Insulating bulk, conducting boundaries
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Topological insulator:
Insulating bulk, conducting boundaries

2\textsuperscript{nd} order topological insulator:
- Recent extension of the classification
→ Predicted in Bi\textsubscript{4}Br\textsubscript{4}
I) Topological protection

Spin-momentum locking:
Opposite directions of propagation have opposite spins

1D helical edge states

Insulating bulk

Topological protection (against non-magnetic disorder)
→ Ballistic transport
I) Bi$_4$Br$_4$ – A truly insulating TI?

Quasi-1D:

- Strong covalent bonds along one direction
- Weak (Van der Waals) bonds along the other two

Noguchi, R. et al. (2021), Nature Materials, 20(4)
I) Bi\(_4\)Br\(_4\) – A truly insulating TI?

**Quasi-1D:**
- Strong covalent bonds along one direction
- Weak (Van der Waals) bonds along the other two

- Large spin-orbit gap (230 meV)
- Evidence of the topological states in ARPES and STM
- Topological states can survive up to **room temperature**
I) Conducting hinges

Perfect $\text{Bi}_4\text{Br}_4$ crystal

Exfoliated $\text{Bi}_4\text{Br}_4$ crystal
1) Conducting hinges

Perfect Bi$_4$Br$_4$ crystal

Exfoliated Bi$_4$Br$_4$ crystal

Edge conduction revealed by our conducting AFM measurements at 300 K
What about its transport properties?
II) Scaling of the resistance

Hints at ballistic transport

\[ R = \frac{\rho L}{S} \]

Diffusive conductors

5 µm - 4 µm - 3 µm - 2 µm - 1 µm
II) Resistance of ballistic channels

Landauer-Büttiker formula:

\[ R = \frac{1}{\mathcal{N}} \times \frac{\hbar}{e^2} \approx \frac{1}{\mathcal{N}} \times 26 \text{ k}\Omega \]

This is a contact resistance
II) Edge state configuration

Number of contacted edge states can vary between contact pairs.
II) Resistance network

Highly anisotropic transport
Supports the 1D nature of transport along hinge states
II) Hall effect

![Graph showing Hall effect data with a magnetic field (T) ranging from -7.5 to 7.5 T and a voltage (V_H) on the y-axis, with a scale of 6 μm.]
II) Hall effect

No Hall effect

Further evidence of conduction by 1D hinge states
III) Quantum interferences

![Graph showing normalized conductance vs magnetic field with peak at T = 25 mK]
III) Quantum interferences

- Normalized conductance ($e^2/h$)
- Magnetic field (T)
- $T = 25$ mK

- Weak Antilocalization
- Universal Conductance Fluctuations
III) Refined model for the contacts

Interdiffusion of Pd inside Bi$_4$Br$_4$ creates a small disordered region near the contacts

→ Quantum interferences at low T
III) Weak Antilocalization

Conductance peak → **Weak Antilocalization**
Indicates strong spin-orbit coupling

Small $L_\phi$
Reasonable considering interdiffusion hypothesis

$T = 25 \text{ mK}$
$B_c \sim 0.7 \text{ kG}$
$L_\phi \sim 180 \text{ nm}$

$B_c = \frac{\phi_0}{L^2_\phi}$
III) Weak Antilocalization

All sections exhibit very similar behavior in $L_\varphi$

$\propto T^{-0.41}$ power law
Dephasing by $e^- - e^-$ interactions
III) Universal Conductance Fluctuations

Conductance fluctuations

\[ G \text{ (e}^2/\text{h}) \]

- **B_c \approx 1 \text{ kG}**
- **L_\Phi \approx 150 \text{ nm}**

**T = 25 \text{ mK}**

Confirms the L_\Phi extracted from Weak Antilocalization

**Strong fluctuations**
II) Self-averaging?

\[
\sqrt{\langle \delta G^2 \rangle} \propto \left( \frac{L_\phi}{L} \right)^{2-\frac{d}{2}}
\]
III) No self-averaging

\[ \sqrt{\langle \delta G^2 \rangle} \propto \left( \frac{L_\phi}{L} \right)^{2 - \frac{d}{2}} \]

Amplitude of the fluctuations

\[ \langle \delta G^2 \rangle \propto \left( \frac{L_\phi}{L} \right)^{2 - \frac{d}{2}} \]

Fluctuations are much larger than expected

\[ \rightarrow \text{No self-averaging} \]
III) Transmission modulated by interferences

Small disordered region ($L_{pd/BiBr} \sim L_\phi$) produces fluctuations of the global conductance of 1D hinge states.

Transmission / reflection coefficient of the left / right disordered region: $T_{R,L}, R_{R,L}$

$G_{1D} = \frac{e^2}{h} \frac{T_L T_R}{1 - R_L R_R}$

Depend on $B$!
Conclusion

- Strongly anisotropic transport suggests the existence of 1D channels

- General lack of length dependence provide good evidence for the **ballisticity** of the 1D hinge states
• Strongly anisotropic transport suggests the existence of 1D channels

• General lack of length dependence provide good evidence for the ballisticity of the 1D hinge states

→ Bi$_4$Br$_4$ appears as an excellent material for the fundamental study of 1D topological states
Conclusion

- Strongly anisotropic transport suggests the existence of 1D channels
- General lack of length dependence provide good evidence for the **ballisticity** of the 1D hinge states

→ Bi$_4$Br$_4$ appears as an excellent material for the fundamental study of 1D topological states

**Aharonov-Bohm oscillations?**

**Interplay with superconductivity?**
Thank you!
A1) Field anisotropy

Diffusion paths do not explore the thickness of the flake → **2D diffusion**

Two smaller lobes in different directions...
A1) Field anisotropy

Direction of the lobes = slope of the side contacts

→ Confirms that the disordered region originates from the contacts
EDX measurement of the spots show Bi and Pd in their composition.
A3) Determination of the resistance network

Measuring the set of all 2-wire resistances (= the resistance distances) allow to recover the resistance network of the sample

Resistance distance matrix: \( R_{ij} \)

Laplacian matrix: \( L_{ij} = -\frac{1}{w_{ij}} \) if \( i \neq j \)

\[
L = 2R^{-1} + \frac{2}{\mu^T R \mu} \mu \mu^T
\]

with \( \mu_i = 2 - \sum_{j=N(i)} R_{ij} \frac{1}{w_{ij}} \)

Bapat, R.B. (2004), Communications in Mathematical and in Computer Chemistry
For LL power law, $k_B T > E_{th}$ → Incompatible with LL

$E_{Th} \in [3.8; 20] \text{ K}$

For DCB:

$\alpha = -2 \frac{R_{env}}{R_Q}$

$R_{env} \sim R_Q/6 - R_Q/3$
A5) Hybridization of Bi$_4$Br$_4$ edges

A - A termination

A
B
A
•
•
•
B
A

A - B termination

A
B
A
•
•
•
B
A
A6) Band structure

**Theory:**

Zhou, J. J. et al. (2015), New Journal of Physics, 17(1).

**ARPES:**

Noguchi, R. et al. (2021), Nature Materials, 20(4)