Orbital Hall Effect

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Historical Picture (22B0458)

- Hall Effect has a long history starting from 1879, but let's start in 2005.
- Bernevig, Hughes & Zhang (2005): Stated the existence of an orbital angular momentum (OAM) current due to spin-orbit coupling (SOC).
- Tanaka, Kontani et al (2008) Proposed the modern Orbital Hall Effect (without SOC)
- Tanaka, Kontani (2009): Theory linking "Orbital Berry Curvature" to orbital moments.
- Go, Jo, Kim, and Lee (2018): Calculated and found large OHE in many metals, and that OHE, through Spin Orbit Coupling, is the origin of SHE in many systems.
- Choi, Jo, Ko et al(2023):experimentally observed of Orbital Hall Effect directly.

Motivation (22B0458)

- Orbital Hall Effect depends on the orbital hybridization and can be used for Low Spin Orbit Coupling metals.
- Orbital Hall Effect may be more fundamental than Spin Hall Effect since it gives rise to SHE in some metals.
- Orbital Angular Momentum may be a cheaper and more efficient degree of freedom to control then Spin Angular Momentum.

Application (22B0458)

- Orbital Hall Effect has been predicted to switching of ferrimagnet magnetizations efficiently.

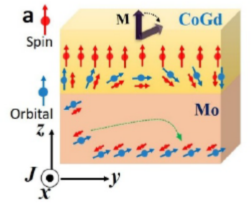


Image source: Orbital Hall Effect Enables Field-Free Magnetization Reversal in Ferrimagnets without Additional Conversion Layer

- It has been predicted to control magnetic memory systems efficiently using Electric Fields.

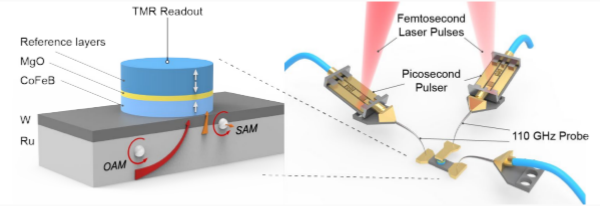
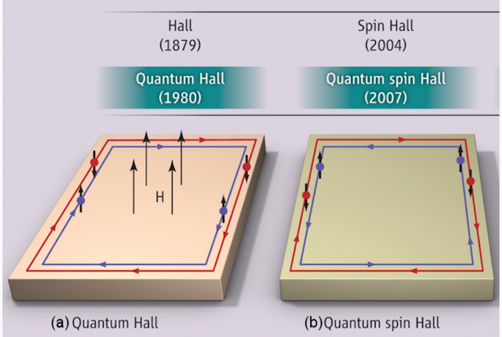


Image source: Giant Orbital Torque-driven Picosecond Switching in Magnetic Tunnel Junctions



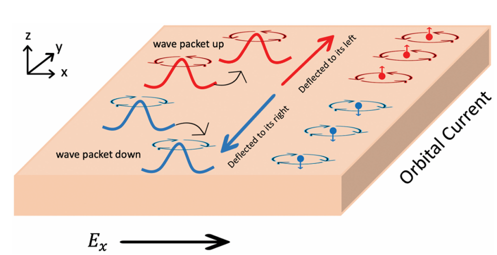


Image source: Universe-Review

Quantum Hall Effect (23B1825)

- Hall conductivity becomes quantized as $\sigma_{xy} = \nu\frac{e^2}{h}$. ($E_F$ crosses discrete levels)
- ρ_{xx} has nonzero value whenever plateau jumps to another level.(E_F lies in the extended states)

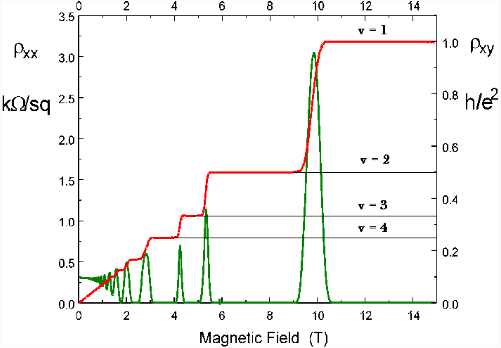


Image source: Cooper et. al.

Edge States & Bulk (23B1825)

- Since TRS is broken by the magnetic field, the reverse path disappears.
- Edge states are **chiral**, they move opposite way along each boundary.
- Inside the bulk electrons move in circular path leading no net current.

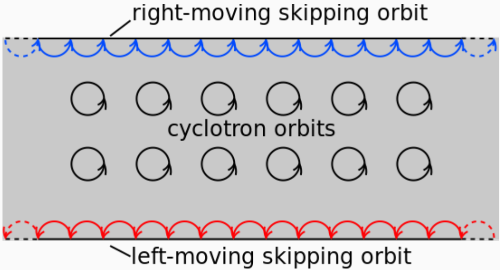


Image source: topocondomat.org

Spin Hall Effect (23B1825)

- In SHE instead of charge, opposite spins flow in opposite direction in edges.
- Unlike QHE here, we don't need any external magnetic field.
- Due to preservation of TRS this leads to dissipationless current.
- It is mostly seen in transition metals, where spin-orbit coupling is prominent.
- As a result spin up electrons drift one way and spin down to other one.

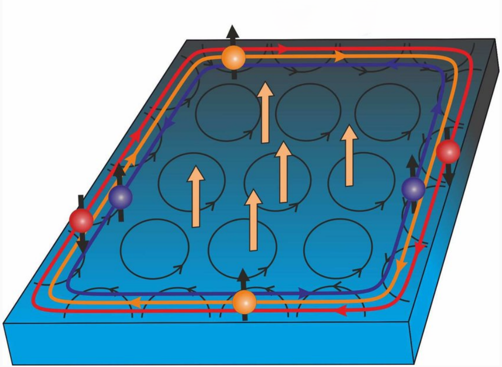


Image source: ResearchGate (I. Yahniuk et al., 2018)

Symmetry Table (23B1825)

Effect	TRS	Observable Current
Quantum Hall	Broken	Charge
Spin Hall	Preserved	Spin
Orbital Hall	Preserved	Orbital

- QHE needs TRS to be broken else there won't be chirality.
- Unlike quantum and spin hall effect it is observed that there is no topological preservation of OHE.

An intuitive picture (24D1081)

- Simplified (d_{xz}, d_{yz}) model on a square lattice
- Intra-orbital NN hopping for the d_{xz} and d_{yz} with hopping integral t
- Inter-orbital NNN hopping between d_{xz} and d_{yz} with hopping integral t'

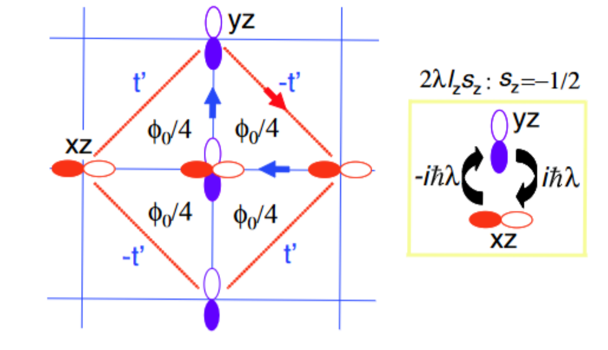


Image source: Kontani et. al. (2008)

An intuitive picture (contd.) (24D1081)

- $R_z(\pm\frac{\pi}{2}) = e^{\pm i\frac{\pi}{2}\hat{l}_z} = \mp i\hat{l}_z$;
  $\hat{l}_z = \pm 1$ for $|xz\rangle$ and $|yz\rangle$
- $\hat{l}_z|xz\rangle = iR_z(\frac{\pi}{2})|xz\rangle = i|yz\rangle$,
  $\hat{l}_z|yz\rangle = -iR_z(\frac{\pi}{2})|yz\rangle = -i|xz\rangle$
- $|l_z = \pm 1\rangle \propto \mp|xz\rangle + i|yz\rangle$
- Rotation of the wave packet by $\frac{\pi}{2}$ results in a phase factor of i

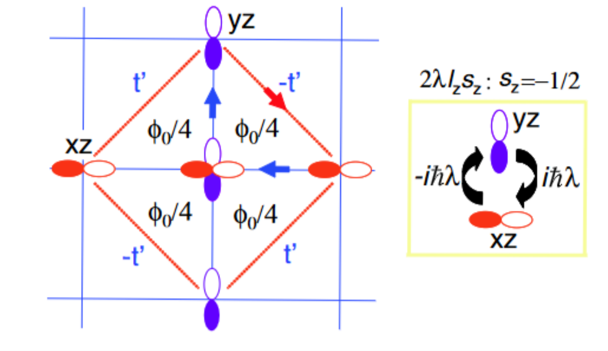


Image source: Kontani et. al. (2008)

Orbital Hall Effect (24D1081)

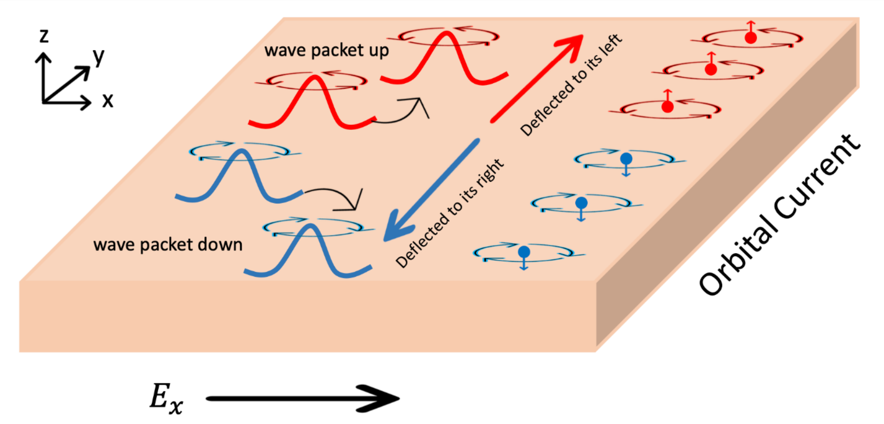


Image source: R. B. Atencia et. al. (2024)

A classical analogy (22B1850)

- Orbital currents can arise despite the orbitals themselves not having intrinsic angular momentum
- Left and right propagating states carry opposite angular momentum, but the net charge current cancels out to zero
- Similar to the classical wheel analogy

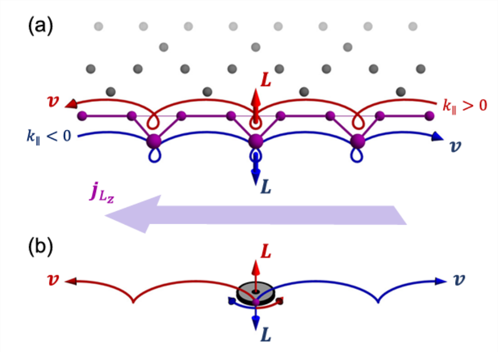


Image source: O. Busch et. al. (2024)

Example: Minimal model (22B1850)

- Consider a kagome lattice with only s-orbitals with hopping term t
- There is no intrinsic angular momentum in the orbitals. However, we still get non-zero OHC on accounting for intersite contribution

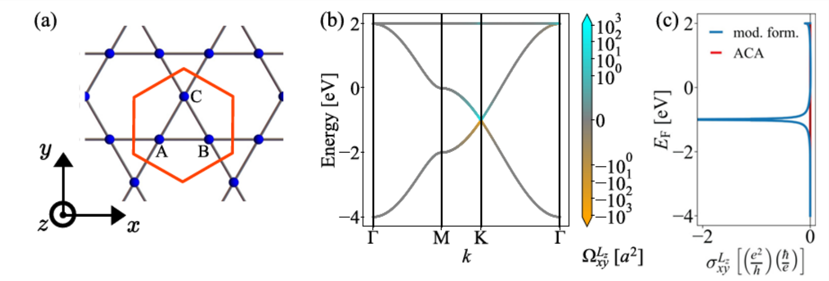


Image source: O. Busch et. al. (2024)

Why is this happening? (22B1850)

- Mathematically, this is happening as there are non-zero off diagonal elements of L_z
- This leads to a finite orbital current, giving non-zero OHC
- Rotation of the wave-packet around its center of mass
- The geometric phase (called Berry phase) gives rise to orbital hall conductivity:

$$\sigma_{xy}^{L_z}(E_F) = \frac{e}{\hbar} \sum_{\nu} \frac{1}{(2\pi)^2} \int_{\varepsilon_{\nu\mathbf{k}} \leq E_F} \Omega_{\nu,xy}^{L_z}(\mathbf{k})\, d^2k \tag{1}$$

The Ω here is the Berry curvature

Ribbon geometry (22B1850)

- The edge state can depend on the geometry of the edge
- A wavepacket with k and $-k$ states can be viewed with the wheel analogy

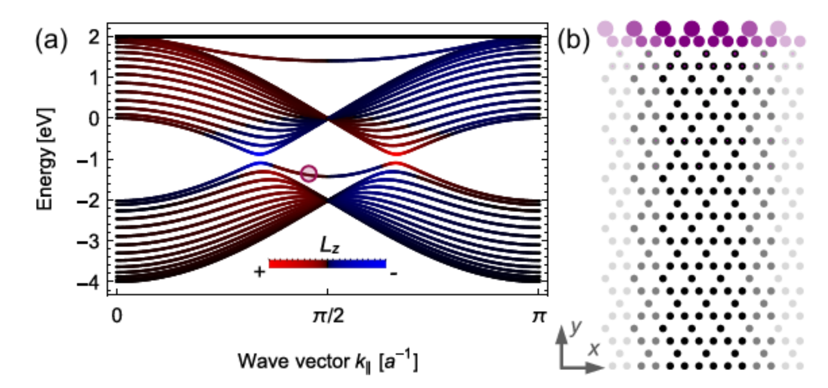


Image source: O. Busch et. al. (2024)

Bandstructure and edge states (22B1850)

- It is possible to distinguish Hall Effects by looking at the band-structure
- The OHE, unlike QHE and QSHE, is not topologically protected; backscattering is allowed, and the edge mode does not cross the bands

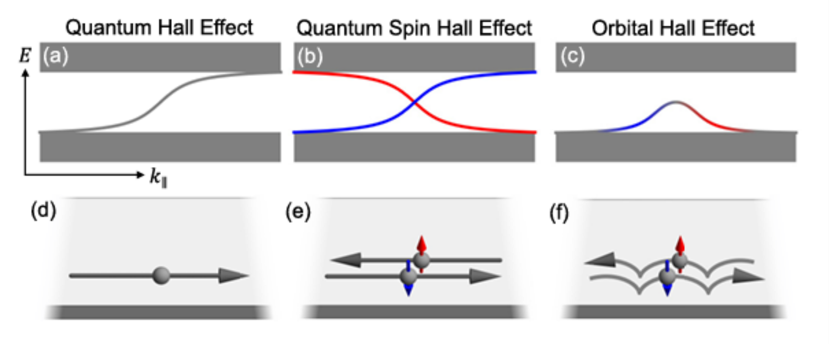


Image source: O. Busch et. al. (2024)

Experimental Observations (25D1072)

- A charge-to-orbital current conversion is required to utilize the effects of the orbital degree of freedom.

Orbital degree of freedom doesn't interact directly with magnetisation since magnetism is mainly a spin-dominated phenomenon.

- Due to this, in addition to charge-to-orbital current conversion, an orbital-to-spin current conversion is also needed for applications towards electric manipulation of magnetisation.

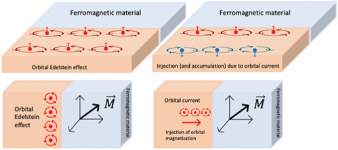


Figure 5. Sketch of the orbital magneto-electric effect and orbital hall effect. The orbital degree of freedom can interact with the local magnetisation in a ferromagnetic material through the spin-orbit coupling in the ferromagnetic material or in the interface between them. It is essential to have orbital-to-spin conversion in order to induce an effect in the magnetisation of the FM.

Orbital angular momentum of Bloch electrons: equilibrium formulation, magneto-electric phenomena, and the orbital Hall effect, Advances in Physics: X, 9:1, 2371972,

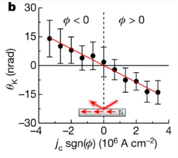
Orbital Angular Momentum (25D1072)

- OAM can be injected from light metals (weak spin-orbit coupling) into an adjacent ferromagnet, exerting orbital torque.
- Enhanced current-induced spin-orbit torque in weak-SOC materials indicates orbital contributions beyond spin mechanisms.
- Direct detection of OAM dynamics achieved through magneto-optical Kerr effect.

Example (25D1072)

Feature	Description	Physical meaning
Linearity	Kerr rotation changes linearly with j_c	Orbital magnetisation $\propto$ applied current (Hall-type response)
Opposite signs	$+j_c \to -\theta_K$, $-j_c \to +\theta_K$	Opposite edges accumulate opposite orbital angular momentum
Zero crossing	$\theta_K = 0$ at $j_c = 0$	No equilibrium magnetisation — non-magnetic system
Error bars	Optical sensitivity $\sim$ few nrad	Small but reproducible signal
Red line	Linear fit to data	Slope $\propto$ orbital Hall conductivity σ_{OH}

Table 1: Kerr rotation vs. current density in Ti — key experimental features of the Orbital Hall Effect.



Choi, YG., Jo, D., Ko, KH. et al. Observation of the orbital Hall effect in a light metal Ti. Nature 619, 52–56 (2023).

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2. Rhonald Burgos Atencia, Amit Agarwal Dimitrie Culcer (2024) Orbital angular momentum of Bloch electrons: equilibrium formulation, magneto-electric phenomena, and the orbital Hall effect, Advances in Physics: X, 9:1, 2371972, DOI: 10.1080/23746149.2024.2371972
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5. Rhonald Burgos Atencia, Amit Agarwal Dimitrie Culcer (2024) Orbital angular momentum of Bloch electrons: equilibrium formulation, magnetoelectric phenomena, and the orbital Hall effect, Advances in Physics: X, 9:1, 2371972, DOI: 10.1080/23746149.2024.2371972

Thank You!