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BOOK OF ABSTRACTS

SPIN & ORBIT

SPEAR Conference on Spin-Orbitronics
& 3rd Orbitronics Workshop

UPV/EHU Psychology Faculty
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SPEAR

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INDEX

Monday, 31 March

SESSION 1 – Chair: Fèlix Casanova

14:45 **ANGELA WITTMANN -** JGU Mainz, Mainz, Germany
Chirality-induced unidirectional spin-to-charge conversion

The observation of spin-dependent transmission of electrons through chiral molecules has led to the discovery of chiral-induced spin selectivity (CISS). The remarkably high efficiency of the spin polarizing effect has recently gained substantial interest due to the high potential for future sustainable hybrid chiral molecule magnetic applications. However, the fundamental mechanisms underlying the chiral-induced phenomena remain to be understood fully. In our recent work, we explore the impact of chirality on spin angular momentum in hybrid metal/ chiral molecule thin film heterostructures [1]. For this, we inject a pure spin current via spin pumping and investigate the spin-to-charge conversion at the hybrid chiral interface. Notably, we observe a chiral-induced unidirectionality in the conversion. Furthermore, angle-dependent measurements reveal that the spin selectivity is maximum when the spin angular momentum is aligned with the molecular chiral axis. Our findings validate the central role of spin angular momentum for the CISS effect, paving the path toward three-dimensional functionalization of hybrid molecule-metal devices via chirality.

[1] A. Moharana et al., Sci. Adv.11, eado4285 (2025).

15:15 **EOIN DOLAN** - CIC nanoGUNE, Donostia-San Sebastián, Spain
Measuring the anisotropy of the spin Hall effect in Nickel and Permalloy via electrical spin injection

The spin Hall effect in ferromagnets is of great interest in the field of spintronics, and while the effect has been quantified in many materials, the dependence of the spin Hall angle on the relative orientation of spin polarization and the magnetization is less well studied. Using a modified lateral spin valve geometry with a copper channel and permalloy spin injector we measure the dependence of the spin Hall effect on magnetisation in permalloy and nickel, using two distinct device geometries. We furthermore quantify the magnetisation dependent spin absorption efficiency, and therefore spin diffusion length, in these materials. By combining experimental data with 3D spin current simulations, we disentangle the contributions of the spin diffusion length and spin Hall angle to the measured voltage. Our results indicate a moderate anisotropy in both the spin diffusion length and spin Hall angle in permalloy, while nickel exhibits a nearly isotropic spin Hall angle and only a slight anisotropy in its spin diffusion length. These findings deepen our understanding of spin-charge interconversion in ferromagnetic materials, with potential applications in spintronic device optimization through magnetisation-dependent spin Hall effects.

15:30 **LUIS E. HUESO** - CIC nanoGUNE, Donostia-San Sebastián, Spain
Spintronics with twisted structures

2D materials are an exciting new material family in which the proximity effect is especially important and opens ways to transfer useful spintronic properties from one 2D material into another. For instance, transition metal dichalcogenides (TMD) can be used to enhance the spin-orbit coupling of graphene. The spin-orbit proximity in such graphene/TMD van der Waals heterostructures leads to spin-charge interconversion of out-of-plane spins due to spin Hall effect, first observed experimentally by using MoS_2 as the TMD [1], of in-plane spins perpendicular to the charge current due to the Rashba-Edelstein effect (REE), first observed by using WS_2 as the TMD [2], or to coherent spin precession with electrical control by using WSe_2 as the TMD [3].

Recent theoretical works have predicted the modulation of spin texture in graphene-based heterostructures by twist angle [4], although an experimental verification is missing. We demonstrate the tunability of the spin texture and associated REE with twist angle in WSe_2/graphene heterostructures by spin precession experiments [5]. For specific twist angles, we experimentally detect a spin component radial with the electron's momentum (an "unconventional" REE), in addition to the standard orthogonal component (conventional REE) and show that the helicity of the spin texture can be reversed by angle twisting, paving the way for the development of novel spin-twistronic devices.

[1] C.K. Safeer et al., Nano Lett. 19, 1074 (2019).
[2] T.S. Ghiasi et al., Nano Lett. 19, 5959 (2019); L.A. Benitez et al., Nat. Mater. 19, 170 (2020).
[3] J. Ingla-Aynés et al., PRL 127, 047202 (2021).
[4] S. Lee et al., PRB 106, 165420 (2022); K. Zollner et al., PRB 108, 235166 (2023).
[5] H. Yang et al., Nat. Mater. 23, 1502 (2024).

16:00 **SERGIO LEIVA** - Martin Luther Universität Halle-Wittenberg, Halle (Saale), Germany
Orbital Edelstein contribution to the spin-charge conversion in Germanium Telluride

The Edelstein effect (EE) is a promising mechanism for generating spin and orbital polarization from charge currents in systems without inversion symmetry. In ferroelectric materials, such as Germanium Telluride (GeTe), the combination of bulk Rashba splitting and voltage-controlled ferroelectric polarization provides a pathway for reversible spin-charge interconversion [1, 2].

In this work, we investigate current-induced spin and orbital magnetization in bulk GeTe using Wannier-based tight-binding models derived from DFT calculations and semiclassical Boltzmann theory. Employing the modern theory of orbital magnetization (MTOM), we demonstrate that the orbital Edelstein effect (OEE) entirely dominates its spin counterpart (SEE). This difference is visualized through the spin and orbital textures at the Fermi surfaces, where the orbital moment surpasses the spin moment by one order of magnitude. Moreover, the OEE remains largely unaffected when we suppress the spin-orbit coupling, highlighting its distinct physical origin compared to the SEE.

[1] D. Di Sante et al., Adv. Mater. 25, 509 (2012).
[2] C. Rinaldi et al., Nano Lett. 18, 2751 (2018).

16:15 **MAYANK SHARMA**- CIC nanoGUNE, Donostia-San Sebastián, Spain
Gate-tunable Exchange Bias and Voltage-controlled Magnetization Switching in a van der Waals Ferromagnet

The discovery of van der Waals magnets has established a new domain in the field of magnetism, opening novel pathways for the electrical control of magnetic properties. In this context, Fe_3GeTe_2 (FGT) emerges as an exemplary candidate owing to its intrinsic metallic properties, which facilitate the interplay of both charge and spin degrees of freedom. Here, we demonstrate the bidirectional voltage control of exchange bias (EB) effect in a perpendicularly magnetized an all-van der Waals FGT/O-FGT/hBN heterostructure. The antiferromagnetic O-FGT layer was formed by naturally oxidizing the FGT surface. The observed EB magnitude reaches 1.4 kOe with a blocking temperature (150 K) reaching close to the Curie temperature of FGT. Both the exchange field and the blocking temperature values are among the highest in the context of layered materials. The EB modulation exhibits a linear dependence on the gate voltage and its polarity, observable in both positive and negative field cooling (FC) experiments. Additionally, we demonstrate gate voltage-controlled magnetization switching, highlighting the potential of FGT-based heterostructures in advanced spintronic devices. Our findings display a methodology to modulate the magnetism of van der Waals magnets offering new avenues for the development of high-performance magnetic devices.

SESSION 2 – Chair: Gabriel Puebla-Hellmann

17:00 **JOHANNA FISCHER** - Spintec-CEA, Grenoble, France
Skyrmions in systems with weak Dzyaloshinskii-Moriya interaction

In ferromagnetic thin films, the domain structure is governed by the interplay between exchange, anisotropy (magnetocrystalline and interface contributions), dipolar and Zeeman interaction. Among these contributions, the antisymmetric exchange term, the Dzyaloshinskii-Moriya interaction (DMI), plays an essential role in inducing a uniform spin rotation direction within the domain walls [1].

In thin films with perpendicular magnetic anisotropy, these homochiral domain walls can enclose small circular domains, leading to the formation of skyrmions [2]. Under an applied current, driven by the spin-orbit torques, skyrmions move in a direction determined by the sign and amplitude of the DMI coefficient D [3]. In a system with low DMI, even slight variations in parameters such as film thickness or oxidation state can induce a DMI sign change and lead to the inversion of skyrmion chirality, and thus reversing the direction of skyrmion motion [4]. Our study focuses on heavy metal/ferromagnet/metal oxide systems [5] and proposes static and dynamic methods for controlling DMI to tune the skyrmions properties, namely size, helicity and current-driven trajectory. Dynamic control is achieved by applying a gate voltage, which triggers oxygen migration and modifies the interfacial magnetic properties [6]. Using hard x-ray photoelectron spectroscopy, we confirm that electric field gating progressively alters the oxidation state of the ferromagnet/metal oxide interface in a capacitor-type device. By analyzing the composition of the ferromagnetic layer beneath the dielectric layer, we demonstrate that changes in perpendicular magnetic anisotropy are indeed due to the migration of oxygen ions [7]. By combining experimental data with ab-initio calculations, we elucidate the mechanisms responsible for DMI sign changes caused by variations in ferromagnet thickness and oxidation state [8]. Micromagnetic simulations further reveal that this chirality control mechanism is scalable to nanometric skyrmions [6]. These findings offer valuable insights into the origins of interfacial DMI and highlight the potential for locally and dynamically reversing domain wall and skyrmion chirality. Such a capability introduces a novel degree of freedom for manipulating individual skyrmions. Finally, we show that this highly sensitive material system holds great promise for emerging applications, such as skyrmionic magnetic field sensors.

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[2] A. Fert et al., Nat. Rev. Mat., 46, 17031 (2017).
[3] A. Thiaville et al., Europhys. Lett., 100, 57002 (2012) ; S. Emori et al., Nat. Mater. 12, 611 (2013).
[4] T. Srivastava et al., Phys. Rev. Applied, 19, 024064 (2023).
[5] R. Kumar et al., Phys. Rev. Appl. 19, 024064 (2023).
[6] C.E. Fillion et al., Nat. Commun., 13, 1 (2022).
[7] C. Balan, et al. Phys. Rev. Appl. 21, 064023 (2024).
[8] C. Gueneau, et al., submitted.

17:30 **VISHESH SAXENA -** University of Hamburg, Hamburg, Germany

Visualizing strain, topology and chirality in an antiferromagnet at the atomic scale

Materials with antiferromagnetic order have recently emerged as promising candidates in spintronics based on their beneficial characteristics such as vanishing stray fields and ultra-fast dynamics [1]. At the same time more complex localized non-coplanar magnetic states as for instance skyrmions are in the focus of applications due to their intriguing properties such as the topological Hall effect [2]. Recently a conceptual shift has occurred to envision the use of such magnetic defects not only in one-dimensional racetrack devices but to exploit their unique properties in two-dimensional networks. Here we use local strain in a collinear antiferromagnet to induce non-coplanar domain wall junctions, which connect in a very specific way to form extended networks. We combine spin-polarized scanning tunneling microscopy with density functional theory to characterize the different building blocks of the network, and unravel the origin of the handedness of triple-junctions and the size of the arising topological orbital moments [3].

[1] T. Jungwirth et al. Nature Nanotech 11, 231–241 (2016)
[2] J. Spethmann, N. Nagaosa, Y. Tokura, Nature Nanotech 8, 899–911 (2013).
[3] Link to the arXiv paper for the above abstract: https://doi.org/10.48550/arXiv.2408.12580

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17:45 **ARTURO RODRÍGUEZ SOTA** - University of Hamburg, Hamburg, Germany
Cr/Nb(110): Structure, magnetism and superconductivity studied by STM

The interest in magnet superconductor hybrids (MSH) has recently increased due to their predicted topological superconductivity and possible applications [1,2]. In particular, antiferromagnetic (AFM) materials in proximity to superconductors have only very recently been experimentally characterized in the work by Bazarnik et al. [3]. In this publication, topological nodal-point superconductivity was reported. This topological phase is understood to arise from the pairing interaction of the superconducting substrate, the AFM order of the magnetic layer, and the spin-orbit coupling. The question whether this topological phase is a general feature of AFM-MSHs calls for additional experimental investigations.

We present here the study of the growth, magnetism, and superconductivity of Cr on Nb(110) using (spin-polarized) scanning tunnelling microscopy (STM) [4]. The monolayer of Cr grows pseudomorphically on Nb(110). Magnetically, the layer exhibits a c(2x2) AFM ordered. Scanning tunnelling spectroscopy below the critical temperature of Nb reveals a superconducting gap also in the Cr monolayer, however, there are also in-gap states appear due to the magnetic Cr atoms. We find an increased zero-bias conductance for Cr island edges along the [001] direction, whereas edges along the [1-11] direction do not show this. This observation suggests that also this AFM-MSH is in a topological nodal point superconducting phase with chiral low-energy edge modes.

[1] J. Bedow et al. Phys. Rev. B, 102, 180504 (2020).
[2] D. Steffensen et al. P. Phys. Rev. Res., 4, 013225 (2022).
[3] M. Bazarnik et al. Nat Commun, 14, 614 (2023).
[4] R. Wiesendanger, Rev. Mod. Phys., 81, 1495 (2009).

18:00 **KIRSTEN VON BERGMANN** - University of Hamburg, Hamburg, Germany
Complex magnetic order in domains and walls of (anti)ferromagnets studied with STM

Complex magnetic order arises due to the competition of different magnetic interactions. One prominent model-type example of a topological non-coplanar antiferromagnet is the triple-q state with 4 atoms in the magnetic unit cell and tetrahedron angles between all neighboring magnetic moments [1]. Whereas the net spin moment is zero, it exhibits topological orbital moments due to its spin texture [2]. Exotic magnetic order can not only arise as the ground state of a system, but also as localized defects in otherwise topologically trivial surroundings. One example is a magnetic skyrmion, but many other spin textures can arise and spin-polarized scanning tunneling microscopy (SP-STM) is well suited to investigate complex magnetic order down to the atomic scale [3]. In this contribution, different topological spin textures in ultra-thin films that represent the magnetic ground state [1,2,4,5] or occur at domain walls [6-8] will be discussed.

[1] J. Spethmann et al., Phys. Rev. Lett. 124, 227203 (2020).
[2] F. Nickel et al, Phys. Rev. B 108, L180411 (2023).
[3] K. von Bergmann et al., J. Phys.: Cond. Mat. 26, 394002 (2014).
[4] M. Gutzeit et al., Nature Commun. 13, 5764 (2022).
[5] F. Nickel et al., arxiv:2405.18088.
[6] J. Spethmann et al., Nature Commun. 12, 3488 (2021).
[7] V. Saxena et al., arXiv:2408.12580.
[8] R. Brüning et al., arXiv:2411.04009.

Tuesday, 1 April

SESSION 3 – Chair: Luis Hueso

9:00 **CAN O. AVCI -** ICMAB-CSIC, Barcelona, Spain
Tunable spin and orbital torques in Cu-based magnetic heterostructures

Current-induced torques originating from earth-abundant 3d elements offer a promising avenue for low-cost and sustainable spintronic memory and logic applications [1]. Recently, orbital currents -transverse orbital angular momentum flow in response to an electric field- have been in the spotlight since they allow current-induced torque generation from 3d transition metals [2-4]. In this work, we report a comprehensive study of the current-induced spin and orbital torques in Cu-based magnetic heterostructures. We show that high torque efficiencies can be achieved in engineered $Ni_{80}Fe_{20}$/Cu bilayers where Cu is naturally oxidized, exceeding the ones found in the archetypical Co/Pt. Furthermore, we demonstrate sign and amplitude control of the damping-like torque by manipulating the oxidation state of Cu via solid-state gating, as shown in Fig.1. Our findings [5] provide insights into the interplay between charge, spin, and orbital transport in Cu-based heterostructures and open the door to the development of gate-tunable spin-orbitronic devices.

[1] J. Kim, and Y. Otani, J. Magn. Magn. Mater., 563, 169974 (2022).
[2] H. An et al., Nat. Commun., 7, 13069 (2016).
[3] T. G. Rappoport, Nature, 619, 38-39 (2023).
[4] D. Go, et al., Europhys. Lett.,135(3) (2021).
[5] S. Damerio, and C. O. Avci. Nano Lett. 2025 (accepted).

9:30 **MARCO HOFFMANN -** ETH Zürich, Zürich, Switzerland
Real-time observation of VCMA-assisted magnetization switching

Voltage control of magnetic anisotropy (VCMA) [1,2] provides interesting options for low-power magnetization switching as required for magnetic random-access memories (MRAM). Specifically, VCMA allows for the reduction of magnetic fields and spin-torques, thus saving energy during the switching process. Although it is well known that VCMA can be the main driver of switching via precession or relaxation of the magnetization in the presence of magnetic fields [3], its effect is often considered to be instantaneous. However, the response of the magnetization does not need to be equally fast, and various factors can contribute to a delayed dynamics. Understanding and controlling these delays is crucial to achieve reliable and fast VCMA-assisted switching in technological applications. Here, we present real-time data of VCMA-assisted switching of magnetic tunnel junctions via relaxation in a magnetic field. In critical conditions, the reversal starts by the end of the applied voltage pulse and is completed by the applied magnetic field only after pulse termination. We show quantitatively how magnetic fields closer to the coercivity or larger voltage pulse amplitudes reduce this delay time. Micromagnetic simulations incorporating the finite charging times of the tunnel junction and the granularity of the magnetic film reproduce the experimental switching traces. Our quantitative analysis of the switching is of interest for the exploitation of the VCMA effect, e.g., for the design of hybrid MRAM or to control topologically protected magnetic textures for information storage [4].

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[3] Wang et al., Nat. Mat. 11, 64 (2012).
[4] Chen et al., Nat. 627, 522 (2024).

9:45 **KULDEEP RAY** - Spintec-CEA, Grenoble, France
Development of SOT-MRAM technology for functional devices

With the growing applications of artificial intelligence and high-performance computing, the need for low-power memory technologies has grown significantly. Recent developments in transistor scaling have significantly increased the static power consumption of volatile memories. The use of non-volatile memories closer to the central processing unit (CPU) can improve energy efficiency and reduce static power consumption [1]. Magnetic random-access memory (MRAM) is one of the leading potential candidates to introduce non-volatility closer to CPU. The magnetic tunnel junction (MTJ), with two magnetic layers (one fixed reference layer and a free layer) sandwiching an oxide barrier, is the core of MRAM. The free layer can be switched by current-induced torques in latest MRAM generations resulting in change of conductance due to parallel and antiparallel orientations [2]. Spin-transfer torque MRAM (STT-MRAM), a two-terminal device, uses spin-polarized current through the MTJ for switching and is already in production. Spin-orbit torque MRAM (SOT-MRAM) uses an in-plane charge current to create an out-of-plane spin current originating from the spin Hall effect and the Rashba effect, which generates torques on the free layer for sub-ns switching. SOT-MRAM is under active research and development, and several challenges need to be addressed before its commercialization [2].

In this work, we tackle three main challenges: the loss of switching determinism, high switching current and energy, and the need for an external magnetic field for deterministic switching [2]. (i) A peculiar decrease in switching probability at high currents in intrinsically stochastic SOT-MRAM devices causes loss of determinism in functional devices [3]. We present a comprehensive study of this backswitching phenomena using experimental write error rate (WER) characterization and macrospin simulations. Based on our results, we experimentally demonstrate a solution to reduce backswitching. (ii) We tackle the challenge of reducing switching current by harnessing orbital torques [4]. We study different material compositions using second harmonic Hall measurements to characterize and understand the various origins of spin and orbital torques acting on the free layer. (iii) The combination of SOT and STT is very promising for overcoming the need for a magnetic field without significant development of materials or single cell design [2]. We present pulsing strategies for achieving low WER (10-5) using this combination.

[1] IEEE IRDS 2023: Beyond CMOS and Emerging Materials Integration.
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[3] Lee et al., Commun Phys 1, 2 (2018).
[4] Lee et al., Nat Commun.12, 6710 (2021).

10:00

HELENA REICHLOVÀ- Institute of Physics, Czech Academy of Sciences, Prague, Czechia

Spin transport in altermagnets

Ferromagnets remain the cornerstone of industrial spintronics applications. However, materials with compensated magnetic order offer several advantages, such as faster dynamics and a broader range of available materials. These benefits have driven significant research into antiferromagnetic spintronics [1], leading to many exciting discoveries. Despite this progress, antiferromagnets are typically not considered robust sources of coherent spin currents. A recently identified class of compensated magnets—altermagnets [2]—combines the advantages of antiferromagnets and ferromagnets, presenting significant potential for spintronics applications. In this talk, I will introduce the concept of altermagnetism and present some of the first experimental verifications of altermagnetic materials [3-6]. I will focus on electronic spin transport in various altermagnetic materials, driven by electric fields or thermal gradient [7]. In the final part, I will discuss the implications of altermagnetism for magnon-mediated spin currents.

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[3] R. D. Gonzalez Betancourt et al., Phys. Rev. Lett. 130, 036702 (2023).
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[5] H. Reichlova et al., Nat. Communications 15 (1), 4961 (2024).
[6] M. Leiviska et al. Phys. Rev. B 109 (22), 224430 (2024).
[7] A. Badura et al., arXiv:2403.12929

SESSION 4 – Chair: Johan Åkerman

11:00

CHRISTIAN BACK - TU Munich, Munich, Germany

Manipulation of the magnetic energy landsscape by spin currents

Spin currents, which represent the flow of electron spin instead of electric charge, are of significant technological interest due to their potential to enable novel functionalities and improve device efficiency in spintronics. Key advantages of spin currents include reduced energy dissipation, high operation speed, and superior scalability. In this work, we explore fundamental effects resulting from the application of spin currents. Specifically, we demonstrate that spin currents can effectively control the magneto-crystalline anisotropy and magnetization in both conventional materials and emerging magnetic 2D materials.

11:30 **SAROJ DASH** - Chalmers University of Technology, Gothenburg, Sweden

Spin and orbital induced magnetization dynamics in van der Waals magnets and heterostructures

Exploring spin, orbital and topological properties of two-dimensional (2D) materials represents a new platform for realizing novel quantum and spin-based phenomena and device applications. Furthermore, engineering 2D heterostructures by combining the best of different materials in one ultimate unit can offer a plethora of opportunities in spintronics. Furthermore, nontrivial topology in the electronic band structure of quantum materials also makes them potential candidates for emerging technologies. We showed that their unique band structure and lower crystal symmetries can provide an unconventional spin polarized current [1] and out-of-plane spin-orbit torque [2] needed for field-free magnetization switching. The out-of-plane spin Hall conductivity in such 2D quantum materials are estimated to be an order of magnitude higher than the conventional materials.

2D magnets are promising owing to their tunable magnetic properties with gating and doping, where the strength of magnetic interactions can be tuned according to the desired applications. We reported above room temperature van der Waals magnet-based spin-valve [3,4] and spin-orbit torque memory [5] devices using all-2D heterostructures. In the latter cases, we could demonstrate energy-efficient and field-free magnetization switching [5].

Furthermore, we utilized van der Waals magnets with co-existence of ferromagnetic and anti-ferromagnetic orders with intrinsic exchange bias in the system, giving rise to a canted magnetism [6]. Such canted magnetism helps in achieving field-free magnetization switching with conventional spin orbit materials such as Pt [6]. Furthermore, I will present some new findings on orbital torque-induced magnetization switching of van der Waals magnets. These findings open a new platform for realizing devices using van der Waals magnets and all-2D heterostructures.

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[3] B. Zhao et al., Advanced Materials, 2209113 (2023).
[4] R. Ngaloy et al., ACS Nano 2024, 18, 7, 5240 (2024).
[5] B. Zhao et al., arXiv:2308.13408
[6] L. Pandey et al., arXiv:2408.13095

12:00 **NIKLAS KERCHER** - ETH Zürich, Zürich, Switzerland

Unconventional Spin-Orbit Torques in a Fe_3GeTe_2-WTe_2 Heterostructure

Current-induced spin-orbit torques (SOTs) enable efficient electrical control of magnetization. Conventionally, achieving deterministic switching of magnets with out-of-plane anisotropy requires a symmetry-breaking in-plane magnetic field [1]. However, in materials with both structural symmetry-breaking and strong spin-orbit coupling, additional spin current components with out-of-plane polarization can arise, allowing for field-free deterministic switching [2,3]. In this context, van der Waals materials have become an essential platform to study unconventional

SOTs. By combining exfoliated 2D magnets with low-symmetry spin source materials, devices with high crystal quality and atomically sharp interfaces can be fabricated [3]. In this contribution, I will present results from harmonic measurements on a Fe3GeTe2(6nm)/WTe2(4 nm) heterostructure, performed in a cryogenic magneto-optical Kerr effect setup. To extract the SOTs, we extended a technique introduced by Montazeri et al. [4], enabling the additional quantification of torque contributions from the out-of-plane spins predicted for this system. Besides the harmonic measurements, we observed further evidence of unconventional torques, including direct current-induced shifts of hysteresis loops and deterministic current-induced magnetization switching without the need for an additional in-plane symmetry-breaking field. By modelling the harmonic measurements with a macro spin framework that includes both conventional y-spins and unconventional z-spins, we successfully reproduced our experimental signals and extracted the ratio of y- to z-spins which is approximately 0.3. These findings provide critical insights into the field-free switching facilitated by unconventional SOTs, as well as the dynamic behaviour of 2D magnetic systems.

[1] A. Manchon et al., Rev. Mod. Phys., 91, 3, 035004 (2019).
[2] A. Roy et al., Phys. Rev. Mater.,6, 4, 045004 (2022).
[3] Y. Liu and Q. Shao,ACS Nano., 14, 8, 9389 – 9407 (2020).
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12:15 **SERGIO VALENZUELA** - Catalan Institute of Nanotechnology, Bellaterra, Spain
Anisotropic spin dynamics and tunable spin-orbit fields in proximitized graphene

Proximity effects in van der Waals heterostructures provide a powerful means to engineer spin-orbit coupling (SOC) in graphene, leading to anisotropic spin relaxation phenomena. In this talk, I will discuss recent progress in understanding the spin dynamics of graphene interfaced with transition metal dichalcogenides (TMDCs), including 2H-TMDCs such as WS_2 and MoS_2, as well as pentagonal $PdSe_2$.

In bilayer heterostructures of graphene and 2H-TMDCs, we observe pronounced spin-lifetime anisotropy, where out-of-plane spin lifetimes exceed in-plane values by over an order of magnitude. This behaviour stems from the imprint of strong spin-valley coupling, demonstrating how SOC in the 2H-TMDC layers profoundly influences spin relaxation in graphene.

By contrast, $PdSe_2$ induces a unique directional dependence in in-plane spin lifetimes due to its anisotropic crystal structure, breaking the symmetry typically observed in heterostructures with 2H-TMDCs. This anisotropy enables a 10-fold modulation of in-plane spin lifetimes and reveals the emergence of a persistent in-plane spin texture component that governs spin dynamics.

These results, robust even at room temperature, underscore the rich spin relaxation phenomena in proximitized graphene and the potential for tailoring spin-orbit fields in two-dimensional materials.

SESSION 5 – Chair: J. Carlos Rojas-Sánchez

14:30 **GABRIEL PUEBLA HELLMANN** - QZabre AG, Zürich, Switzerland

Scanning NV magnetometry: nanoscale magnetic imaging for spintronic devices

Spintronics and nanoscale magnetism are often strongly intertwined. While electron transport is comparatively accessible, quantitative information about the magnetic properties is hard to obtain, especially at the device scale of often tens of nanometres. Scanning Nitrogen Vacancy Magnetometry is a recently developed technique that uses as single spin as an atomic size magnetic field sensor. By scanning in close proximity over the surface, quantitative maps of the magnetic stray field can be obtained with a resolution down to 25 nm or less.

This talk will give an introduction to the basic principles of the technique, it's strengths and boundaries. We will showcase several prominent use cases, such as extracting information from domain boundaries and imaging skyrmions. Moving beyond simple protocols, we will discuss the working principle of gradiometry, which uses the scanning probe motion to probe gradients with increased sensitivity and show examples of sub micro-Tesla stray field imaging.

Last, we will highlight some of the results obtained from the SPEAR project regarding minimal resolution as well as reconstruction of magnetization from the stray field.

15:00 **KAIQUAN FAN** - imec, Leuven, Belgium

Balancing key factors for selective operation in multi-pillar VG-SOT MRAM

Spin-orbit torque magnetic random-access memory (SOT-MRAM) has emerged as a promising candidate for next-generation non-volatile memory technologies, offering ultrafast writing speed and high endurance. However, the implementation of these devices still faces challenges including high switching current and limited integration density resulting from their 3-terminal configuration. Recently, the concept of voltage-gated SOT (VG-SOT) has been studied to address these challenges. Applying a gate voltage on top of magnetic tunnel junctions (MTJs) can effectively lower the required SOT switching current due to the voltage-controlled magnetic anisotropy (VCMA) effect. However, it also generates spin-transfer torque (STT) and Joule heating effects which affect device operation. Therefore, understanding and mitigating these effects are crucial for precise control of the SOT switching current, a key requirement for selective operation in multi-pillar SOT-MRAM devices. In this work, we examined VG-SOT MRAM devices with varying resistance-area (RA) products in MTJ devices to investigate the interplay among STT, VCMA, and Joule heating effects under the application of gate voltages. By performing global fittings on switching fields extracted from hysteresis loops, we translated the switching behavior into effective magnetic fields that quantify each effect under varying gate voltages. Our results display that three effects compete with each other, determined by the direction and amplitude of gate voltage. It also reveals that lower gate voltages are dominated by the VCMA effect, assisting a relatively linear modulation of the switching field. At higher voltages, however, STT and Joule heating become more pronounced, particularly in devices with RA lower than 100 $\Omega{\cdot}\mu m^2$, thereby deviating from linear behavior. Additionally, we explore the RA and MTJ size dependence of all effects. While STT and Joule heating effects decrease rapidly with increasing RA, the VCMA effect remains constant. In contrast, varying MTJ size exhibits a negligible effect on all effective fields which is consistent with our model. This suggests that optimizing RA is key to preserving near-linear gate-voltage control of the switching current which is crucial for the operation of multi-pillar designs aimed at high-density and low-power. As a proof of concept, we demonstrated the selective write operation in two-pillar SOT-MRAM on a shared SOT track by using gate voltage. Therefore, this study provides insight into the balance between STT, VCMA, and Joule heating effects in VG-SOT multi-pillar MRAM, offering strategies for optimizing switching efficiency and enabling high-density integration for high-performance MRAM applications.

15:15 **ZHEWEN XU** - QZabre AG, Zürich, Switzerland
Minimizing sensor-sample distances in scanning nitrogen-vacancy magnetometry

Scanning magnetometry with nitrogen-vacancy (NV) centers in diamond has led to significant advances in the sensitive imaging of magnetic systems. The spatial resolution of the technique, however, remains limited to tens to hundreds of nanometers, even for probes where NV centers are engineered within 10nm from the tip apex. Here, we present a correlated investigation of the crucial parameters that determine the spatial resolution: the mechanical and magnetic stand-off distances, as well as the sub-surface NV center depth in diamond. We study their contributions using mechanical approach curves, photoluminescence measurements, magnetometry scans, and nuclear magnetic resonance (NMR) spectroscopy of surface adsorbates. We first show that the stand-off distance is mainly limited by features on the surface of the diamond tip, hindering mechanical access. Next, we demonstrate that frequency-modulated atomic force microscopy (FM-AFM) feedback partially overcomes this issue, leading to closer and more consistent magnetic stand-off distances (26 – 87 nm) compared to the more common amplitude-modulated (AM-AFM) feedback (43 – 128 nm). FM operation thus permits improved magnetic imaging of sub-100-nm spin textures, shown for the spin cycloid in BiFeO3 and domain walls in a CoFeB synthetic antiferromagnet. Finally, by examining 1H and 19F NMR signals in soft contact with a polytetrafluoroethylene surface, we observe capillary bridge formation by molecular adsorbates and demonstrate a minimum NV-to- sample distance of 7.9 nm.

15:30 **BYONG-GUK PARK** - KAIST, Daejon, South Korea
Unconventional spin-orbit torques in magnetic trilayers

Spin-orbit torque (SOT), arising from spin currents induced by spin-orbit coupling, can manipulate the magnetization direction. Energy-efficient, commercially viable SOT technology requires field-free switching of perpendicular magnetization at low currents. In this regard, magnetic trilayers have garnered significant attention as they generate unconventional SOT with out-of-plane spin polarization, enabling effective field-free SOT switching of perpendicular magnetization. In this talk, we first present the reduction of field-free switching current by exploiting three spin polarization in magnetic trilayers, which is possible by engineering the magnetic easy axis of the bottom ferromagnet to deviate from the charge current direction. Then, we demonstrate stochastic SOT switching in magnetic trilayers by controlling the sign and magnitude of the unconventional SOT, which allows for the reliable generation of SOT-based probabilistic bits.

16:00 **JEAN ANNE INCORVIA -** University of Texas at Austin, Austin (TX), USA
Application-Tailored Neuromorphic Computing using Magnetic Domain Walls

Neuromorphic computing promises efficient computing for artificial intelligence using co-design from materials through devices, circuits, systems, and applications. We will present on our results using magnetic spin textures such as domain walls driven by spin orbit torque to function as stochastic artificial neurons that are noise-resilient [1], multi-weight synapses that have high cycling stability [2], and leaky, integrate, and fire neurons that can mimic higher-order neuronal functions [3-4]. We show the domain wall based neuron can operate with high reliability over many cycles and have spontaneous and tunable leaking due to shape anisotropy. We will show the developed devices are radiation tolerant for edge computing [5]. These results show the promise of an across-the-stack approach to AI for hardware-aware computing.

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[3] C. Cui et al., Nano Letter 25, 1 (2025).
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SESSION 6 – Chair: Kirsten von Bergmann

17:00 **NICOLAS REYREN -** Laboratoire Albert Fert, Paris, France
Skyrmions in multilayers with spin-orbit coupling: applications for artificial neural networks

Metallic multilayers are versatile structures allowing the controlled modulations of many parameters necessary to stabilize magnetic textures such as skyrmions. We studied in detail the Pt|Co-based multilayers, and in particular how the Dzyaloshinskii-Moriya interaction is localized at the first atomic layers next to the interface [1], and how it depends on a third element X in Pt|Co|X [2]. We also studied the role of the atomic structure (strain, oxidation, etc.) in Pt|Co|Al for the perpendicular anisotropy [3] and the spin-orbit torques [4]. Building on this experience, we designed multilayers in which we can precisely control the nucleation of magnetic skyrmions and detect them electrically using the anomalous Hall effect [5]. Seeking for applications, and realizing that the ultimate skyrmion nucleation energy is close to the one to free neurotransmitters from vesicles in the biological synapses, we designed a basic unit for an artificial neural network (ANN) based on skyrmions: the weighted sum. Indeed, in most of the ANN, the artificial neuron operation consists simply in a weighted sum followed by a non-linear activation function. We demonstrated that, using skyrmions, we could perform the weighted sum locally, using a single physical measurement [6], opening motivating perspective to reduce the concerning AI energy cost.This work is supported by the Horizon 2020 Framework Program of the European Commission under FET-Proactive Grant SKYTOP (no. 824123), by the European Research Council advanced grant GrenaDyn (no. 101020684), by the EU project SkyANN (no. 101135729) and from a France 2030 government grant managed by the French National Research Agency (grant no. ANR-22-EXSP-0002 PEPR SPIN CHIREX).

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[2] F. Ajejas et al. Phys. Rev. Mater. 6, L071401 (2022).
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17:30 **ISMAEL RIBEIRO** - Martin Luther University Halle-Wittenberg, Halle, Germany
From magnetic skyrmions to neuroscience: Emulating LIF neurons with skyrmion dynamics

Magnetic skyrmions are nanoscale magnetic whirls that are highly stable and can be moved by currents, making them promising candidates for neuromorphic computing devices. A key challenge in neuromorphic computing is designing power-efficient devices that emulate the dynamics of neurons, the fundamental building blocks of the brain. One approach focuses on replicating the leaky integrate-and-fire (LIF) model, one of the simplest and most widely used models for describing biological neurons. In this model, neurons act as RC circuits, integrating ionic currents and firing an action potential when the neuron's membrane potential, which corresponds to the capacitor's voltage, crosses a threshold due to ionic imbalances. In this talk, we demonstrate that skyrmions can accurately emulate the dynamics of LIF neurons. We propose two device concepts. In the first, we show that the equation of motion of a current-driven skyrmion in a quadratic energy landscape is mathematically equivalent to the differential equation describing an RC circuit and, consequently, a LIF neuron. The applied current acts as the input voltage, while the skyrmion's position corresponds to the capacitor's output voltage. This behavior is verified through micromagnetic simulations. Furthermore, we show the skyrmion's ability to replicate the low-pass filter behavior of RC circuits by suppressing high-frequency input signals. In the second concept, we explore more advanced neuronal dynamics by leveraging the unique behavior of skyrmions to go beyond the LIF model. Specifically, we demonstrate how skyrmions can emulate the refractory period, a critical feature of biological neurons, thereby paving the way for more biologically realistic neuromorphic devices.

17:45 **MAHA KHADEMI** - NanOsc, Gothenburg, Sweden
High Output Power and Giant Quality Factor for single Spin Hall Nano-Oscillators using SiC substrates

Spin Hall nano-oscillators (SHNOs) are emerging as a leading alternative for spintronic oscillators, particularly in unconventional computing applications. Despite their potential, their performance has been hampered by low output power, primarily due to limited anisotropic magnetoresistance. We tackle the issue by manipulating the thermal budget of SHNO systems using various substrates, facilitating the optimization of thicker ferromagnetic NiFe layers (up to 7 nm). Utilizing SiC substrates with superior thermal conductivity, we significantly reduce thermal jitter, leading to enhanced auto-oscillation signal stability. This advancement results in a marked increase in output power and a sharper signal linewidth. Specifically, we achieve an output power exceeding 33 pW and a quality factor (Q) greater than 80,000 from a single SHNO—representing nearly a 100-fold increase in power and a 10-fold improvement in Q compared to earlier designs. Additionally, our findings underscore the importance of electrical insulation in determining SHNO performance, as evidenced by their width-dependent behavior.

18:00 **JOHAN ÅKERMAN -** NanOsc, Gothenburg, Sweden

Ultra-large mutually synchronized networks of 10 nm spin Hall nano-oscillators

Mutually synchronized spin Hall nano-oscillators (SHNOs) [1] can be used for neuromorphic computing [2,3]. However, the number of mutually synchronized SHNOs remains limited to 50 in chains [4] and 64 in 2D arrays [2]. To synchronize larger arrays, one must increase the oscillator coupling strength, for example, by packing them more closely, which requires smaller SHNOs. Here, we present a detailed update on how we have shrunk the width of nano-constriction SHNOs down to 10 nm and used them in mutually synchronized SHNO arrays where the nano-oscillators are only 24 nm apart. We show that current shunting through the Si substrate becomes problematic at extreme miniaturization, resulting in poor scaling below 50 nm. We, therefore, investigate the use of different seed layers and find that an ultra-thin (3 nm) AlOx layer between the Si substrate and the W layer in W/CoFeB/MgO-based SHNOs provides a dramatic improvement. Using further optimization of the spin-orbit torque, replacing W with a W88Ta12 alloy [5], we demonstrate 10 nm SHNOs operating at threshold currents as low as 30 uA [6]. We finally fabricate very large SHNO arrays based on this optimized stack and find that we can synchronize thousands of SHNOs [7].

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[2] M. Zahedinejad et al., Nature Nanotechnology 15, 47 (2020).
[3] M. Zahedinejad et al., Nature Materials 21, 81 (2022).
[4] A. Kumar et al., Nano Letters 23, 6720 (2023).
[5] N. Behera et al., Phys. Rev. Appl. 18, 024017 (2022)
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Wednesday, 2 April

SESSION 7 – Chair: Michel Viret

9:00 **ALBERT FERT** - Paris Saclay University, Paris, France

Some results on orbital polarization induced by charge current, RF excitation, heat flow or light

We want to illustrate the different ways (listed below) for the production or detection of orbital accumulation and orbital current by a selection of our experimental (and theoretical) results

1. Production by conversion of charge current, as, for example, conversion by orbital textures and Edelstein effect at interfaces between metals as Co/Al or Ni/Al or interfaces with oxides as Cu/CuO_x [1-4]. The orbital detection can be achieved by torque [1, 3-4] or inverseconversion by Seebeck effect, IOHE or IOEE (cf poster by M. Yactayo and lecture by J-C. Rojas-Sanchez)
2. 2: Production by RF excitation of ferromagnetic (FMR) with detection by bulk or interfacial inverse conversion [5-6].
3. Production by light pulse on ferromagnets with inverse conversion by interfacial Edelstein and THZemission [7-8], see invited talk by Yong Xu.
4. Production by conversion of light-induced spin accumulation into orbit accumulation with example of conversion by Pt [9] (see also invited talk by Henri JAFFRES with other types of intercalation effects).
5. Open problem: explaining that efficient orbital productions seem to be found for some specific materials (as Ni) or specific interfaces (FM/Al, metal/oxide); whatever the mode of production (electrical current, heat, RF or light). Additional questions: Production in a single magnetic layer with asymmetric interfaces? Existence of quadratic orbital accumulation and current?

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[3] J. Kim et al., Phys. Rev. Mat., 7, L111401 (2023).
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[7] Y. Xu et al., Nat.Com. (2024)15:2043
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9:30 **PIETRO GAMBARDELLA** - ETH Zürich, Zürich, Switzerland

Conversion and damping of angular momentum in metallic bilayers with large orbital Rashba-Edelstein effect

Orbital currents generated by the orbital Hall effect (OHE) and orbital Rashba-Edelstein effect (OREE) in nonmagnetic conductors require conversion into spin currents in order to generate spin-orbital torques in magnetic layers. This conversion can occur within the nonmagnetic layer, at the interface, or inside the magnetic layer. Conversely, the spin currents generated by the dynamics of the magnetization inside a magnetic layer require conversion into orbital currents in order to be effectively damped by a nonmagnetic layer with weak spin-orbit coupling.

In this talk I will report on the generation of orbital torques in the RE-TM ferrimagnet Gd_yCo_{100-y} coupled to a partially oxidized CuO_x layer, which serves as the source of nonequilibrium orbital current induced by the OREE. The RE atoms in the magnetic layer enhance the orbital-to-spin conversion ratio by a factor five compared to Co, proportional to the spin-orbit coupling of the d-states of Gd. The sign of the orbital torque changes from positive in Co/CuO_x to negative in Gd_yCo_{100-y}/CuO_x due to the opposite spin-orbit coupling of Co and Gd. Furthermore, the orbital torque increases by one order of magnitude upon cooling the sample from 300 to 10 K, which is attributed to the increased conversion efficiency resulting from the magnetic ordering of the Gd and Co.

While CuO_x is an efficient source of orbital torque, measurements of the Gilbert damping in $CoFe/CuO_x$ indicate that it is an inefficient sink of the spin current generated by a precessing magnetization. This property, combined with the small orbital–to–spin current ratio generated by ferromagnetic resonance in CoFe, results in a negligible increase of damping of $CoFe/CuO_x$ bilayers, as opposed to CoFe/Pt bilayers.

Overall, these results indicate that the orbital torque can be significantly amplified and even changed in sign by tuning the orbital-spin conversion efficiency in metallic systems, without necessarily increasing magnetic damping.

10:00 **INGRID MERTIG** - Martin Luther University Halle-Wittemberg, Halle, Germany

Transversal transport coefficients and topological properties

Spintronics is an emerging field in which charge, spin and orbital moment of electrons are utilized for transport. Most of the spintronic effects—like giant and tunnel magnetoresistance—are based on spin-polarized currents which show up in magnetic materials; these are already widely used in information technology and in data storage devices. The next generation of spintronic effects is based onspin currents which occur in metals as well as in insulators, in particular in topologically nontrivial materials. The latest development is related to currents of the orbital moment. Spin and orbital currents are a response to an external stimulus—for example electric field or temperature gradient. The spin currents are always related to the spin-orbit interaction. An orbital current can be generated whenever an object has a translational and rotational degree of freedom. All effects offer the opportunity for future low energy consumption electronics.

The talk will present a unified picture, based on topological properties, of a whole zoo of transversal transport coefficients: the trio of Hall, Nernst, and quantum Hall effects, all in their conventional, anomalous, spin and orbital moment flavor. The formation of transversal charge, spin and orbital moment currents as response to longitudinal gradients is discussed. Microscopic insight into all phenomena is presented by means of a quantum mechanical analysis based on the Dirac equation in combination with a semi-classical description which can be very elegantly studied within the concept of Berry curvature.

SESSION 8 – Chair: Ingrid Mertig

11:30 **YONG XU** - Beihang University, Beijing, China
Terahertz Emission Drive by Orbital Currents

Orbitronics is based on the use of orbital currents as information carriers. In this talk, we demonstrate that orbital currents can also be generated by femtosecond light pulses on Ni. In multilayers associating Ni with oxides and nonmagnetic metals such as Cu, we detect the orbital currents by their conversion into charge currents and the resulting terahertz emission. In addition, the analysis of the time delays of the terahertz pulses leads to relevant information on the velocity and propagation of orbital carriers. Moreover, we report a more efficient light-induced generation of orbital current from a CoPt alloy, and the terahertz emission from CoPt/Cu/MgO is comparable to that of benchmark spintronic terahertz emitters. Our study provides strong evidence for the efficient orbital current generation in Ni and CoPt alloy, paving the way for efficient orbital terahertz emitters.

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[2] Xu, Y. et al., Nat Commun, 15 (1), 2043 (2024).

11:30 **YURIY MOKROUSOV** - Jülich Research Center, Jülich, Germany
Orbitronics with magnetic 2D materials

Orbitronics has recently emerged as a valid alternative to the field of spintronics, with the orbital degree of freedom serving as the main variable for transportation and magnetization manipulation [1]. Currently, the majority of envisioned applications in orbitronics are associated with the generation and utilization of the orbital Hall effect hosted by non-magnetic bulk materials. On the other hand, magnetic two-dimensional (2D) materials are steadily moving to the center of materials research owing to their outstanding properties and prospects in novel magnetic applications. In my talk, I will discuss the interplay of topological features in the electronic structure of 2D magnets with current-induced orbital magnetism and orbital Hall effect [2, 3]. Taking as an example a novel family of Eu- and Gd-based rare-earth dichalcogenides, I will demonstrate how the electronic structure engineering of p-d-f hybridization in two dimensions can give rise to prominent topological orbital response very susceptible to the details of crystal lattice design [4, 5]. Moreover, I will discuss the role of current-induced orbital magnetism in 2D dichalcogenides in mediating torques on the magnetization [6], finally introducing the effect of orbital pumping [7] in 2D magnetic materials.

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12:00 **KAZUYA ANDO -** Keio University, Minato, Japan
Orbital currents coupled with magnetization dynamics

Advances in spintronics have been driven by investigations into the interplay between spin currents and magnetization. In ferromagnetic/nonmagnetic bilayers, this interplay manifests through two fundamental phenomena: spin torque and spin pumping. While these phenomena have been extensively studied, the role of orbital currents—flows of orbital angular momentum—has remained largely unexplored until recently. This work focuses on the orbital counterparts of spin torque and spin pumping—orbital torque and orbital pumping. We demonstrate the generation of orbital torque via the orbital Hall effect in metallic bilayers and show that a key distinction of orbital torque is its long-range behavior, enabled by the longer propagation distances of orbital currents compared to the spin dephasing length in ferromagnets. Our results also indicate that orbital currents and orbital torque contribute even in prototypical spintronics systems based on heavy metals. Furthermore, we demonstrate the reciprocal effect of orbital torque—orbital pumping. This process generates orbital currents from dynamical magnetization, highlighting the critical role of orbital currents in angular momentum dynamics in solid-state devices.

12:30 **THIERRY VALET -** MPhysX OÜ, Tallin, Estonia
Quantum Kinetic Approach to Orbital Effects in Centrosymmetric Normal Metals

We demonstrate that for nonmagnetic centrosymmetric metals, in the vanishing spin-orbit coupling (SOC) limit, there is generically no semiclassical continuity equation connecting the electronic orbital angular momentum (OAM) density with the intrinsic orbital Hall effect (OHE) current in its usual definition. Beyond the OAM non conservation, this stems from its purely interband character in the absence of extended orbital degeneracy at the Fermi level. While this questions the interpretation of recent observations of orbital edge accumulation (OEA) in thin films of Cr and Ti [1-3] as evidence of intrinsic OHE, we propose an alternate mechanism for OEA generation, which does not sensitively depend on the SOC nor requires exceptional orbital band degeneracy. As recently predicted [4], spatial gradients in the intraband longitudinal response to an electric field, which are ubiquitous near conductor boundaries on the length scale of the electron mean free path [5, 6], are a local source of interband quantum coherence, which here translates into OEA. This new mechanism may allow to reconciliate the observations of OEA extending over several nanometers with the expected very short-range nature of OAM transport in weak SOC centrosymmetric normal metals, as found from first-principles calculations [7] and confirmed by our quantum kinetic approach. We also discuss some possible implications on current induced torques susceptible to act on the magnetization of neighboring magnetic layers.

This research is supported by the EIC Pathfinder OPEN grant 101129641 "OBELIX" and by a France 2030 government grant managed by the French National Research Agency (grant no. ANR-22-EXSP-0009 PEPR SPIN SPINTHEORY).

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SESSION 9 – Chair: Marcos Guimarães

14:30 **GYUNGMIN CHOI -** Sungkyunkwan University, Seoul, South Korea
Magneto-optical observation of electrically generated orbital polarization in pristine Cu and oxidized Cu

Understanding the electron orbital transport and in particular its difference from the spin transport is an important problem. We measure the longitudinal magneto-optical Kerr effect to probe the current-induced magnetic moment accumulation in Cu, a material with well-established spin transport. We find that both pristine and oxidized Cu films exhibit large Kerr signals. Their characteristic length scales are orders of magnitude shorter than the spin length scales, implying that the signals are due to the orbital angular momentum. The Kerr signals of pristine and oxidized films show different film thickness dependences, which indicate bulk and interfacial origins of orbital generation, respectively. We estimate that the orbital diffusivity of the pristine Cu films is two orders of magnitude smaller than the charge diffusivity, in clear contrast to spin diffusivity being comparable to charge diffusivity in many materials. This difference indicates orbital transport to be significantly different from spin transport.

15:00 **TATIANA RAPPOPORT -** Minho University, Minho, Portugal
Disorder-Induced Orbital Transport Effects in 2D Materials and Mesoscopic Devices

I will present recent insights into the impact of disorder on orbital transport phenomena, with a focus on the orbital Hall effect (OHE) and orbital relaxation mechanisms in two-dimensional (2D) materials. First I will provide an overview of extrinsic effects in the spin Hall effect (SHE), including skew scattering and side-jump mechanisms, to draw a parallel with the disorder-driven mechanisms influencing the OHE. This comparison offers a foundation for understanding how impurities and short-range defects can create or enhance transverse currents of orbital angular momentum through similar extrinsic processes in the OHE. The core of the presentation will discuss recent theoretical work on disorder-enhanced OHE, detailing how extrinsic contributions influence orbital transport in 2D systems, and how these effects can even dominate over intrinsic contributions in certain regimes [1]. In parallel, I will also present numerical work with mesoscopic devices, where disorder plays a crucial role in both enhancing the OHE and providing direct insights into orbital relaxation processes.

[1] A. Veneri, T.G. Rappoport, A. Ferreira, arXiv:2408.04492

15:30 **ANTONIO AZEVEDO** - Federal University of Pernambuco, Recife, Brazil
Spin-Orbitronics and Orbitronics: Anomalous Hall Effects, Orbital Currents, and Charge Conversion

We present a comprehensive exploration of spin-orbitronics and orbitronics through novel phenomena driven by spin and orbital currents in ferromagnetic, antiferromagnetic, and semiconducting systems. Using orbital pumping experiments, we investigate the interplay of spin-orbit coupling and orbital-charge conversion mechanisms. Our study of YIG/Pt/IrMn heterostructures reveals a remarkable sevenfold enhancement of the anomalous inverse orbital Hall effect (AIOHE) in an out-of-plane configuration, suggesting a tensorial expansion of the orbital Hall angle analogous to the spin Hall angle. This work establishes a new paradigm for spin-orbital current manipulation in antiferromagnets [1]. In Ge thin films, we uncover a strong negative inverse orbital Hall effect, where orbital-to-charge conversion dominates despite negligible spin-to-charge conversion, demonstrating Ge's potential as a unique orbitronic material. Additionally, our investigations of YIG/Pt/CuO_x structures highlight significant enhancement of spin-to-charge conversion due to the inverse orbital Rashba-Edelstein effect at the Pt/CuO_x interface. Conversely, studies of CuO_x layers on different heavy metals, such as W and Ti, elucidate material-dependent orbital-charge conversion. Together, these findings provide profound insights into the rich interplay between spin, orbital, and charge transport, opening new avenues for developing next-generation spin-orbitronic and orbitronic technologies.

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16:00 **JUAN CARLOS ROJAS-SÁNCHEZ** - Jean Larmour Institute, Nancy, France
Giant and anisotropic charge current production in double Rashba interface Fe/Gr/Pt

The Spin Hall effect (SHE) in 3D systems and the Edelstein effect (EE) in 2D systems for the interconversion of charge current into spin current due to spin-orbit coupling (SOC) play a crucial role in today's spin-orbitronics. A gain for such an interconversion has been shown in 2D systems dominated by the Inverse Edelstein effect, IEE, such as on α-Sn compared to 3D systems such as Pt [1]. In an initial control experiment by spin pumping voltage at ferromagnetic resonance condition (SPV-FMR), we show that the current production of the Fe/Gr magnetic Rashba interface almost offsets the inverse SHE of Ir at the FMR condition of Fe. Then, we report a giant and anisotropic gain combining 2D systems such as epitaxial graphene intercalated between 3D systems such as Fe and Pt [2]. We found a 34-fold gain in the double Rashba interface quantum system, Fe/Gr/Pt, to the reference, Fe/Pt. This is in sharp contrast when the ferromagnetic layer is Co where there is a reduction of the overall efficiency in Co/Gr/Pt [3]. Ad-hoc first-principles theoretical calculations account for this difference [2]. The figure of merit that accounts for the efficiency of charge current production due to the injected spin current is 4.8 nm, higher than the one for α-Sn, 2.1 nm, or the equivalent for Pt, 0.2 nm. Our results show a new record of efficiency at room temperature and it is a highly robust system (withstanding several lithography and baking steps) for new experiments and technological applications.Funding from EU-H2020-RISE project Ultra Thin Magneto Thermal Sensoring ULTIMATE-I grant ID 101007825, and ERC CoG project MAGNETALLIEN grant ID 101086807, among others [2], is gratefully acknowledged.

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SESSION 10 – Chair: Jagoda Sławińska

17:00 **TOBIAS KAMPFRATH** - Freie Universität Berlin, Berlin, Germany
Ultrafast spin-orbitronics with terahertz electromagnetic pulses

To take advantage of the electron spin and orbital angular momentum in future electronics, angular momentum needs to be transported and detected. To probe the initial elementary steps that lead to the formation of spin and orbital currents, we need to launch and measure transport on femtosecond time scales. Consequently, we apply optical femtosecond laser pulses to induce a transient spin [1] and orbital [2] accumulation in a ferromagnetic-metal layer FM. The resulting spin-orbital current is injected into an adjacent nonferromagnetic-metal layer NM and probed there by conversion into a charge current and detection of the concomitantly emitted terahertz electromagnetic pulse [2]. This approach provides insight into the transport of spin [3] and orbital currents [2] on their natural (femtosecond) time scale. Finally, one can implement a reciprocal experimental scheme and use intense terahertz electromagnetic pulses to drive electric currents and control magnetic order on ultrafast time scales through spin and orbital torque, for example, Néel spin-orbit torques [4].

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[3] Rouzegar et al., Nano Letters 24, 7852-7860 (2024).
[4] Behovits et al., Nature Communications 14, 6038 (2023).

17:30 **AURELIEN MANCHON** - Interdisciplinary Center of Nanoscience of Marseille, Marseille, France
Theory of orbital torque and orbital pumping

Recent progress in the physics of spin-charge interconversion mediated by spin-orbit coupling has shed new light on the orbital angular momentum degree of freedom. Indeed, while the orbital ordering driven by the crystal-field potential governs the interplay between crystal structure and electronic properties of strongly correlated materials such as Mott insulators, the possibility of transporting the orbital information in these materials has remained an open question so far. In the context of metallic spintronics though, it has been progressively realized that the orbital angular momentum can be generated out of equilibrium, transported, and detected, rather similarly to the spin angular momentum.

In this presentation, I intend to discuss the theoretical aspects of orbital transport, torque, and pumping. I will first present a quantum theory of orbital diffusion and uncover several mechanisms governing orbital torque and magnetoresistance phenomena, including orbital diffusivity, spin-orbit polarization, orbital swapping, and orbital mixing conductance [1]. These new concepts are crucial to the understanding of experimental results and can be computed from first principles. Then, I will discuss a phenomenological model of orbital diffusion, torque, and pumping, emphasizing the key differences with spin-orbit torque [2]. Finally, I will present first-principles calculation of orbital pumping in selected realistic bilayers [3].

[1] X. Ning et al., arXiv:2310.04763
[2] X. Ning et al., arXiv:2412.08340
[3] A. Pezo et al., arXiv:2411.13319

18:00 **HENRI JAFFRÈS** - Laboratoire Alberte Fert, Paris, France
Orbitronics, spin-orbit and orbital torques in 3d ferromagnet /Cu oxide systems

In the field of spintronics, the aim to enhance device performances by using pure spin currents via spin-orbit interactions (SOI) becomes a major topic. A clear benefice is an electrical control of the magnetization, e.g. for SOT-MRAM [1] and for spin-LED technology [2], constituting an energy-efficient alternative to magnetoelectronic devices. A better understanding of inherited fundamental concepts as spin and orbital charge conversion phenomena such as spin-Hall (SHE) or Rashba-Edelstein (REE) effects and reciprocals is then mandatory.

Very recently, the physics of orbital angular momentum (OAM) has been the focus of important breakthroughs. The framework of orbital torque [3] relies on the generation of polarized OAM, its transport over nanometric distance. Several different mechanisms may be at the origin of the OAM production such as the orbital hall effect, the orbital Rashba-Edelstein effect (OREE). Those have been shown to overcome their analog pure spin effects in some cases [4-5]. In order to exert a magnetic torque on a ferromagnet via exchange process, the orbital currents have to be converted into spin using SOI. The orbit-to-spin conversion may occur in the ferromagnetic (FM) itself during the torque process or into an intermediate non-magnetic layer (NM). In the case of light materials, the orbital torque offers comparable efficiencies than Pt, a reference SHE material. By combining light and heavy metal orbit-to-spin converters, a large enhancement of torques has been thus demonstrated in several material and geometry devices [4-6]. In my talk, I will present our main results obtained on various systems and more particularly on systems integrating Co 3d ferromagnet and oxidized Cu as orbital-current generator [6-8]. I will present second-harmonic f-2f measurements in different geometries showing torque enhancement by CuO_x [6] by varying both the Pt and Co thickness in Co|Pt|CuO_x as well as in Co|CuO_x. In the light of a recent literature, I will discuss the different possible origins of the torque enhancement observed.

[1] Gupta, R. et al., Nat Commun 16, 130 (2025).
[2] Dainone et al., Nature 627, 783–788 (2024).
[3] D. Go et al., Phys. Rev. Lett. 121, 086602 (2018).
[4] S. Ding et al., Phys. Rev. Lett. 125, 177201 (2020).
[5] G. Sala et al., Phys. Rev. Research 4, 033037 (2022).
[6] S. Krishnia et al., APL Mater. 12, 051105 (2024).
[7] J. Kim et al., Phys. Rev. B 103, L020407 (2020).
[8] J. Kim et al., Phys. Rev. Materials 7, L111401 (2023).

Thursday, 3 April

SESSION 11 – Chair: Aurelien Manchon

9:00 **KYUNG-JIN LEE** - KAIST, Daejon, South Korea
Magnetic octupole Hall effect in altermagnets

Altermagnets have recently attracted significant attention due to their unique combination of momentum-dependent spin splitting and antiferromagnetic ordering [1]. The order parameters in altermagnets are the antiferroic Néel order and the ferroic magnetic octupole order [2, 3], with the latter driving the momentum-dependent spin splitting. Since the order parameter dictates all responses, magnetic octupole currents are inherently present in altermagnets. In this talk, we will theoretically explore the magnetic octupole Hall effect in altermagnets, with a focus on the crucial role of orbital transport. Moreover, we will discuss multipole exchange interactions.

[1] L. Šmejkal, J. Sinova, and T. Jungwirth, Phys. Rev. X 12, 040501 (2022).
[2] S. Bhowal and N.A. Spaldin, Phys. Rev. X 14, 011019 (2024).
[3] P.A. McClarty and J. G. Rau, Phys. Rev. Lett. 132, 176702 (2024).

9:30 **JAGODA SŁAWIŃSKA** - University of Groningen, Groningen, Netherlands
Unconventional charge-to-spin conversion in materials with low crystal symmetry

Materials exhibiting spin-orbit-related phenomena hold great promise for advancing memory and computing technologies beyond the limits of the von Neumann architecture. One interesting approach toward developing all-electric, energy-efficient electronic devices is the symmetry-based design of spintronic materials. In this talk, I will explore the properties of several recently (re-)discovered materials that reveal intriguing spin-orbit-related phenomena, as well as different methods for controlling spins. In particular, the use of symmetries in material design has proven to be a powerful approach for manipulating spins and enabling unconventional configurations of charge-to-spin conversion, helping in the generation of highly efficient spin-orbit torques. Additionally, I will highlight the potential of chiral crystals that exhibit collinear charge-to-spin conversion, akin to chirality-induced spin selectivity observed in molecules. Examples include elemental tellurium, Weyl semimetal $TaSi_2$, and B20 compound OsSi, which demonstrate efficient charge-to-spin conversion and show persistent spin textures contributing to extended spin lifetimes. In summary, materials with strong spin-orbit coupling and low crystal symmetry—particularly chiral crystals—offer promising solutions to one of the most critical challenges of spintronics: achieving high charge-to-spin conversion efficiency while maintaining long spin lifetimes

[1] A. Roy, M. Guimarães, J. Sławińska, Physical Review Materials 6, 045004 (2022).
[2] A. Roy, et al., npj Computational Materials 8 (1), 243 (2022).
[3] K. Tenzin, et al., Physical Review B 107, 165140 (2023).
[4] K. Tenzin, et al., Physical Review B 108, 245203 (2023).
[5] J. Sławińska, Applied Physics Letters 123, 240504 (2023).
[5] E. Barts, K. Tenzin, J. Sławińska, arXiv:2407.01187 (2024).

10:00 **ROLAND KAWAKAMI** - Ohio State University, Columbus (OH), USA
Spin and Orbital Currents in Magnetic Heterostructures

The flow of angular momentum as spin currents and orbital currents form the basis of spintronics and orbitronics. Analogous to the spin Hall effect (SHE) where a charge current produces a transverse spin current, an orbital Hall effect (OHE) can generate a transverse orbital current. Together, these can be utilized for current-induced magnetization switching for energy-efficient magnetic memories. In this talk, I will discuss our efforts involving van der Waals materials and transition metal multilayers for spintronics and orbitronics. Using molecular beam epitaxy, we have synthesized a variety of magnetic heterostructures including 2D magnet Fe_3GeTe_2 on topological insulator Bi_2Te_3 [1], Ni/Cr, and Ni/Pt [2]. Magneto-optical probes are utilized to quantify the spin and orbital torques that are imparted on the magnetic layers [2,3]. Furthermore, magneto-optics have been used to directly detect the accumulation of orbital magnetic moments that are generated by the OHE [4].

[1] W. Zhou et al., Phys. Rev. Materials 7, 104004 (2023).
[2] I. Lyalin, R. K. Kawakami, Phys. Rev. B 110, 104418 (2024).
[3] I. Lyalin et al., Nano Letters 21, 6975 (2021).
[4] I. Lyalin et al., Phys. Rev. Lett. 131, 156702 (2023).

SESSION 12 – Chair: Pietro Gambardella

11:00 **MATHIAS KLÄUI** - Johannes Gutenberg University Mainz, Mainz, Germany
Orbitronics: Orbital Torques, Orbital Magnetoresistance and Non-Reciprocity

Experimentally, orbital currents for efficient manipulation of magnetization have only recently started to be explored. In order to generate orbital currents, materials with orbital Hall effects can be used that can be light metals and thus cheap, abundant and environmentally friendly. In our work we explore orbital torques, orbital magnetoresistance and transport effects. We start with spin orbit torques generated in TmIG/Pt/(Cu(O)x) heterostructures that are enhanced by a factor up to 16 if the CuOx is added on top of the Pt compared to the conventional TmIG/Pt stack [1]. We found that the Orbital Rashba-Edelstein Magnetoresistance can be observed in Py/Cu(O)x, which is an orbital magnetoresistance effect related to the conventional spin Hall magnetoresistance

[2]. In particular, in this work, the length scale of the orbital to spin current conversion in Py could be identified as a key step to harnessing orbital currents efficiently even without a heavy metal based orbital to spin conversion layer [3,4]. For MRAM devices, we show that using orbital torques, reduced switching current densities can be realized, which is a key step to functional devices [5]. Finally, we observe that in non-local spin valve devices the transport using Ru-based OHE and iOHE is non-reciprocal [6].

[1] S. Ding et al., Phys. Rev. Lett. 125, 177201 (2020).
[2] S. Ding et al., Phys. Rev. Lett. 128, 067201 (2022).
[3] D. Go et al., Perspectives Review in EPL 135, 37001 (2021).
[4] A. Bose et al., Phys. Rev. B 107, 134423 (2023).
[5] R. Gupta et al., Nature Commun. 16, 130 (2025).
[6] O. Ledesma et al., Nano Lett. (in press 2025).

11:30 **PETER OPPENEER** - Uppsala University, Uppsala, Sweden

First-principles theory of magneto-optical detection of electrically generated orbital angular momentum

First-principles calculations have recently predicted that an electrical current can generate large orbital angular moments, even in materials with very small spin-orbit coupling, opening up for novel orbital-based device technology [1]. Electrically generated orbital moments can manifest themselves in two ways, as a large orbital conductivity due to the orbital Hall effect (OHE) [2] or as a local orbital moment generated in inversion-symmetry-broken systems by the orbital Rashba-Edelstein effect (OREE) [3]. So far however the orbital moments due to the OHE and OREE have been difficult to investigate as it is hard to distinguish them from their relativistic spin counterparts, because spin and orbital phenomena obey the very same symmetry properties. We investigate here theoretically the signatures of orbital moment accumulation in light centrosymmetric metals as expected for magneto-optical Kerr effect (MOKE) measurements. We show that the predicted orbital response is quite different from the spin response, which offers possibilities to distinguish spin and orbital responses using MOKE. While orbital accumulation due to the OHE has been observed in recent MOKE experiments on Ti and Cr thin films [4,5], the local OREE has escaped direct observation. We therefore investigate computationally signatures of the OREE in magneto-optical responses of a metallic ferromagnet/nonmagnetic interface and analyze possible ways to detect the local orbital polarization induced by the OREE at the interface.

[1] D. Go et al., EPL 135, 37001 (2021).
[2] D. Go et al., Phys. Rev. Lett. 121, 086602 (2018).
[3] L. Salemi et al., Nat. Commun. 10, 5381 (2019).
[4] Y.-G. Choi, et al., Nature 619, 52 (2023).
[5] I. Lyalin, et al., Phys. Rev. Lett. 131, 156702 (2023).

12:00 **SEBASTIEN COUET -** Vertical Compute, Leuven, Belgium
Bringing SOT-MRAM from lab to fab

SOT-MRAM technology is currently one of the most promising candidates to supplement on-chip SRAM by providing larger capacity high speed caches. In this presentation, I will review the progress made in the recent years to transition Spin Orbit Torque from fundamental research to potential industrial applications.

12:30 **PAUL HANEY -** National Institute of Standards and Technology, Gaithersburg (MD), USA
Current-induced orbital accumulation and circular dichroism

Current-induced transport of orbital angular momentum provides a new and powerful tool for the electrical control of magnetic materials. However, the quantitative measurement of orbital transport is challenging. Circular dichroism is a well-established method of directly measuring orbital angular momentum and has been recently used to measure current-induced spin and orbital accumulation. To clarify the relationship between circular dichroism and orbital accumulation, we directly compute both quantities in a thin film of Pt, where the orbital accumulation is computed with the atom-centered approximation (ACA). The frequency-integrated circular dichroic absorption, which yields the self-rotating part of the orbital angular momentum, is generally larger than the ACA orbital accumulation by roughly an order of magnitude. We find that the spatial profile of both quantities is limited to a few atomic layers from the surface, while the surface total versus layer thickness varies with a length scale set by the mean free path.

SESSION 13 – Chair: Tobias Kampfrath

14:30 **HYUN-WOO LEE -** Pohang Institute of Science and Technology, Pohang, South Korea
Electron orbital dynamics in solids

Electron orbital dynamics in time-reversal-symmetric centrosymmetric systems is examined theoretically. We demonstrate that some aspects of orbital dynamics are qualitatively different from spin dynamics because the algebraic properties of the orbital and spin angular momentum operators are different. We first discuss the Bernevig-Hugh-Zhang Hamiltonian and its generalized version for p-orbital dynamics and illustrate their connection with the orbital texture in momentum space. We also show that their spin 1/2 version is not possible due to the algebraic property difference. This difference in the Hamiltonian structure implies that the description of the orbital dynamics requires not only the orbital angular momentum expectation values but also so-called orbital angular position expectation values. In particular, we demonstrate that not only the Hall effect of the orbital angular momentum, which amounts to the conventional orbital Hall effect, but also the Hall effect of the orbital angular position is also possible. The Hamiltonian difference also affects the relaxation dynamics. For orbital angular momentum relaxation, we demonstrate that not only Elliot-Yafet-type relaxation, in which momentum scattering makes the orbital relaxation time shorter, but also Dyakonov-Perel-type relaxation becomes possible, in which momentum scattering makes the orbital relaxation time longer. We find that the Dyakonov-Perel-type relaxation is more dominant in the weak scattering regime, whereas the Elliot-Yafet-type relaxation is more dominant in the strong scattering regime. Finally, we discuss the correlation between spin and orbital angular position, which may be relevant in d-wave altermagnets.

15:00 **JUAN CARLOS IDROBO -** University of Washington/PNNL, Seattle (WA), USA
Direct Detection of Chiral Signals in the Electron Microscope with Sub-Nanometer Spatial Resolution

Scanning transmission electron microscopy (STEM), when combined with electron energy-loss spectroscopy (EELS), has the potential to detect properties associated with quantum materials with unprecedented spatial resolution. These properties include the emergence of magnetic ordering, valley polarization, phonon chirality, and topological characteristics such as Hall effects. In this study, we will show that achieving such measurements requires a configuration that ensures that electron momentum transfer in EELS mimics the role of polarization in light and X-rays.

Here, we will present two examples. [1] The first example demonstrates the detection of ferromagnetic ordering in lanthanum strontium manganite (LSMO) at room temperature. [2] The second example illustrates that orbital angular momentum, through the orbital Hall effect (OHE), can be detected and characterized at the nanometer scale. [3] Additionally, we will discuss other chiral and topological signals—such as the conventional, spin, and valley Hall effects—that can potentially be directly detected using EELS under the right acquisition and sample conditions. Finally, we will enumerate the main experimental challenges that must be addressed to enable these measurements and outline the conditions necessary to achieve atomic resolution.

[1] This work was supported by the U.S. Department of Energy (DOE), Office of Science (SC), Basic Energy Sciences, Material Sciences and Engineering Division, Electron and Scanning Probe Microcopies Program, FWP 83244. The electron microscopy instrumentation part of this research was supported by the Center for Nanophase Materials Sciences, which is a Department of Energy Office of Science User Facility. This research was conducted, in part, using instrumentation within ORNL's Materials Characterization Core provided by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy.
[2] J.C. Idrobo et al. unpublished (2025).
[3] J.C. Idrobo, et al., arXiv:2403.09269 (2024).

15:30 **PAUL KELLY -** University of Twente, Enschede, Netherlands
Describing currents of orbital angular momentum with scattering theory

With a view to understanding the role of various types of disorder in the orbital Hall effect, we extend quantum mechanical scattering calculations to generate and study currents of orbital angular momentum (OAM). The orbital Hall conductivities that we find have the same order of magnitude as found in other theoretical work, with little dependence on thermal lattice disorder and considerably more structure as a function of energy which largely tracks the density of states [1].

From the decay of a fully spin-polarized current injected into a thermally disordered scattering region we determined the spin-flip diffusion length lsf and interface spin memory loss parameter \delta for various systems of experimental interest. For the 5d transition metal elements, values of lsf ranging from 3 to 50 nm were found at room temperature [2]. By contrast, currents of OAM are found to decay on a length scale of the electronic interatomic hopping, shorter than a nanometre [3]. They can convert to spin-currents at an interface leading to the suggestion that the large length scale extracted from experiment may in fact be lsf.

[1] M. Rang and P.J. Kelly, arXiv:2409.20526.
[2] R.S. Nair et al., Physical Review Letters 126, 196601 (2021).
[3] M. Rang and P.J. Kelly, Physical Review B 109, 214427 (2024).

Friday, 4 April

SESSION 14 – Chair: Henri Jaffrès

9:00 **MARCOS GUIMARÃES** - University of Groningen, Groningen, Netherlands
Efficient Magnon Injection and Detection via the Orbital Rashba-Edelstein Effect

Magneto-electronics provides a promising route for energy-efficient devices for data processing and storage. Devices that explore spin-waves (magnons) are particularly appealing since they provide a nearly non-dissipative way to transmit and process information. In order to further develop and improve such devices there is a strong need to identify suitable materials for hosting magnons and understand the microscopic mechanisms for magnon generation, transport and detection. Due to their versatility nonlocal magnon transport devices have been widely used to explore different material platforms and unveiling their magnonic properties. This, however, relies on the possibility to efficiently inject and detect magnons with a static electrical current using spin-charge interconversion effects which are usually rather inefficient, in the order of 10% electric current to spin current conversion. Devices that explore the orbital degree-of-freedom of the electron have shown to be able to boost the efficiency of spintronic devices by exploiting the fact that the orbital component of the angular momentum can be much larger than the spin contribution. In this talk I will discuss our recent work [1] where we demonstrate a dramatic increase in the output signal of yttrium iron garnet (Y3Fe5O12 – YIG)-based nonlocal magnon transport nanodevices by exploiting the orbital Rashba-Edelstein effect (OREE) at the Pt/CuO_x interfaces. We observe a 7-fold increase in the signal generated by electrically injected magnons and a factor of 4 increase in the signal by thermally injected magnons. These different magnon generation mechanisms in our devices allow us to show that the interconversion of a charge current into an orbital current, and the reciprocal effect - an orbital current into a charge current - do not have the same efficiencies. Our measurements provide valuable information for the further understanding of the microscopic mechanisms at play in the interconversion between orbital and charge currents and highlight the power of orbital effects for the improvement of magnonic devices.

[1] A. Mendoza-Rodarte et al., Phys. Rev. Lett. 132, 226704 (2024).

9:30 **DONGWOOK GO -** Jülich Research Center, Jülich, Germany
Topological Chiral Crystals for Orbitronics

The recent discovery of orbital currents [1] and their application to magnetic memory devices [2–4] have established a new paradigm of orbitronics, which exploits the dynamics and transport of nonequilibrium orbital angular momentum (OAM) for device applications [5,6]. A key challenge in orbitronics is identifying materials that enable efficient generation and transport of the OAM. To date, most studies have focused on transition metals, leaving alternative materials largely unexplored. In this talk, I introduce topological chiral crystal as a promising platform for orbitronics. In these materials, the OAM encodes the chirality information and strongly couples to the chiral lattice structure. Using CoSi as a prototypical example, we demonstrate that the low-energy excitations of l=1 multifold chiral fermions—orbital analogs of Weyl fermions—exhibit monopole-like OAM textures in k-space, determined by the crystal chirality [7,8]. This unique property facilitates the efficient generation, detection, and manipulation of OAM via electrical currents, where our first-principles calculations show a negligible spin contribution [9]. Finally, I will propose experimental approaches to validate these findings and discuss their broader implications for orbitronic applications. This work has been done in collaboration with Ying-Jiun Chen, Kenta Hagiwara, Christian Tusche, and Yuriy Mokrousov.

[1] Y.-G. Choi et al., Nature 619, 52 (2023).
[2] S. Ding et al., Phys. Rev. Lett. 125, 177201 (2020).
[3] D. Lee et al., Nat. Commun. 12, 6710 (2021).
[4] T. Gao et al. Nat. Phys. 20, 1896 (2024).
[5] D. Go et al., Europhys. Lett. 135, 37001 (2021).
[6] D. Jo et al., npj Spintronics 2, 19 (2024).
[7] S. S. Brinkman et al., Phys. Rev. Lett. 132, 196402 (2024).
[8] K. Hagiwara et al. arXiv: 2410.20607.
[9] D. Go, Y.-J. Chen, C. Tusche, and Y. Mokrousov, In Preparation.

MAIRBEK CHSHIEV - Spintec, Grenoble, Spain

10:00 *Theoretical engineering of spin-orbit effects in nanostructures based on transition metals, oxides and 2D materials*

In the context of spin-orbitronics [1] and two-dimensional (2D) spintronics [2,3,4], this talk will focus on engineering of spin-orbitronic phenomena by elucidating their microscopic mechanisms at interfaces made of oxide (O), ferromagnetic (FM), nonmagnetic (NM) and/or 2D materials. First, perpendicular magnetic anisotropy (PMA) [1,5-8] and Dzyaloshinskii-Moriya interaction (DMI) [9-19] enhancement recipes at FM/O [5,6], FM/NM [10,12], (NM)/FM/O [11,12] and FM/2D [13,14] interfaces and their variation under applied electric field (VCMA and VCDMI) [7,12,20], via hydrogenation [15] or ionic migration are proposed [20,21]. Next, DMI mechanisms along the possibility of inducing skyrmions with the chirality control by electric field in 2D van der Waals materials including magnets [4,16-19] are presented. Finally, the potential of these materials for spin-orbit torques and spin-charge conversion effects is discussed [22,23].

[1] B. Dieny and M. Chshiev, Rev. Mod. Phys. 89, 025008 (2017).
[2] S. Roche et al., 2D Mater. 2, 030202 (2015).
[3] H. Yang et al., Nature 606, 663 (2022).
[4] Q.H. Wang et al., ACS Nano 16, 6960 (2022).
[5] A. Hallal et al., Phys. Rev. B 88, 184423 (2013); ibid. 90, 064422 (2014).
[6] L. Vojáček et al., Phys. Rev. Applied 15, 024017 (2021).

[7] F. Ibrahim et al., Phys. Rev. B 93, 014429 (2016).
[8] H.X. Yang et al., Nano Lett. 16, 245 (2016).
[9] H.X. Yang et al., Phys. Rev. Lett. 115, 267210 (2015).
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[11] O. Boulle et al., Nat. Nanotech. 11, 449 (2016).
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[13] H.X. Yang et al., Nat. Mater. 17, 605 (2018) .
[14] A. Hallal et al., Nano Lett. 21, 7138 (2021).
[15] B. Yang et al., Phys. Rev. B 101, 014406 (2020).
[16] J. Liang et al., Phys. Rev. B 101, 184401 (2020).
[17] T.-E. Park et al., Phys. Rev. B 103, 104410 (2021).
[18] Z. Shao et al., Phys. Rev. B 105, 174404 (2022).
[19] D. Yu et al., Nat. Sci. Rev. 9, nwac021 (2022).
[20] F. Ibrahim et al., Phys. Rev. B 98, 214441 (2018).
[21] J. de Rojas et al., Nat. Commun. 11, 5871 (2020).
[22] L. Vojáček et al., Nano Lett. 24, 11889 (2024).
[23] K. Abdukayumov et al., Adv. Mater. 36, 2304243 (2024).

SESSION 15 – Chair: Tatiana Rappoport

11:00

MICHEL VIRET - CEA, Saclay, France

Electric field effect on the conversion of angular momentum into charge in Rashba split interfaces

Creating and manipulating dissipation-less pure spin currents have been crucial challenges for the spintronic community for the past ten years. A central handle to achieve low consumption pure spin-based computing is the inter-conversion of spin and charge, if possible at very short timescales. All known mechanisms rely here on the Spin-Orbit Coupling (SOC) interaction, whereby spins couple with moving charges [1]. So far, the most reliable mechanism in the DC range is the (inverse) Spin Hall effect (ISHE) obtained in the bulk of metallic heavy elements like Pt or W. Another type of SOC, called spin galvanic or (inverse) Edelstein effect (IEE), has also been used based on the Rashba interaction [2,4]. It stems from the action of an electrical built-in potential onto the two-dimensional electron systems existing at interfaces between two different materials. Often, this effect offers the advantage to be controllable by an externally applied electric field [5]. To measure the conversion effect, one needs an injector, i.e. a ferromagnetic layer, in contact with the convertor. Here, we use the spin Seebeck technique by producing temperature gradients perpendicular to metallic bi- or tri-layers in which different 3d ferromagnets are used to inject angular momentum [5]. This geometry allows for top gating, achieved using dielectric layers deposited on top. I will discuss here the electric field effect on the interface states and show that this allows distinguishing Inverse Edelstein Effects from Inverse Spin(orbital) Hall Effects. The nature of the injection ferromagnets will also be analyzed in structures of the type FM/MgO, FM/Cu/MgO and FM/$LaAlO_3$/$SrTiO_3$ giving hints for the spin or orbital nature of the angular momentum.

[1] M. Dyakonov and V. Perel, JETP Lett. 13, 467 (1971).
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[3] J.-C. Rojas-Sanchez et al., Nature Comm. 4, 2944 (2013).
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[5] A. El Hamdi et al., Nature Physics 19, 1855–1860 (2023).

11:30 **JOSE HUGO GARCÍA** - Catalan Institute of Nanoscience and Nanotechnology, Bellaterra, Spain
Spin-orbit torque in two-dimensional materials as a platform for efficient and nonvolatile memories

Spin-orbit torque (SOT) is pivotal for advancing non-volatile memory technologies by improving efficiency and reducing energy consumption. By minimizing reliance on reference magnets, SOT simplifies memory architectures, enhancing their efficiency and reliability. Two-dimensional materials are ideal for SOT applications due to their unique crystalline interfaces when combined in Van der Waals heterostructures, where the direct coupling between the magnet and the metal is predicted to significantly enhance SOT efficiency. In this presentation, we introduce a novel theoretical framework based on symmetry to derive the allowed contributions to two-dimensional SOT. This framework is complemented by a high-throughput analysis of a 2D materials database and a systematic classification of all possible torques in 2D. Additionally, we present a semiclassical theory that expresses these torques in terms of spin textures, validated through state-of-the-art linear-scaling quantum transport calculations. Finally, we discuss the potential of AI-powered high-throughput workflows for determining the magnetic properties of 2D magnetic materials.

12:00 **IVO SOUZA** - Materials Physics Center, Donostia-San Sebastián, Spain
Magnetoelectric and quadrupolar effects in broken-symmetry conductors

In this presentation, several orbitronics effects are formulated as the low-frequency limit of optical spatial dispersion in crystals (the optical response at nonzero wavevector q of light). Specifically, at first order in q one recovers (i) the spin and orbital Edelstein effects, understood as dissipative (or "kinetic") magnetoelectric effects in gyrotropic conductors; (ii) a purely orbital and nondissipative magnetoelectric effect, and (iii) an electric-quadrupolar effect, both occurring in conductors that break time-reversal symmetry along with spatial inversion. The quantum metric of the conduction electrons is shown to contribute to the latter effects, and some discrepancies between their Kubo and semiclassical formulations will be discussed.

12:30 **FÈLIX CASANOVA -** CIC nanoGUNE, Donostia-San Sebastián, Spain

Hanle magnetoresistance caused by the orbital Hall effect in Vanadium

In spintronics, the spin Hall effect (SHE) has been widely used to generate and detect spin currents in materials with strong spin-orbit coupling (SOC) such as Pt and Ta. However, recent theoretical studies have published that the orbital Hall effect (OHE) is more common and fundamental than the SHE because it does not require SOC [1]. In particular, it has been theoretically predicted that 3d transition metals may have orbital Hall conductivities in the order of ~103 – 104 $(\hbar/e)(\Omega cm)^{-1}$, which are comparable or higher than the spin Hall conductivity of Pt, the prototypical SHE material [1,2]. Recently, a significant Hanle magnetoresistance (HMR) has been experimentally observed in the 3d transition metal Mn and attributed to the accumulation of orbital angular momentum at the edges of the thin film [3].

Here, we report a HMR of the order of 10-4 in sputtered vanadium (V) thin films deposited on top of Si/SiO2 substrates and capped in situ to prevent oxidation [4]. A patterned Hall bar allows to perform longitudinal and transverse magnetotransport measurements by rotating the sample along different axis and sweeping the magnetic field up to 9 T. A magnetoresistance is observed with a symmetry consistent with that of the HMR in samples of different thicknesses ranging from 4 nm to 30 nm. Control experiments using YIG as a substrate shows small but clear spin Hall magnetoresistance (SMR) of the order of 10-6, confirming that the HMR is dominated by the orbital angular momentum accumulation rather than the spin accumulation. By applying the standard HMR equations, we quantify the orbital Hall conductivity and the orbital diffusion length of V. From the variation of these quantities with the resistivity of the V thin films, we can infer the mechanisms of the orbital transport.

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[3] G. Sala, et al., Phys Rev Lett 131, 156703 (2023).
[4] M.X. Aguilar-Pujol, F. Casanova, et al., in preparation.

Poster Session

Thursday, 3 April at 16:00

3 **Xiaobai Ning** - Aix-Marseille University, Marseille, France

Modeling Orbital Torque and Orbital Mixing Conductance in Metallic Bilayer Structures

Spin-orbit torque (SOT) induced by electrical current plays a vital role in spintronics applications. Apart from the conventional spin effects such as spin Hall effect and Rashba-Edelstein effect, it has been recently found that another channel of angular momentum can be carried by orbital currents, giving rise to new perspectives in analyzing and manipulating the SOT strength. In this work, we acquire a comprehensive drift-diffusion model that includes both the spins and the orbitals in the complete NM/FM bilayer structure. By examining scenarios of spin-orbit and orbit-spin polarization, we can integrate both the spin precession and the spin-orbit coupling of FM into the model. The spin torque can be straightforwardly described by the spin diffusion from NM to FM, while the orbital torque involves the orbital diffusion, the orbit-spin polarization, as well as the spin back-diffusion. As for the mixing conductance, the connection between NM/FM interfacial conductance and FM bulk conductance is series for spin and parallel for orbital, resulting in different correlations and sensitivities to spin precession and interfacial conditions.

4 **Börge Göbel** - Martin Luther University Halle-Wittenberg, Halle, Germany

Orbital Hall effect accompanying quantum and topological Hall effects

The quantum Hall effect emerges when two-dimensional samples are subjected to strong magnetic fields at low temperatures: Topologically protected edge states cause a quantized Hall conductivity in multiples of e^2/h. As we have recently shown, the quantum Hall effect is accompanied by an orbital Hall effect [1]. Our quantum mechanical calculations fit well the semiclassical interpretation in terms of "skipping orbits". The chiral edge states of a quantum Hall system are orbital polarized akin to an orbital version of the quantum anomalous Hall effect in magnetic systems. The orbital Hall resistivity scales quadratically with the magnetic field, making it the dominant effect at high fields.

In this talk, I will also consider topologically non-trivial magnetic textures, such as magnetic skyrmions, that exhibit a topological Hall effect. It quantifies the transverse electric current once an electric field is applied and occurs as a consequence of the emergent magnetic field of the skyrmions. Therefore, it is closely related to the quantum Hall effect described above. Additionally, an orbital magnetization is generated due to the emergent field [2].

As I will demonstrate, the transverse charge currents are orbital polarized even though the conduction electrons couple to the skyrmion texture via their spin. The topological Hall effect is accompanied by a topological orbital Hall effect even for s electrons without spin-orbit coupling [3]. Furthermore, antiferromagnetic skyrmions that have a compensated emergent field exhibit a pure topological orbital Hall conductivity that is not accompanied by charge transport and can be orders of magnitude larger than the topological spin Hall conductivity. Other magnetic quasiparticles beyond skyrmions like magnetic bimerons are briefly discussed as well [4].

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7 **Alberto Anadón** - INMA-CSIC, Zaragoza, Spain

Large spin accumulation signals in ultrafast magneto-optical experiments

Efficient generation and detection of ultrafast electrical signals can lead to significant advancements in material science, data processing and communication technology. In this sense, THz spin currents from magnetic materials provide a promising framework to overcome some of the challenges of current THz technology, primarily due to their large bandwidth and tunability [1]. Therefore, accurately quantifying and understanding such ultrafast spin currents is a major challenge in the field of ultrafast magnetism. For this reason, the spintronics community has invested vastly into studying both the process of ultrafast demagnetization [2] and the transport of spin currents into other layers either by THz spectroscopy [1], analysis of ultrafast spin torques [3] or even direct optical detection of the resulting spin accumulation [4-6]. In this work, we carefully analyze magneto-optical signals in a series of ferromagnetic samples, in order to deconvolute the signals resulting from the changes in local magnetization and angular momentum transport across layers. During this talk, we will show different signatures of the magneto-optical signals, we will compare rotation and ellipticity and will present a simple model that describes the detected signals. These observations could shed some light into the longstanding controversy on the differences observed in the rotation and ellipticity in the magneto-optical signals at ultra-short time scales [7-10].

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9 **Mahmoud Zeer** - Johannes Gutenberg-Universität Mainz, Mainz, Germany

Colossal Orbital Torques and Pumping in Two-Dimensional Rare-Earth Dichalcogenides

The design of spin-orbit torque (SOT) properties in two-dimensional (2D) materials represents a key challenge in modern spintronics [1]. Building on our previous work on GdX_2 and EuX_2 monolayers, which demonstrated robust magnetism, pronounced orbital polarization, and significant spin-orbit interaction effects [2,3], we now explore ferromagnetic Janus H-phase monolayers of 4f-Eu rare-earth dichalcogenides—EuSP, EuSSe, and EuSCl—using first-principles calculations. Our findings reveal that these compounds exhibit substantial SOT, primarily driven by the colossal current-induced orbital response of Eu f-electrons. Additionally, the resulting orbital torques can generate strong in-plane currents of orbital angular momentum with non-trivial orbital polarization directions. These results establish f-based 2D materials as a highly promising platform for in-plane orbital pumping and SOT applications, positioning f-based 2D materials as a promising platform for next-generation orbitronic and spintronic technologies.

11 **Armando Pezo** - Laboratoire Albert Fert, Palaiseau, France
Spin-Orbit-Torque in Co/Al interfaces

Recent efforts to manipulate electronic quantum properties in materials have highlighted the significance of the orbital degree of freedom. In this context, the emergence of the orbital Hall effect, driven by orbital textures, and the generation of Orbital-Rashba effects at light metal interfaces present remarkable alternatives to the heavy-metal-based materials traditionally used in Spintronics over the past few decades. In this study, we conduct a theoretical investigation into the emergence of Spin-Orbit Torque in Co/Al bilayers. Starting with state-of-the-art density functional theory (DFT) simulations, we further apply linear response theory to calculate the actual values of the torque exerted on the magnetic layer, we also addressed the influence of proximity effects with Pt and the role of strain.

12 **Berkay Kilic** - University of Groningen, Groningen, Netherlands
Universal symmetry-protected persistent spin textures in nonmagnetic solids

The significance of Mendeleev's periodic table extends beyond the classification of elements; it lies in its remarkable predictive power for discovering new elements and properties, revealing the underlying symmetrical patterns of nature that were only fully understood with the advent of quantum mechanics. Fundamental material properties, such as electron transport and magnetism, are also governed by crystal symmetry. In particular, spin transport depends on the spin polarization of electronic states and recently discovered materials where the electron spin polarization is independent of momentum - a property known as a persistent spin texture (PST) - promise extended spin lifetime and efficient spin accumulation. In this work, we establish the general conditions for the existence of symmetry-protected PST in bulk crystals. By systematically analyzing all 230 crystallographic space groups, similar to elements in the periodic table, we demonstrate that PST is universally present in all nonmagnetic solids lacking inversion symmetry. Using group theory, we identify the regions within the Brillouin zone that host PST and determine the corresponding directions of spin polarization. Our findings, supported by first-principles calculations of representative materials, open the route for discovering robust spintronic materials based on PST.

13 **Olena Gomonay -** Johannes Gutenberg-Universität Mainz, Mainz, Germany
Dynamics of the antiferromagnetic insulator CoO induced by orbital angular momentum pumping

The pumping of orbital angular momentum can induce magnetic dynamics and thus find various applications in spintronics. However, the bottleneck that limits the efficiency of orbital torques is the need for conversion between the orbital and spin degrees of freedom mediated by relatively small spin-orbit interactions. In this work we consider an antiferromagnet with the unquenched orbital moment, exemplified by CoO, in which the external orbital torques interact directly with the internal orbital angular momentum. This interaction is mediated by the crystal field and can significantly overcome weak spin-orbit interactions. Using a phenomenological model, we show that the orbital pumping creates nonequilibrium orbital quadrupole moments L_jL_k, which in turn interact with the magnetic moments, modifies the magnetic anisotropy landscape, and thus can excite magnetic dynamics. We calculate the combined dynamics of the magnetic and orbital moments for different geometries of orbital pumping and external magnetic field. We also relate the induced dynamics and the corresponding losses in the antiferromagnetic layer to the additional contribution to the resistance that can be associated with the spin (or orbital) magnetoresistance effect. Our findings open a way to tailor spintronic devices by using a combination of orbital and spin torques and magnets with the unquenched orbital moment.

14 **Theodoros Adamantopoulos -** Johannes Gutenberg-Universität Mainz, Mainz, Germany
Spin and Orbital Magnetism by Light in Rutile Altermagnets

While the understanding of altermagnetism is still at a very early stage, it is expected to play a role in various fields of condensed matter research, for example spintronics, caloritronics and superconductivity [1]. In the field of optical magnetism, it is still unclear whether altermagnets can exhibit magnetisation dynamics effects distinct from ferromagnets and antiferromagnets. Here we choose RuO2, a prototype metallic altermagnet with a giant spin splitting, and CoF2, an experimentally known insulating altermagnet, to study the inverse Faraday effect (IFE) in altermagnets from first principles [2]. We predict large and canted induced spin and orbital moments after the optical excitation which are distinct on each magnetic sublattice. By resorting to microscopic tools, we interpret our results in terms of the altermagnetic spin splittings and of their reciprocal space distribution. Overall, in accordance with our symmetry analysis, we demonstrate that the behavior of altermagnets when exposed to optical pulses incorporates both ferromagnetic and antiferromagnetic features.

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16 **Giacomo Sala** - University of Geneva, Geneva, Switzerland
Nonlinear magnetotransport induced by the spin and orbital quantum geometry

Quantum materials are characterized by electromagnetic responses that are directly related to the geometry and topology of electronic wavefunctions. These properties are encoded in the Berry curvature and quantum metric. Berry curvature-mediated transport effects such as the anomalous Hall [1] and nonlinear Hall effects [2] have been observed in various magnetic and nonmagnetic materials. However, transport effects governed by the quantum metric remain limited to a handful of materials [3-5].

Here [6], we show that spin-momentum-locked electronic bands are endowed with an inherent quantum metric that activates a nonlinear and nonreciprocal magnetoresistance. We observe the occurrence of this phenomenon and its gate-tunability in 111-oriented LaAlO3/SrTiO3 interfaces. The additional presence of the (spin-sourced) Berry curvature and (orbital-sourced) Berry curvature dipole allows us to probe magnetotransport responses associated with both the spin and orbital degrees of freedom. Our findings extend the application of quantum geometry to all materials with spin-momentum-locked bands and provide new strategies for designing electronic functionalities based on the geometric properties of electronic wavefunctions.

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21 **Daegeun Jo** - Uppsala University, Uppsala, Sweden
Unconventional orbital currents in ferro-rotational systems

We demonstrate the electrical generation of orbital currents induced by an electric hexadecapole moment in ferro-rotational systems. Driven by an intrinsic and nonrelativistic mechanism, these rotation-induced orbital currents exhibit unconventional directions: (i) longitudinal orbital currents polarized along the ferro-rotational axis, and (ii) unconventional orbital Hall currents with polarization collinear with either the charge or orbital current. We examine these effects in the ferro-rotational material TiAu4 using first-principles calculations. Our findings reveal a new pathway for generating orbital currents beyond the conventional orbital Hall effect, broadening the scope of orbitronics research to novel ferroic materials and higher-order electric multipoles.

23 **Jone Mencos Frechilla** - CIC nanoGUNE, Donostia-San Sebastián, Spain
Observation of the orbital Hall effect by electrical orbital injection

Orbitronics is a new field of electronics which aims at exploiting the orbital angular momentum of the electron, similar to what spintronics does with the spin angular momentum. When an electric field is applied to a material, electrons with opposite orbital angular momentum will be deflected to opposite directions creating a transverse orbital current, known as the orbital Hall effect (OHE), analogous to the spin Hall effect (SHE). Remarkably, spin-orbit coupling (SOC) is needed for the SHE but not for the OHE. Theoretical predictions show that the orbital current generated by the OHE can be much larger than the SHE-induced spin current. However, orbital current cannot directly exert a torque on ferromagnets because orbital magnetization is usually negligible, thus requiring a conversion from orbital current to spin current in order to manipulate the magnetization. The best ferromagnetic candidate for orbitronics seems to be Ni, which has the largest SOC among the ferromagnetic 3d transition metals and, therefore, will give the possibility to create and detect orbital currents.Here, we report the observation of OHE by electrical orbital injection. By using lateral T-shaped devices, we electrically inject spin/orbit currents from a ferromagnet (Py and Ni) into a SHE/OHE material (Pt and Ta), which generates a transverse current, detected as an open-circuit voltage. By combining these materials, we can disentangle the spin from the orbital origin of the measured voltage, probing the SHE for Py and the OHE for Ni. Importantly, the spin Hall conductivity can be positive (Pt) or negative (Ta) whereas the orbital Hall conductivity is predicted to be positive for all transition metals. 3D simulations of the devices have been performed to discard the possible contributions of other effects to the measured signal, such the anomalous Hall effect of the ferromagnets. Our results introduce a new technique to study orbit currents by electrical orbital injection.

25 **Chao Chen Ye** - University of Groningen, Groningen, Netherlands

First-principles studies of spin and orbital effects on altermagnet MnTe

Altermagetism has been recently identified as a new type of collinear magnetism characterized by spin splitting, in both real and momentum spaces, and zero non-relativistic net magnetization. Nevertheless, materials with strong spin-orbital coupling can break this collinear arrangement, leading to a net weak ferromagnetic behavior. MnTe is an ideal material for both experimental and theoretical studies in this area. In this work, we perform ab initio simulations to study the spin and orbital effects of the magnetic ground state of MnTe, which has the Néel vector along y-axis. We find that the net orbital magnetization along the z-direction is at least one order of magnitude stronger than the spin contribution, while the x- and y-components are negligible. This finding highlights the significant role of orbital effects in this kind of material. Moreover, its direct connection with Dzyaloshinskii–Moriya interaction supports the origin of the net weak ferromagnetism. Lastly, by analyzing the dependence of both spin and orbital magnetizations on doping, we prove that the magnetic canting surely originates from the unfilled (filled) states in the valence (conduction) band.

33 **Armando Consiglio** - Istituto Officina dei Materiali - Consiglio Nazionale delle Ricerche, Bologna, Italy

Flat band separation and robust spin Berry curvature in bilayer kagome metals

In this poster, the spin and electronic structure of the XV6Sn6 (X = Tb, Ho, Sc) kagome metals are presented. Our study uncovers a finite spin Berry curvature at the Brillouin zone center, where spin-orbit coupling causes the nearly flat band to separate from the Dirac band. In the charge density wave state of ScV6Sn6, we further analyze the spin

Berry curvature, demonstrating its persistence despite the temperature-driven transition to an ordered phase. Harnessing angle-resolved photoemission spectroscopy's sensitivity to spin and orbital angular momentum, this work characterizes the spin Berry curvature in topological kagome metals and defines its spectroscopic signature. This study provides clear evidence of the multidimensional topology of the 166 kagome family, encompassing both surface and bulk states. It positions these materials as a novel platform for exploring correlated topological metallic behavior, characterized by a non-trivial spin Berry curvature of the wave function manifold.

35

Chao Chen Ye - University of Groningen, Groningen, Netherlands

First-principles studies of spin and orbital magnetizations of the altermagnetic MnTe

Altermagetism has been recently identified as a new type of collinear antiferromagnetism characterized by spin splitting, in both real and momentum spaces, and zero net magnetization. Nevertheless, materials with strong spin-orbit coupling can break the collinear arrangement, leading to a net weak ferromagnetic behavior induced by the Dzyaloshinskii–Moriya interaction. MnTe is an ideal material for both experimental and theoretical studies in this area. In our work, we perform ab initio simulations to study the spin and orbital magnetizations of the magnetic ground state of MnTe, which has the Néel vector along the y-axis. We reveal the weak ferromagnetism along the z-axis and we find that the net orbital magnetization along this direction is at least one order of magnitude stronger than the spin contribution, while its x- and y-components are negligible. This finding highlights the significant role of orbital effects in this material. Lastly, by analyzing the dependence of both spin and orbital magnetizations on doping, we prove that the magnetic canting originates from the unfilled (filled) states in the valence (conduction) band.

41

Liyang Liao - University of Tokyo, Tokyo, Japan

Nonlocal Electrical Detection of Reciprocal Orbital Edelstein Effect

Current-induced nonequilibrium orbital angular momentum (OAM) offers a promising method to manipulate nanomagnets efficiently using light elements. Despite extensive research, understanding the Onsager reciprocity of orbital transport—fundamentally rooted in the second law of thermodynamics and time-reversal symmetry—remains elusive. In this study, we experimentally test the Onsager reciprocity of orbital transport in an orbital Edelstein system by utilizing nonlocal transport. Identifying the chemical potential generated by the orbital accumulation avoids the limitations associated with orbital torque and pumping measurements. Remarkably, we observe that the direct and inverse orbital-charge conversion processes produce identical electric voltages, confirming Onsager reciprocity in orbital transport. Additionally, we find that the orbital decay length, approximately 100 nm at room temperature, is independent of Cu thickness and decreases with lowering temperature, revealing a distinct contrast to spin transport behavior. Our findings provide valuable insights into the reciprocity of the charge-orbital interconversion and the nonlocal correlation of the orbital degree of freedom.

49 **Meritxell Valls Boix** - Johannes Gutenberg-Universität Mainz, Mainz, Germany
Theory of Magnetization Dynamics Control by Phonons

Spin-lattice coupling plays a crucial role in facilitating angular momentum exchange between the lattice and magnetic subsystems. In this work, we explore how this coupling can be harnessed to enhance the lifetime of magnons in ferromagnetic materials. Specifically, we focus on the interaction between propagating surface acoustic waves and a proximate magnetic system, where these waves generate a torque on the spins. Using perturbation theory, we derive the effective field arising from magneto-rotational coupling and subsequently define the resulting torque. In particular, we investigate whether a dampinglike component of the torque can emerge, which could act as an antidamping mechanism to counteract the intrinsic magnon damping.

50 **Rodrigo Torrão Victor** - Laboratoire Albert Fert, Palaiseau, France
Magnetization switching for circular polarized LEDs

Information processing, storage and transmission are the pillars of technology. While information processing is performed using electron charge and data transfer is based on emitted light, information storage depends mainly on the interaction of electron spin and charge in the presence of ferromagnetic materials. However, an integration of these three branches in the same device is still expected. A promising solution for a single device integration has recently been proposed by using semiconductors light-emitting diodes (LEDs) with circularly polarized light. The light polarization is defined by the magnetic orientation of a ferromagnetic material, which can be controlled by an electric current in an adjacent layer through the spin-orbit torque (SOT) effect. However, implementing such devices is not an easy task as they need to fulfill several requirements. For example, they must be compatible with current growth technologies, have low power consumption, be low cost, and operate at room temperature. In addition, as the magnetization is controlled by a charge current in a layer on top of a semiconductor multilayer structure, it is extremely important that this current does not exceed the metal-insulator-semiconductor (MIS) Schottky barrier to avoid shunting problems. Furthermore, it is also desirable to be able to control the magnetization in an ultra-fast regime, which demands the magnetization reversibility with current pulses in the order of nanoseconds.

To meet these requirements, we investigate a promising system composed of heavy metal materials with high spin-orbit coupling (SOC) and spin Hall effect (SHE), such as Pt and W coupled with light metal materials, which have recently been explored due to their high orbital Hall effect (OHE). In this work chromium has been used as a light metal forecasting the presence of several desirable properties. For instance, it shows a reduction in the critical current of the magnetization switch. Additionally, when chromium is partially oxidized, the interface between the Cr and the CrOx can also lead to the Rashba Edelstein effect (REE). In order to induce or prevent the oxide layer formation, different stack combinations were studied. To investigate the influence of the OHE and REE we employed the 2nd harmonic Hall techniques to measure both damping-like (DL) and field-like (FL) SOT contributions, and further correlated these torques with the magnetization switch critical current measured by anomalous Hall effect (AHE) and magneto-optical Kerr effect (MOKE) microscopy. Density functional theory (DFT) calculations are intended to support the results.

54 **Adrián Gudín Holgado** - Universidad Autónoma de Madrid /IMDEA, Madrid, Spain
Nanociencia Isotropic spin and inverse spin Hall effect in epitaxial (111)-oriented Pt/Co systems

The conversion of spin current into charge current and vice versa is one of the main operation for the development of novel low energy consumption spintronic devices. In the last years, an active investigation in materials, interfaces and spin injection schemes aims at increasing the efficiency of the spin-to-charge conversion, which is mainly due to the spin-orbit coupling (SOC).

Pt is a material that exhibits one of the largest intrinsic SOC and hence one of the most studied and employed in magnetic multilayers [1]. We have recently exploited the strong SOC interaction in FM/Pt interfaces for the induction of spin orbit torques in Co [2] as well as the stabilization of chiral spin textures [3]. Nevertheless, there is still an open debate on the efficiency of spin-charge interconversion measured by using different techniques in the same material. The discrepancy found in the experimental results points to a possible anisotropy of such efficiency, so that a renewed interest in the study of the spin charge interconversion in epitaxial Pt along different crystallographic directions and interfaced with different FM layers such as Fe [4,5], CoFeB [6] or Co [7] has speeded up.

In this context, we have evaluated the in-plane anisotropy of spin-charge interconversion in epitaxial (111)-oriented Co/Pt bilayers deposited on (0001)-oriented Al2O3 single crystals using an array of complementary spin Hall and inverse spin Hall techniques, which cover the coherent and incoherent excitation in the ferromagnet. By performing a Pt thickness dependence, we obtain information about the spin-charge interconversion in epitaxial Pt providing insight into the role of the interfaces.

Our results are compatible across all three techniques within experimental error, indicating no significant anisotropy in the spin conversion behaviour.

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55 **You Ba** - CIC nanoGUNE, Donostia-San Sebastian, Spain
Spin-to-charge conversion in ferromagnetic/heavy metal nanostructures

The discovery of spin–orbit coupling (SOC) phenomena, including the spin Hall effect (SHE) in bulk materials and the Edelstein effect in Rashba interfaces and topological insulators, has paved the way for a new generation of spintronic devices. These devices promise high-density memory integration with high-speed operations. Moreover, reciprocal effects like the inverse SHE (ISHE) and inverse Edelstein effect have been proposed for magnetic state readout in magnetoelectric spin–orbit (MESO)-based logic devices, proposed as low-power alternatives to CMOS. Achieving the required high output voltage (100 mV) for such devices requires both high spin-to-charge conversion (SCC) efficiency and high resistivity, making the selection and optimization of SOC materials a central focus. In this work, we investigate various SOC materials to demonstrate SCC readout signals and estimate SCC efficiency. Specifically, ferromagnet (FM)–heavy-metal (HM) nanostructures are explored for magnetic state readout in MESO logic by locally injecting spin-polarized currents and measuring SCC via the spin Hall effect. However, local configurations are susceptible to spurious signals, including the anomalous Hall effect (AHE), which has the same symmetry as the ISHE and complicates signal disentanglement. To address this, we combine electrical measurements with three-dimensional finite-element-method (3D FEM) simulations to estimate and separate the AHE contribution, ensuring accurate analysis of SCC in FM/HM nanostructures. These findings advance the understanding of SOC materials for MESO logic applications and contribute to the development of efficient spintronic technologies.

62 **Nabil Menai -** University of Bristol, Bristol, United Kingdom
Optimizing Spin Hall Angle in Mn-based Antiferromagnetic Alloys

Antiferromagnets (AFMs) have emerged as crucial materials for spintronic technologies for their ability to host spin-dependent transport phenomena, despite their zero net magnetization. Their robustness against external magnetic fields and ultrafast spin dynamics make them ideal for efficient spin-charge interconversion, offering significant potential for advanced spintronic applications. In this theoretical study, we use density functional theory and Green's function methods to investigate the transport properties of Mn-based binary alloyed AFMs. Our focus is on the total spin Hall conductivity (SHC), accounting for both the intrinsic contributions from Berry curvature and the extrinsic effects from skew scattering and side-jump mechanisms. The objective is to identify AFM materials that exhibits a high spin Hall angle (SHA); with an efficient charge-to-spin Hall current conversion ratio. Our results reveal that doping MnPt with Ir ($MnPt_xIr_{1-x}$) significantly enhances the SHA, achieving a value of 8% at room temperature; an improvement that should be experimentally observable. In contrast, doping with Pd produces lower SHA values but demonstrates stability with respect to temperature variations. Additionally, we examine the effects of substituting Mn atoms with magnetic transition metals such as Fe and Ni. These findings underscore the potential of antiferromagnetic alloys for efficient spin current generation.

65 **San Ko -** Korea Advanced Institute of Science and Technology, Daejeon, South Korea
Effect of CuOx stoichiometry on orbital Rashba Edelstein effect at CuOx/Cu interface

Orbital current, predicted to surpass spin Hall currents in magnitude, has emerged as a key mechanism for efficient magnetization control via orbital torque, positioning it as a cornerstone for next-generation spintronics [1,2]. Among these, the orbital Rashba Edelstein effect at interfaces has been widely studied for generating orbital currents, primarily in naturally oxidized Cu systems [3,4]. However, uncontrolled oxidation in these studies limits tunability and understanding. This work addresses the role of CuOx stoichiometry in orbital torque generation, focusing on how oxidation degree impacts the orbital Rashba Edelstein effect at the CuOx/Cu interface.To investigate the stoichiometric dependence of orbital torque, we fabricated CuOx/Cu/Py trilayer structures by depositing Cu and Py on polycrystalline CuOx. The CuOx layers were prepared by annealing Cu films in an Ar and O2 mixed-gas atmosphere at specific temperatures, enabling precise control of stoichiometry. X-ray diffraction (XRD) analysis confirmed the formation of distinct phases: Cu2O at 200°C and CuO at 350°C. The orbital torque was quantified through harmonic Hall voltage measurements, extracting the damping-like effective field (BDLT) to assess its stoichiometric dependency. Cu2O phases exhibited significantly large BDLT values (0.72 mT/107Am-2), comparable to those observed in heavy metals like Ta. In contrast, CuO phases yielded considerably small BDLT=0.17 mT/107Am-2. These findings demonstrate that precise stoichiometric control of CuOx is critical for optimizing orbital torque efficiency, paving the way for high-performance spin-orbitronic devices.

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68 **Inés García Manuz** - IMDEA Nanociencia, Madrid, Spain

Tuning the interfacial properties by work function engineering in W|Co|Cu| heterostructures

The breaking of inversion symmetry at interfaces, combined with a significant spin-orbit coupling, plays a crucial role in surface magnetism and spintronics. Controlling the sign and strength of the interfacial Dzyaloshinskii-Moriya interaction (iDMI) is a big challenge [1]. One promising approach to tune the iDMI is the variation of the work function difference (Δϕ) between two adjacent layers, typically HM|Co| (HM=Heavy metal) [2]. In this sense, recent studies have shown that it is possible to manipulate iDMI in heavy metal/ferromagnet/metal trilayers by adjusting the surface potential based on the grain orientation of the bottom film [2,3]. In this study, we report on W|Co|Cu| heterostructures to examine how changes in the Δϕ affect the interfacial phenomena like iDMI and the field-like term of the spin-orbit torque, while maintaining a constant breaking of inversion symmetry and spin-orbit interaction. We change the orientation of W from [110] ($\Delta\phi \approx +0.22$ eV) to [100] ($\Delta\phi \approx -0.34$ eV). By inverting the Δϕ, we have observed that the field-like torque amplitude is double depending on the orientation of W. Moreover, we analyze the W thickness dependence of the torques discriminating between bulk and interfacial contributions. This approach enables us to correlate the field-like and dampinglike torques with the Δϕ.

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71 **Capucine Gueneau** - SPINTEC-CEA, Grenoble, France

Micromagnetic analysis of skyrmion trajectories in weak Dzyaloshinskii-Moriya interaction system

Magnetic skyrmions are two-dimensional chiral swirling spin textures stabilized by the antisymmetric exchange interaction called Dzyaloshinskii-Moriya interaction (DMI) [1-2]. Their ability to be efficiently manipulated by electric currents [3] makes them promising for applications such as skyrmions racetrack memory [4-5], logic devices [5] or neuromorphic computing [6]. Understanding and controlling the physics of skyrmion, particularly their current-driven trajectory, is crucial for these applications. While skyrmion dynamics has been extensively studied, most of these studies focus on Néel-type skyrmions in high DMI systems [7]. Recent experiments show control of helicity and chirality by material tuning or gate voltage [8-10], enabling intermediate states between Bloch and Néel skyrmions. This highlights the need to investigate intermediate skyrmions in weak DMI systems.Here we will present a micromagnetic analysis of the skyrmion trajectories under current in low-DMI systems, focusing on the influence of helicity and damping. Using Mumax3.10 software [11] we simulated the motion of skyrmions under electric current in Heavy Metal(HM)/ Ferromagnet(FM)/ Metal Oxide tri-layer system with varying DMI. The motion is driven by spin-orbit torques (SOTs) present in this type of stack. Skyrmion trajectories are expected to be straight and deflected from the current direction by an angle ϕ_{traj}, given by: with p the skyrmion polarity, α the damping parameter, δDW the domain wall width, R the skyrmion radius and ξ the helicity. The first term, ϕ_{SkHE}, named skyrmion Hall effect (SkHE) represents the deflection of the skyrmion's trajectory from that induced by the SOT. Our simulations show first that, as expected, the DMI strength strongly influences the radius, helicity and trajectory for the skyrmion, allowing skyrmion motion in all directions at 360° for low currents (1010A/m2). For higher currents (1011A/m2), some trajectory directions are unreachable. Secondly, we show that ϕ_{SkHE} varies with DMI due to its dependence on the skyrmion radius. Comparing simulated trajectories with analytical predictions shows good agreement for damping values of 0.05, 0.5 and 1, validating equation (1) in the weak DMI regime. Importantly, this control of current-induced skyrmion trajectory simulated by tuning the DMI strength and chirality, can be achieved experimentally via material engineering or dynamically and locally via voltage gating [9]. This paves the way for precise and individual skyrmion control in advanced spintronic applications.

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73 **Junhyeon Jo** - CIC nanoGUNE, Donostia-San Sebastian, Spain
Anomalous nonlinear magnetoconductivity in van der Waals magnet CrSBr

Nonlinear magnetoconductivity (MC), also known as unidirectional magnetoresistance, is a nonreciprocal charge transport phenomenon arising in noncentrosymmetric materials. However, applying a magnetic field to break time-reversal symmetry is required to generate the ordinary nonlinear MC, limiting its potential for applications. In this study, we report the observation of anomalous nonlinear MC controlled by internal magnetic order parameters such as the magnetization vector or Néel vector. We achieve this response by breaking both inversion symmetry and time-reversal symmetry in artificial van der Waals heterostructures based on the two-dimensional van der Waals magnet CrSBr and insulating boron nitride (BN). The nonreciprocal signal can be tuned between two different states in ferromagnetic monolayer CrSBr, as the top BN layer breaks the inversion symmetry of the ferromagnetic CrSBr. In particular, the antiferromagnetic bilayer CrSBr generates nonreciprocal responses in four different states, thanks to its metamagnetic transition between antiferromagnetic and ferromagnetic states. Remarkably, this output signal in the ferromagnetic (antiferromagnetic) state of CrSBr is three (one) orders of magnitude higher than those previously measured in magnetic topological insulators. A conductivity scaling analysis reveals the Berry connection polarizability as the origin of the anomalous nonlinear MC. Our results pave the way for high-frequency rectifiers with magnetically switchable output polarity as well as for an efficient electrical readout of the magnetic state of antiferromagnetic materials.

77 **Alba Guio** - IMDEA Nanociencia, Madrid, Spain
Enhanced spin-orbit torque efficiency via graphite thickness in Co/Pt multilayers

The use of the spin in devices –spintronics – has led to remarkable fundamental discoveries and applications ranging from the giant magnetoresistance, hard-disks read heads or the magnetic random-access memory (MRAM). Until very recently, the most efficient way found to operate magnetic memory devices relied on the use of spin currents generated from the electric flow (spin-charge inter-conversion, SCC) in systems with strong spin-orbit coupling (SOC). When transverse spin currents are absorbed by a magnetic material, they produce spin-orbit torques (SOT), an emerging technology that enables the efficient manipulation of magnetic order parameters in spintronic devices. To date, most memory applications have primarily focused on utilizing torques generated from the bulk of the films, with interfacial effects receiving less attention. The antidamping-like (AD) torque originating in the bulk of heavy metals (HMs) plays a dominant role in switching the polarization of magnetic dots. However, symmetry breaking at interfaces can also be a powerful tool for controlling field-like (FL) torques and switching dynamics [1]. Interfacial interactions [2] and symmetry-protected (topological) [3] provide a rich platform for achieving lossless charge and spin transport, which are crucial for future information technology and spintronic applications. Therefore, exploiting symmetry breaking at interfaces can be a powerful tool for controlling field-like (FL) torques and switching dynamics. In this study, we investigate the properties of spin-orbit torques (SOT) in thin metallic structures grown, namely, 0.6nm Co layer sandwiched between Pt and a graphite overlayer ranging from 0.5nm to 4nm. Using the second harmonic Hall measurement technique, we precisely determine the amplitude of the SOT vs the graphite thickness. We find an increase of the Damping-like torque for thinner graphite layers together with a drastic rise in the Field-like torque, resulting in unexpectedly HFL/HDL ratios much larger than 1. The results evidence the role of interfacial effect and pave the way towards the optimization of low consumption spin-orbit electronics.

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78

Melissa Yactayo - Institut Jean Lamour, Nancy, France

Orbitronics: Quantification of inverse orbital Edelstein effect at Cu/MgO and Ti/MgO interfaces

The generation and detection of spin and orbital currents play an important role in spintronics and orbitronics. In this work we quantify the inverse orbital Edelstein effect (IOEE) [1,2] in Ni/Cu/MgO by DC voltage at ferromagnetic resonance condition of Ni. The origin of this signal is due to the orbital angular moment pumped from Ni and converted into a charge current at Cu/MgO interface. There is a damping enhancement in Ni/Cu/MgO with respect to MgO/Ni/MgO. The IOEE conversion efficiency, λ_{IOEE}, results about 0.07 nm, in the same order of Pt (0.2 nm) [4]. Our findings demonstrate the way to quantify orbital current to charge current conversion efficiency which is lacking in THz emission experiments [3].

Other systems that are good orbital current producers are being explored. One option are alloys of a simple magnetic material such as Fe or Co with Pt which also provides an important spin-orbit coupling to the magnetic layer. By THz emission experiments it has been shown a higher signal using CoPt/Cu/MgO than Ni/Cu/MgO [5]. So, we have chosen the CoPt alloy to study CoPt/Cu/MgO and CoPt/Ti/MgO. We observe a signal in CoPt/Ti(tTi)/MgO. However, unlike other reports [6], we did not find a variation in the charge current production Ic with the thickness of the Ti layer. Therefore, the effect would come from the Ti/MgO interface or from the CoPt layer itself, as shown for FePt [7], or a combination of both contributions.

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82 **Bhuvneshwari Sharma -** National Institute of Science Education and Research, Bhubaneswar, India
Stabilization of Skyrmions in Synthetic Ferrimagnets of Co/Gd Multilayer

The magnetic skyrmion holds promise for future spintronics-based devices due to its inherent topological protection and the potential for efficient data transport benefits: high speed, high data density, and low power consumption [1,2]. The problem with ferromagnetic skyrmions is that they exhibit the skyrmion Hall effect (SkHE) [3]. In addition, due to strong magnetic dipolar interactions, the probability of obtaining ultra-small skyrmions is small. On the contrary, ferrimagnets possess a weak net magnetic moment which reduces the dipolar fields and helps in nucleating small skyrmions and achieving higher velocity [4,5,6]. In this work, we have fabricated synthetic ferrimagnets of Co/Gd with perpendicular magnetic anisotropy (PMA). We have prepared Si/Ta(3)/Pt(6)/[Pt(2)/Co(1.25)/Gd(0.8)]N/Ta(5)/Pt(3) multilayers with N= 3,5,7 on Si/SiO2(100) substrates by magnetron sputtering. All the thicknesses shown in the parentheses are in nm. Hysteresis loops have been measured via magneto-optic Kerr effect (MOKE) based microscope in polar mode at room temperature. The low remanence slanted hysteresis loops indicate the presence of skyrmion in these samples. Magnetization vs. field and/or temperature has been measured via a SQUID-VSM. We have studied the magnetic properties of these films at room temperature and below room temperature. The decreasing nature of saturation magnetization (Ms) with temperature indicates the ferrimagnetic nature of these multilayers. Further magnetic force microscopy (MFM) has been performed to confirm the presence of chiral spin textures. Labyrinth domains have been observed breaking into skyrmions when the external magnetic field is applied in an out-of-plane direction. The diameter of observed skyrmions ranges from 110 to 190 nm.

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86 **Manuel Suárez Rodríguez -** CIC nanoGUNE, Donostia-San Sebastian, Spain
Electrical Magnetochiral Anisotropy in Elemental Tellurium

Chiral materials offer an ideal platform for exploring the interplay between symmetry, spin & orbital effects, and electronic transport [1]. Among them, chiral elemental tellurium (Te), with its adequate electronic conductivity and one of the simplest crystalline chiral structures, emerges as an exceptional candidate. In this study, we synthesized single-crystalline Te flakes using a hydrothermal process and determined their handedness via transmission electron microscopy analysis. First, we investigated the electrical magnetochiral anisotropy (eMChA) along the chiral z-axis of Te crystals [2]. The observed nonlinear magnetoresistance, also referred to as unidirectional magnetoresistance (UMR) or bilinear magnetoresistance (BMR), is gate-tunable, chiral-dependent, and maximized when the external magnetic field and the applied current are collinear. The origin of the eMChA is attributed to the Edelstein effect, which arises from the radial angular momentum texture of Te along the chiral axis. This texture points inward or outward, depending on the handedness of the crystal, explaining the opposite sign of eMChA for opposite crystal handedness. Second, to comprehensively study the components of the eMChA conductivity tensor, we fabricated star-like devices and measured the eMChA along different crystallographic directions in both longitudinal and transverse configurations [3]. The data collected across all geometries align perfectly with the symmetry of chiral Te. In the longitudinal configuration, eMChA is observed when the current and the magnetic field are both along the x-axis, highlighting the radial angular momentum texture of Te in all directions, and not only along the z-axis. In the transverse configuration, eMChA is also detected when the current is applied along the x-axis and the magnetic field along the z-axis. This demonstrates that eMChA is permitted in the transverse configuration, even in the absence of magnetic ordering or hexagonal wrapping. Finally, new experiments are proposed to disentangle the spin and orbit contributions to the eMChA signal. The all-electric generation, control, and detection of angular momentum polarization in chiral Te flakes pave the way for leveraging chirality in the design of solid-state spin and orbitronic devices.

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Paul Noël - IPCMS, Strasbourg, France

88 *Nonlinear longitudinal and transverse magnetoresistances due to current-induced magnon creation-annihilation processes*

Materials with high spin-orbit torque (SOT) efficiency are essential for the development of new spin-orbitronic devices that enable storage and logic technologies that are fast, nonvolatile, and endurant. The proper metrology of these SOTs is pivotal for the technological development and for the understanding of their underlying physical mechanisms. Several techniques have been developed to quantify the SOTs, but there appear to be recurrent inconsistencies in the reported results on the SOT efficiency suggesting that the understanding of the involved processes is incomplete, even for the most studied Pt-based systems. Harmonic Hall resistance measurements are widely used to evaluate SOT effects, and more particularly the efficiency of the dampinglike (DL) torque and the fieldlike (FL) torque in normal metal (NM)/ferromagnet (FM) bilayers. The usual harmonic Hall resistance analysis assumes a constant magnetization, unaffected by the current and magnetic field. However, this reasoning does not hold in general, as the creation or annihilation of magnons induced by the spin current affects the magnetization. The excitation of magnons by an interfacial spin accumulation depends on the relative direction of the accumulated spins and the magnetization. Spin-flip scattering leads to the creation (annihilation) of magnons when the magnetization M is parallel (antiparallel) to the spin accumulation. In turn, the modification of the magnon population by a spin current leads to a change of the magnetization.

All magnetoresistances that depend on the magnitude of the magnetization, such as the anisotropic magnetoresistance, spin Hall magnetoresistance, planar Hall effect, and anomalous Hall effect, thus have a nonlinear contribution that depends on the current density. The change of magnon population due to spin currents in NM/FM bilayers give rise to transverse and longitudinal nonlinear magnetoresistances due to magnon creation or annihilation. We call this set of nonlinear magnetoresistances the magnon creation-annihilation magnetoresistances (m†mMRs). In particular, the transverse magnetoresistances due to the nonlinear planar Hall effect (m†mPHE) and nonlinear anomalous Hall effect (m†mAHE) were previously not accounted for in the harmonic Hall resistance measurements. Due to their similar symmetry to the SOT contributions, the torques can be strongly misestimated. Consequently, the widespread harmonic Hall resistance measurement technique that has been used to study heavy metals should include the m†mMRs to provide a correct estimation of the torque efficiency.

93 **Insu Baek** - POSTECH, Pohang, South Korea
Orbital Hall Conductivity Calculation through Hybrid Functionals

Narrow-gap semiconductors can have small charge conductivities with large spin Hall conductivities (SHCs) so that their spin Hall angles are larger than that of transition metals. Narrow-gap semiconductors may also have large orbital Hall conductivities (OHCs) because OHC generates SHC through spin-orbit coupling. However, in comparison to metals, a first-principle calculation for narrow-gap semiconductors has barely been discussed. Here, we investigate OHCs in diamond cubic Si, Ge, and α-Sn and zincblende GaAs, InAs, and InSb using the first-principle calculations with the hybrid functional. We find that these semiconductors have large negative OHCs except Si. The sign of OHC of Si becomes positive when the anomalous position is introduced, while the previous report predicted the negative sign [Baek et al. Phys. Rev. B 104, 245204 (2021)].

96 **Zoltán Kovács-Krausz** - Budapest University of Technology and Economics, Budapest, Hungary
Pressure-induced topological phase transition in ZrTe5

The transition metal pentatelluride ZrTe5 is a quasi-2D layered material in which the spin-orbit interaction leads to a topological insulator (TI) phase. While the monolayer is expected to be a 2D quantum spin Hall insulator, the multilayer, when grown using chemical vapor transport (CVT) techniques, appears to be in the weak TI phase, but close to the topological phase transition to strong TI.[1] The band structure is also highly sensitive to small changes in lattice constants, suggesting that application of hydrostatic pressure could be an effective avenue for studying the topological phase.[2] By fabricating ZrTe5 nanodevices and integrating them into a piston-cylinder pressure cell,[3] we perform detailed magnetotransport measurements on the devices at multiple pressures up to 2 GPa. The pressure-dependent magnetotransport results are analyzed through a multicarrier transport model to obtain band structure information. The signature of a topological phase transition is observed, evidenced by the closing and subsequent re-opening of the direct gap at the Γ point with increasing pressure, corresponding to a transition from weak to strong TI.[4] Such a transition is consistent with ab initio band structure calculations, as well as experimental observation of the weak topological phase in CVT-grown ZrTe5 in ambient conditions. The findings further substantiate that pressure is a valuable investigative tool for tuning the spin-orbit interaction in novel 2D and quasi-2D layered materials.

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99 **Jong-Guk Choi** - University of Gothenburg, Gothenburg, Sweden
Heavy metal-free orbital Hall nano oscillator

The orbital Hall effect (OHE) has attracted significant attention with various theoretical predictions and experimental reports suggesting it can generate giant angular momentum than the spin Hall effect (SHE). This has fueled interest in leveraging OHE for making energy-efficient spintronic devices. What remains interesting is the conversion of orbital angular moment into the spin counterpart and disentangling the contributions from spin Hall effect. The orbital currents can be converted into spin current using the spin-orbit coupling with two potential mechanisms: (1) indirect conversion, where the orbital current is converted into spin currents via an inserted heavy metal (HM) layer before exerting torque on the FM, or (2) direct conversion, the orbital current is directly converted into spin currents within the FM itself, generating the spin torque. The second mechanism, which involves direct conversion within the FM, guarantees a pure orbital torque effects with negligible effects from SHE, proving the existence and operation of orbital torque more clearly.

Here, we demonstrate auto-oscillations in a heavy metal-free Ti/Ni/NiFe structure, which we introduce as the first orbital Hall nano-oscillator (OHNO). In this heterostructure, the orbital currents generated in Ti thin films are converted to spin currents by large spin -orbit coupling in the Ni layer. However, since Ni has a large Gilbert damping, we utilize lower damping NiFe thin films as the active FM layer which experiences a converted spin torque. Our results show that the effective field from orbital torque is maximized at a Ti thickness of 10 nm and increases with Ni thickness. These results provide strong evidence for the direct mechanism, where pure orbital currents through their conversion in FMs induce auto-oscillations via orbital torque. Notably, the threshold current density flowing into the Ti layer in Ti(10 nm)/Ni(3 nm)/NiFe(4 nm) structure is 0.54×10^{12} A/m^2, which is less than the threshold current density of 0.56×10^{12}A/m^2 flowing into the Pt layer of Pt(10 nm)/Ni(3 nm)/NiFe(4 nm) structure. It indicates that the torque efficiency of this Ti/Ni/NiFe structure is comparable to that of Pt/Ni/NiFe structures, which relies on SOC-rich HMs. Our findings pave the way for utilizing orbital currents in spintronic devices, highlighting the potential for energy-efficient and heavy metal-free devices for more cost-effective and eco-friendly system.

100 **Antonio Bianco** - University of Genoa, Genoa, Italy
Highly efficient field free spin-orbit torque valve based on MoS2 operating at room temperature

Charge-to-spin and spin-to-charge conversion mechanisms in large spin-orbit materials are the new frontier of memory devices that operate via spin-orbit torque (SOT) switching of a magnetic electrode, driven by an applied charge current. In this work, we propose a novel memory device based on the semiconducting high-symmetry transition metal dichalcogenide (TMD) MoS_2, that operates as a SOT device in the writing process and a spin valve in the reading process. The device is composed of a heterostructure of MoS_2 and h BN flakes mechanically exfoliated from bulk single crystals and then deterministically stacked over a Si/SiO_2 substrate. Afterwards, electrical Ti-Au contacts on the MoS_2 flake and Co-valves on h BN flake are patterned using e-beam lithography. In this device, we demonstrate that stable voltage states at room temperature can be deterministically controlled by an extremely low switching current density even in zero field. Our device is competitive in terms of energetic efficiency.

102 **Sambit Ghosh -** University of Gothenburg, Gothenburg, Sweden

Fast and Long-Range communications with rapidly-tuned Spin-Torque Nano-oscillators

Wireless Sensor Networks (WSN) have seen an immense rise in the past decade. These networks have been employed in fields such Internet of Things (IoT), environmental monitoring, smart agriculture, lighting etc. Most of these applications work at relatively low data rates with low power consumption and data transmission ranges. Chirped Spread Spectrum (CSS) is a type of communication technique which has emerged to fulfil the market demands leading to a rapid growth of the WSN technology. Long Range (LoRa) communication protocol is one of the CSS techniques which allows up to 333 kms of theoretical data transmission range at 1 kbit/s data rate and upto 253 kbit/s at 8 metres in a free space line of sight (LoS) environment [1, 2]. Due to the growing demand of computations related to AI applications, there is now a need for faster long-range communications. The limitation of the current spread spectrum communications technique which are based on Phase Lock Loop (PLL) system with macro-sized CMOS voltage-controlled oscillators (VCO) is slow frequency tunability of the VCOs due to large parasitic reactive parameters such as inductance and capacitances. Spin-torque-nano-oscillators (STNOs), on the other hand are spintronic oscillators which have very small parasitic reactance parameters and demonstrate very fast frequency tunability due to their nano-scale size [3]. Here, we demonstrate a fast and long-range communication protocol based on a rapidly sweep-tuned STNO. The fast data rate is achieved due to intrinsically small amplitude-relaxation constant of a nano-sized STNO (100ns). This demonstration is performed using a vortex-state STNO operating at around 300 MHz. We have shown that STNO-based fast and long-range communication can be implemented with the data transmission rate up to 16 Mbit/s with a spreading factor of 1-4 with a low bit error rate. Furthermore, we demonstrate with the help of simulations that by using uniform magnetization state STNOs and/or GHz frequency range spin hall nano-oscillators we can increase the data rate to hundreds of Mbits/s working at higher operating frequencies.

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103 **Javier Sivianes Castaño -** Centro de Física de Materiales, Donostia-San Sebastián, Spain
Optical signatures of spin symmetries in unconventional magnets

The traditional framework of magnetism, centered on ferromagnetism and antiferromagnetism, is being redefined by emerging concepts like altermagnetism and unconventional p-wave magnetism. These phases are classified using spin group symmetries, which describe independent transformations of spins and lattices, unlike magnetic group symmetries. Altermagnets exhibit compensated collinear magnetism but differ from antiferromagnets via time-reversal (T) and rotation symmetries, enabling T-odd effects such as anomalous Hall and Nernst responses. Their spin-split Fermi surfaces with even rotational symmetry, observed via ARPES, make them ideal for surface-sensitive studies. In contrast, unconventional p-wave magnets host compensated noncollinear magnetism in parity (P)-odd systems, where T and fractional translation symmetries create a P-odd Fermi surface with large non-relativistic spin-splitting (~0.5 eV).This work explores spin symmetry effects on photoconductivity in unconventional magnets, focusing on the shift current in p-wave systems, which serve as an ideal platform for investigating the interplay between magnetism and nonlinear optical responses. Using the magnetic compound Mn_5Si_3 as a case study, we analyze its noncollinear p-wave phase, which emerges below 60 K and has been associated with various proposed magnetic orderings. Specifically, we investigate two distinct magnetic structures: a non-coplanar and a coplanar configuration, representing different classes of p-wave magnets. Through ab-initio calculations, we uncover the p-wave characteristics of these structures, characterized by spin polarization in k-space. Notably, in the coplanar phase, the spin polarization is perpendicular to the magnetization plane in real space, which can only be understood from spin symmetry arguments.The two structures differ in symmetry: the non-coplanar phase lacks crystal symmetry, while the coplanar phase belongs to space group $Pc222_1$. This distinction governs allowed shift current tensor components. Spin symmetry analysis further shows that the coplanar phase's constraints restore effective inversion symmetry, fully suppressing shift current. In contrast, the non-coplanar phase remains unrestricted. Ab-initio calculations of the shift photoconductivity spectra in both magnetic phases show that spin symmetries decisively determine the dominant photoconductivity contributions. This arises from spin symmetries being exact in the non-relativistic limit. Given that Mn_5Si_3 exhibits weak spin-orbit coupling, non-relativistic contributions dominate, making spin symmetries key to the understanding the photoconductivity response. Based on the calculated photoconductivity for both structures, we estimate the current expected to arise in a linear photogalvanic experiment. By exploiting the distinct symmetry properties of these structures, we propose a protocol to distinguish between the two magnetic configurations through their characteristic current responses to polarized light.

105 **Tom G. Saunderson -** Johannes Gutenberg Universität Mainz, Mainz, Germany
Orbital Rashba effects with Superconductivity

Modern spintronics must adapt to meet the challenges of the new era. Computer processors can no longer follow Moore's law yet the demand for greater computational power is ever increasing. Inventive solutions are therefore required to achieve the desired processing power whilst also being more energy efficient to combat the increasing effects of climate change. Recently "altermagnetism" [1], orbitronics [2], chiral magnetization dynamics [3] have been pushing the boundaries of what can be achieved using the spin of an electron for classical computation, whilst combining magnetic impurities, superconductivity and spin-orbit coupling provides a new platform for the generation of Majorana zero-modes needed for topological quantum computation [4]. Furthermore, recent advancements in orbitronics demonstrate remarkable efficiency gains using cost-effective materials [5], while spin-Hall mediated responses notably intensify near the superconducting transition [6]. Breaking inversion or time-reversal symmetry efficiently extracts these unconventional currents, however for material-specific predictions first principles techniques are essential.

Although theoretical methods for orbital currents are well-established, first principles techniques for supercurrents are still in their infancy. This talk aims to explore two approaches. Firstly, we employ maximally localized Wannier functions to investigate the influence of p-d hybridizations on enhancing the orbital Rashba Edelstein effect on particular surfaces of known metallic systems. Secondly, we utilize a Green's function-based superconducting first principles code which incorporates superconductivity [7] and magnetism [8] with substitutional impurities [7–10] on the same footing. This method combines the full complexity of the underlying electronic structure and Fermi surface geometry of the normal state with an effective parametrization of the superconducting state. Here, we will induce unconventional triplet densities in superconductors featuring complex orbital degrees of freedom and inversion symmetry breaking. Such methods will pave the way for first principles-based modeling of superconducting spintronics.

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106 **Hojun Lee** - Pohang University of Science and Technology, Pohang, South Korea
Modern theory calculation of the orbital Hall effect by Wannier interpolation

The orbital Hall effect (OHE), the orbital analog to the spin Hall effect, is a useful method to generate the flow of the electron's orbital angular momentum in solids. Large OHE has been predicted to exist for d-band transition metals [1,2]. However, most of these theoretical predictions have used the so-called atom-centered approximation (ACA). This approximation captures the contribution due to the motion of the electrons around the nuclei only and neglects the contribution from the interstitial region. Thus, it leads to a severe misestimation of the OHE. Recent studies [3,4] have tried to apply the modern theory of orbital magnetization to the OHE and reported the sizable inter-atomic contribution to OHE. The efficient and accurate first-principles approach for computing the OHE is based on Wannier interpolation. Here, we present the first-principles scheme that allows the OHE to be evaluated accurately and efficiently. We find that the additional terms related to the position operator, which were missed in the previous works [3,4], are essential to evaluate the OHE accurately. These terms are nonequilibrium analogs to the additional terms that appear in the equilibrium orbital magnetization calculation [5,6]. We present the OHE for several real materials. In most materials, the modern theory OHE is significantly larger than the OHE evaluated by the ACA, and the additional terms are comparable to the terms corresponding to the previous studies. We also reveal the physical meaning of the additional terms. It deepens understanding of the relationship between the OHE evaluated by the modern theory and the OHE evaluated by the ACA.

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Growth, characterization and THz time-domain spectroscopy of BiSb/Co

The efficient conversion of spin currents into charge currents is a key challenge in spintronics for next-generation memory and logic devices. Heterostructures of ferromagnets (FM) and heavy metals typically achieve this via the spin Hall and inverse spin Hall effects. Topological insulators (TIs), such as BiSb alloys, offer an alternative with superior spin-to-charge conversion (SCC) efficiency due to their robust surface states with perpendicular spin-momentum locking. However, integrating TIs into functional devices is challenging because their surface states are susceptible to degradation by exchange coupling with FM layers, breaking time-reversal symmetry. In this study, we fabricated $Bi_{0.89}Sb_{0.11}$ (x nm)/Co (2 nm)/Al (2.5 nm) heterostructures via RF magnetron sputtering on sapphire (0001) substrates, with aluminum capping to prevent oxidation. To distinguish bulk and surface contributions to SCC, we varied the BiSb thickness and implemented pre- and post-annealing treatments. Thinner films exhibited incomplete coverage, while thicker films developed vertical columnar growth. Growth optimization revealed that BiSb films in the 7.5–15 nm range, pre-annealed at 600–1280ºC and post-annealed at 225–275ºC, achieved high-quality, continuous coverage. Reflection high-energy electron diffraction (RHEED)patterns confirmed bidimensional growth. Terahertz time-domain spectroscopy (THz-TDS) revealed that BiSb films of 7.5 nm, grown on pre-annealed sapphire (1100ºC) and post-annealed at 275ºC, exhibited the highest SCC efficiency. The measured SCC efficiency was comparable to that of Pt/Co, one of the best-known SCC systems. Simultaneously, we are exploring the growth of BiSb using molecular beam epitaxy (MBE) on various substrates to compare the structural and electronic properties of samples obtained via sputtering and MBE. The objective is to achieve precise control over BiSb growth, enabling a systematic investigation of the different mechanisms contributing to spin-to-charge conversion. Specifically, this study aims to disentangle the roles of surface and bulk states, as well as distinguish between spin and orbital contributions, thereby providing deeper insight into the underlying physics of SCC in topological insulator/ferromagnet heterostructures.

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Spin-charge conversion efficiency with elemental Bi

As the rise in energy consumption of computers becomes increasingly problematic, spintronics has been proposed as a promising energy-efficient solution to complement classical CMOS transistor technology. In particular, the MagnetoElectric Spin-Orbit (MESO) device architecture, which encompasses both a non-volatile information storage (via a ferromagnet) and an all-electrical writing and readout, is a prime candidate for integrating spin logic into the existing electronics industry. Critical to the performance of such a device is the spin-charge conversion efficiency employed for the readout, so that a high output signal ΔR_{ISHE} could switch the magnetoelectric writing module of another downstream MESO device. While there have been demonstrations of the implementation of such devices, most efforts on the readout SO module demonstrated relatively low ΔR_{ISHE} at room temperature. As a Dirac semi-metal and one of the heaviest elements of the periodic table, Bi is expected to exhibit a large spin-orbit coupling (SOC) and peculiar transport properties that make Bi-based compounds promising candidates as spin-charge converters. According to some reports, elemental Bi displays indeed an advantageous combination of a high spin Hall angle θ_{SH}, a high spin diffusion length λ_s, as well as a high resistivity ρ_{Bi}, which should be key ingredients to improve the output signal of MESO devices. However, a certain disparity in the reported values for these material parameters is observed.

In this work, we carefully investigate how the growth and materials stacking by magnetron sputtering can influence the morphology of Bi and thus its integrability into nanoscale devices and, more importantly, how the spin-charge conversion efficiency is modulated by such parameters.

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Non-Trivial Spin-Orbit Torques in Co/Al and Ni/Al bilayers

The orbital Hall effect is a more general version of the spin Hall effect [1-4]. It allows for the conversion of a charge current into a transversal flow of angular momentum, potentially widening the palette of materials utilizable in spinorbitronics applications. The integration of ferromagnetic materials (FM) with light metals (LM) in bilayer devices provides a novel platform for exploring magnetic state manipulation utilizing orbital angular momentum. While the orbital Hall effect of the majority of transition light metals has been already explored with different techniques [5-9], the electrical measurement of orbital torque generations in Ti and Al based devices remains rather unexplored. In this comparative study of FM/Al, FM/Ti, and FM/Pt bilayers, we analyze the sp-case of Al. Independent measurements of harmonic Hall voltages and spin torque ferromagnetic resonance show giant spin-orbital Hall conductivities in Co/Al bilayers with opposite sign with respect to Co/Ti and Co/Pt. The thickness dependencies of both the nonmagnetic (Al, Ti) and ferromagnetic (Co) layers reveal a trend of spin-orbital Hall conductivities which suggests a dominant bulk contribution, and sign consistent with theoretical predictions for Al. However, cross-sectional TEM reveals a Co_xAl_x interlayer thickening with Al thickness, and additional measurements on Ni/Al and reversed-stack configurations show that the spin-orbital conductivity can switch sign upon replacing Co with

Ni or inverting the FM/NM stacking order. These observations, along with the anomalously large spin-orbital Hall conductivities, highlight the presence of extrinsic and interfacial mechanisms which play a crucial role for the torque generation both in sign and magnitude. Our findings underscore the potential of Al for spin-orbitronics applications but also highlight the lack of understanding on the mechanisms regulating the torque generation assisted by orbital angular momentum, thus the necessity of further studies to disentangle the interplay of bulk OHE, interface effects, and FM self-torque in light-metal-based heterostructures.

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