Frontiers of Orbital Physics: Statics, Dynamics, and Transport of Orbital Angular Momentum (SYOP)

jointly organised by
the Magnetism Division (MA),
the Surface Science Division (O),
the Crystalline Solids and their Microstructure Division (KFM),
the Thin Films Division (DS),
the Semiconductor Physics Division (HL) and
the Low Temperature Physics Division (TT)

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The interplay of orbital, spin, and lattice leads to not only exotic phases of matter such as orbital ordering in multiferroic materials and orbital Chern insulator states in twisted bilayer graphene but also dynamic phenomena including orbital Hall effect, orbital torque, and topological orbital magnetoelectric response. While so far the focus has been on spin currents, orbital currents, the flow of the electrons with finite orbital angular momentum, is found to be extremely efficient in many materials and can outperform conventional spin current effects. As recently demonstrated, orbital currents can additionally play a pivotal role in generating spin currents thus leading to torques with unprecedented amplitude to manipulate magnetization. On the other hand, optical means including vortex beams provide a potentially outstanding means of generating and manipulating orbital order and orbital transport. So far these effects have been observed in metallic heterostructures where light metals and their oxides generate strong orbital currents as well as oxidic 2DEG heterostructures that show efficient orbital to charge conversion thus showing that orbital currents can play a role in many systems. Developing methods and materials for harnessing orbital currents can thus potentially have significant impact and open a new direction in spintronics research. This session brings experts on the orbital physics from different areas of condensed matter physics in one place to promote collaborations beyond the boundaries of each community, share knowledge on cutting edge theoretical and experimental methods, and discuss challenges and future directions of the orbital physics. The invited speakers include not only experts on oxide multiferroic materials and spintronic devices but also on new experimental techniques that can unambiguously detect the orbital ordering and dynamics in solids and optical methods.

Overview of Invited Talks and Sessions

(Lecture hall H1)

Invited Talks

SYOP 1.1	Mon	9:30–10:00	H1	**Orbital degeneracy in transition metal compounds: Jahn-Teller effect, spin-orbit coupling and quantum effects** — •Daniel Khomskii
SYOP 1.2	Mon	10:00–10:30	H1	**Orbital magnetism out of equilibrium: driving orbital motion with fluctuations, fields and currents** — •Yuriy Mokrousov
SYOP 1.3	Mon	10:30–11:00	H1	**Orbitronics: new torques and magnetoresistance effects** — •Mathias Kläui
SYOP 1.4	Mon	11:15–11:45	H1	**Orbital and total angular momenta dichroism of the THz vortex beams at the antiferromagnetic resonances** — •Andrei Sirenko
SYOP 1.5	Mon	11:45–12:15	H1	**Observation of the orbital Hall effect in a light metal Ti** — •Gyung-Min Choi

Sessions

SYOP 1.1–1.5	Mon	9:30–12:15	H1	**Frontiers of Orbital Physics: Statics, Dynamics, and Transport of Orbital Angular Momentum**

SYOP 1: Frontiers of Orbital Physics: Statics, Dynamics, and Transport of Orbital Angular Momentum

Time: Monday 9:30–12:15 Location: H1

Invited Talk SYOP 1.1 Mon 9:30 H1
Orbital degeneracy in transition metal compounds: Jahn-Teller effect, spin-orbit coupling and quantum effects — •Daniel Khomskii — II Physikalisches Institut Universitaet zu Koeln Zuelpicher Str. 77 50937 Koeln, Germany

Transition metal compounds with orbital degeneracy display a number of specific interesting properties [1, 2]. Among them there are first of all the cooperative Jahn-Teller (JT) effect and corresponding orbital ordering. For t2g electrons also spin-orbit coupling (SOC) may play crucial role: for these states orbital moment is not quenched by crystal field. There may be a very nontrivial effects connected with the mutual influence of Jahn-Teller effect and SOC. In most cases SOC suppresses JT effect, but there are situation in which it can instead promote, activate it. Also very nontrivial quantum effects can occur in this case. In my talk, after a short general introduction, I will discuss in particular this mutual interplay of JT effect and SOC for different situations [3, 4]. [1] Daniel I. Khomskii and Sergey V. Streltsov, "Orbital Effects in Solids: Basics, Recent Progress, and Opportunities", Chem. Rev. 121, 2992-3030 (2021) [2] D.I. Khomskii ,"Orbital physics: glorious past, bright future", ECS J. Solid State Sci. Technol. 11, 054004 (2022) (special issue in honour of 100 birthday of J.B. Goodenough) [3] S. V. Streltsov, D. I. Khomskii,"Jahn-Teller effect and spin–orbit coupling: friends or foes?", Phys.Rev. X 10, 031043 (2020) [4] Sergey V. Streltsov, Fedor V. Temnikov, Kliment I. Kugel, and Daniel I. Khomskii, "Interplay of the Jahn–Teller Effect and Spin-Orbit Coupling: The Case of Trigonal Vibrations", Phys. Rev. B 105, 205142 (2022)

Invited Talk SYOP 1.2 Mon 10:00 H1
Orbital magnetism out of equilibrium: driving orbital motion with fluctuations, fields and currents — •Yuriy Mokrousov — Forschungszentrum Jülich GmbH, Jülich, Germany — Johannes Gutenberg-University Mainz, Mainz, Germany

In modern spintronics properties of non-equilibrium orbital polarization and orbital currents start to attract significant attention. In this talk we will review the theory of orbital magnetism in low-symmetric crystals and corresponding current-induced orbital magnetization. We will in particular show that applied electrical currents and optical pulses can drive non-equilibrium orbital magnetism and currents of orbital angular momentum. These orbital currents can be used to transmit angular momentum over large distances in solids, and can be utilized to exert sizeable orbital torques on magnetization thus enabling magnetic switching even in light materials with weak spin-orbit interaction. Moreover, we will underline that in fluctuating magnets spin excitations can mediate a significant orbital response which can be coupled to temperature gradients so as to ignite thermal orbital currents. We will thus attempt to promote a paradigm that unleashing non-equilibrium orbital physics and entanglement of spin and orbital degrees of freedom in diverse classes of materials can lead to much richer physics than previously expected, and might provide a key to realization of novel properties of matter out of equilibrium as well as energy-efficient applications.

Invited Talk SYOP 1.3 Mon 10:30 H1
Orbitronics: new torques and magnetoresistance effects — •Mathias Kläui — Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany

Experimentally, orbital currents for efficient manipulation of magnetization have only recently started to be explored. We studied spin orbit torques generated in TmIG/Pt/(Cu(O)x) heterostructures. Varying the CuOx and Pt layer thicknesses, we realized a 16x increase of the spin orbit torques exerted on the TmIG compared to conventional TmIG/Pt [1]. Such an enhancement is extremely surprising if one considers only conventional spin-charge interconversion based on spin orbit coupling effects and given the low spin-orbitcoupling of Cu and Cu(O)x one does not expect large torques. However, the results can be naturally explained as Cu(O)x can generate large orbital currents that are then converted to spin currents in the Pt layer, which then manipulate the TmIG extremely efficiently. In addition, we found in Py/Cu(O)x a Orbital Rashba-Edelstein Magnetoresistance effect related to the conventional spin Hall magnetoresistance [2]. In particular in this work, the length scale of the orbital to spincurrent 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]. [1] S. Ding, MK et al., Phys. Rev. Lett. 125, 177201 (2020) [2] S. Ding, MK et al., Phys. Rev. Lett. 128, 067201 (2022) [3] D. Go, MK et al., Perspectives Review in EPL 135, 37001 (2021)

15 min. break

Invited Talk SYOP 1.4 Mon 11:15 H1
Orbital and total angular momenta dichroism of the THz vortex beams at the antiferromagnetic resonances — •Andrei Sirenko — Department of Physics, New Jersey Institute of Technology, Newark, New Jersey 07102, USA

Light beams with orbital angular momentum (OAM), or vortex beams, can couple to magnetism exhibiting dichroisms in a magnetized medium. Terahertz (THz) vortex beams with various combinations of the orbital angular momentum L=+/-1, +/-2, +/-3, and +/-4 and spin angular momentum S = +/-1, or conventional circular polarization, were used for studies of the magnon spectra at the antiferromagnetic resonance conditions in TbFe3(BO3)4 and Ni3TeO6 single crystals. In both materials we observed strong vortex beam dichroism for the magnon doublet, which is split in an external magnetic field applied along the spin ordering direction. The absorption conditions at the magnon frequencies depend on the total angular momentum of light J that is determined by the combination of the spin and orbital angular momenta: J=S+L. For the higher orders of l, the selection rules for AFM resonances dictated by l completely dominate over that for conventional circular polarization. Our results demonstrate the high potential of the vortex beams with OAM as a new spectroscopic probe of magnetism in matter. This work was performed in collaboration with T. N. Stanislavchuk, P. Marsik, L. Bugnon, M. Soulier, C. Bernhard, V. Kiryukhin, and S.-W. Cheong.

Invited Talk SYOP 1.5 Mon 11:45 H1
Observation of the orbital Hall effect in a light metal Ti — •Gyung-Min Choi — Sungkyunkwan University, Suwon, Korea

The orbital angular momentum is a core ingredient of orbital magnetism, spin Hall effect, giant Rashba spin splitting, orbital Edelstein effect, and spin-orbit torque. However, its experimental detection is tricky. In particular, direct detection of the orbital Hall effect remains elusive despite its importance for the electrical control of magnetic nanodevices. Here we report the direct observation of the orbital Hall effect in a light metal Ti1. The Kerr rotation by the accumulated orbital magnetic moment is measured at Ti surfaces, whose result agrees with theoretical calculations semi-quantitatively. As another evidence, we measured the orbital torque in the Ti/ferromagnet heterostructures, from which we determine the orbital Hall angle >0.21. Our experimental results confirm the orbital Hall effect in a light metal Ti and hint at opportunities in the emerging field of orbitronics.