Orbitronics 2026

Les Miléades, Carry-le-Rouët, France

May 5-7, 2026

Venue

The workshop will be held at Les Miléades holiday village on the Côte Bleue in Carry-le-Rouët. This location is ideal for getting together and discussing physics, while enjoying privileged access to the sea and nature, allowing participants to disconnect and relax.

DURING YOUR STAY

The workshop will take place in the “Grand Large” conference room, right by the sea.

The poster session will take place in “Salle 6-7” as indicated on the map.

ACCESS CODES

Code for the barrier: 2843 A
Code for the gate: 8329 A
Wifi Network : La calanque (no password)

BEYOND SCIENCE

During your stay, you can enjoy Les Mileades’ private beach and take advantage of the Thalasso & spa. It’s free, but you need to book a slot at the desk.

The bar is open until 11 pm, and animations will be offered by the resort.

Scientific Committee

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Hyun-Woo Lee, Postech

Felix Casanova, CIC Nanogune

Stefania Pizzini, Néel Institute

Lisa Michez, CINaM

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Organization Committee

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Q-Spintronics

Franco-Japanese collaboration in quantum spintronics, fundred through the ASPIRE program of the Japan Science and Technology Agency.

Program

Speakers, please ensure that your connection is working before the session starts
Invited talks will be 25 min-long, followed by 5 minutes for questions
Contributed talks will be 15 min-long, followed by 5 minutes for questions
Poster sessions will take place in Room 6-7 as indicated on the map

	Monday 4	Tuesday 5		Wednesday 6		Thursday 7	
9-9.30	**Arrival**	invited	*Chair: Shilei Ding*	invited	*Chair: Thierry Valet*	invited	*Chair: Mario Cuoco*
			Saul Velez		**Yuxuan Yao**		**Annika Johansson**
9.30-10			**Hendrik Bentmann**		**Dimi Culcer**		**Aeron McConnel**
10-10.30			**Silvia Damerio**		**Chika Otani**		**Takeo Kato**
10.30-11			**Break**		**Break**		**Break**
11-11.20		contributed	*Chair: Remi Arras*	contributed	*Chair: Daegeun Jo*	contributed	*Chair: William Legrand*
			Lennart Schmipf		**Luciano D'onofrio**		**Aurélien Manchon**
11.20-11.40			**Michel Viret**		**William Legrand**		**Anil Anakha**
11.40-12			**Mahmoud Zeer**		**Sanaz Alikhah**		**Georgios Stylianou**
12-12.20			**Jone Mencos**		**Simon Oyarzun**		**Henri Jaffrès**
12.20-14.30			**Lunch break**		**Lunch break**		**Lunch break**
		invited	*Chair: Mairbek Chshiev*	invited	*Chair: Cyrille Barreteau*	invited	*Chair: Yaohan Xu*
14.30-15			**Albert Fert**		**Tatiana Rappoport**		**Nicola Spaldin**
15-15.30			**Roberto Raimondi**		**Kevin Garello**		**Jingsheng Chen**
15.30-16			**Break**		**Break**		**Break**
16-16.30			**Shilei Ding**		**Chaired Discussion**		**Zhiming Wang**
16.30-17			**Sachin Krishnia**				**Kyung-Jin Lee**
		Posters (Room 6-7)		**Posters (Room 6-7)** **20h Gala Dinner**		**End of Conference**	

Tuesday, May 5

X-ray detection and acoustic pumping of orbital moments

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Orbital angular momentum currents generated from current flow in light materials and interfaces have emerged as a promising route for operating magneto-electronic devices. However, most experiments to date relied on indirect techniques based on orbit-to-spin conversion to investigate orbital phenomena.

In the first part of the talk we will present the direct detection of orbital angular momentum accumulation driven by electric currents at Cu/oxide interfaces. For this, we perform x-ray circular dichroism (XMCD) experiments across the $L_{2,3}$ absorption edges of Cu in Cu/oxide devices while applying electric currents [1]. Our experiments reveal a dominant orbital origin of the detected signals with an estimated average orbital momentum at the probing depth of the x-ray beam of $(-1.9 \pm 0.2) \times 10^{-12}$ and $(-0.84 \pm 0.36) \times 10^{-12}$ $\mu_{\mathrm{B}}\mathrm{A}^{-1}\mathrm{cm}^{2}$ in Cu/CuO$_x$ and Cu/AlO$_x$, respectively, per Cu atom. By considering the orbital diffusion length and relaxation time inferred from transport experiments in Cu, we estimate the effective charge-orbit conversion efficiency in Cu/CuO$_x$ to be $q_{\mathrm{OREE}} \sim 0.013 \pm 0.01$, which is about twice that of the charge-to-spin conversion $q^{*}{}_{REE}$ in Pt. Our results show that XMCD techniques can be used to disentangle spin and orbit contributions and quantify charge-to-orbit conversion efficiencies.

Moving beyond conventional charge-to-orbital conversion mechanisms for generating orbital currents, we demonstrate that acoustic phonons can also be used to generate sizable orbital currents (Fig. 1) [2]. This is evidenced by the buildup rectified voltages in Ni/Ti and Ni/Cr bilayers upon the application of surface acoustic waves (SAWs) [2,3]. In contrast, Co-based heterostructures and Ni/Al devices exhibit weaker signals, consistent with the lower orbital conductivities and conversion efficiencies expected for these systems. Our results show that SAWs are a powerful tool for proving orbital phenomena in light metals and at interfaces, and that angular momentum can be transferred between the crystal lattice and conduction electrons without involving spin-orbit coupling.

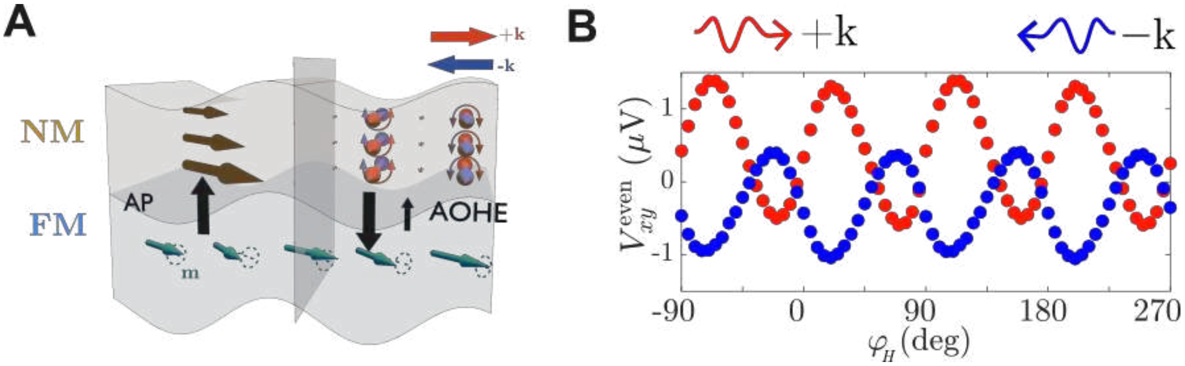

Figure 1: **A**, Schematic of acoustically driven orbital currents in a FM/NM bilayer. Two distinct contributions are identified: acoustic pumping (AP) and the acoustic orbital Hall effect (AOHE). These can be disentangled from experiments via their different symmetry responses to the applied magnetic field and propagation vector **k** of the acoustic phonons. **B**, Angular dependence of the AOHE voltage for the two opposite SAW propagation directions. The signal reverses sign upon inversion of **k**, consistent with the reversal of the vorticity of the SAWs.

[1] P. Pradeep et al., *in preparation*.
[2] M. Rovirola et al, Chiral-phonon generation of orbital currents in light transition metals, arxiv:2512.08385 (2025).
[3] M. Taniguchi et al, Acoustic generation of orbital currents, Nature Comm. **16**, 8038 (2025).

Orbital angular momentum in topological and chiral materials

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Abstract:

Bloch wave functions in crystals can carry spin but also orbital angular momentum (OAM) which underlies the emerging field of orbitronics. I will discuss how angle-resolved photoelectron spectroscopy (ARPES) in combination with linear and circular dichroism can provide spectroscopic information about OAM distributions in momentum space [1]. We applied this approach in several case studies, which will be presented in an overview. For a monolayer AgTe, we provide experimental evidence showing that OAM formation due to orbital hybridization underlies the spin Rashba effect in two-dimensional systems [2]. Furthermore, OAM momentum distributions are related to the Berry curvature and topological properties. Our experiments for TaAs revealed characteristic momentum textures of the OAM at Weyl points [3] and at Weyl nodal lines [4], reflecting their topological charge. Finally, I will show how structural chirality in CoSi induces unconventional OAM textures which depend on crystalline handedness [5]. These results suggest that the OAM, besides its potential in orbitronics, is a useful quantity for a fundamental understanding of electronic structure in quantum materials. As an outlook, I will present parallel efforts in our laboratory towards probing momentum distributions of the spin angular momentum (SAM).

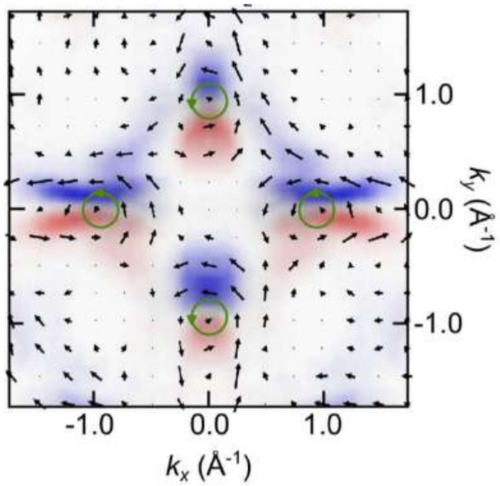

Figure: Vectorial imaging of OAM vorticity in momentum space using circular dichroism in angle-resolved photoelectron spectroscopy [4]. The OAM vortices (indicated in green) emerge from Weyl nodal lines in the electronic band structure and reflect their topological charge (π Berry phase).

[1] D. Oh, H. Bentmann, R. Comin, *Interplay of orbital angular momentum and chirality,* Nat. Phys. (2025) [https://doi.org/10.1038/s41567-025-03113-2]

[2] M. Ünzelmann, H. Bentmann, *et al*, *Orbital-driven Rashba effect in a binary honeycomb monolayer AgTe*, Phys. Rev. Lett. **124**, 176401 (2020).

[3] M. Ünzelmann, H. Bentmann, *et al., Momentum-space signatures of Berry flux monopoles in a Weyl semimetal,* Nat. Commun. **12**, 3650 (2021).

[4] T. Figgemeier, …, H. Bentmann, *Tomography of orbital vortex lines in a topological semimetal,* Phys. Rev. X **15**, 011032 (2025).

[5] S. S. Brinkman, …, H. Bentmann, *Chirality-Driven Orbital Angular Momentum and Circular Dichroism in CoSi*, Phys. Rev. Lett. **132**, 196402 (2024).

Gate-tunable devices for spin and orbitronics applications

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Abstract:

The increasing dependence of everyday life on information processing requires the development of advanced computing technologies for energy efficient manipulation and storage of large amounts of data. Such technologies often require individual chips to display mixed functionality, such as co-localized memory and logic capabilities as well as volatile and non-volatile storage [1]. In this work, we aim to realize gate-tunable devices, depicted in Fig.1a, where the local control of the materials properties allows to switch dynamically between different states. Specifically we investigate the effect of oxidation and reduction of CuO_X to tune the orbital torques applied on an adjacent magnetic layer [2] and the nitrogen concentration in ferrimagnetic Mn_4N_X films to change the magnetic anisotropy [3]. In the former case, we demonstrate that voltage-driven O^{2-} ion migration is an effective means to manipulate the sign and amplitude of the damping-like torque (Fig.1b) by turning on and off the orbital contribution when Cu is oxidized or metallic, respectively [4]. In the latter case, we show that the coercivity and amplitude of the anomalous Hall effect of Mn_4N (Fig.1c) can be reversibly controlled by exchanging N^{3-} ions with an adjacent Ta or V layer under the effect of an electric field [5]. We propose that this can be exploited in energy efficient devices, where information can be written in the low anisotropy state and retained long-term in the high coercivity one.

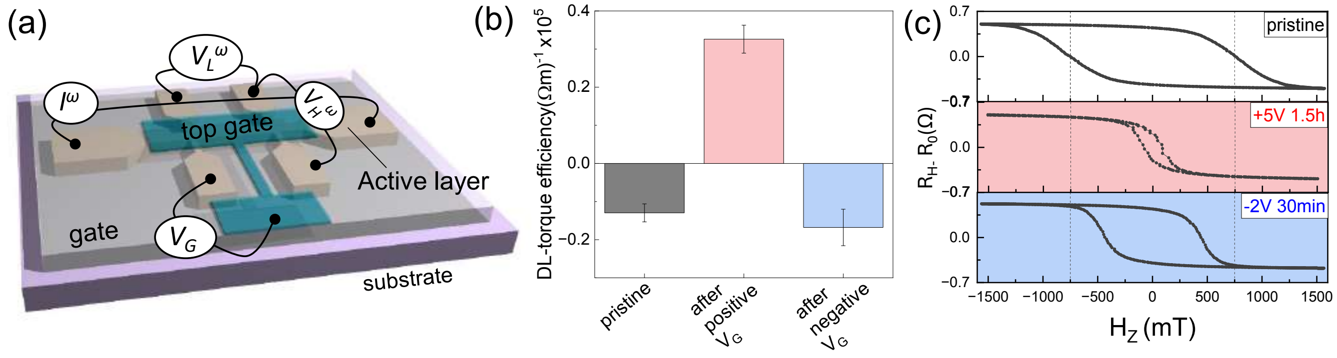

Figure 1: a) Schematic representation of a gate device and electrical connections. b) plot of the damping-like torque efficiency at different gate stages in Cu-based heterostructures. c) Anmalous Hall resistance as a function of out-of-plane field of Mn4N at different gate stages.

[1] J. Grollier, D. Querlioz, K. Y. Camsari, K. Everschor-Sitte, S. Fukami, and M. D. Stiles, *Neuromorphic spintronics*, Nature Electronics, **3**, 360–370 (2020)

[2] S. Ding, et. al., *Harnessing Orbital-to-Spin Conversion of Interfacial Orbital Currents for Efficient Spin-Orbit Torques*, Physical Review Letters, **125**, 177201 (2020)

[3] N. López-Pintó, et. al., *Room-Temperature Solid-State Nitrogen-Based Magneto-Ionics in* $Co_xMn_{1-x}N$ *Films*, Advanced Functional Materials, **34**, 2404487 (2024)

[4] S. Damerio, and C.O. Avci, *Tunable Spin and Orbital Torques in Cu-Based Magnetic Heterostructures*, Nano Letters, **25**(6), 2181-2187 (2025)

[5] S. Damerio, T. Apetrei and C.O. Avci, *Magneto-ionic control of perpendicular anisotropy in epitaxial* Mn_4N *films*, Applied Physics letters, **127**, 262405 (2025)

Chirality-induced orbital Edelstein effect in an analytically solvable model

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Abstract:

Chirality-induced spin selectivity (CISS), a phenomenon wherein chiral structures selectively determine the spin polarization of electron currents flowing through the material, has garnered significant attention due to its potential applications in areas such as spintronics, enantioseparation, and catalysis. The underlying physical effect is the Edelstein effect that converts charge to angular momentum. Besides a spin contribution, there exists a contribution based on the orbital angular momentum but the precise mechanism for its generation remains yet to be understood. Here, we introduce the minimal model for explaining the phenomenon based on the orbital Edelstein effect [1]. We consider nonlocal intersite contributions to the current-induced orbital angular momentum and reveal the underlying mechanism by analytically calculating the Edelstein susceptibilities in a tight-binding and Boltzmann approach. While the orbital angular momentum is directly generated by the chirality of the crystal, the spin contribution of each spin-split band pair relies on spin-orbit coupling. Using tellurium as an example, we show that the orbital contribution surpasses the spin contribution by orders of magnitude.

[1] B.Göbel, L. Schimpf, I. Mertig, *Chirality-induced orbital Edelstein effect in an analytically solvable model*, Phys. Rev. Res. **7**, 033180 (2025)

On the preponderence of orbital physics in interfaces of 3d metals

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Abstract:

Rashba-split states residing at interfaces are ideal for producing spin galvanic effects because of the coupling between the free electrons trajectories and the effective electric field induced by the interface [1]. With the advent of orbital physics, it has been suggested that the chiral spin textures induced in k-space by the interfaces are in fact secondary effects of preponderant orbital textures [2]. Because in light elements, spin-orbit coupling is small, orbital physics should dominate for 3d materials. This has been shown to be the case for the the $LaAlO_3/SrTiO_3$ interface where orbital to charge conversion is ten times greater than its spin-charge conversion counterpart [3]. In this system, the combination of very different spin and orbital textures for each relevant band, along with the possibility to gate the 2-D state, is essential for the clear demonstration of this effect, coined 'inverse orbital Edelstein'.

Another possible way of measuring orbital versus spin efficiencies would be to vary the angular momentum injection into the interface, essentially by changing L/S. This is the strategy we adopt here for interface states generated when an insulator (like MgO) is deposited on top of CoFeB. In this case, the induced Rashba-split state resides in the metallic CoFeB, which offers the advantage of a direct angular momentum injection not relying in some complicated interface transparency [4]. The variation of L/S is done by inducing an anisotropy in the ferromagnet. Although small, the slight changes of L due to the anisotropy, and measured by X-ray circular dichroism and ferromagnetic resonance, induce a visible effect in the conversion of angular momentum into charge. The measurements using spin Seebeck injection as a function of angle, indeed show a clear anisotropic behaviour, in contrast with reference samples (CoFeB/Pt) in which the conversion is due to Inverse Spin Hall Effect in Pt.

These results provide further evidence for the central role of orbital effects in interfacial states of light elements, particularly as far as angular momentum conversion into charge is concerned.

[1] S. D. Ganichev et al., *Spin-galvanic effect*, Nature 417, 153–156 (2002).

[2] D. Go, D. Jo. H.-W. Lee, M. Kläui, Y. Mokrousov, *Orbitronics: Orbital currents in solids*, EPL 135, 37001 (2021)

[3] El Hamdi A.et al., *'Observation of the orbital inverse Rashba-Edelstein effect'*, Nat. Phys. 19, 1855 (2023).

[4] O. Rousseau, C. Gorini, F. Ibrahim, J.-Y. Chauleau, A. Solignac, A. Hallal, S.Toelle, M. Chshiev, and M. Viret, 'Spin-charge conversion in ferromagnetic Rashba states', Phys. Rev. B 104, 134438 (2021).

Current-induced orbital dynamics in magnetic oxides

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Stefan Blügel,[1, 2] Mathias Kläui,[3, 7] Olena Gomonay,[3] and Yuriy Mokrousov[1, 3]

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Magnetic oxides provide an ideal platform for exploring orbital degrees of freedom emerging from strong orbital angular momentum and spin–orbit coupling. The resulting unquenched orbital moments enable rich orbital-transport phenomena, particularly in antiferromagnetic systems. In this work, we investigate current-induced orbital dynamics in representative transition-metal oxides using first-principles calculations in both bulk and thin-film geometries. We identify sizable orbital response and highly efficient orbital-to-spin conversion mechanisms, which give rise to substantial torque components on the magnetic sublattices [1]. In addition, we analyze the contributions of dipole, quadrupole, and octupole magnetic moments to the overall orbital response. Our findings establish magnetic oxides as a promising and realistic platform for harnessing orbital degrees of freedom for next-generation spin-orbital technologies.

[1] S. Krishnia, C. Schmitt, M. Zeer et al., under review.

Direct demonstration of time-reversal-symmetry-breaking spin injection from a compensated magnet

Jone Mencos,[1, 2] Antonin Badura,[3, 4] Eoin Dolan,[1, 2] Sebastian Beckert,[5] Rafael González-Hernández,[6, 7] Ismaïla Kounta,[8] Matthieu Petit,[8] Charles Guillemard,[8] Anna Birk Hellenes,[3, 7] Warlley Campos,[7, 9] Javier Rial,[10] Dominik Kriegner,[3] Vincent Baltz,[10] Luis E. Hueso,[1, 11] Jairo Sinova,[7] Olena Gomonay,[7] Tomás Jungwirth,[3, 12] Libor Smejkal,[9, 13, 3] Lisa Michez,[8] Helena Reichlova,[3] and Fèlix Casanova[1, 11]

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The injection, propagation and detection of spin currents are essential physical processes in spintronics. So far, the separation of charge and spin currents was facilitated by a direct exploration of the electrical spin injection from a ferromagnet [1] or the injection by a relativistic spin Hall effect [2]. The devices employed are lateral spin valves comprising spatially well-separated injection and detection electrodes, connected by a spin-propagation channel. The time-reversal (T) symmetry-breaking ferromagnetic spin injection is realized in an experimental geometry with an electrical bias applied between the injection electrode and the channel, and is modeled by a conserved spin-polarized drift current generated along the applied bias. In contrast, the spin injection by the T-symmetric relativistic spin Hall mechanism is driven by an electrical bias applied across the injection electrode alone, and is modeled by a nonconserved spin current transverse to the applied bias [3]. In this work, we use a lateral spin valve with a Mn_5Si_3 injection electrode to directly demonstrate a T-symmetry-breaking spin injection from a compensated magnet with a vanishing net magnetization [4]. Specifically, the T-symmetry breaking is demonstrated by the fact that switching between time-reversed states of the compensated magnet changes the detected spin signal. Moreover, the T-symmetry-breaking nature of the spin injection is observed in both experimental geometries with the different electrical biasing, while using the same detection electrode. We show that this unconventional spin-injection phenomenology is consistent with different magnitudes and propagation angles of electrical currents in the spin-up and spin-down channel in a d-wave altermagnet. [5]

References:

[1] Jedema, F. J., Filip, A. T. & van Wees, B. J. Electrical spin injection and accumulation at room temperature in an all-metal mesoscopic spin valve. Nature 410, 345-348 (2001).
[2] Sagasta, E. et al. Tuning the spin Hall effect of Pt from the moderately dirty to the superclean regime. Physical Review B 94, 060412 (2016).
[3] Sinova, J., Valenzuela, S. O., Wunderlich, J., Back, C. H. & Jungwirth, T. Spin Hall effects. Reviews of Modern Physics 87, 1213-1260 (2015).
[4] Reichlova, H. et al. Observation of a spontaneous anomalous Hall response in the Mn_5Si_3 d-wave altermagnet candidate. Nature Communications 15, 4961 (2024).
[5] Smejkal, L., Sinova, J. & Jungwirth, T. Emerging Research Landscape of Altermagnetism. Physical Review X 12, 040501 (2022).

Unconventional views on orbitronics supported by experiments.

A. Fert[1], H. Jaffres[1], M. Yaranga[2], C. Rojas-Sanchez[2], M. Hehn[2], S. Petit[2], J.L. Ampuero[2], Y. Xu[3], A. Pezo[1,4]

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Abstract:

Orbitronics is generally described by considering the production of orbital accumulation (OA) by Orbital Hall Effect (OHE) like Spin Hall Effect (SHE) in spintronics and the propagation of OA at long distances by orbital currents like spin currents. However, this view is challenged by theoretical works claiming that, in perfect inversion and time reversal metallic lattices, only very small intrinsic OAs can be obtained by OHE and, secondly, OA cannot be propagated beyond atomic distances [1-2]. In this view, OA is mainly produced by extrinsic effects (as at interfaces by Orbital Rashba Edelstein Effect (OREE) and gradients of composition or current density) and cannot be propagated by orbital currents.

Our main experiments are with orbital production from Nickel by FMR (pumping) or temperature gradient (plus some results with light pulses). Our samples are Ni/Ti/Au, Ni/Ti/X/Au, Ni/Pt/Ti/X/Au, Ni/Y/Ti/Pt/Au multilayers, with high quality quasi-epitaxial Ti layers (2nm to 60 nm). Results [3] are summarized below:

1) The OA produced by FMR or T-gradient have a very short propagation lenght in Ti (about 1 nm) and are predrominantly converted into charge current signal (detection) by interfacial effects (such as Inverse OREE).

2) The dependence of the voltage signal on X in Ni/Ti/X/Au shows that both Ni/Ti and Ti/X interfaces are involved in the signal. Tests with different Ti/X interfaces show that some OA has been transported from Ni to Ti/X across Ti by the process described as: conversion from OA to SA at the Ni/Ti interface, transport across Ti by spin current, reconversion from S to OA at the top interface before conversion to charge current . Confirmation: as one knows that a heavy metal as Pt enhances the conversion between O and S, we verify that inserting a thin Pt layer between Ni and Ti enhances the sig nal by 6. Other tunings are done by insertion of Pt between Ti and X.

T-gradient or light-induced OA leads to similar results.

3) Emerging scenario for the propagation of orbital effects at relatively long distance: local conversion from OA to SA followed by propagation of spin current to distances of the order of spin diffusion length and inverse conversion to OA. O to S conversion (loading of OA into S current) appears to be more efficient than S to O (unloading). General conclusion: orbitronics maily controlled by extrinsic orbital productions and conversions between orbital and spin.

4) Open question: role of disorder for orbital propagation ? (work in progress).

[1] T. Valet *et al,* PRL 135, 256301 (2025), + PRB 111, (2025)

[2] M. Rang and P. Kelly, PRB 109, 214427(2024)

[3] M. Yaranga et al, in preparation

Quantum Kinetic Theory of Multiband Electron Systems: Applications to Spintronics and Orbitronics

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Abstract:

In a series of papers [1-4], we have developed a kinetic theory for weakly disordered multi-band Hamiltonian electron systems. The theory is based on a systematic $\hbar$-expansion and, while recovering the semiclassical transport theory at lowest order, is able to include the effects of quantum geometry in the next order. By using a gradient-Moyal product and the Wilson-line technique, the resulting kinetic equations are manifestly gauge-invariant. In this talk, after a brief presentation of the theory, a number of applications are discussed in the context of spintronics and orbitronics. In particular, I will also report on a recent calculation about the orbital angular momentum accumulation observed in metallic systems.

[1] Valet, Raimondi, *Semiclassical kinetic theory for systems with non-trivial quantum geometry and the expectation value of physical quantities*, EPL **143**, 26004 (2023).
[2] Valet and Raimondi, *Quantum Kinetic Theory of the Linear Response for Weakly Disordered Multiband Systems*, Physical Review B **111**, L041118 (2025).
[3] Raimondi, Valet, *Quantum Kinetic Theory of the Spin Hall Effect for Disordered Graphene with Rashba Spin–Orbit Coupling,* Condensed Matter **10**, 4 (2025).
[4] Valet, Jaffrès, Cros, Raimondi, *Quantum Kinetic Anatomy of Electron Angular Momenta Edge Accumulation,* PRL **135**, 256301 (2025).

Beyond Spin: Emerging Orbital Torque in Light-Metal Systems

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Abstract:

Electronic devices based on charge transport have been extensively studied and are widely used in modern technology. Beyond charge, however, electrons also carry spin and orbital angular momentum. Nonequilibrium spin and orbital currents can transfer angular momentum to adjacent magnetic materials, enabling efficient manipulation of magnetization and the development of spin-orbitronic devices. Decoupling these angular-momentum currents from charge flow opens new opportunities for electrical control of magnetization with reduced energy dissipation.

In this talk, I will present our studies on orbital torque in different light-metal systems. Orbital-to-spin conversion plays a crucial role in generating orbital torque, and the conversion layer can be the ferromagnetic metal itself or nonmagnetic metals with 3d, 4f, or 5d character. Our results demonstrate that the magnitude of orbital torque can exceed that of conventional spin torque. These findings provide new insight into efficient current-induced torques based on orbital currents and highlight the potential of low-cost, environmentally friendly light metals for next-generation spin-orbitronic devices.

Orbital torque and orbital magnetoresistance with orbital magnets

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Abstract:

Generation and transport of orbital angular momentum (OAM) current in solids have gained significant theoretical and experimental interest in recent years with the advent of a new research field called orbitronics [1–3]. Unlike spintronics, where the generation of spin current from charge current relies on relatively weak spin–orbit coupling (SOC) mechanisms (such as in Pt), OAM current can be directly generated from charge current because the crystal momentum of charge carriers (i.e., electrons) couples directly to their orbital angular momentum. This leads to a more robust and orders-of-magnitude larger current-induced OAM generation, even in light, abundant, inexpensive, and environmentally friendly materials (Cu, Al, Cr and Ti) [4-5]. These advantages position new emerging field of orbitronics as a promising platform for future energy-efficient information processing, storage, and neuromorphic technologies [3].

In this talk, I will present recent experimental results demonstrating a large enhancement of torques on 3d-ferromagnetic layers by employing various light elements [4,7]. We utilize these orbital torques to reduce the switching power of magnetic memory bits by up to 50% [6]. Next, in non-local device geometries, we observe non-reciprocal transport behavior when using Ru as an OAM current source [6]. Going beyond the convential spin-based magnets, we have identified a new class of magnetic materials, including some oxides and rare-earth nitrides, in which the orbital angular momentum contributes significantly (and in some cases even dominates) to the net magnetization. In these materials the orbital moments provide a direct pathway for interaction between OAM current and static orbital magnetization, thereby eliminating the need for orbital-to-spin conversion and allowing to harness the full potential of orbitronics effects. By integrating such materials into all-orbitronic device, we demonstrate up to two orders of magnitude enhancement in orbitronic effects, paving the way for next-generation, energy efficient all-orbital green devices [8].

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Wednesday, May 6

Giant Orbital Torque-driven Picosecond Switching in Magnetic Tunnel Junctions

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Abstract:

Orbital effects and orbital torque (OT) were recently discovered as a novel pathway for driving magnetic moment. However, the development of OT-based magnetic memories suffers from low orbital-to-spin conversion efficiency and incompatibility with magnetic tunnel junctions (MTJs). Here we demonstrate OT-MTJ devices based on Ru/W bilayer, achieving an effective spin-orbit Hall conductivity of -12,600 $\hbar/2e$ Ω^{-1}cm^{-1}. The giant orbital torque originates from the strong orbital effects in the Ru layer and an orbital-to-spin conversion efficiency exceeding 90% in the α-W layer because of the large orbit-spin diffusivity. By harnessing the giant orbital torque, we experimentally achieve switching of OT-MTJs by short pulses down to 28.7 picoseconds, with picosecond-switching dynamics captured. Compared with β-W-based spin-orbit torque-MTJs, the OT-MTJs offer a five to eight-fold reduction in driving voltages, and a highly uniform resistance distribution of <1Ω across write channels. Our work bridges the critical gap between orbital effects and magnetic memory applications.

Non-equilibrium orbital dynamics in Bloch electron systems

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Abstract:

In this talk I will discuss a series of insights into non-equilibrium phenomena involving the orbital angular momentum (OAM) of Bloch electron systems. Recent years have witnessed a surge of interest in the orbital angular momentum of Bloch electrons, motivated by its emerging applications in spintronics and magnetic memory [1]. I will first show that disorder plays a crucial role in the orbital Hall effect, at least when the OAM current is evaluated according to the conventional prescription of multiplying the matrix elements of the OAM by those of the velocity [2]. Building on this insight I will show that, more importantly, the conventional evaluation of the orbital Hall effect suffers from a fundamental flaw. Evaluations of the orbital Hall effect have only retained inter-band matrix elements of the position operator. I will outline the correct way to evaluate the OHE including all matrix elements of the position operator, including the technically challenging intra-band elements [3]. They also give rise to a giant OHE in the bulk states of topological insulators, which greatly exceeds spin-related effects [4]. Finally I will discuss our recent insights into the orbital magneto-electric effect. I will show that the OME is partly the result of a non-equilibrium dipole moment generated via Zitterbewegung and proportional to the quantum metric. Our results suggest quantum metric engineering as a route towards maximizing orbital torques [5]. In closing I will give an overview of outstanding questions in the field which include the full role of disorder, inhomogeneities, and the non-conservation of the OAM due to intrinsic mechanisms, which our group has also identified [6].

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Nonlocal Signatures of Orbital Angular Momentum: Transport or Interface Effects?

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Abstract:

Orbitronics has recently emerged as a new direction in spin–orbit physics by identifying the orbital angular momentum (OAM) of electrons as an active degree of freedom for signal generation and torque phenomena. While a growing number of experiments report orbital-related responses extending over tens to nearly one hundred nanometers, the physical origin of such long-range behavior remains highly controversial. Conventional intuition based on orbital quenching by crystal fields suggests that orbital currents should relax on atomic length scales, raising a fundamental question: do these observations reflect genuine long-range orbital transport, or are they manifestations of local generation mechanisms that mimic transport?

In this invited talk, I address this question using nonlocal measurement geometries, which provide one of the most stringent experimental probes of orbital transport [1]. By spatially separating the regions of orbital generation and detection, nonlocal devices suppress spurious effects and directly test whether orbital correlations persist beyond the charge injection region. Focusing on nonlocal orbital Edelstein measurements in Cu/CuO$_x$-based lateral devices, I will show that the observed orbital signals decay laterally over ~100 nm at room temperature, obey Onsager reciprocity between direct and inverse configurations, and exhibit a strong dependence on the ferromagnetic detector material. At the same time, the vertical penetration depth is much shorter, and the lateral decay length is independent of the metal thickness, ruling out simple bulk diffusion of orbital currents.

These experimental findings are interpreted in light of recent theoretical advances, including orbital Dyakonov–Perel relaxation and quantum kinetic theories of electron angular momentum. In particular, I will discuss how strong intrinsic relaxation suppresses true intraband orbital currents, while interband coherence and interfacial orbital Rashba states enable mesoscopic propagation of orbital polarization along interfaces. This leads to a unified picture in which long-range orbital signals arise from the interplay of local generation, rapid bulk relaxation, and interfacial band-mediated propagation, rather than from conventional orbital-current diffusion.

The results clarify the physical meaning of orbital nonlocality and establish interface engineering as a central strategy for future orbitronic devices.

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Filtering Spin and Orbital Moment in Centrosymmetric Systems

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The control of spin and orbital angular momentum in nonmagnetic materials is commonly achieved by breaking inversion symmetry, enabling charge-to-spin conversion and spin-selective electron transport in chiral systems. In this work, we show that orbital moment filtering can also be realized in centrosymmetric systems, where electron states can be selectively manipulated to favor the transmission of electrons with a specific orientation of their orbital moment. We demonstrate that this effect arises from orbital couplings that simultaneously break mirror and rotational symmetries, and we identify the corresponding symmetry requirements for efficient orbital filtering. Furthermore, we show that atomic spin–orbit coupling within the centrosymmetric medium leads to the joint filtering of spin and orbital moments. These results allow one to identify optimal regimes for achieving highly efficient and simultaneous spin and orbital moment filtering.

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Orbital Pumping in Ferrimagnetic Insulators

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Abstract:

Recent advances in orbitronics have sparked interest into the inverse phenomenon of orbital torque, that is, how magnetization dynamics can generate charge currents through orbital effects [1]. This orbital pumping has been recently demonstrated both directly from a ferromagnet [2], and indirectly via the conversion of a pumped spin current into an orbital current [3], thereby completing evidence for orbital currents obtained by optical or even magneto-transport [4] approaches. However, the presence of a strong spin-orbit coupling in ferromagnetic-metal or in heavy-metal layers within these systems complicates the distinction between spin and orbital transport. Spectroscopic exploration of orbital currents, generated directly from magnetization dynamics in an insulator and without any spin-orbital interconversion stage, is expected to provide crucial insight into fundamental principles of orbital electronics.

In this contribution, we report the detection of pure orbital currents generated by both coherent and thermal magnons in the magnetic insulator Bi-doped yttrium iron garnet (BiYIG) [5]. Taking advantage of the absence of charge currents in BiYIG, we attempt to isolate the orbital current contribution from possible spin current contributions. For this, we jointly investigate orbital/spin pumping in nanodevices [Fig. 1(a,b)] featuring electrodes of naturally oxidized Cu, pure Cu, Pt, and Cr. Our findings reveal negligible spin-to-charge conversion in oxidized Cu; this shows that the signal in BiYIG/oxidized Cu directly arises from orbital magnetization dynamics in the insulator. Conversely, the signal in YIG/oxidized Cu is very small [Fig. 1(c,d)], owing to a negligible orbital pumping from YIG. In Cr, the signal is dominated by the negative spin Hall effect rather than the positive orbital Hall effect, indicating that orbital currents constitute a minority of the total flow of angular momentum pumped from BiYIG. Additionally, we show that improving interfacial transparency not only enhances pumping efficiency for spin, but also for orbital currents. Overall, these results provide a path to deepen our understanding of orbital, spin, and charge interconversion phenomena.

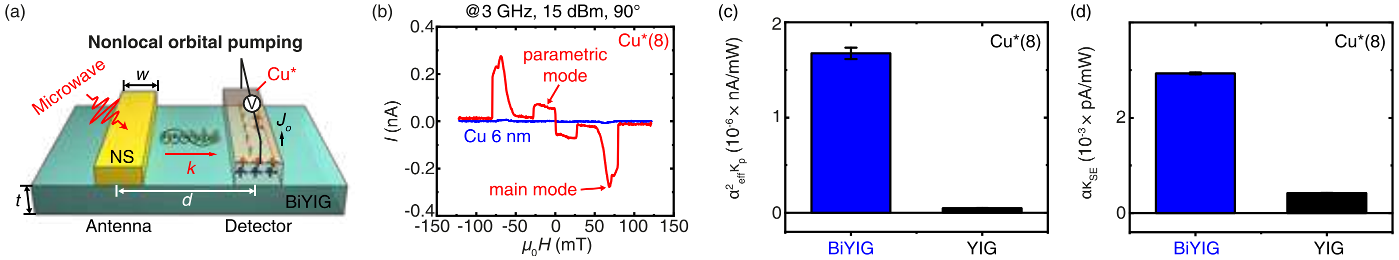

Figure 1: (a) illustrative diagram of the nonlocal orbital pumping device; (b) field-dependent converted currents with an excitation frequency of 3.0 GHz, measured in oxidized Cu(8 nm) vs. pure Cu(6 nm) detector, with magnetic field applied transverse to the wire and 15 dBm power; (c) coherent and (d) thermal charge generation efficiencies estimated from the linear regime, normalized for actual precession amplitude. All devices incorporate Ar$^+$-etched interfaces.

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Theory for Magneto-Optical Detection of the Interfacial Orbital Rashba-Edelstein Effect

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Abstract:

Charge-to-orbital conversion via the orbital Rashba-Edelstein effect (OREE) represents a key functionality for orbitronics. In this work, we combine first-principles density functional theory, linear-response theory, and magneto-optical modeling to reveal how an interfacial OREE can be detected optically through the quadratic magneto-optical Voigt effect in Co/Pt bilayers. We find that, in the Co/Pt bilayer, the current-induced orbital angular momentum can exceed the spin counterpart by nearly a factor of three, underscoring the importance of the OREE. We further show that this orbital angular momentum produces a large current-induced Voigt effect in addition to the equilibrium Voigt effect. Our atom-resolved study reveals that Pt, despite being nominally nonmagnetic, can generate larger Voigt effect than Co, in the presence of the proximity-induced and OREE-induced magnetic moments. These findings establish a pathway for magneto-optical detection of the OREE in magnetic heterostructures.

Orbital to charge current conversion in copper oxide heteroestructures.

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We report orbital-to-charge current conversion in CoFeB/CuO bilayers investigated via ferromagnetic resonance (FMR). Under FMR conditions, the precessing magnetization in CoFeB injects orbital angular momentum into the adjacent CuO layer, generating a transverse dc voltage through the inverse orbital Hall effect (IOHE) [1].

Figure 1 presents the quantitative comparison between the measured symmetric voltage and the orbital diffusion model as a function of CuO thickness. The voltage increases for thin layers and saturates beyond several nanometers, consistent with diffusive orbital transport with relaxation. From this analysis, we extract an orbital diffusion length of 6 nm and an orbital Hall angle of approximately 2%. Broadband FMR measurements reveal a small but finite damping enhancement, consistent with CuO acting as an orbital angular momentum sink.

These findings demonstrate robust diffusive orbital transport in fully oxidized CuO and establish transition-metal oxides as promising platforms for orbitronic devices based on orbital angular momentum transfer and conversion.

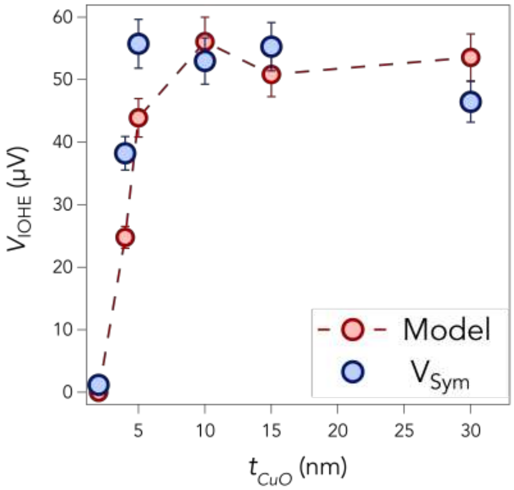

Figure 1.Blue circles correspond to the symmetric voltage component V_{Sym} as a function of the CuO thickness t_{CuO}, showing an increasing trend from 2 to 30 nm. Red circles correspond to the values obtained for the voltage using the orbital diffusion model.

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Real-Space Spectral Approach to Orbital Magnetization

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Orbital magnetism is becoming increasingly relevant in orbitronics, but computing it reliably in realistic materials and device-like geometries remains challenging.
In this talk, I will present a simple and efficient real-space strategy to obtain the equilibrium orbital magnetization in large systems, including disordered and inhomogeneous samples, without relying on explicit eigenstates or delicate gauge constructions. The approach naturally treats finite geometries with boundaries, making it well-suited to connect modern theory with structures encountered in orbitronic devices.

I will benchmark the method on the Haldane model and show how the orbital magnetization evolves across trivial and topological regimes, as well as under Anderson disorder and vacancy defects. A practical outcome is a direct way to identify topological phases from equilibrium orbital-magnetization trends, complementary to transport-based probes.

Finally, I will outline an ongoing direction on itinerant orbital antiferromagnetism, where staggered orbital order emerges from band structure and geometry rather than atomic-like local moments. I will discuss how real-space orbital-magnetization tools can be used to characterize this orbital order and its robustness to disorder and boundaries.

Orbital-to-Spin Conversion exploration and Integration in 3-terminal S/OT-MTJs

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The adoption of Spin-transfer Torque Magnetic Random Access Memory (STT-MRAM) technology by leading microelectronics companies marks a significant achievement in spintronics R&D. With its unique combination of CMOS voltage compatibility, write speed, and write endurance, MRAM addresses memory applications that other emerging non-volatile memory technologies cannot as effectively. Today, STT-MRAM is being integrated into chips as a replacement for embedded FLASH. To overcome the speed and power limitations of STT mechanisms, Spin-orbit Torque (SOT) MRAM has emerged as a promising next-generation technology, targeting SRAM-like application.

However, current materials suffer from limited efficiency and high resistivity, failing to meet write-current requirements. The writing efficiency, which is strongly related to the charge-to-spin conversion efficiency (ξ_{SOT}) of the SOT material, typically reaches only 45% in conventional industrial materials like W, far below the projected 80% needed for advanced transistor nodes. Recent studies highlight orbital phenomena as a potential route to enhance SOT efficiency, due to their larger magnitudes and broader material availability. However, the use of orbital currents in MRAM require an orbital-to-spin conversion mechanism, motivating investigations into conversion mechanisms and materials that can be employed, and associated physics.

In this presentation, I will first provide an overview of MRAM technology and its potential benefits for embedded memories. I will then discuss some challenges in advancing SOT-MRAM, from material and stack optimization to device properties and technology specifications. In the second part, I will present our recent efforts to assess orbital currents in various systems, and optimize stack design to improve SOT-MRAM write performance. Specifically, I will discuss our findings in Ta/W systems of a significant additional spin-torque contribution from Ta, resulting in a fourfold increase compared to the spin Hall effect in Ta alone, attributed to orbital contribution.

Finally, leveraging these findings, I will present their implementation into 3-terminal S/OT-MTJ devices, achieving performance levels similar to W-based systems. Our results show that orbital physics can be easily integrated into SOT-MTJ systems, offering a viable strategy to enhance SOT-MRAM efficiency.

This work was supported by the France 2030 government investment plan, managed by the French National Research Agency under grant reference PEPR Electronique (ANR-22-PEEL-0009); by the French RENATECH network, implemented on the Upstream Technological Platform in Grenoble (PTA) (ANR-22-PEEL-0015); by the Carnot project PRIME SPOT (ANR P-22-03813); by the Horizon Europe grant 101183277 in the framework of the Chips JU NanoIC Pilot Line; and by ORCHID program (project 52694UJ), funded by the French Ministry for Europe and Foreign Affairs, and for Higher Education and Research and the National Science and Technology Council.

Thursday, May 7

Current-induced spin and orbital magnetization in Rashba 2DEGs and ferroelectric bulk semiconductors

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Abstract:

Harnessing spin and orbital degrees of freedom for spintronic and orbitronic technologies requires mechanisms that efficiently generate and control spin and orbital currents and polarizations. The *Edelstein effect* [1] enables charge-to-spin and charge-to-orbital conversion: In systems with broken inversion symmetry, an electric field can induce not only a charge current, but also a finite magnetization with both spin and orbital contributions. Notably, the orbital Edelstein effect often exceeds its spin counterpart [2].

In this talk, I will introduce the microscopic origins of the Edelstein effect within semiclassical Boltzmann transport theory. Originally, the Edelstein effect has been explored in two-dimensional systems with structural inversion asymmetry hosting Rashba-split energy bands, such as surfaces and interfaces. I will highlight perovskite-oxide-based two-dimensional electron gases, e.g. the $SrTiO_3/AlO_x$ interface, as promising Rashba-like platforms for efficient and tunable charge-spin and charge-orbital conversion via the spin and orbital Edelstein effects [3,4]. I will discuss their spin and orbital transport properties from a theoretical perspective and summarize recent experimental observations.

However, charge-spin and charge-orbital conversion via the Edelstein effect is not restricted to quasi-two-dimensional systems, but may also occur in crystals with bulk inversion asymmetry. In the ferroelectric semiconductor GeTe, polar atomic displacement leads to a Rashba-like splitting of the bulk band structure. I will demonstrate that GeTe exhibits a pronounced orbital Edelstein effect, whose sign can be controlled electrically via ferroelectric polarization reversal [5].

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Orbital driven angular momentum conversion in CoFe/Cu probed by THz emission and spin-orbit torque

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The generation and interconversion of angular momentum at metallic interfaces is a central topic in orbitronics. While heavy metals with strong spin-orbit coupling are widely studied for spin Hall and spin-charge conversion, recent theoretical and experimental advances suggest that orbital angular momentum currents can emerge even in systems with weak intrinsic spin-orbit coupling [1]. These orbital currents can convert into spin currents at ferromagnetic interfaces, providing an alternative channel for angular momentum transduction beyond conventional spin Hall mechanisms. Here, we investigate charge-orbital and orbital-charge conversion processes in CoFe/Cu heterostructures. spin-orbit torque efficiencies are quantified using harmonic Hall measurements, enabling extraction of effective damping-like and field-like torques [2]. In parallel, femtosecond laser excitation is employed to generate terahertz (THz) emission from the same material platform. Optical excitation drives ultrafast non-equilibrium angular momentum dynamics in the ferromagnet, leading to transient spin and possibly orbital current injection into the adjacent Cu layer. The resulting sub-picosecond charge current is detected via time-domain THz spectroscopy. This ultrafast emission process is commonly interpreted within the framework of inverse spin Hall conversion in magnetic heterostructures [3]. In the present work, we extend this concept to explore the possibility of orbital-to-charge conversion mechanisms, inverse orbital Hall effect, in a light-metal system like Cu.

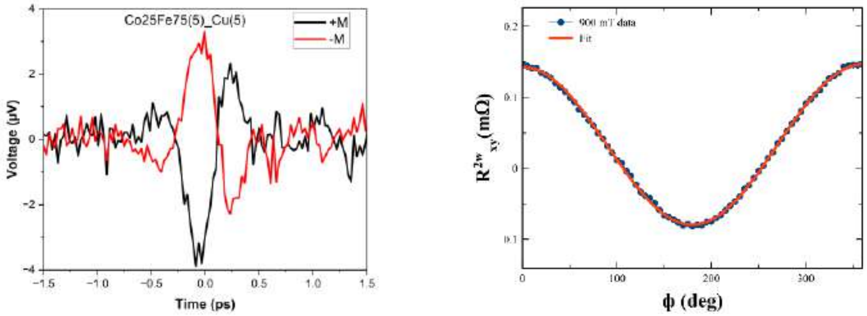

Figure 1(a). Time-domain terahertz (THz) emission waveform from the CoFe(3)/CuOx(5) heterostructure measured under opposite in-plane magnetization directions (±M), 1(b) In-plane angular dependence of the second-harmonic Hall resistance $R_{xy}^{2\omega}$measured under an external magnetic field of 900 mT and an applied current of 10 mA. The characteristic angular symmetry enables separation of damping-like and field-like torque contributions.

By systematically varying ferromagnetic layer thicknesses, we compare quasi-static torque efficiencies with ultrafast THz emission amplitudes in the same material platform. The absence of strong spin Hall materials provides a framework to disentangle spin and orbital mediated transport contributions. Our results aim to clarify the role of orbital angular momentum transduction in light-metal heterostructures and establish a comparative platform for charge-orbital and orbital-charge conversion.

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Polymer Enhanced Spin-Orbitronic THz Emission

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Spintronic terahertz (THz) emitters provide a versatile platform for generating broadband THz radiation through ultrafast spin-charge conversion processes. In conventional ferromagnet/heavy-metal heterostructures, femtosecond optical excitation drives spin currents that are converted into ultrafast charge currents, typically via the inverse spin Hall effect (ISHE), producing a radiated THz pulse. Recent theoretical and experimental work has shown that orbital angular momentum transport can play an important role in these processes through the inverse orbital Hall effect (IOHE), enabling a range of new THz emitter materials and geometries.

This talk will present recent experiments investigating THz emission from ferromagnet/polymer heterostructures designed to probe the contribution of orbital currents to ultrafast angular momentum-charge dynamics. Using thin ferromagnetic films interfaced with doped semiconducting polymers, we observe enhanced THz emission relative to reference structures lacking the polymer layer. The results are consistent with the generation of orbital currents in the ferromagnet that propagate across the interface and undergo orbital-to-charge conversion through the IOHE, providing an additional pathway for THz emission. We also show that performing chiral dopant exchange in these polymers further enhances the signal and induces a small rotation of the emission polarization that depends on the dopant chirality.

These findings highlight the potential role of orbital angular momentum transport in spin-orbitronic THz emitters and suggest that hybrid ferromagnet/organic structures offer a promising platform for exploring ultrafast orbitronic phenomena.

Generation of electronic orbital angular momentum by chiral phonons

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Abstract:

Chiral phonons are lattice excitations in which atoms vibrate with circular motion in a plane perpendicular to the propagation direction, and they have attracted attention as carriers of angular momentum flow transported by phonons [1]. To date, chiral phonons have often been discussed as phenomena intrinsic to non-centrosymmetric crystals, materials with valley degrees of freedom, or chiral crystals. However, from the viewpoint of angular momentum conservation, they can more generally drive the orbital degrees of freedom of electronic systems. In particular, in the context of "orbitronics," coupling to phonons with diverse spectra and timescales appears highly promising. Indeed, recent experiments have reported the observation of orbital current generation induced by chiral phonons [2].

In this talk, we theoretically formulate the effect of chiral phonons that statically polarize the orbital angular momentum of electrons (orbital accumulation effect) without invoking magnetism or spin-orbit interaction [3]. Focusing on orbital-dependent electron-lattice coupling, we derive general expressions for orbital accumulation in two setups: (i) driving by coherent lattice dynamics externally excited, such as surface acoustic waves, and (ii) driving by a nonequilibrium phonon flow injected from an adjacent chiral material. The derivation employs a geometric formulation based on Berry curvature, linear response theory, and the nonequilibrium Green's function method, and we confirm that mutually consistent expressions are obtained.

As a concrete example, we consider a multi-orbital tight-binding model on a square lattice (see Figure) and show that hopping modulation induced by lattice displacements generates hybridization between different orbitals. As a result, in this model chiral phonons primarily couple to the electronic orbital quadrupole moment. This coupling drives a time-dependent orbital dipole response, and as a secondary effect, a uniform static orbital angular momentum accumulation is generated via a rectification effect. In the case of a nonequilibrium phonon flow, an imbalance in the average occupation numbers of phonons with opposite chiralities acts as the driving force, and orbital accumulation can be generated even when the average lattice displacement is zero. Our numerical estimates show that the absolute magnitude of the generated orbital accumulation is proportional to the phonon frequency and is therefore smaller than that of optically induced orbital generation by circularly polarized light in the visible range. On the other hand, the conversion efficiency normalized by the injected energy per unit time can be of the same order as that of circularly polarized light–induced orbital generation.

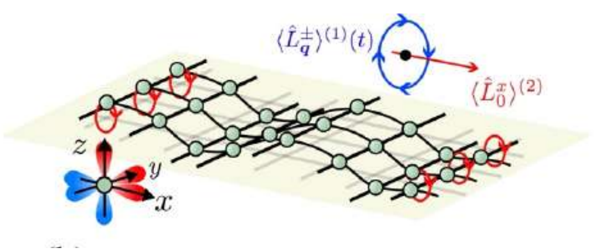

Figure: Our model for electrons and chiral phonons.

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Orbital relaxation and dipole-quadrupole coupling

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Orbital angular momentum transport has recently emerged as a promising direction for beyond-spintronic technologies. Yet it raises a fundamental puzzle. Unlike spin—which is only perturbatively affected by spin–orbit coupling—the orbital moment couples strongly to the crystal field and is not a conserved quantity. This interaction is expected to quench the non-equilibrium orbital moment extremely rapidly, which appears incompatible with the long orbital diffusion lengths reported experimentally (up to 60 nm in Ti in Choi et al.). As a matter of fact, a recent theory [1] showed that orbital diffusivities in transition metals are one to two orders of magnitude smaller than spin diffusivities, consistent with experiments reporting values around 1–2 mm²/s. However, the mechanism of orbital relaxation remains unclear. In analogy with spin transport, strong disorder may compete with the crystal field and suppress relaxation via a D'yakonov–Perel' (DP)-like effect, yet this has lacked a transparent analytical demonstration and accurate examination. Because the orbital moment is not a good quantum number, perturbative approaches fail, leaving no controlled framework for understanding long-range orbital transport.

In this poster, I will present a recently-developed fully nonperturbative analytical formalism that resolves this difficulty and yields exact orbital relaxation dynamics for a model t_{2g} crystal-field environment [2]. Our method is valid across the entire disorder range, revealing a clear crossover between DP-like and Elliott–Yafet (EY)–like regimes. Furthermore, lowering the crystal field symmetry, we uncover a dipole–quadrupole coupling that produces oscillatory relaxation—a qualitative departure from spin dynamics that suggests unique multipolar orbital transport signatures [3].

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Orbital Hall and anomalous spin Hall Effects for nonlocal magnon spin injection and detection

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Magnonic devices hold great potential as alternative platforms for the information industry – either as substitutes for or complements to classical electronics and spintronics. Similarly to spintronic devices, they offer non-volatile means for data transfer and processing, but with the additional benefit of lacking Joule heating, since information is now conveyed not by electrons but by spin waves (magnons). This project seeks to combine spin and orbital-based phenomena with magnon transport, aiming to explore ways for boosting the injection and detection efficiencies of such non-local signals [1].

Generation and detection of spin waves is achieved by using two parallel metallic electrodes on top of a Yttrium Iron Garnet (YIG) substrate. The first electrode generates magnons (injector) while the other detects them (detector). The electrodes consist of a ferromagnetic (FM) material – Ni – capped with Pt and should provide an angular momentum current to charge current interconversion through various effects: conventional spin Hall effect (SHE), anomalous spin Hall effect (ASHE) [2], and orbital Hall effect (OHE). While the conventional SHE is independent on the magnetization, for ASHE, the spin polarization to charge current conversion depends on the magnetization direction. Finally, we explore the recently discovered OHE, for which little is known about the role of magnetization in orbital-to-charge interconversion. In our devices, the signal profiles under the influence of an external magnetic field can help us decouple the spin and orbital contributions. Through careful current, magnetic field, and layer thicknesses dependences we characterize and quantify the thermal, SHE, and ASHE contributions for maximizing magnon spin injection and detection efficiencies and investigate possible influences of OHE in our devices [3].

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Harnessing Chromium Orbital Polarization for Ultra-Fast and Field-Free Magnetization Switching

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Abstract:

Controlling the magnetization of a ferromagnetic layer via spin-orbit torques (SOT) generated by a current in an adjacent layer represents one of the most promising pathways for advanced spintronic and orbitronic devices. For instance, recent proposals integrate information processing, storage, and transmission through spin light-emitting diodes (spin-LEDs) emitting circularly polarized light [1]. In these architectures, light polarization is defined by the orientation of a magnetic layer controlled via SOTs. However, implementing such devices remains challenging; the control current must not exceed the metal-insulator-semiconductor (MIS) Schottky barrier breakdown voltage to prevent detrimental current shunting effects. Furthermore, achieving magnetization control in the ultra-fast regime is highly desirable.

To address these challenges, the utilization of light metals capable of generating orbital momentum accumulation, such as Chromium (Cr), proves stronger efficiency [2-4]. We demonstrate that introducing a Cr layer into traditional heavy-metal-based systems (specifically CoFeB/W and Co/Pt) significantly enhances SOT efficiency compared to heavy metals that rely solely on the spin Hall effect. This enhancement is assigned to a current-induced orbital polarization in Cr, which is efficiently converted into a spin current either in the heavy metal or the ferromagnetic layer; this additional contribution reinforces the spin current from the heavy metal, thereby exerting a stronger spin-orbit torque.

Using harmonic Hall measurements, we show that this orbital contribution increases the damping-like torque efficiency by up to 5 times compared to samples free of Cr layer. Consequently, the switching threshold, evaluated via magneto-transport and Kerr microscopy, is considerably reduced. Moreover, due to the lower resistivity of Cr compared to traditional heavy metals like β-W and ferromagnets such as CoFeB, Cr-based devices exhibit a more than fourfold reduction in power consumption for magnetization switching. This low-voltage operation is critical for preserving the integrity of sensitive interfaces like the MIS barrier.

Additionally, we present a comprehensive study on the dependence of switching behavior on Cr thickness, pulse width, and in-plane magnetic field. Our analysis reveals that the reversal initiates with domain nucleation followed by expansion, indicating that the switching mechanism is governed by domain-wall depinning rather than coherent macrospin rotation. Finally, utilizing the optimized Cr thickness, we observe reproducible and deterministic magnetization reversal in the ultra-fast and field-free regimes, eliminating the need for external in-plane magnetic fields usually required in standard SOT geometries. These results establish Chromium as an effective orbital-torque material for low-power and ultra-fast magnetization control

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Hunting for Hidden Order

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Most magnetic materials, phenomena and devices are well described in terms of the magnetic dipoles arising from the spin of their constituent electrons. There is mounting evidence, however, of intriguing magnetic behaviors that can't be explained in terms of electron spin dipole moments; these behaviors are often attributed to "hidden order" since their origin is difficult to decipher with conventional experimental probes. In this talk I will discuss some unusual magnetic effects, such as electric-field induced magnetism, magnetism on apparently non-magnetic surfaces, and unconventional spin splitting of energy bands, and show that they can be understood in terms of a "hidden order" of higher-order magnetic multipoles, beyond the magnetic dipole. While there are clear experimental signatures of such hidden multipolar order, and it is captured nicely in our computer simulations, attempts at direct measurement have so far proved elusive, and I will close with a plea for better ideas.

Electrical manipulation of non-colinear antiferromagnetic order by orbital Hall effect

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Abstract:

Antiferromagnet as an active component in devices has recently been attracting intense attention due to its negligible stray field and ultra-fast magnetic dynamics, making it very promising for the high-density and fast-speed memory devices. The switching of antiferromagnetic (AFM) order by current induced spin-orbit torque (SOT) has already been realized. However, the critical switching current density should be further reduced for energy efficient memory. Furthermore, SOT-induced bidirectional switching of AFM order in perpendicular geometry, especially in the absence of external magnetic field, remain unveiled, which is essential for the practical application. Recent works suggest that current-induced orbital Hall effect (OHE) can effectively manipulate the ferromagnetic order, thanks to the high orbital torque generation efficiency. In this presentation, I will report demonstration of deterministic switching of antiferromagnetic order in Weyl semimetal Mn_3Sn by OHE originated from metal Mn or oxide CuO_x. While Mn_3Sn is proven to be able to convert orbit torques to spin torques by itself, we find that inserting a heavy metal layer like Pt with proper thickness can effectively reduce the critical switching current density and improve the switching efficiency.[1] Furthermore, we experimentally demonstrate field-free perpendicular switching of the magnetic octupole moct in chiral AFM Mn_3Sn by combining in-plane and out-of-plane SOTs generated by two-dimensional van-der Vaals WTe_2. The out-of-plane SOT breaks the in-plane inversion symmetry and leads to deterministic bidirectional switching of moct in polycrystalline Mn_3Sn even without a fixed perpendicular moct easy axis. The switching ratio reaches up to 80% instead of commonly reported 20-30% in polycrystalline Mn_3Sn and the critical current density is also reduced to the order of 1 MA/cm^2.[2]

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Harnessing the Orbital Hall Effect in Oxide Heterostructures: From Unconventional Scaling to Efficient Field-free Switching

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Abstract:

Orbital angular momentum transport offers a rich landscape for magnetization control, promising superior torque efficiencies compared to conventional spin currents. In this talk, I will present our recent progress in unraveling the mechanisms of the orbital Hall effect (OHE) and exploiting them for energy-efficient spintronics. First, using $SrRuO_3$ as a model system, we report an unconventional scaling of orbital Hall conductivity with longitudinal conductivity. Unlike the spin Hall effect, the OHE is strikingly enhanced as conductivity decreases, highlighting the dominant role of the Dyakonov-Perel-like orbital relaxation mechanism [1]. Building on this insight, we further demonstrate a strategy to achieve efficient, field-free switching of perpendicular magnetization. By engineering a lateral device structure that breaks geometric mirror symmetry, we unlock the out-of-plane polarization while concurrently tuning the $SrRuO_3$ conductivity to harness disorder-induced scattering. This synergistic approach enables ultra-low-power operation, reducing switching power consumption by an order of magnitude compared to spin-based counterparts [2]. Our findings establish a generic paradigm that integrates structural engineering with orbital physics to unlock the full potential of high-symmetry materials for next-generation spintronics.

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Current-Induced Electric Quadrupole as a Nonequilibrium Manifestation of Quantum Metric

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Abstract:

The geometric structure of electronic wave functions is fully encoded in the quantum geometric tensor [1], which decomposes into two distinct components: the imaginary, antisymmetric Berry curvature and the real, symmetric quantum metric. The physical consequences of the Berry curvature have been extensively explored, underpinning topological phases and phenomena such as the anomalous Hall effect. In contrast, the physical significance of the quantum metric—which defines the notion of "distance" between quantum states—has only recently begun to be investigated. Representative studies include the nonlinear Hall effect in space–time inversion symmetric systems with vanishing Berry curvature [2,3], superconductivity emerging in flat bands due to a nontrivial quantum metric [4], and photoemission measurements of the quantum metric in black phosphorus [5].

In this talk, we show that a charge current can induce an electric quadrupole, which is a nonequilibrium manifestation of the quantum metric. The distinct symmetry of the electric quadrupole, compared with that of the magnetic dipole, enables an unambiguous separation of the electric quadrupole from spin and orbital angular momentum. The close relationship between the electric quadrupole and the orbital quadrupole suggests that it provides a route for purely electrical control of orbital anisotropy, acting as a conjugate field that can manipulate orbital order.

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Posters

Modern Approach to Orbital Hall Effect Based on Wannier Picture of Solids

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Abstract:

In the field of orbital dynamics and orbital transport, a particularly important quantity is the so-called orbital Hall conductivity (OHC), which is expressed in terms of operators of velocity and orbital angular momentum (OAM) [1]. To overcome the difficulties in treating the unbounded position operator, very often atom-centered approximations are used, which capture only a part of the local contributions to the OAM operator [2,3]. Here, we promote a new approach to quantify the OAM operator in the basis of Wannier functions, which is based on the modern theory of orbital magnetization and which captures both local and itinerant contributions to the OHC. By performing first-principles calculations for various materials, we show that significant corrections to the OHC by non-local effects arise when compared to common approximations. Our approach improves the understanding of the OAM in solids and allows for a precise estimation of various orbital effects in complex materials.

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Orbital dynamics through chiral phonons in low-Z materials

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In recent years, the exploration of the orbital degree of freedom has opened up new avenues for controlling quantum mechanical transport properties in materials, even in the presence of strong spin-orbit coupling [1]. Unlike the typical interaction observed between itinerant spins and magnetization in heavy metal/ferromagnet (HM/FM) interfaces [2], the orbital counterpart of these effects exhibits a distinct entanglement between the material's orbital characteristics and the transport environment. Essentially, it is the lattice that interacts strongly with this degree of freedom, as demonstrated in recent studies[3,4]. In this work, we perform numerical simulations to evaluate the advantages of leveraging such capabilities. We focus on light elements for our transport calculations and demonstrate that this interplay can be effectively utilized in future spintronic devices, including considerations for temperature effects.

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Orbital-driven field-free switching in low-symmetry van der Waals heterostructures

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Abstract:

The interplay between spin and orbital degrees of freedom provides new opportunities for the electrical control of magnetism through orbital torques [1], paving a promising route toward one of challenges in spintronics: energy-efficient, field-free switching of perpendicular magnetic anisotropy (PMA) states. In conventional spin–orbit torque (SOT) devices made of 2D materials, deterministic reversal of PMA magnets typically requires an external in-plane magnetic field to lift symmetry constraints, complicating device operation and limiting scalability [2]. By contrast, low-symmetry quantum materials such as $1T_d$ transition metal dichalcogenides (TMDs), including $MoTe_2$ and WTe_2, as well as Weyl semimetals such as $TaIrTe_4$, possess reduced mirror symmetries that naturally enable out-of-plane (OOP) spin and orbital densities, and therefore OOP torque components [3]. Experimentally, both OOP field-like and damping-like torques have been reported in these systems [4,5], generally coexisting with relative strengths that depend sensitively on device geometry and interfacial properties. Although field-free switching has been demonstrated in such heterostructures, the microscopic origin of these unconventional OOP torques remains actively debated.

Here, we develop a microscopic model for orbital-driven, field-free magnetization switching in low-symmetry van der Waals heterostructures. Using minimal tight-binding descriptions of a 1Td TMD interfaced with a ferromagnet (FM), we show that the reduced symmetry of the TMD is transferred to the FM through interfacial orbital hybridization, generating unconventional OOP SOT components even when the FM is intrinsically high-symmetry. The dominant mechanism is the orbital Rashba–Edelstein effect (OREE), whereby an in-plane electric field induces a non-equilibrium orbital polarization that produces effective torques and enables deterministic switching without external magnetic fields. Combining analytical theory with numerical simulations, we obtain excellent agreement for the critical switching threshold and predict field-free reversal of a PMA state at current densities on the order of 5×10^7 A cm^{-2}, establishing an efficient orbital pathway for magnetization control in van der Waals platforms.

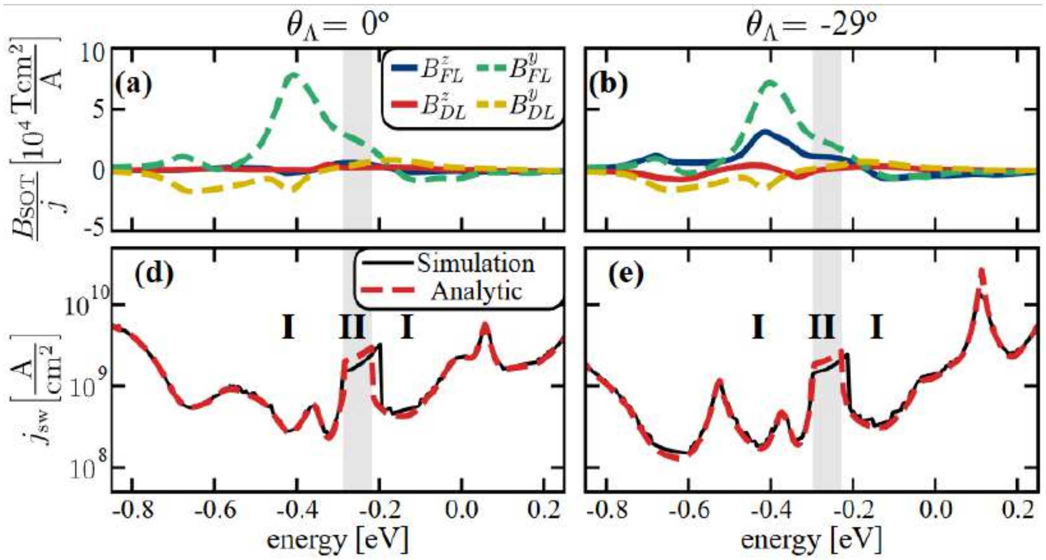

Figure 1: (a-b) SOT effective field linear response coefficients for the IP and OOP FL and DL torques, for the TMD SOC field angle. (d-e) Critical switching current computed by numerical simulation of the LLG equation (black solid curves) and by analytic calculations (dashed red curves), for their respective SOC field angles, respectively.

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Disorder Effects on Orbital Hall Transport Using Chebyshev Expansion

Kevin J. U. Vidarte and Tatiana G. Rappoport

The orbital Hall effect has emerged as a fundamental phenomenon in orbitronics, offering a robust mechanism for generating orbital currents without the need for strong spin-orbit coupling. In this work, we investigate the effect of disorder on orbital Hall transport in a sp3 model using a tight-binding model on a cubic lattice. To handle large-scale systems and incorporate the effects of atomic-scale disorder, we employ the Kubo-Bastin formalism expanded via Chebyshev polynomials. This approach allows for an efficient numerical calculation of the orbital Hall conductivity across the entire energy spectrum. We analyze how different types of disorder—such as Anderson-like site potential fluctuations, vacancies and bond disorder—affect the stability and magnitude of the orbital Hall response. Our results provide insights into the resilience of orbital currents in realistic, disordered environments, which is crucial for the development of future orbitronic devices.

Generation of phonons with angular momentum during ultrafast demagnetization

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Abstract:

Understanding how angular momentum is redistributed during ultrafast demagnetization remains a central challenge in condensed matter physics. While recent experiments by Tauchert et al. [1] suggest that the angular momentum lost by electrons is transferred to atomic rotations, a microscopic theoretical confirmation has so far been lacking. Here, we present a first-principles investigation of phonons carrying angular momentum during the ultrafast demagnetization of $L1_0$ FePt [2,3]. By combining time-dependent density-functional theory (TDDFT) with Ehrenfest nuclear dynamics, we simulate the coupled electron–nuclear response under femtosecond laser excitation. Our results reveal that sub-100-femtosecond quenching of spin angular momentum drives circular atomic motion. We further show that both ultrafast demagnetization and the generation of phonons with angular momentum emerge from symmetry constraints imposed by spin–orbit coupling. These findings provide fundamental insight into spin–phonon interactions and highlight novel pathways for femtosecond control of angular momentum in solids.

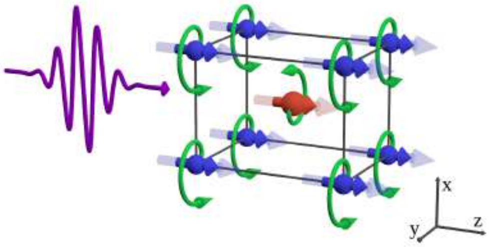

Figure: Graphical illustration of the generation of phonons with angular momentum in FePt following ultrafast demagnetization. The blue and red spheres represent Fe and Pt atoms, respectively. Transparent (solid) arrows represent their magnetic moments before (after) the laser pulse (purple curve).

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Interfacial orbital transmission, conversion, and mechanical torque in metals

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Abstract:

Interfacial orbital transport remains far less understood than its bulk counterpart despite its central role in orbitronic experiments. Here, we theoretically investigate the transmission and conversion of orbital angular momentum across a metallic interface using a model Hamiltonian incorporating crystal-field effects [1]. We show that an injected orbital dipole moment undergoes pronounced oscillations driven by the crystal field and generates characteristic quadrupole moments determined by the orbital orientation relative to the interface. Unlike spin precession, the dipole relaxes toward a finite value away from the interface. We further quantify interfacial orbital memory loss and demonstrate that orbital absorption produces a sizable mechanical torque obtained from the orbital continuity equation.

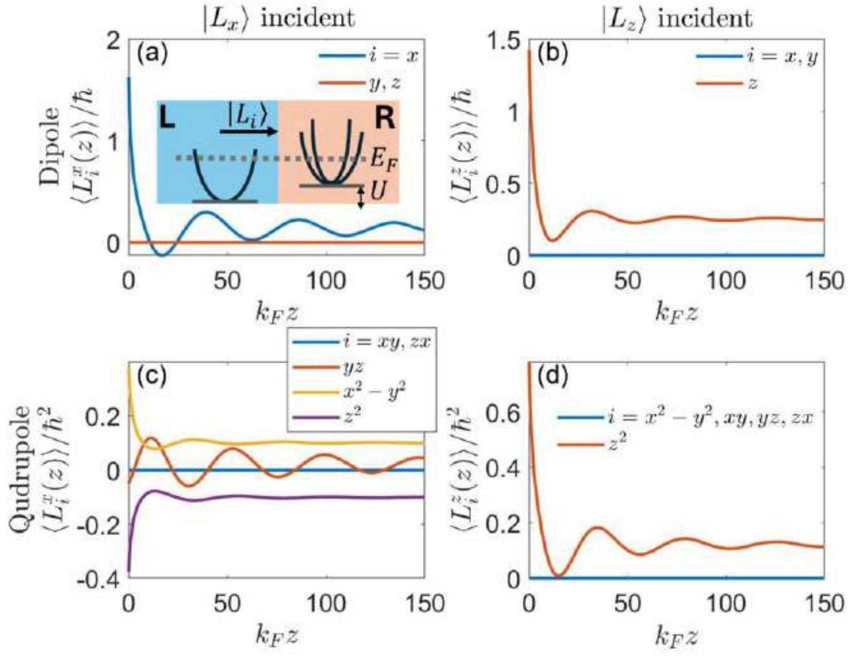

Figure: (a-b) Orbital dipole and (c-d) quadrupole moments as a function of z in the right layer induced by incident $|L_x\rangle$ and $|L_z\rangle$ dipole moments from the left layer.

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Giant Orbital Magnetoresistance in Orbital Magnets

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The emerging field of orbitronics aims to exploit orbital angular momentum (OAM) currents [1] as an alternative to spin currents for energy-efficient information technologies using light and environmentally friendly materials. While most experimental approaches rely on orbital-to-spin conversion in heavy metals to manipulate the magnetization of spin-based magnets (Co, Ni, Fe, etc.) [2], direct coupling between orbital currents and orbital magnetization remains largely unexplored. In particular, magnets, including antiferromagnets with unquenched orbital moments, offer a promising platform for energy-efficient operations combining ultimate stability with THz dynamics.

Here, we report the observation of a giant orbital magnetoresistance (OMR) in orbital-magnet/Cu* heterostructures [3]. By combining orbital currents generated in Cu* with the unquenched OAM of the orbital-magnet, we detect a magnetoresistance (MR) signal that exceeds conventional spin Hall magnetoresistance (SMR) in Pt-based reference structures by two orders of magnitude [3]. Notably, the absence of a heavy metal layer with large spin-orbit coupling (SOC) and the electrical insulating nature of the orbital-magnet exclude involvement of SOC-driven spin-current mechanisms as the dominant origin of the observed MR. The large enhancement therefore points toward a direct interaction between orbital currents and the large unquenched OAM (> 1 μ_B/atom) in the orbital-magnet [3].

To investigate further the underlying mechanism of the observed OMR, we measure its dependence on the orbital-magnet thickness. The OMR exhibits a non-monotonic behavior as a function of orbital-magnet thickness, with a pronounced saturation at about 10 nm [4]. In contrast, the OMR is not influenced by the Cu* thickness [3]. This behavior indicates that the dominant mechanism is not governed by bulk transport in Cu* but instead arises from orbital-current generation at the Cu/CuOx interface [5]. The pronounced enhancement in orbital-magnet/Cu* is consistent with substantial interfacial OAM accumulation, likely driven by inversion symmetry breaking and the orbital Rashba–Edelstein effect [5].

To check the universality of the observed OMR beyond Cu*, we have performed control experiments on orbital-magnet/Cr bilayers and they exhibit significantly larger magnetoresistance signals [3] compared to the pure spin-based orbital-magnet/Pt system.

Our results demonstrate that by using OAM-dominated materials, we can harness the benefits of giant orbital currents for orbitronics-based devices without the need for orbital-to-spin conversion. These benefits have not been achievable using conventional spin-dominated magnets.

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[2] S. Ding, et al., *Harnessing Orbital-to-Spin Conversion of Interfacial Orbital Currents for Efficient Spin-Orbit Torques,* Phys. Rev. Lett., **125**, 1772201 (2020)
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Ab initio study of orbital moments in transition-metal oxides

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Recent advances in spintronics have enabled the development of non-volatile memories with low-energy consumption, as well as magnetic oscillators and sensors. Current research often focuses on devices that rely on the generation of spin currents to manipulate spin magnetization. The production of their building-block components requires the use of scarce and heavy elements (e.g., Pt, Ta, W, Bi) with strong spin–orbit coupling. To overcome this limitation, recent studies have shown that using currents of orbital angular momentum[1,2,3] could be an alternative to spin currents. This approach would both reduce energy consumption and enable the use of light and abundant elements (e.g., CuOx, Ti, Zr, Al). While various materials have already been explored to generate orbital currents, transition-metal oxides have been overlooked, while they appear to be promising candidates, as they are known to possess a large variety of highly-tunable atomic structures, which would provide an efficient way to modulate orbital currents through the modifications of their associated crystal field.

This work employs *ab initio* calculations to investigate the emergence and control of orbital moments within transition-metal oxides. Preliminary results show that nickel and cobalt monoxides seem to exhibit robust orbital physics[4,5].

We will present the electronic and magnetic properties of interfaces between CoO and various transition-metal thin films. Using DFT-based methods, we aim to understand the interplay between crystal field symmetry and interfacial hybridization, the fundamental mechanisms governing the orbital response. By identifying these structural and chemical parameters, we seek to explore how these interfaces can be engineered to maximize orbital angular momentum transfer and transport for the next generation of energy-efficient orbitronic devices.

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Keywords : Spintronics, Orbitronics, Orbital Angular Momentum, Density Functionnal Theory (DFT), Transition-Metal Oxides.

Unconventional orbital currents and torques due to ferro-rotational orbital textures

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Abstract:

Orbital angular momentum transport has emerged as a promising route for manipulating magnetic devices, yet its generation has largely relied on the conventional orbital Hall effect. Here, we show that ferro-rotational order enables the electrical generation of unconventional orbital currents. These orbital currents represent the orbital counterparts of spin currents due to ferromagnetic order, but arise from rotation-induced symmetry breaking rather than time-reversal symmetry breaking or spin-orbit coupling. Using tight-binding models, we identify the underlying intrinsic, nonrelativistic mechanism categorized as an electric hexadecapole moment and corroborate our findings with first-principles calculations for the ferro-rotational material $TiAu_4$. We further show that these rotation-induced orbital currents lead to surface orbital accumulation and unconventional orbital torque in a ferro-rotational/ferromagnetic metallic bilayer, allowing deterministic field-free switching. Our findings unveil a novel pathway for generating orbital currents beyond the conventional orbital Hall effect, broadening the landscape of orbitronics research to include novel ferroic materials and higher-order electric multipoles.

Impact of Structural Imperfections on the Ultrafast Orbital Hall Effect in Metallic Nanoribbons

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Abstract:

The ultrafast orbital Hall effect (UOHE) arises when a femtosecond laser pulse drives a transient orbital current. We investigate how structural defects affect the UOHE in a Cu nanoribbon [1]. Using Evolve, a real-space tight-binding framework for finite systems [2], we simulate the laser-induced electron dynamics and compute the orbital angular momentum (OAM) and its associated currents with atomic resolution. Defects significantly alter the OAM landscape: while defect-free ribbons exhibit pronounced edge accumulation, imperfections redistribute OAM toward defect sites. Furthermore, we analyze the phase relation between the p- and d-orbital contributions to the OAM in interface geometries. Our results reveal the pivotal influence of defects on ultrafast orbital transport and dynamics.

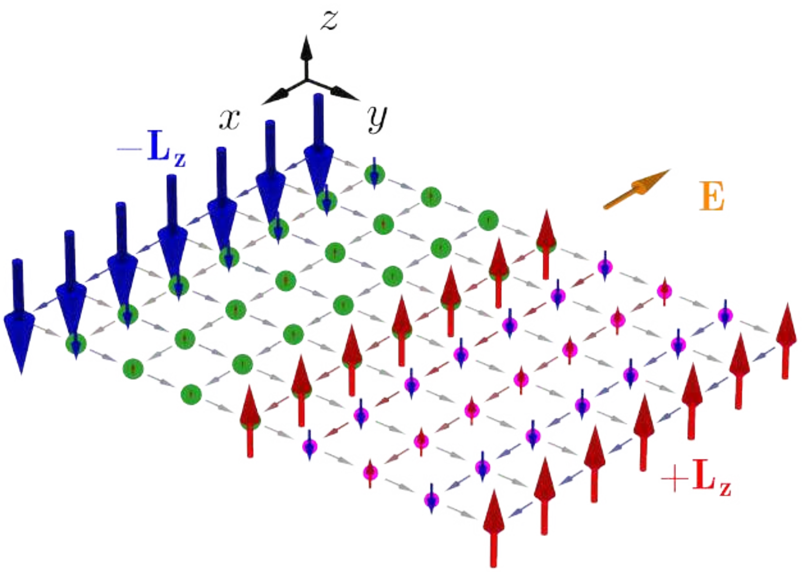

Figure: Snapshot of the ultrafast orbital Hall effect in the interface system of Al (green dots) and Cu (magenta dots). The orbital angular momentum (OAM) is accumulated with opposite orientation at the edges.

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Orbital angular momentum-driven phenomena in magnetic systems

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Abstract:

Orbitronics, a burgeoning research field exploiting the intrinsic property of orbital angular momentum (OAM) of electrons, offers a complementary approach for information transport and manipulation in solid-state devices [1–3]. While the field of spintronics relies on the generation of spin currents from charge current and vice versa and depends on the spin-orbit coupling (SOC), OAM current can arise from the direct coupling between the crystal momentum and the orbital angular momentum of electrons. This effect is stronger even in light and widely available metals such as Cu, Cr, Al and Ti, despite their weak SOC. The resulting orbital currents can be orders-of-magnitude larger and more robust than spin currents and open new ways towards energy-efficient information transport [3,4].

In this work, we use an enhancement of torques on TmIG magnetic layers through the introduction of light elements at the Cu/CuOx interface [2]. To functinalized the OAM, a Pt layer converts it into a spin current, which subsequently exerts a torque on magnetic layers, in which the magnetization is dominated by spin angular momentum. These orbital torques can reduce the switching power in a magnetic memory up to 50% [5]. Additionally, light metals like Vanadium reveal an orbital Hall effect with large orbital Hall conductivity and long orbital diffusion lengths, emphasizing the role of both localized and delocalized contributions [6]. Complementary, orbital pumping effects are investigated through sign reversal of the measured voltage in Nb/Ni and Nb/CoFeB bilayers. Here, the sign reversal originates from the opposing contributions of the spin and orbital effects in Nb, highlighting the nature of orbital pumping compared to conventional spin pumping [7]. Furthermore, non-reciprocal transport behavior is observed in non-local device geometries when Ru serves as an OAM current source [8].

More recently, we identify a new class of magnetic materials in which orbital moments contribute significantly to the magnetization over spin contribution. This includes certain oxides and rare-earth nitrides, where OAM plays a central role in determining the overall magnetic moment. In these materials the orbital contribution to the magnetization enables direct coupling to the OAM currents, which enables a more efficient utilization of orbital transport. The enhancement of orbital effects in these materials and the integration into orbitronic devices can lead to next-generation energy-efficient device concepts based on orbital transport [9].

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Engineering altermagnetic Mn_5Si_3 thin films via epitaxial growth

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Abstract:

To date, four altermagnetic materials have been experimentally proven, in order of discovery: RuO_2; Mn_5Si_3; MnTe and CrSb. Among these materials, Mn_5Si_3 presents incomparable advantages. First, it is composed of light elements with weak spin-orbit coupling, making it possible to unequivocally link its altermagnetic character to the intrinsic, non-relativistic specific arrangement of the staggered magnetic moments with respect to its crystalline symmetries. Then, its magnetic structure is extremely sensitive to tiny changes in the crystal structure, offering a variety of magnetic behaviours: non-collinear and collinear antiferromagnet [1], p-wave [2] and d-wave [3, 4] altermagnets. Epitaxy is therefore a powerful tool to explore this model system and disentangle the various contributions driving the altermagnetic properties. In this context, we report routes to grow epitaxial Mn_5Si_3 thin films "under strain" using molecular beam epitaxy [5]. Theory [4,7], a strong anomalous Hall effect in the absence of magnetic field and magnetization [4], its variant-dependent anisotropic behavior [6,7], a sizeable Nernst effect [8] despite the absence of magnetization, coupled with a clear influence of crystallinity, are all signatures of the altermagnetism of Mn_5Si_3. They are all consistent with the stabilization via epitaxy of a specific crystal and spin structure [7]. The control and optimization of the altermagnetic properties by epitaxy therefore represent a new and promising avenue in the field of spintronics, offering distinct opportunities for advancing both fundamental physics and technological applications.

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Study of spin and orbital Hall angles using Lateral Spin Valves

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Abstract:

Lateral Spin Valves (LSV) are widely used devices for the characterization of fundamental spintronic properties of materials, such as the spin diffusion length and spin polarization of ferromagnets [1, 2] .

They employ a first ferromagnetic stripe to create a spin accumulation at the interface with a nonmagnetic layer, by means of electrical spin injection. This spin accumulation then diffuses along the nonmagnetic channel, and it is finally detected through a nonlocal voltage between the nonmagnet and a second ferromagnetic stripe. The sign of this voltage can be controlled by switching an in-plane magnetic field, parallel to the easy axes of the ferromagnets, achieving parallel or antiparallel configurations for their magnetizations.

If this measurement is performed for different lengths of the nonmagnetic channel, it is possible to extract the spin diffusion length of the nonmagnet and the spin polarization of the ferromagnet. Moreover, if another stripe is added in the middle as a spin absorber, its spin diffusion length can also be found.

The amazing versatility of these devices allows the study of the most disparate materials. An interesting application is, for example, using materials which present significant orbital Hall conductivities, such as vanadium [3], in order to study the generation of orbital currents.

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Superconducting Orbitronics: Controlling Quantum States with Electric and Strain Fields

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Abstract:

Orbitronics extends beyond conventional electronics and spintronics by harnessing the electron's orbital angular momentum and orbital textures as active degrees of freedom for device functionality. In this talk, I will discuss emerging concepts in superconducting orbitronics and illustrate how orbital degrees of freedom open new directions for quantum materials research.

After introducing orbital moments and orbital currents in the context of Cooper pairing, I will present an alternative route to unconventional superconducting states that does not rely on magnetic fields. Whereas conventional approaches use magnetism to manipulate spin singlet and triplet configurations, I will show how superconducting states with large orbital angular momentum can be engineered through lowering of the crystalline symmetry [1], as for instance by electrical and mechanical means [1].

This strategy enables a variety of novel phenomena, including the generation of non-Abrikosov vortices driven by electric or strain fields [2], colossal magnetoelectric responses mediated by the orbital Edelstein effect [3,4], and orbital antiphase pairing with π-Josephson coupling in multiorbital superconductors without breaking time-reversal symmetry. I will conclude by discussing candidate realistic material platforms [5], predicting how high-orbital moment Cooper pairs can be detected [5] and potential device implementations enabled by superconducting orbitronics.

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Intrinsic Magnetoelectric Bilinear Hall Effect from Layer-Orbital Quantum Geometry

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Abstract:

We propose a new mechanism for an intrinsic nonlinear magnetoelectric Hall response in multilayer van der Waals materials. The predicted Hall conductivity is bilinear in an out-of-plane gate field and a magnetic field, independent of scattering time, and can arise even in nonmagnetic systems with weak spin–orbit coupling. This response originates from an emergent "layer-orbital" quantum geometry whose sign reverses with the gate field, tracking the underlying layer polarization. Our comprehensive symmetry analysis reveals that a large class of polar and chiral nonmagnetic materials can permit this Hall response. Using the gated rhombohedral pentalayer graphene as a representative platform, we demonstrate sizable magnetoelectric Hall signals. These results reveal an intrinsic nonlinear transport channel that broadens the landscape of magnetoelectric phenomena and establishes "layer-orbital" quantum geometry as a key tool for novel transport-based material characterization.

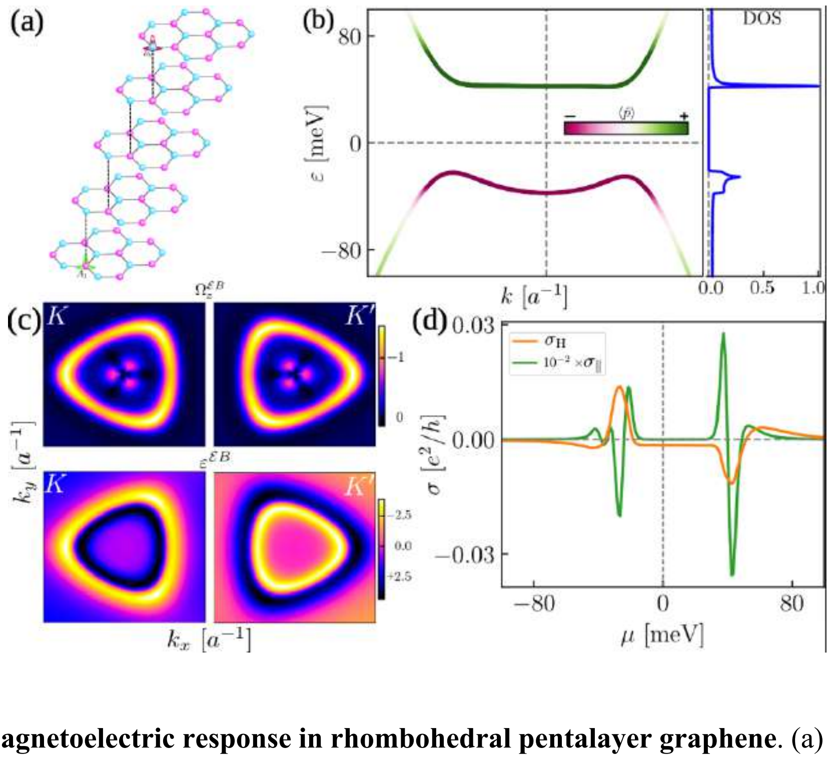

Figure: **Intrinsic magnetoelectric response in rhombohedral pentalayer graphene**. (a) Side view of atomic stacking registry in rhombohedral pentalayer graphene (R5G), the low-energy states are localized on opposite outer layers. (b) The layer composition-weighted low-energy band spectrum of R5G (K valley) with an interlayer potential of 80 meV and a valley polarization of 5 meV. The normalized density of states is plotted in the adjacent figure, illustrating the van-Hove singularity at energy ~ 42 meV due to the flat conduction band. (d) The upper (lower) panel shows the ***k***-space distribution of the field-corrected Berry curvature proportional to out-of-plane electric and magnetic field (energy correction) for the first conduction, for both the K and K' valleys. (d) The intrinsic Hall and extrinsic longitudinal magneto-electric conductivities as a function of chemical potential evaluated at temperature T = 15 K.

Probing Orbital Photogalvanic Effects in a Rashba $LaAlO_3/SrTiO_3$ 2DEG Using Structured Vortex Light

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Abstract:

Orbitronics extends spin-charge conversion concepts by exploiting the orbital angular momentum (OAM) as an additional degree of freedom of Bloch electrons. In systems with strong interfacial spin-orbit coupling, such as the two-dimensional electron gas (2DEG) formed at the $LaAlO_3/SrTiO_3$ interface [1], Rashba interactions enable light-helicity-dependent photogalvanic effects that have been investigated in the context of spin angular momentum (SAM) [2], [3]. On the other hand, the transfer of optical orbital angular momentum to electronic degrees of freedom has also been demonstrated in tungsten ditelluride (WTe_2), a Weyl semimetal, where structured light can generate surface current vortices reflecting the quantised OAM of the beam [4]. Beyond local orbital dynamics, macroscopic orbital-to-charge conversion should lead to the existence of an orbital photogalvanic effect in Rashba 2DEGs.

In this work, we investigate the photogalvanic response of the $LaAlO_3/SrTiO_3$ interface under structured light excitation carrying a well-defined OAM quantum number $l = \pm1$. OAM beams are generated using a q-plate in combination with a linear polariser and a quarter-wave plate (QWP), allowing the selection of the OAM sign independently of the polarisation state of the light. For each fixed OAM state, the beam is focused onto the LAO/STO surface while a second QWP is rotated, continuously tuning the incident polarisation state. The resulting photovoltage is measured between metallic contacts deposited on the sample, using homodyne detection with an optical chopper. This protocol mirrors previous helicity-dependent measurements performed without OAM, which successfully reproduced established behaviours of the SAM-induced inverse Rashba-Edelstein effect (IREE) [3].

For OAM-carrying beams, the photovoltage retains a dominant second-harmonic modulation with respect to the polarisation rotation angle, consistent with symmetry-allowed photogalvanic contributions, despite noticeable phase shifts of the harmonic components with respect to the reference signal used for homodyne detection. Although no amplitude-related trend distinguishing $l = +1$ from $l = -1$ emerges within the current experimental results, the voltage signals present intriguing phase variations.

These results suggest a subtle influence of the light-OAM sign on the charge conversion in the LAO/STO 2DEG. Further investigations are required in order to better isolate orbital- from spin-related IREE contributions, as additional momentum- and intensity-related effects may blur the clear distinctions between the two.

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Dynamical Orbital Pumping in Altermagnets

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Abstract:

Altermagnets [1] constitute a recently recognized class of magnetic materials in which symmetry breaking between sublattices and orbital degrees of freedom gives rise to unconventional magnetic responses. A direct consequence of this symmetry structure is that time-dependent magnetization generates a purely orbital pumping mechanism, $\partial_t \langle \mathbf{L} \rangle_\alpha = \chi^L_{\alpha\beta} (\hat{\mathbf{m}} \times \partial_t \hat{\mathbf{m}})_\beta$, mediated by spin-orbit coupling. We investigate this effect by driving the Néel order dynamics in a minimal tight-binding model defined on a square altermagnetic lattice [2] (Fig. 1(a)). The model is built upon an antiferromagnetic spin array coupled to an orbital crystal field (Fig. 1(b)) that simultaneously breaks rotational and sublattice exchange symmetries, giving rise to a spin-split band structure between the spin-up and spin-down components (Fig. 1(c)). Our results reveal a pronounced sublattice dependence of the orbital response, providing a clear microscopic distinction between antiferromagnetic and ferromagnetic configurations. Employing the Bastin–Smrčka–Středa formulation of the Kubo linear response theory [3,4], we compute the full orbital response tensor and demonstrate that orbital pumping naturally decomposes into two robust contributions, in direct analogy with the field-like and damping-like torque components familiar from spintronics. These findings establish orbital pumping as a distinctive dynamical signature of altermagnets and highlight its potential to enable next-generation orbitronic functionalities.

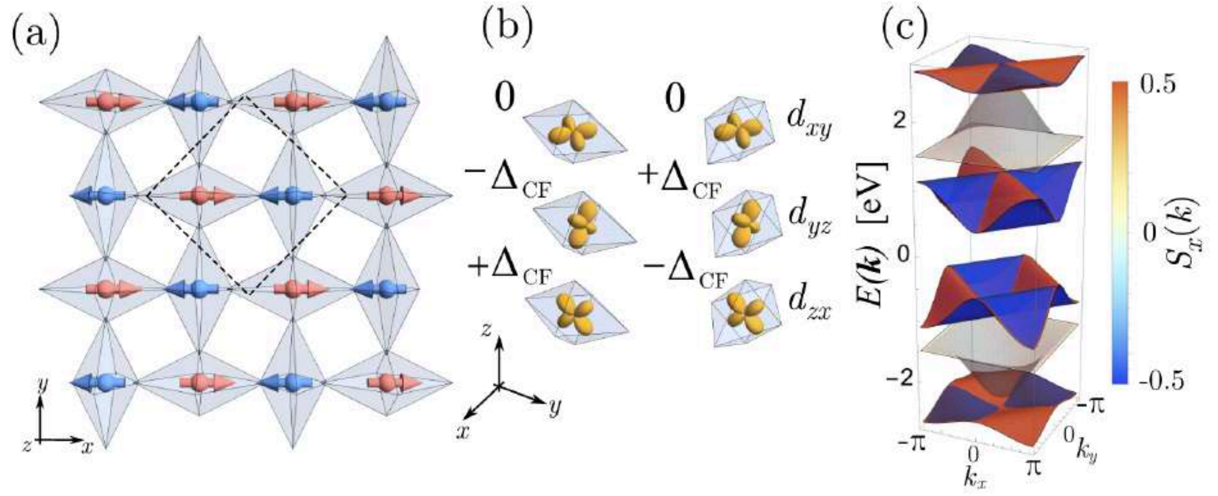

Figure 1: (a) Altermagnetic square lattice illustrating the sublattice arrangement and the antiferromagnetic spin alignment. (b) Staggered orbital crystal field breaking both rotational and sublattice exchange symmetries. (c) Resulting band structure along high-symmetry paths of the Brillouin zone, showing the momentum-dependent spin splitting between the spin-up and spin-down projections characteristic of altermagnetic order.

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Abnormal Magnetic Moment within the Relativistic Foldy-Wouthuysen Framework

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Abstract:

The notion of the magnetic moment of an electron is widely used in the analysis of multiple phenomena in spintronics, orbitronics and magnetism. In orbitronics, the focus shifts to the orbital angular momentum and its associated orbital magnetic moment, which couples directly to external magnetic fields and drives orbital transport phenomena such as the orbital Hall effect. A precise theoretical description of this magnetic moment, including relativistic corrections, is essential for understanding and controlling orbital currents in crystalline solids.

Starting from the Foldy–Wouthuysen (FW) transformed Dirac Hamiltonian [1], we derive the abnormal magnetic moment of the electron. The resulting effective Hamiltonian contains both nonrelativistic and relativistic corrections, including spin–orbit coupling and higher-order spin–orbit interaction terms. The magnetic moment is then obtained by evaluating the derivative of the Hamiltonian with respect to the external magnetic field. Alternatively, within an operator formalism, it can be computed by taking the commutator of the Hamiltonian with $-\partial/\partial\mathbf{B}$. However, since the FW transformation operator itself depends explicitly on the magnetic field $\mathbf{B}$, the magnetic-field derivative operator must also be consistently transformed under the same unitary transformation. The difference between the magnetic moment obtained directly from the FW-transformed Hamiltonian and that derived from the properly transformed magnetic-field derivative operator defines the abnormal magnetic moment of the electron [2, 3]. We find that this abnormal magnetic moment acquires distinct contributions from the orbital term, the spin term, and higher-order spin–orbit coupling corrections.

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Electric field switching of altermagnetic skyrmions

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Abstract: Magnetic skyrmions are localized magnetic structures that retain their shape and stability over time, thanks to their topological nature. Recent theoretical and experimental progress has laid the groundwork for understanding magnetic skyrmions characterized by negligible net magnetization and ultrafast dynamics. Notably, skyrmions emerging in materials with altermagnetism, a novel magnetic phase featuring lifted Kramers degeneracy—have remained unreported until now. In this study, we demonstrate that BiFeO3, a multiferroic renowned for its strong coupling between ferroelectricity and magnetism, can transit from a spin cycloid to a Néel-type skyrmion under antidamping spin-orbit torque at room temperature. Strikingly, the spin splitting within $BiFeO_3$ skyrmion can be reversed through the application of an electric field, revealed via the Circular photogalvanic effect. This quasiparticle, which possesses a neutral topological charge, holds substantial promise for diverse applications—most notably, enabling the development of unconventional computing systems with low power consumption and magnetoelectric controllability.

Intrinsic Gyrotropic Magnetic Current of Orbital Origin

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Abstract:

Recently, orbital mechanisms have emerged as a dominant source of a wide range of electronic responses in quantum materials, often surpassing spin contributions even in systems with finite spin–orbit coupling. In this work, we identify a previously unexplored orbital contribution to the gyrotropic magnetic current (GMC), thereby providing an intrinsically orbital route to magnetic field driven charge transport.

GMC refers to the generation of an electrical current by a time-dependent magnetic field $\boldsymbol{B}(t)$ in gyrotropic crystals. Its conventional origin is attributed to the magnetic field induced band energy corrections and the associated Fermi-surface oscillations [1]. More recently, a spin-driven magnetic displacement contribution was identified [2], revealing an intrinsic component to the effect. However, the corresponding orbital contribution has remained unexplored.

In this work, using a density-matrix formulation that incorporates both minimal coupling and spin–Zeeman interactions, we derive the electronic equations of motion in the presence of an oscillating magnetic field. Our formulation uncovers a previously unexplored orbital contribution to the wavepacket velocity arising from a magnetic field induced correction to the Berry connection. We characterize this correction through a band-geometric quantity, the orbital magnetic Berry connection polarizability (MBCP).

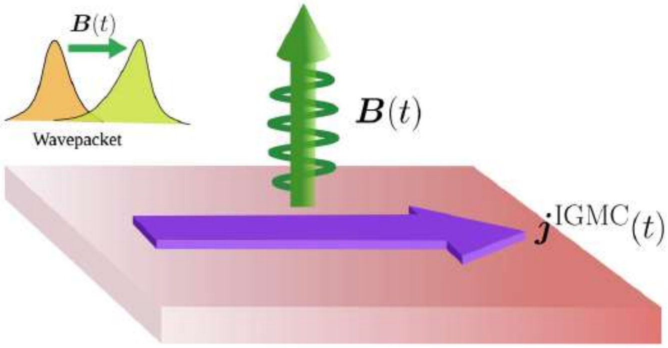

Figure 1: Schematic of the intrinsic gyrotropic magnetic current.

Physically, this orbital contribution arises from the time variation of the magnetic field induced charge polarization. In the low-frequency transport regime, this mechanism becomes purely intrinsic ($\boldsymbol{j}^{\text{IGMC}}(t)$). Unlike the conventional Fermi-surface contribution, this response is a Fermi-sea effect and remains finite in both metals and insulators. Importantly, it survives in inversion-broken systems that preserve combined parity–time reversal symmetry, where conventional gyrotropic responses vanishes.

As a concrete realization, we demonstrate the effect in the parity–time reversal ($\mathcal{PT}$) symmetric antiferromagnet CuMnAs. We find that the orbital contribution dominates over its spin counterpart by nearly an order of magnitude. Moreover, the intrinsic GMC is odd under time reversal and reverses sign upon Néel-vector reversal, establishing it as a direct and experimentally accessible probe of antiferromagnetic order.

Our results identify orbital magnetic displacement current as a novel mechanism of GMC and broaden the scope of magnetotransport studies in quantum materials.

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