MA 21: Phd Focus Session: Altermagnets: Foundations and Experimental Evidence

Altermagnetism, a new type of collinear magnetism, is emerging as a platform to explore a wide array of physics and applications, from topology and superconductivity to dissipationless currents, ultrafast dynamics, efficient charge-to-spin conversion, and giant magnetoresistance. Altermagnets are magnetically compensated and collinear, with opposite magnetic moments residing on crystal-sublattices connected by rotation or mirror symmetries, which, notably, makes their spin symmetries mutually exclusive from collinear ferromagnets and antiferromagnets. Remarkably, as a consequence, particles such as electrons moving inside altermagnets can be strongly spin-polarized and spin-split, even though the magnetism overall compensates. The unconventional splitting sets altermagnets apart as intriguing spin-active material alternatives to conventional ferromagnets and materials with large spin-orbit coupling. In this session, we explore altermagnetism and its potential properties in various areas of solid-state physics by fostering discussion between communities and between young and experienced scientists. Starting from a pedagogical introduction to the field, we will uncover spectroscopic evidence of the spin-polarized electrons, magnetotransport, emerging phenomena in superconductor hybrid systems, and octupolar order, positioning altermagnetism as a new paradigm for addressing diverse applied and fundamental challenges in solid-state research.

Organizers: Anna Birk Hellenes (Johannes Gutenberg University Mainz), Alfred Dal Din (University of Nottingham), Marius Weber (Technical University Kaiserslautern-Landau), Bjørnulf Brekke (Norwegian University of Science and Technology), Miina Leiviskä (Czech Academy of Sciences)

Time: Wednesday 9:30–13:15 Location: H 1058

Invited Talk MA 21.1 Wed 9:30 H 1058

Altermagnets: An unconventional magnetic class — •Tomas Jungwirth — Institute of Physics, Czech Academy of Sciences, Cukrovarnicka 10, 162 00 Praha 6, Czech Republic

Conventional magnets can be divided in two basic classes - ferromagnets and antiferromagnets. In the first part of the talk, we will recall that the ferromagnetic order offers a range of phenomena for energy efficient IT, while the vanishing net magnetization in antiferromagnets opens a possibility of combining ultra-high energy efficiency, capacity and speed of future IT. In the main part of the talk we will move on to our recent predictions of instances of strong time-reversal symmetry breaking and spin splitting in electronic bands, typical of ferromagnetism, in crystals with antiparallel compensated magnetic order, typical of antiferromagnetism. We resolved this apparent fundamental conflict in magnetism by symmetry considerations that allowed us to classify and describe a third basic magnetic class. Its alternating spin polarizations in both crystal-structure real space and electronic-structure momentum space suggested a term altermagnetism. A d-wave spin polarization order in altermagnets is a direct counterpart of the unconventional d-wave superconducting order in cuprates. We will discuss predictions and initial experimental verifications in which altermagnets combine merits of ferromagnets and antiferromagnets, that were regarded as principally incompatible, and have merits unparalleled in either of the two conventional magnetic classes.

Invited Talk MA 21.2 Wed 10:00 H 1058

Experimental evidence of time-reversal symmetry breaking in altermagnetic RuO_2 — •O. Fedchenko[1], J. Minar[2], A. Akashdeep[1], S.W. D'Souza[2], D. Vasilyev[1], O. Tkach[1], L. Odenbreit[1], Y. Lytvynenko[1], Q. Nguyen[3], D. Kutnyakhov[4], N. Wind[4], L. Wenthaus[4], M. Scholz[4], K. Rossnagel[5,4], M. Hoesch[4], M. Aeschlimann[6], B. Stadtmüller[1], M. Kläui[1], G. Schönhense[1], T. Jungwirth[7,8], A. Birk Hellenes[1], G. Jakob[1], L. Šmejkal[1,7], J. Sinova[1,7], and H.-J. Elmers[1] — [1]JGU Mainz, Germany — [2]NTC UWB, Czech Republic — [3]SLAC, USA — [4]DESY Hamburg, Germany — [5]CAU Kiel, Germany — [6]RPTU, Kaiserslautern, Germany — [7]Institute of Physics ASCR, Czech Republic — [8]University of Nottingham, UK

Our experimental study focuses on epitaxial RuO_2, the material of the altermagnetic (AM) class. This class has been predicted to combine properties of ferromagnets (FMs) and antiferromagnets (AFMs). Thus, like AFMs, AMs exhibit compensated magnetic order, and moreover, like FMs, they promote strong spin polarization in the band structure [1]. The corresponding unconventional mechanism is the time-reversal symmetry breaking without magnetization – the primary signature of AMs. Using time-of-flight momentum microscopy, we have spectroscopically measured the key signature of the AM phase, i.e. a magnetic circular dichroism (MCD), for the collinear compensated altermagnet RuO_2 [2].

[1] L. Šmejkal *et al.*, Phys. Rev. X **12**, 011028 (2022).
[2] O. Fedchenko *et al.*, arXiv 2306.02170v1 (2023).

MA 21.3 Wed 10:30 H 1058

Magneto-transport and magnetometry measurements in altermagnetic RuO_2 — •Ruben Dario Gonzalez Betancourt[1,4], Teresa Tschirner[1,2], Philipp Kessler[2,3], Tommy Kotte[5], Dominik Kriegner[4,6], Bernd Büchner[1,2,6], Joseph Dufouleur[1], Libor Šmejkal[4,7], Jairo Sinova[4,7], Ralph Claessen[2,3], Tomas Jungwirth[4,8], Simon Moser[2,3], Helena Reichlová[4,6], and Louis Veyrat[1,2,3] — [1]IFW Dresden — [2]Würzburg-Dresden Cluster of Excellence ct.qmat, Germany — [3]Physikalisches Institut, Universität Würzburg, Germany — [4]Institute of Physics, AV ČR, Prague — [5]HLD-EMFL, Helmholtz-Zentrum Dresden-Rossendorf — [6]IFMP, TU Dresden — [7]JGU, Mainz — [8]University of Nottingham

Altermagnets are a newly identified class of magnetic materials [1] that exhibit alternating spin polarization in both their real and reciprocal space. This intriguing feature allows altermagnetic materials to demonstrate important spintronic effects, such as the anomalous Hall effect (AHE), previously believed to be absent in collinear compensated systems. RuO_2 has emerged as an altermagnetic model material, and in this presentation, I will summarize the experimental evidence of the AHE in this material [2,3]. Additionally, I will focus on detailed magnetometry measurements on RuO_2 thin films grown on TiO_2 substrates with various orientations and compare the results with transport measurements.

[1] L. Šmejkal et al., Phys. Rev. X. 12.031042 (2022) [2] Feng, Z., et al. Nat. Electron. 5, 735*743 (2022) [3] T. Tschirner et al., APL Mater. 11, 101103 (2023)

MA 21.4 Wed 10:45 H 1058

Imaging the altermagnetic domain structure in MnTe — •Oliver Amin[1], Alfred Dal Din[1], Evangelos Golias[2], Yuran Niu[2], Alexei Zakharov[2], Sarnjeet Dhesi[3], Tomas Jungwirth[4], Kevin Edmonds[1], and Peter Wadley[1] — [1]University of Nottingham, Nottingham, UK — [2]MAX IV, Lund, Sweden — [3]Diamond Light Source, Harwell, UK — [4]Institute of Physics, Prague, Czech Republic

Altermagnets are collinear, fully compensated magnetic systems, in which the sublattice magnetisations are connected through a rotation symmetry combined with time inversion. This reduced symmetry arises from the asymmetric local environments surrounding the magnetic sites and, as a result, the electronic band structure exhibits large momentum-dependent spin splitting that allows for time-inversion broken phenomena, unique in a compensated magnetic material. Understanding the domain structure of altermagnetic materials is crucial for elucidating the connection between the orientation of the compensated moment, called the Néel vector, and the emergence of time symmetry breaking phenomena. Here we show, in thin film altermagnetic candidate material, α-MnTe, that X-ray magnetic circular dichroism in combination with photoemission electron microscopy (XMCD-PEEM) can be used to spatially resolve domain structure related to the altermagnetic symmetries. We confirm that the orientation of the Néel domains is essential in determining the sign of the XMCD signal and uniquely defines a map of the local sublattice magnetisation direction.

MA 21.5 Wed 11:00 H 1058

Supercell Altermagnets — •Rodrigo Jaeschke-Ubiergo[1], Venkata Krishna Bharadwaj[1], Tomáš Jungwirth[2], Libor Šmejkal[1], and Jairo Sinova[1] — [1]Institut für Physik, Johannes Gutenberg Universität Mainz, Germany — [2]Inst. of Physics Academy of Sciences of the Czech Republic, Praha, Czech Republic

Altermagnets are compensated magnets with unconventional d, g, and i-wave spin order in reciprocal space. So far the search for new altermagnetic candidates has been focused on materials in which the magnetic unit cell is identical to the non-magnetic one, i.e. magnetic structures with zero propagation vector. Here, we substantially broaden the family of altermagnetic candidates by predicting supercell altermagnets. Their magnetic unit cell is constructed by enlarging the nonmagnetic primitive unit cell, resulting in a non-zero propagation vector for the magnetic structure. This connection of the magnetic configuration to the ordering of sublattices gives an extra degree of freedom to supercell altermagnets, which can allow for the control over the order parameter spatial orientation. We identify realistic candidates $MnSe_2$ with a d-wave order, and $RbCoBr_3$, $CsCoCr_3$, and $BaMnO_3$ with g-wave order. We demonstrate the reorientation of the order parameter in $MnSe_2$, which has two different magnetic configurations, whose energy difference is only 5 meV, opening the possibility of controlling the orientation of the altermagnetic order parameter by external perturbations.

MA 21.6 Wed 11:15 H 1058

Spontaneous formation of altermagnetism from orbital ordering — •Johannes Knolle[1], Valentin Leeb[1], Alexander Mook[2], and Libor Smejkal[2] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, TQM, 85748 Garching, Germany — [2]Institute of Physics, Johannes Gutenberg-University Mainz, Staudingerweg 7, Mainz 55128, Germany

Altermagnetism has emerged as a third type of collinear magnetism. In contrast to standard antiferromagnets, sublattices of anti-aligned spins are not connected by simple translations or inversion but require additional real-space rotations. Therefore, most proposals for materials realization concentrate on crystals that already have this low symmetry. Here, we show that altermagnetism can also form spontaneously as an interaction-induced electronic instability in a high symmetry crystal. We provide a microscopic example of a two orbital model showing that the coexistence of antiferromagnetic and orbital order realizes an altermagnetic phase. We quantify experimental observables like the spin conductivity and discuss possible material candidates with orbital ordering.

15 min. break

Invited Talk MA 21.7 Wed 11:45 H 1058

Is my altermagnet ferromagneto-octupolar or ferromagneto-triakontadipolar (and does it matter)? — •Nicola Spaldin — Materials Theory, ETH Zurich, Switzerland

The non-relativistic spin splitting characteristic of altermagnets is usually understood in terms of local antiferromagnetically ordered spin magnetic dipole moments and their associated symmetries. Sometimes it can be helpful, however, to work with a *ferroic* ordering of local entities, all of which have the same size and orientation, rather than an antiferroic arrangement. In particular, ferroic orders often carry a readily identifiable associated macroscopic thermodynamic measurable quantity, such as the magnetization in ferromagnets or the polarization in ferroelectrics. In this talk I will show that d-wave altermagnetism results from the ferroic ordering of local non-relativistic magnetic octupoles. Using MnF_2 as an example, we'll see that this *ferromagneto-octupolarization* provides a convenient framework for understanding or predicting properties such as time-reversal symmetry breaking, piezomagnetism, neutron-scattering asymmetry, surface magnetization and second-order magnetoelectric response, as well as the usual non-relativistic spin splitting. In g-wave altermagnets, the corresponding ferroically ordered quantity is the magnetic triakontadipole, which gives us yet more interesting physics as well as a spectacularly good name.

Invited Talk MA 21.8 Wed 12:15 H 1058

Negative critical current in an altermagnet Josephson junction — •Carlo Beenakker — Instituut-Lorentz, Leiden University, The Netherlands

Altermagnets (metals with a d-wave magnetization that alternates direction in momentum space) differ from ferromagnets and antiferromagnets in that they combine a spin-polarized Fermi surface with a vanishing net magnetization. This unusual combination radically modifies the flow of a supercurrent in a junction where an altermagnet connects two superconductors (Josephson junction). The sign of the supercurrent oscillates as a function of the length of the junction, because of a spin-polarisation of the bound states in the junction (Andreev levels): Spin-up and spin-down levels are phase-shifted in opposite directions.

MA 21.9 Wed 12:45 H 1058

Superconductor-altermagnet memory functionality without stray fields — •Hans Gløckner Giil and Jacob Linder — Center for Quantum Spintronics, Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

A novel class of antiferromagnets, dubbed altermagnets, exhibit a non-relativistically spin-split band structure reminiscent of d-wave superconductors, despite the absence of net magnetization. This unique characteristic enables utilization in cryogenic stray-field-free memory devices, offering the possibility of achieving high storage densities. We here determine how a proximate altermagnet influences the critical temperature T_c of a conventional s-wave singlet superconductor. Considering both a bilayer and trilayer, we show that such hybrid structures may serve as stray-field free memory devices where the critical temperature is controlled by rotating the Néel vector of one altermagnet, providing infinite magnetoresistance. Furthermore, our study reveals that altermagnetism can coexist with superconductivity up to a critical strength of the altermagnetic order as well as robustness of the altermagnetic influence on the conduction electrons against non-magnetic impurities, ensuring the persistence of the proximity effect under realistic experimental conditions.

MA 21.10 Wed 13:00 H 1058

Dynamic paramagnon-polarons in altermagnets — •Charles Steward[1], Rafael Fernandes[2], and Joerg Schmalian[1] — [1]Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]University of Minnesota, Minneapolis, USA

The combined rotational and time-reversal symmetry breakings that define an altermagnet lead to an unusual d-wave (or g-wave) magnetization order parameter, which in turn can be modeled in terms of multipolar magnetic moments. Here, we show that such an altermagnetic order parameter couples to the dynamics of the lattice even in the absence of an external magnetic field. This coupling is analogous to the nondissipative Hall viscosity and describes the stress generated by a time-varying strain under broken time-reversal symmetry. We demonstrate that this effect generates a hybridized paramagnon-polaron mode, which allows one to assess altermagnetic excitations directly from the phonon spectrum. Using a scaling analysis, we also demonstrate that the dynamic strain coupling strongly affects the altermagnetic phase boundary, but in different ways in the thermal and quantum regimes. In the ground state for both 2D and 3D systems, we find that a hardening of the altermagnon mode leads to an extended altermagnetic ordered regime, whereas for nonzero temperatures in 2D, the softening of the phonon modes leads to increased fluctuations that lower the altermagnetic transition temperature. In 3D even at finite temperatures, the dominant effect is the suppression of quantum fluctuations