MA 23: Focus Session: Magneto-Transport and Magneto-Optics of Higher Orders in Magnetization I

Magneto-transport and magneto-optic effects linear in the magnetization M (e.g. anomalous Hall effect (AHE), Faraday effect or magneto-optic Kerr effect (MOKE)) are important magnetic phenomena in spintronics and magneto-optics for the characterization of magnetic samples by vectorial magnetometry, microscopy, spectroscopy and pump probe experiments. However, already some time ago, it has been shown that the angular dependence of the anisotropic magnetoresistance and of magneto-optic effects contains higher-order-in-M terms. In the last decade, these effects beyond the linear dependence on M, e.g. quadratic effects proportional to M^2, have been mainly utilized to investigate antiferromagnetic materials.

Recently, the third-order MOKE proportional to M^3, so-called cubic MOKE, was reported to be sensitive to the structural domain twinning in thin-film samples of (111) orientation. By investigating AHE and MOKE of higher orders in M, the multipolar structure of the Berry curvature in magnetization space can be probed. These additional higher-order contributions in standard Hall or polar MOKE setup geometries are able to trace the in-plane magnetization while the linear effect keeps sensitive to the out-of-plane magnetic moment. This can be utilized, for example, to detect spin-orbit torques magneto-optically.

This Focus Session introduces the main magneto-transport and magneto-optic effects of higher orders in magnetization, draws connections between both research fields, distinguishes between already known and new higher-order effects and presents first applications beyond the study of antiferromagnets by quadratic effects.

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Time: Wednesday 9:30–13:00 Location: H20

Invited Talk MA 23.1 Wed 9:30 H20

Magneto-transport effects in crystalline magnetic films — •Sebastian T. B. Goennenwein — Fachbereich Physik, Universität Konstanz, Konstanz, Germany

The magneto-transport response of magnetically ordered materials – such as the anisotropic magneto-resistance (AMR), or the anomalous Hall effect (AHE) – has been extensively studied in the last decades. While the magneto-transport response of amorphous or polycrystalline samples can often be described by comparatively simple expressions, the implications of crystal symmetry lead to a much richer and more complex response in single-crystalline specimens [1]. In particular, higher-order terms with a seemingly 'unconventional' dependence on the magnetization can be allowed by symmetry, and indeed also be detected in experiment [2].

In the presentation, I will first review the implications imposed onto the magneto-transport response by crystal symmetry, and then discuss typical experimental results, focusing on crystalline (Ga,Mn)As films as a prototypical and well-studied example [3,4]. If time permits, I will furthermore touch upon the impact of crystalline symmetry onto the magneto-thermopower response.

[1] R. R. Birss, *Symmetry and Magnetism* (North-Holland, Amsterdam, 1966)
[2] P. K. Muduli *et al.*, Phys. Rev. B **72**, 104430 (2005)
[3] W. Limmer *et al.*, Phys. Rev. B **74**, 205202 (2006)
[4] W. Limmer *et al.*, Phys. Rev. B **77**, 205210 (2008)

Invited Talk MA 23.2 Wed 10:00 H20

Cubic magneto-optic Kerr effect in thin films depending on structural domain twinning and crystal orientation — •Robin Silber[1], Maik Gaerner[2], Jaroslav Hamrle[3], and Timo Kuschel[2] — [1]VSB - Technical University of Ostrava, Czechia — [2]Bielefeld University, Germany — [3]Charles University, Czechia

Many of the second-order effects in magnetization in magneto-transport and magneto-optics are of practical importance in research and applications today. In the case of magneto-optic Kerr effect (MOKE), the second-order effect (quadratic MOKE) has been utilized to e.g. study antiferromagnetics [1] or to investigate spin-orbit torques in insulating structures [2], while the third-order effect (cubic MOKE, CMOKE) has only been discussed rarely so far [3, 4]. Here we provide a solid theoretical background for the phenomenological description of CMOKE for (111)- and (001)-oriented cubic crystal structures and compare the results with the experimental data collected on Ni(111) and Ni(001) thin film samples. CMOKE manifests as a three-fold angular dependence in Ni(111) thin films while for Ni(001) a four-fold angular dependence of CMOKE is predicted. The dependence on the incidence angle is changing from one to the other crystal orientation. Furthermore, the strength of the CMOKE is also sensitive to the degree of twinning of the Ni(111) thin film [4].

[1] V. Saidl et al., Nat. Photonics 11, 91 (2017).
[2] M. Montazeri et al., Nat. Commun. 6, 8958 (2015).
[3] A. V. Petukhov et al., J. Appl. Phys. 83, 6742 (1998).
[4] M. Gaerner et al., Phys. Rev. Applied 22, 024066 (2024).

MA 23.3 Wed 10:30 H20

Unconventional Magneto-Optical Effects — •Rudolf Schäfer and Ivan Soldatov — Leibniz Institute for Solid State and Materials Research (IFW), Dresden, Germany

Numerous magneto-optical reflection effects will be discussed that have hardly been considered in the past and that lead to intensity-based domain contrast in the absence of analyser and compensator in a wide-field magneto-optical microscope: (i) The transverse Kerr effect can be applied for in-plane magnetized material. (ii) In- and out-of-plane magnetized material can be imaged by circularly polarized light, leading to domain contrasts with different symmetry as the conventional Kerr contrast. (iii) Plane-polarized light at a specific angle can be employed for both in-plane and perpendicular media (Oppeneer effect). (iv) Perpendicular light incidence leads to a contrast on in-plane materials that is quadratic in the magnetization and to a domain boundary contrast. In case (iii), the contrast is generated by magnetic circular dichroism, while magnetic linear dichroism is responsible for the contrast in case (iv). The latter, being due to the diagonal elements in the quadratic dielectric magneto-optical tensor has a different symmetry as the conventional linear birefringence (Voigt) effect which is due to the off-diagonal elements. The domain*boundary contrast is caused by the magneto-optical gradient effect, which also exists as birefringence and dichroic effect. Reference: R. Schäfer, et al., Appl. Phys. Rev. 8, 031402 (2021)

MA 23.4 Wed 10:45 H20

Multipolar anisotropy in anomalous Hall effect from spin-group symmetry breaking — •Zheng Liu — University of Science and Technology of China, Hefei, China

Traditional view of the anomalous Hall effect (AHE) in ferromagnets is that it arises from the magnetization perpendicular to the measurement plane and that there is a linear dependence on the latter. However, this view is squarely challenged by a number of experiments recently, urging for a thorough theoretical investigation on the fundamental level. We find that for strong magnets, it is more appropriate and fruitful to regard the AHE as a spin-group symmetry breaking phenomenon where the critical parameter is the spin-orbit interaction strength, which involves a much smaller energy scale. Born out of our framework is a rich multi-polar relationship between the anomalous Hall conductivity and the magnetization direction, with each pole being expanded progressively in powers of the spin-orbit coupling strength. For the leading order contribution, i.e., the dipole, its isotropic part corresponds to the traditional view, and its anisotropic part can lead to the in-plane AHE where the magnetization lies within the measurement plane. Beyond the dipolar one, the octupolar structure offers the leading order source of nonlinearity and hence introduces unique anisotropy where the dipolar structure cannot. The dipolar and octupolar structure offers a unified explanation for the in-plane AHE recently observed in various ferromagnets. Our theory lays the ground for decoding the coupling between various transport and optical phenomena and the magnetic orders.

15 min. break

Invited Talk MA 23.5 Wed 11:15 H20

electrical and optical detection of the multipolar structure in the magnetization space — •Dazhi Hou — University of Science and Technology of China, Hefei, China

The anomalous Hall effect (AHE) in ferromagnetic materials has traditionally been understood to originate from a dipolar magnetization, with the effect typically showing sensitivity to out-of-plane magnetization. In contrast, we present compelling evidence that the AHE fundamentally arises from multipolar contributions to the magnetization. This discovery enables the observation of AHE under in-plane magnetization in cubic ferromagnets such as iron and nickel, challenging the conventional view. The magnitudes of these multipoles align with theoretical predictions from our recently proposed multipolar structure of Berry curvature in magnetization space. Notably, the octupole term can dominate the AHE in certain conditions, as observed in a van der Waals ferromagnet. Furthermore, we introduce a novel MOKE geometry that detects both the magnitude and direction of the perpendicular magnetization component, enabled by the multipolar structure of Berry curvature. This orthogonal MOKE geometry reveals unique angle-dependent behaviors, providing a direct probe of the magnetization multipoles at optical frequency. Our findings offer new insights into the quantum geometry of magnetization and open new avenues for probing magnetic orders across both electrical and optical domains, offering a unified framework for the study of multipolar magnetization in the context of Berry curvature.

MA 23.6 Wed 11:45 H20

Polarization variation method for investigation of magnetic and magneto-optical anisotropies — •Tomáš Ostatnický, Zeynab Sadeghi, Jozef Kimák, Peter Kubaščík, Eva Schmoranzerová, Lukáš Nádvorník, František Trojánek, and Petr Němec — Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic

We present a newly developed method for all-in-one measurement of both magnetic anisotropy and anisotropy of magneto-optical (MO) coupling in magnetic materials. It fully relies on the quadratic MO response (in magnetization) of a sample. The method works in both the reflection and transmission at near-normal incidence, it is not limited by presence of components with linear MO response in setup and it does not require sample rotation during the experiment; it therefore allows measurements with a sample placed inside a cryostat. Measurement scheme is based on a scanning of the probe beam polarization change upon rotation of external magnetic field for several linear polarization of the probe laser. Numerical analysis of the full set of data allows us to recover magnitude and anisotropy of the MO coupling coefficient and we further determine the magnetic anisotropy of the sample by a fitting procedure. We demonstrate the precision of the method by characterizing several GaMnAs ferromagnetic samples with different Mn contents. Reliability of the method is confirmed by a perfect fit of the MO coupling constants with the predictions based on the G-tensor formalism and by a mutual agreement of magnetic anisotropic constants, determined from data acquired at different wavelengths.

MA 23.7 Wed 12:00 H20

Magnetic polymorphism in 2D layered antiferromagnets — •Shiwei Wu — Department of Physics, Fudan University

Polymorphism, commonly denoting the variety of molecular or crystal structures, is a vital element in many natural science disciplines. In van der Waals layered antiferromagnets, a new type of magnetic polymorphism is allowed by having multiple layer-selective magnetic structures with the same total magnetization. However, resolving and manipulating such magnetic polymorphs remain a great challenge. In this talk, I will report the use of phase-resolved magnetic second-harmonic generation microscopy to elucidate such magnetic polymorphism in the 2D semiconducting layered antiferromagnet CrSBr, and demonstrate how the magnetic polymorphs can be deterministically switched in an unprecedented layer-selective manner. With the nonlinear magneto-optical technique unveiling the magnetic symmetry information through the amplitude and phase of light, we could unambiguously resolve the polymorphic spin-flip transitions in CrSBr bilayers and tetralayers. Remarkably, the deterministic routing of polymorphic transitions originates from the breaking of energy degeneracy via a magnetic layer-sharing effect: the spin-flip transitions in a tetralayer are governed by the laterally extended bilayer, which acts as a *control bit*. We envision such controllable magnetic polymorphism to be ubiquitous for van der Waals layered antiferromagnets, and could lead to conceptually new design and construction of spintronic and opto-spintronic devices for probabilistic computation and neuromorphic engineering.

MA 23.8 Wed 12:15 H20

Anisotropy of the contributions to the orbital magnetization — •Milan Vrána[1,2] and Jaroslav Hamrle[1,2] — [1]Charles University, Prague, Czech Republic — [2]Czech Technical University, Prague, Czech Republic

The general definition of orbital magnetization is the change in the grand canonical potential, Ω, with respect to the external magnetic field: $\mathbf{m}_{\text{orb}} = -\partial\Omega/\partial\mathbf{B}$. The orbital magnetization consists of two distinct contributions [1]. The first term originates from the orbital motion of electrons and is given by $\mathbf{m}_{\text{dip}} = -\frac{e}{2}\langle\psi|\mathbf{r}\times\mathbf{v}|\psi\rangle$. The second term, $\mathbf{m}_{\text{kden}}$, has been reinterpreted as arising from changes in the density of **k**-points in phase space due to the concurrent presence of both the magnetic field and the Berry curvature, $\mathbf{\Omega}$ [2]. This violates Liouville's theorem, leading to an expansion or contraction of the phase space volume by a factor of $(1+\frac{e}{\hbar}\mathbf{B}\cdot\mathbf{\Omega})$. In the model material bcc Fe, we demonstrate that $\mathbf{m}_{\text{kden}}$ is negligible in the [100] magnetization direction, whereas $\mathbf{m}_{\text{dip}}$ is negligible in the [111] direction. It demonstrates different nature of the orbital magnetization for different magnetization directions. However, the magnitude of the total orbital magnetization, $\mathbf{m}_{\text{orb}} = \mathbf{m}_{\text{dip}} + \mathbf{m}_{\text{kden}}$, remains nearly independent of the magnetization direction.

[1] F. Aryasetiawan, K. Karlsson, *Modern theory of orbital magnetic moment in solids*, J. Phys. Chem. Solids **128**, 87 (2019).

[2] Di. Xiao, *Berry Phase Modification to Electron Density of States and Its Applications*, dissertation, Texas University (2007).

Invited Talk MA 23.9 Wed 12:30 H20

Ultrafast Néel order dynamics detected by time-resolved magneto-optical Voigt effect — •Haibin Zhao — Fudan University, Shanghai, China

The time-resolved magneto-optical (MO) Voigt effect can be principally utilized to study the Néel order dynamics in antiferromagnetic (AFM) materials. In this talk, I will present the quench of AFM order by ultrafast laser pulses in both collinear and noncollinear AFM spin configurations in antiferromagnets with negligible net magnetization probed by the time-resolved MO Voigt effect. For CoO with collinear spin configuration, the quench time of Néel order slows down pronouncedly near the Néel temperature (TN). In contrast, for Mn3Sn with an inverse triangular spin structure, The AFM order quench time shows negligible change with increasing temperature approaching the TN. This atypical behavior can be explained by the influence of weakened Dzyaloshinskii-Moriya interaction rather than the smaller exchange splitting on the diminished AFM order near TN. The temperature-insensitive ultrafast spin manipulation can pave the way for high-speed spintronic devices either working at a wide range of temperature or demanding spin switching near TN. The modulated Voigt angle in Mn3Sn is significantly larger than the polarization rotation due to the crystal-structure related linear dichroism effect and the modulated MO Kerr angle arising from the ferroic ordering of cluster magnetic octupole.