Interfacing Low and High-Energy Physics with Topological Matter

797. WE-Heraeus-Seminar

15 Oct - 18 Oct 2023

at the Physikzentrum Bad Honnef, Germany

The WE-Heraeus Foundation supports research and education in science, especially in physics.
The Foundation is Germany's most important private institution funding physics.

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Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 797. WE-Heraeus-Seminar:

Understanding and exploiting the robustness of topological metals and insulators and their unique quantum mechanical properties is a thriving avenue to develop new quantum technologies. Gapless topological phases in particular have been shown to host exotic phenomena, and repeatedly enabled to discover a rich set of possibilities beyond those predicted in high-energy physics. This conference aims to bring together leading experts, postdocs and students in theoretical and experimental condensed matter physics, with a strong focus on gapless topological phases, material science and high energy physics to explore these exotic phenomena, and the increasing list of candidate materials for their realization. We will accept submissions from a representative number of topics to portray a global picture of recent developments including materials such as topological semimetals and new magnetic topological matter and their classification, as well as novel phenomenology such as correlation effects, superconductivity, anomalies and transport phenomena, non-linear transport and optical responses or topological catalysis.

Scientific Organizers:

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Introduction

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Registration:

Martina Albert (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (16:00 h – 20:00 h)
and Monday (08:00 – 12:30 h)

Program

Program

Sunday, 15 October 2023

16:00 – 20:00	**Registration**	
From 17:30	*BUFFET SUPPER*	
18:45 – 19:00	Scientific organizers	**Opening and Welcome**

Session: Topological phenomena I

19:00 – 19:45	Ivo Souza	**Multipole theory of optical spatial dispersion in crystals**
19:45 – 20:30	Yang Qun	**Monopole-like orbital-momentum locking and the induced orbital transport in topological chiral semimetals**
20:30	**Informal get together**	

Monday, 16 October 2023

08:00	*BREAKFAST*	

Session: Topological (meta) materials I

09:00 – 09:45	Andrew Boothroyd	**Topological electronic states induced by helimagnetic order**
09:45 – 10:30	Chiara Devescovi	**Axion topology in photonic crystal domain walls**
10:30 – 11:00	*COFFEE BREAK*	

Session: Topological Transport I

11:00 – 11:45	Claudia Felser	**Chirality and Topology**

Program

Monday, 16 October 2023

11:45 – 12:30	David Carpentier	**From black hole's atmosphere to thermal quenches: probing the gravitational anomaly in quantum materials**
12:30	*LUNCH*	
14:00 – 14:45	Bernd Gotsmann	**Transport in the topological semimetal CoSi: From chiral transport to technological applications**
14:45 – 15:30	Zengwei Zhu	**Anomalous transverse thermal and thermoelectric response in topological magnets**
15:30 – 16:00	*COFFEE BREAK*	

Session: Topological Transport II

16:00 – 16:45	Philip Moll	**Correlated order at the tipping point in the kagome metal CsV3Sb5**
16:45 – 17:30	Stanislaw Galeski	**Electrons, phonons and quantum anomalies: thermal transport and sound propagation in relativistic semimetals**
17:30 – 17:45	Corentin Morice	**Gravitational horizons in quantum matter**
17:45 – 18:00	David Rodríguez	**Couette and Poiseuille hydrodynamic fluid flows through a stable and causal hydrodynamic formulation**
18:00 – 18:15	Daniel Varjas	**Weyl node merging in symmetric crystals**
18:15 – 18:30	Enriquo Rico	**Two-way communication between high-energy physics and (topological) quantum matter**
18:30 – 18:45	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
19:00	*DINNER*	

Program

Tuesday, 17 October 2023

08:00	*BREAKFAST*	
Session: QFT I		
09:00 – 09:45	Roni Ilan	**Anomalous wave-packet dynamics in non-Hermitian systems**
09:45 – 10:30	Alexander Altland	**Fragility of spectral flow in topological insulators**
10:30 – 11:00	*COFFEE BREAK*	
Session: QFT II		
11:00 – 11:45	Johanna Erdmenger	**Hydrodynamics in strongly correlated kagomé metals**
11:45 – 12:30	Karl Landsteiner	**Black Hole Quantum Matter**
12:30	*LUNCH*	
Session: Topology and correlations		
14:00 – 14:45	Ana Akrap	**Physics in high magnetic fields: Landau level spectroscopy of topological semimetals**
14:45 – 15:30	Silke Buehler-Paschen	**Strongly correlated topological semimetals**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 17:30	**Poster session**	
17:30 – 18:15	Joel Moore	**Connecting ground states with intermediate-frequency behavior in topological materials**
18:15 – 18:30	Mikel Iraola Iñurrieta	**Cummulative topology for heavy fermion insulators by means of topological quantum chemistry**
18:30 – 18:45	Gunnar Felix Lange	**Projected spin textures as a bulk signature of fragile topology**
19:00	***HERAEUS DINNER*** *(social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 18 October 2023

08:00	*BREAKFAST*	

Session: Topology phenomena II

09:00 – 09:45	Inti Sodemann Villadiego	**The Floquet Fermi Liquid**
09:45 – 10:30	Duncan Haldane	**Geometry of the Quantum Hall Effect**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:15	Federico Balduini	**Probing the Fermi surface of Weyl semimetals using Transverse Electron Focusing**
11:15 – 11:30	Julia Hannukainen	**Electric manipulation of domain walls in magnetic Weyl semimetals via the axial anomaly**
11:30 – 12:00	**Discussions**	
12:00 – 12:15	Scientific organizers	**Poster Prize Awards & Closing Remarks**
12:15 – 14:00	*LUNCH*	

End of the seminar and departure

Posters

Posters

Baptiste Bermond	**Analog curved spacetime and anomalies in condensed matter**
Joan Bernabeu	**Ultraquantum Limit of Axionic Charge Density Waves**
Francesco Buccheri	**Smooth interfaces in nodal-line semimetals**
Selma Franca	**Topological diffusive metal in amorphous transition metal mono-silicides**
Wojciech Jankowski	**Disorder-induced topological quantum phase transitions in Euler semimetals**
Jia Grace Lu	**Proximitized Superconductivity in Topological Sb_2Te_3 Nanowires**
George Moethrath	**Flux periodic oscillations in topological insulator GeTe nanowires**
Antonio Morales-Pérez	**Transversality-Enforced Tight-Binding Model for 3D Photonic Crystals aided by Topological Quantum Chemistry**
Winder Moura-Melo	**Emergent phenomena in bilayer artificial spin ices**
Avedis Neehus	**Dirac fermions with topological mass disorder**
Inigo Robredo	**New magnetic topological materials from high-throughput search**
Justin Schirmann	**Amorphous Kramers-Weyl Semimetals**

Abstracts of Lectures

(in alphabetical order)

Physics in high magnetic fields: Landau level spectroscopy of topological semimetals

A. Akrap[1]

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In this talk I will give a broad overview of our recent progress on Landau level spectroscopy of Dirac and Weyl semimetals. With infrared light, one can excite carriers from one Landau level into another, causing inter-Landau level transitions. This technique, known as Landau level spectroscopy, has been widely employed since the early 1950s as an extremely sensitive probe of semimetal and semiconductor band structures.

Through recent advances, one can resolve intricate complexities of topological materials' bands, all while discovering new physics. I will present a new analysis of highly detailed inter-Landau level transition maps in extreme magnetic fields, focusing on select topological materials: Dirac semimetals [1,2], a weak topological insulator $ZrTe_5$ [3,4], and a Weyl semimetal TaAs [5]. I will discuss a novel approach which enables us to further exploit the rich magneto-optical spectra, and gain deeper knowledge of topological semimetals.

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Fragility of spectral flow in topological insulators

Alexander Altland[1] , Piet W. Brouwer[2] , Johannes Dieplinger[3], Matthew S. Foster[4], Mateo Moreno-Gonzalez[1]

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Topological insulators and superconductors support extended surface states protected against the otherwise localizing effects of static disorder. Specifically, in the Wigner-Dyson insulators belonging to the symmetry classes A, AI, and AII, a band of extended surface states is continuously connected to a likewise extended set of bulk states forming a ``bridge'' between different surfaces via the mechanism of spectral flow. In this talk we will discuss how this principle becomes fragile in the majority of non-Wigner-Dyson topological superconductors and insulators. In these systems, all but one state (the surface state of zero energy) are spatially localized, or can be made so without violating physical principles. We will considering the three-dimensional insulator in class AIII
as a case study, to discuss this phenomenon, and its methodological and applied consequences. In particular, we show that low-energy Dirac approximations in the description of surface states can be treacherous in that they tend to conceal the localizability phenomenon. We also identify markers defined in terms of Berry curvature as measures for the degree of state localization in lattice models, and back our analytical predictions by extensive numerical simulations. A main conclusion of this work is that the surface phenomenology of non-Wigner-Dyson topological insulators is a lot richer than that of their Wigner-Dyson siblings.

References

1. arXiv:2308.12931

Probing the Fermi surface of Weyl semimetals using Transverse Electron Focusing

F. Balduini[1], A. Molinari[1], L. Rocchino[1], V. Suess[2], C. Felser[2], C. Zota[1], H. Schmid[1], and B. Gotsmann[1],

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Weyl semimetals are generally characterized by a multitude of charge carriers pockets, some of which host trivial fermions that contribute in parallel to transport and hinder Weyl fermions' properties. To enable focused study and isolation of Weyl fermions in transport experiments, we employ transverse electron focusing (TEF) on microstructured single-crystals of Weyl semimetals. TEF allows separating in real space charged quasiparticles with different momenta, thereby generating distinct signals associated with trivial and Weyl bulk fermions. By combining TEF with Shubnikov de Haas experiments on a NbP single crystal, we gain valuable insights into the Fermi surface shape of Weyl fermions, and we can extract their Fermi momenta, character, and masses. We find that the extremely high mobility of NbP originates from bulk, achiral and relativistic electrons.
This approach paves the way for the study of the unique behavior of Weyl fermions, specifically related to their chiral character.

Topological electronic states induced by helimagnetic order

Andrew T Boothroyd[1]

[1] *Department of Physics, Oxford University, Oxford, OX1 3PU, U.K.*

Topological electronic band states in crystals can be protected by various different symmetries. In this talk I shall focus on materials in which non-trivial electronic topologies are induced by magnetic order (i.e. broken time-reversal symmetry). Such materials are of interest because their topological transitions and the associated transport and magneto-electrical properties can potentially be controlled by magnetism or magnetic fields. I shall present recent experimental results and related theory on compounds containing Eu which order into helimagnetic phases. Among these are found candidates for Weyl semimetals and axion insulators [1,2]. I especially wish to highlight the strengths of scattering experiments using advanced synchrotron radiation and neutron techniques for probing key aspects of the magnetic structures.

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Strongly correlated topological semimetals

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Gapless electronic topology driven by strong correlations is an emerging field of great interest, with heavy fermion compounds at its forefront. I will introduce the notion of a Weyl-Kondo semimetal [1-3], discuss the giant signatures of topology observed in $Ce_3Bi_4Pd_3$ [1,3,4], the first representative of this class, and the genuine topology control that can be achieved by magnetic field tuning, leading to the annihilation of the material's Weyl nodes at moderate magnetic fields [5]. I will also discuss design strategies for further correlation-driven topological semimetals, ranging from symmetry considerations [6] to the role of quantum criticality [7,8] and emergence [9].

This work was supported by the Austrian Science Fund (I4047, I5868 - FOR 5249 QUAST, F86 - SFB Q-M&S), the European Union's Horizon 2020 Research and Innovation Programme (824109, EMP), and the European Research Council (ERC Advanced Grant 101055088, CorMeTop).

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From black hole's atmosphere to thermal quenches: probing the gravitational anomaly in quantum materials

Baptiste Bermond[1], Maxim Chernodub[2], Adolfo G. Grushin[3] and David Carpentier[1]

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Einstein famously argued that energy has mass, which distorts spacetime. Conversely, as spacetime distorts, the energy density varies. This classical phenomenon applies even to massless particles: their thermal energy must vary in an inhomogeneous spacetime. The latter observation underlies an equivalence between a slowly varying temperature profile and a weakly curved spacetime. This equivalence, proposed by Luttinger, is at the core of the formalism describing the heat current generated by a varying temperature.

In this talk, I will show that this useful equivalence neglects quantum fluctuations induced by a strong curvature of spacetime, or equivalently large local variations of temperature. When this curvature increases, these quantum fluctuations alter the energy conservation, a phenomenon known as the gravitational anomaly of relativistic quantum field theories.

Taking into account such fluctuations is essential to describe the heat current close to a black hole. The recent advent of quantum material with relativistic low energy excitations offer new perspectives to probe such exotic properties in a laboratory. I will discuss new experimental routes to probe these elusive curvature-induced quantum effects in a laboratory.

Axion topology in photonic crystal domain walls

Chiara Devescovi[1], Antonio Morales-Perez[1], Yoonseok Hwang[2], Mikel Garcia-Diez[1,3], Iñigo Robredo[4,1], Juan Luis Mañes[3], Barry Bradlyn[2], Aitzol Garcia-Etxarri[1,5], and Maia G. Vergniory[1,4]

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Axion insulators (AXI) are 3D magnetic higher-order topological insulators, protected by inversion (*I*)-symmetry, which support hinge-localized chiral channels and quantized topological magnetoelectric effects. Recent studies have suggested that AXI may detect dark-matter axion-like particles by coupling to their axionic excitations. Beyond its fundamental theoretical interest, designing a photonic AXI offers the potential to enable the development of magnetically-tunable photonic switch devices through magnetic manipulation of AXI modes and their chiral propagation. Motivated by this, we propose an approach to induce axionic band topology in gyrotropic 3D Weyl photonic crystals (PhC) gapped by supercell modulation (SM). To quantize an axion angle, we create domain walls in *I*-symmetric PhC, incorporating a phase-obstruction in the SM of their dielectric elements. This binds chiral channels on *I*-related hinges, leading to an axionic chiral channel of light. By controlling the gyrotropic response, we manipulate the AXI modes via a small external magnetic bias, providing a topological switch between different 1D chiral photonic fiber configurations. The unidirectional AXI hinge states in the photonic AXI are buried in a fully connected 3D dielectric structure, protected from radiation in the electromagnetic continuum, making them suitable for guided-light communication, where preservation and non-reciprocal propagation of photonic signals are crucial.

Hydrodynamics in strongly correlated kagomé metals

J. Erdmenger[1]

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A current challenge in condensed matter physics is the realization of strongly correlated, viscous electron fluids. These fluids are not amenable to the perturbative methods of Fermi liquid theory, but can be described by holography, that is, by mapping them onto a weakly curved gravitational theory via gauge/gravity duality. The canonical system considered for realizations has been graphene, which possesses Dirac dispersions at low energies as well as significant Coulomb interactions between the electrons. In [1] we show that Kagome systems with electron fillings adjusted to the Dirac nodes of their band structure provide a much more compelling platform for realizations of viscous electron fluids, including non-linear effects such as turbulence. In particular, we find that in stoichiometric Scandium (Sc) Herbertsmithite, the fine-structure constant, which measures the effective Coulomb interaction and hence reflects the strength of the correlations, is enhanced by a factor of about 3.2 as compared to graphene, due to orbital hybridization. We employ holography to estimate the ratio of the shear viscosity over the entropy density in Sc-Herbertsmithite, and find it about three times smaller than in graphene. These findings put, for the first time, the turbulent flow regime described by holography within the reach of experiments. - A further aspect in this context, studied in [2,3], concerns the analysis of parity breaking via a magnetic field in channel flow hydrodynamics.

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Chirality and Topology

Claudia Felser, Dresden, DE

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Chirality is a very active field of research in organic chemistry, closely linked to the concept of symmetry. Topology, a well-established concept in mathematics, has nowadays become essential to describe condensed matter [1,2]. At its core are chiral electron states on the bulk, surfaces and edges of the condensed matter systems, in which spin and momentum of the electrons are locked parallel or anti-parallel to each other. Magnetic and non-magnetic Weyl semimetals, for example, exhibit chiral bulk states that have enabled the realization of predictions from high energy and astrophysics involving the chiral quantum number, such as the chiral anomaly, the mixed axial-gravitational anomaly and axions [3-5]. Chiral topological crystals exhibit excellent chiral surface states [6,7] and different orbital angular momentum for the enantiomers, which can be advantageous in catalysis. The potential for connecting chirality as a quantum number to other chiral phenomena across different areas of science, including the asymmetry of matter and antimatter and the homochirality of life, brings topological materials to the fore [8].

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Electrons, phonons and quantum anomalies: thermal transport and sound propagation in relativistic semimetals.

S. Galeski[1]

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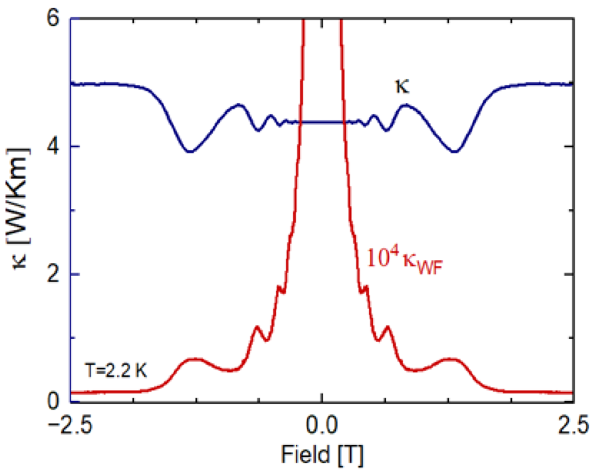
The ability of solids to transport entropy or heat is one of the most fundamental properties of matter. In most metals electrons are believed to transport heat and charge with similar efficiency leading to a proportionality between electrical and thermal conductivity (Widemann-Franz law).However recent results on topological quantum systems have challenged our intuitive understanding of thermal transport suggesting that it could be a sensitive tool for detecting effects originating from topologically non-trivial states of matter [1, 2, 3].

In this talk I will discuss the role of electron phonon coupling in thermal transport of Dirac and Weyl semimetals $ZrTe_5$ and NbP. I will demonstrate using results from ultrasonic attenuation and thermal transport measurement how the electronic subsystem can imprint its properties into the lattice, giving rise to dramatic, non trivial effects such as appearance of giant quantum oscillations in thermal conductivity. The talk will be finished with the discussion on how the same coupling can lead to emergence of unconventional temperature dependances of electrical resistance and the Shubnikov de-Haas effect. The presented results will highlight the importance of detailed understanding the e-p coupling in studies of thermal properties of topological matter.



Apparent violation of the Widemann-Franz Law: Comparison of thermal conductivity of ZrTe5 measured as a function of magnetic (blue) with and estimate of the electronic contribution based on the Widemann-Franz and measured electrical conductivity under the same conditions (red)

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Transport in the topological semimetal CoSi: From chiral transport to technological applications

B. Gotsmann[1]

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The chiral semimetal cobalt monosilicide (CoSi) has recently attracted considerable attention because of its nearly ideal topological properties of the electron system. Hosting only two chiral fermions in the Brillouin zone, CoSi exhibits very long Fermi arcs of maximum length, which are orders of magnitude larger than those found in other chiral Weyl fermion semimetals. Moreover, CoSi possesses a remarkably large topologically non-trivial energy window, allowing the measurement of topological chiral fermions without the need for fine-tuning the Fermi level position.

We have studied the electrical transport behavior of CoSi crystals looking at various magneto-transport effects. These comprise angle-dependent magnetoresistance and quantum oscillations, Hall effect, and temperature-dependent resistivity studies. In combination, we gather some evidence for the remarkable lifetime of chiral carriers in this system.

Topological semimetals in general hold a certain promise to meet scaling challenges in micro-electronics. To exploit the topological transport effects in a micro-electronic context, it is necessary to grow thin films and wires. We show a study of CoSi samples ranging from single crystals, via textured polycrystalline films to amorphous thin films grown using molecular beam epitaxy. We observe competitive scaling trends for size-dependent electrical conductivity and discuss the use of a-CoSi and other materials for reduction of the resistance of interconnects – one of the most pressing issues in the industry.

Finally, we will briefly discuss novel device types that could exploit properties of topological semimetals.

The results shown were obtained in several collaborations between IBM Research Europe – Zurich, Max Planck Institute for the Chemical Physics of Solids, Institut Neel, IBM Research Yorktown, University of Basel, University of Zurich, EMPA, ETHZ and EPFL.

Geometry of the Quantum Hall Effect

F. D. M. Haldane

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Crystalline condensed matter has three subsystems: elastic (the lattice), electromagnetic, and electronic. The quantum Hall effect (QHE) is exhibited by an incompressible state of the electronic subsystem in condensed matter, where there are no low-energy electronic excitations,. In contrast to the familiar case of band insulators, where the electron density is completely fixed by the lattice degrees of freedom (the local Bragg vectors fields which define the local Brillouin zone volume), in the QHE, part of the electron density in a 2D lattice plane (a “Hall plane”) is proportional to the magnetic flux density through the plane (according to the Streda formula). The part of the electron density that has been “captured by the electromagnetic field” forms an “incompressible 2D quantum fluid” with a gap for excitations that carry electric polarization tangent to the Hall plane, and has an intrinsic (“primitive”, as opposed to “traceless”) electric quadrupole moment density[1] that characterizes the internal geometry of the quantum fluid. Just as a crystalline solid has an elementary quantized unit (the “unit cell”), the incompressible Hall fluid has an intrinsic unit (the “composite boson”) with a geometry described by by the second moment (“primitive quadrupole”) of its electronic charge distribution relative to its center of inversion. Spatial variation of the quadrupole density in response to gradients of the tangential electric field in the Hall plane allows a partial screening response similar to “skyrmion” effects in quantum Hall ferromagnets, and the discontinuity of electric quadrupole density at the fluid edge gives rise to a universal edge polarization of QHE fluids. The dissipationless “Hall viscosity” of the QHE fluid is also given by a new formula[1], in terms of the electric quadropole density. In the fractional QHE, part of the quadrupole density derives from from an emergent (gapped) “graviton-like” dynamical field with dynamics analogous to a SO(2,1) variant of a SO(3) Ferromagnet with a Zeeman field, corresponding to the long-wavelength limit of the Girvin-MacDonald Plazman collective mode. This may be viewed as the “Goldstone” mode that accompanies the “flux attachment” responsible for the fractional QHE, although no symmetry is broken.

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Electric manipulation of domain walls in magnetic Weyl semimetals via the axial anomaly

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We show how the axial (chiral) anomaly induces a spin torque on the magnetization in magnetic Weyl semimetals. The anomaly produces an imbalance in left- and right-handed chirality carriers when non-orthogonal electric and magnetic fields are applied. Such imbalance generates a spin density which exerts a torque on the magnetization, the strength of which can be controlled by the intensity of the applied electric field. We show how this results in an electric control of the chirality of domain walls, as well as in an improvement of the domain wall dynamics, by delaying the onset of the Walker breakdown. The measurement of the electric field mediated changes in the domain wall chirality would constitute a direct proof of the axial anomaly. Additionally, we show how quantum fluctuations of electronic Fermi arc states bound to the domain wall naturally induce an effective magnetic anisotropy, allowing for high domain wall velocities even if the intrinsic anisotropy of the magnetic Weyl semimetal is small.

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Anomalous wave-packet dynamics in non-Hermitian systems

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Berry phases strongly affect the properties of crystalline materials, giving rise to modifications of the semiclassical equations of motion that govern wave-packet dynamics. In non-Hermitian systems, generalizations of the Berry connection using the bi-orthogonal formalism have been argued to characterize the topology of these systems. I will discuss how to extend the semiclassical equations of motion for wave-packet dynamics for a system governed by a non-Hermitian Hamiltonian, including corrections induced by the Berry connection and curvature. Since generally for non-Hermitian systems the adiabatic theorem fails, I will discuss how to apply the single band limit to observables that are relevant for the dynamics, and show that in the presence of electric fields, non-Hermiticity is manifested in an additional equation of motion for the weight rate. I will show that the equations for the weight rate and velocity contain anomalous terms that are present already in one-dimensional systems. I will also discuss the conditions for observing the anomalous contributions and potential extensions of the formalism to include complex electric fields and magnetic fields.

Topological quantum chemistry based analysis of multiple topological gaps in SmB6

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The application of the formalism of topological quantum chemistry (TQC) to the ab initio-based search of topological materials showed that non-trivial topology is more common than it had been believed. However, the number of heavy-fermion insulators predicted as topological is still scarce. In this talk, we will discuss the origin of topology in heavy-fermion insulators in terms of topological quantum chemistry, and propose these systems as candidates to host multiple topological gaps close to the Fermi level. We will revisit SmB_6 from this viewpoint, which will yield a detailed classification of the strong and crystalline topological features of its band structure. Furthermore, we will identify and classify three topological gaps close to the Fermi level.

Black Hole Quantum Matter

Karl Landsteiner

Instituto de Física Teórica UAM-CSIC

I will introduce the idea of using Chern-Simons terms on black hole backgrounds in D+1 dimensions as effective action for quantum matter in D dimensions. I will discuss the quantum anomalous Hall and thermal Hall effects, the chiral magnetic and chiral vortical effects and finally superconductivity as Chern-Simons terms with higher degree form.

Stable and fragile topology of projected spin textures

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Electronic energy band topology has been extensively studied in recent years and rich classification schemes have been developed. Quite recently [1], there has been interest in topology in other sectors of a band theory, such as spin. In this talk, I will discuss these developments, and how topology in these other degrees of freedom relate to the topology in the energy sector. In particular, I will discuss an intriguing connection to *fragile* topology in the energy sector. I will show that, within specific symmetry settings, this type of topology can be understood from a spin picture. This talk will largely be based on [2].

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Correlated Order at the Tipping Point in the Kagome Metal CsV_3Sb_5

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Materials that can host different states of electronic order form a recurring theme in physics and materials science, and they are of particular interest if they are coupled strongly. A famous example are ferroelectrics, in which electric polarization and magnetism not only coexist but are strongly linked. This both unveils a rich physics of correlated states, and also opens unexpected application avenues as the coupling promises to manipulate one state by a stimulus that primarily acts on another – say switching magnetism using electric fields.

Recently, materials based on the structural motif of the Kagome web have attracted significant attention for their tendency to host such strongly coupled phases. In particular, the centro-symmetric layered Kagome metal (K,Cs)V_3Sb_5 have entered the focus of experimental and theoretical research. They host a charge-density-wave type transition at elevated temperatures ~100K, followed by a superconducting transition at 3K (exact values depend on composition). Yet there is another type of electronic order which thus far eludes exact microscopic identification. A series of experimental probes detects the onset of anomalous behavior around T'~30-40K, including thermal Hall, mSR, NMR, magnetic torque, Kerr rotation. The anomalous low-temperature state carries the characteristics of a chiral, nematic and time-reversal-symmetry breaking fluid (all of which are under most active debate currently).

Yet what crystallizes out of the current state of experimental data is a highly entangled system which is extraordinarily responsive to external perturbations. This materials main strength is equally its weakness, the unusual degree of coupling between states can hinder its systematic investigation. However, it is already clear that it provides a platform to explore strongly coupled correlated phases, and as a result it displays a thus-far unknown electromagnetic response, a diode in which the forward direction can be switched by the application of a magnetic field. I will review the current state of the field, and discuss ongoing projects in my department.

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Connecting ground states with intermediate-frequency behavior in topological materials

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The first topological phases to be discovered, such as the integer and fractional quantum Hall effects, show quantized adiabatic transport. While topology is often thought of as a ground-state or low-energy property, there are now several examples where dynamical properties at nonzero frequency are the most convenient way to reveal topological behavior. In the case of some Weyl semimetals, there is even a form of quantization of a nonlinear optical property. This talk covers theoretical work on optical properties of semimetals and on inelastic neutron scattering on spin liquid candidates. The goal is to show how dynamical properties are crucial in understanding for several existing and proposed phases of matter.

Gravitational horizons in quantum matter

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We propose a class of lattice models realizable in condensed matter systems whose low-energy dynamics exactly reduces to Dirac fields subjected to gravitational backgrounds. Wave-packets propagating on the lattice exhibit eternal slowdown, signaling the formation of black hole event horizons. We show that the semiclassical wave packets trajectories coincide with the geodesics on (1+1)D dilaton gravity, paving the way for new and experimentally feasible routes to mimic black hole horizons and realize (1+1)D spacetimes as they appear in certain gravity theories.

Monopole-like orbital-momentum locking and the induced orbital transport in topological chiral semimetals

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The interplay between chirality and topology nurtures many exotic electronic properties. For instance, topological chiral semimetals display multifold chiral fermions which manifest nontrivial topological charge and spin texture [1-2]. They are an ideal playground for exploring chirality-driven exotic physical phenomena. In this work, we reveal a monopole-like orbital-momentum locking texture on the three-dimensional Fermi surfaces of topological chiral semimetals with B20 structures (e.g., RhSi and PdGa). This orbital texture enables a large orbital Hall effect (OHE) and a giant orbital magnetoelectric (OME) effect in the presence of current flow. Different enantiomers exhibit the same OHE which can be converted to the spin Hall effect by spin-orbit coupling in materials. In contrast, the OME effect is chirality dependent and much larger than its spin counterpart. Our work reveals the crucial role of orbital texture for understanding OHE and OME effect in topological chiral semimetals and paves the path for applications in orbitronics, spintronics and enantiomer recognition.

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Two-way communication between high-energy physics and (topological) quantum matter

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UPV/EHU & DIPC & Ikerbasque

We will present the results of an interdisciplinary collaboration between groups working in high-energy physics and (topological) quantum matter during these last years. First, we will show how it is possible to do the "Quantum Simulation of Light-Front Parton Correlators" [Phys. Rev. D 104, 014512 (2021)] where quantum technologies can help to calculate ab-initio correlators that characterize non-perturbative aspects of QCD. Second, we will show how enters the "Role of anomalous symmetry in 0-π qubits" [Phys. Rev. B 105, L201104 (2022)] and how the notion of the anomaly explains the robustness of this qubit to decoherence.

References:

Quantum Simulation of Light-Front Parton Correlators" Phys. Rev. D 104, 014512 (2021)
Role of anomalous symmetry in 0-π qubits" Phys. Rev. B 105, L201104 (2022)

Electric conductivity in non-hermitian holography

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We study the phase structure and charge transport at finite temperature and chemical potential in the non-Hermitian PT-symmetric holographic model of [2]. The non-Hermitian PT-symmetric deformation is realized by promoting the parameter of a global U(1) symmetry to a complex number. We check that the Ferrell-Glover-Tinkham sum rule for the AC conductivity holds in all the three phases. We also investigate a complexified U(1) rotor model with PT-symmetric deformation, derive its phase structure and condensation pattern, and find a zero frequency spectral weight analogous to the holographic model.

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The Floquet Fermi Liquid

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We demonstrate the existence of a non-equilibrium "Floquet Fermi Liquid" state arising in partially filled Floquet Bloch bands weakly coupled to ideal fermionic baths, which possess a collection of "Floquet Fermi surfaces" enclosed inside each other, resembling matryoshka dolls. We elucidate several properties of these states, including their quantum oscillations under magnetic fields which feature slow beating patterns of their amplitude reflecting the different areas of the Floquet Fermi surfaces, consistent with those observed in microwave induced resistance oscillation experiments. We also investigate their specific heat and thermodynamic density of states and demonstrate how by controlling properties of the drive, such as its frequency, one can tune some of the Floquet Fermi surfaces towards non-equilibrium van-Hove singularities without changing the electron density.

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Multipole theory of optical spatial dispersion in crystals

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Natural optical activity is the paradigmatic example of an effect originating in the weak spatial inhomogeneity of the electromagnetic field on the atomic scale. In molecules, such effects are well described by the multipole theory of electromagnetism, where the coupling to light is treated semiclassically beyond the electric-dipole approximation. That theory has two shortcomings: it is limited to bounded systems, and its building blocks - the multipole transition moments - are origin dependent. In this work, we recast the multipole theory in a translationally-invariant form that remains valid for crystals. Working in the independent-particle approximation, we introduce “intrinsic” multipole transition moments that are origin independent and transform covariantly under gauge transformations of the Bloch eigenstates. Electric-dipole transitions are given by the interband Berry connection, while magnetic-dipole and electric-quadrupole transitions are described by matrix generalizations of the intrinsic magnetic moment and quantum metric. In addition to multipole-like terms, the response of crystals at first order in the wavevector of light contains band-dispersion terms that have no counterpart in molecular theories. The full response is broken down into magnetoelectric and quadrupolar parts, which can be isolated in the static limit where electric and magnetic fields become decoupled. The rotatory-strength sum rule for crystals is found to be equivalent to the topological constraint for a vanishing chiral magnetic effect in equilibrium, and the formalism is validated by numerical tight-binding calculations.

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Weyl node merging in symmetric crystals

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Weyl-nodes are generic and stable degeneracy points in band structures, that can only be moved by small perturbations, but not destroyed. Under large deformations, two Wely-points of opposite charge can collide and annihilate, while same-charge Weyl-points may merge to form multi-Weyl nodes, then split again. We investigate the stability of such processes in terms of different “Weyl worldline” configurations using tools of singularity theory. We find that instead of the direct collision of a pair of same-charge nodes, processes involving creation and annihilation of additional Weyl-node-pairs and collision of three nodes are favoured in systems with C2T symmetry. We illustrate our results on models of MoTe2, SrSi2 and bilayer graphene in the presence of external electromagnetic fields and strain.

Anomalous transverse thermal and thermoelectric response in topological magnets

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The anomalous transverse responses due to heat transport in magnetic topological materials will be presented: 1. For anomalous transverse heat conductivity transport (thermal Hall effect), we found the anomalous Hall effect is influenced by the Fermi surface quasiparticle in Mn_3Sn[1], and the finite-temperature violation of the Wiedemann-Franz Law is caused by a mismatch between the thermal and electrical summations of the Berry curvature and not by inelastic scattering[2]; The thermal Hall effect was also to study other kinds of topological carriers, such as phonons [3]. 2. In terms of transverse anomalous thermoelectricity, we found an anticorrelation between the amplitudes of carrier mobility and the anomalous Nernst signal was found due to the intrinsic origin on $Co_3Sn_2S_2$[4]; and the universal relationship between anomalous transverse thermal conductivity and anomalous Hall conductivity, that is, $\alpha^A_{ij}/\sigma^A_{ij}$ is a sizable fraction of k_B/e at room temperature[5], and thus we found the magnetic field-induced Berry curvature in the topological magnetic antiferromagnetic Mn_3Sn[6] based on these knowledge; 3. We also verified a cornerstone of irreversible thermodynamics in topological transport: the Onsager's reciprocal relations between anomalous transverse coefficients in an anisotropic antiferromagnet $YbMnBi_2$[7]. Our study intuitively reveals that the nature of intrinsic anomalous transverse transports are determined by the Berry phase related to the three physical quantities: mean free path, Fermi wavelength and de Broglie thermal wavelength.

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Abstracts of Posters

(in alphabetical order)

Analog curved spacetime and anomalies in condensed matter

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General relativity is a fascinating yet strange formalism. Following the work from W.Unruh [1], it is possible to design to design tabletop experiments probing exotic curved spacetimes physics phenomenon within condensed matter analog., such as the Hawking radiation. Another surprising effect in curved spacetime concerns the physics of quantum fluctuation. In the presence of spacetime curvature, these excitations can break the usual spacetime symmetries, a phenomenon know as gravitational anomalies .

In this poster, I will propose three different setup enabling the observation of such anomalous fluctuation in analog gravity systems. After introducing the notion of gravitational anomalies, we will study the signature of anomalous quantum fluctuations in a system submitted to a sudden variation of the quenches or of the local temperature that we interpret as metric quenches. Then, reconsidering quantum fluids analogs, we will show that it is also possible to observe signatures of these fluctuations in the local energy density of time dependent cavities.

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Ultraquantum Limit of Axionic Charge Density Waves

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Magnetic Catalysis (M.C.) of Chiral Symmetry Breaking is the mechanism whereby a magnetic field induces a gap in an otherwise gapless system of weakly-interacting chiral fermions [1]. It has been explored extensively in the context of the QCD phase transition in high-energy physics. However, the advent of 3D Dirac/Weyl semimetals has raised the possibility of observing the phenomenon in condensed matter systems as well in the form of Axionic Charge Density Waves [2,3].

Models of the phenomenon often rely on the fact that the energy scale provided by the magnetic field is lower than the UV cutoff of the theory, which in condensed matter systems is at most of the order of the inverse lattice spacing. We consider the opposite scenario where the magnetic field scale is of the order or larger than the UV cutoff, a scenario originally proposed in the context of the QCD [4]. Among other consequences, we find that in that case there is a wider parameter window for which M.C. can observably take place and that dimensional reduction from 3 to 1 spatial dimensions becomes stronger than in the moderate magnetic field regime, enabling a beyond mean-field description through 1D bosonization [5].

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Smooth interfaces in nodal-line semimetals

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We study a smooth interface between a topological nodal-line semimetal and a topologically trivial insulator. Using a low-energy effective Hamiltonian, we show that a set of massive states localized at the interface appears, we identify the parameter range in which this happens and provide a material-independent way to detect and identify them via their signatures in optical conductivity and absorption spectroscopy in magnetic field.

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Topological diffusive metal in amorphous transition metal mono-silicides

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In chiral crystals crystalline symmetries can protect multifold fermions, pseudo-relativistic masless quasiparticles that have no high-energy counterparts. Their realization in transition metal mono-silicides has exemplified their intriguing physical properties, such as long Fermi arc surface states and unusual optical responses. Recent experimental studies on amorphous transition metal mono-silicides suggest that topological properties may survive beyond crystals, even though theoretical evidence is lacking. Motivated by these findings, we theoretically study a tight-binding model of amorphous transition metal mono-silicides. We find that topological properties of multifold fermions survive in the presence of structural disorder that converts the semimetal into a diffusive metal. We characterize this topological diffusive metal phase with the spectral localizer, a real-space topological indicator that we show can signal multifold fermions. Our findings showcase how topological properties can survive in disordered metals, and how they can be uncovered using the spectral localizer.

References

Selma Franca and Adolfo G. Grushin, arXiv 2306.17117 (2023)

Disorder-induced topological quantum phase transitions in Euler semimetals

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We study the effect of disorder in systems having a non-trivial Euler class [1]. As these recently proposed multi-gap topological phases come about by braiding non-Abelian charged band nodes residing between different bands to induce stable pairs within isolated band subspaces [2,3], novel properties that include a finite critical phase under the debraiding to a metal rather than a transition point, and a modified stability may be expected when the disorder preserves the underlying C_2T (two-fold rotation composed with time-reversal) or spinless PT (spatio-temporal inversion) symmetry on average. Employing elaborate numerical computations, we verify the robustness of associated topology by evaluating the changes in the average densities of states and conductivities for different types of disorders. Upon performing a scaling analysis around the corresponding quantum critical points, we retrieve a universality for the localization length exponent for Euler-protected phases, relating to 2D percolation models. We generically find that quenched disorder drives Euler semimetals into critical metallic phases. Finally, we show that magnetic disorder can also induce topological transitions to quantum anomalous Hall plaquettes with local Chern numbers determined by the initial value of the Euler invariant.

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Proximitized Superconductivity in Topological Sb_2Te_3 Nanowire

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Topological insulators interfaced with superconducting electrodes constitute promising building blocks for achieving topological quantum bits (qbits) based on Majorana fermions.[1-3] In order to create Majorana fermion based qbits, one-dimensional structures of topological insulators are required. To induce the superconducting state in the topological insulator, it has to be proximitized by an *s*-type superconductor. In many cases, topological insulators are grown by molecular beam epitaxy or thin layers are prepared by exfoliation. However, in both cases it is rather difficult to form one-dimensional structures since the required etching step often deteriorates the material. As an alternative approach, quasi one-dimensional nanowires can be created by chemical vapor deposition technique.

Here we present the transport properties of Sb_2Te_3 topological insulator nanoribbon/superconductor hybrid structures. These hybrid structures are thoroughly characterized at low temperatures, in order to gain information on the inducted proximity effect in the topological insulator nanoribbon.[4] All measurements are performed in a four-terminal configuration. We find a clear signature the Josephson effect in the current-voltage characteristics. Its occurrence is due to two proximitized regions connected by a weak link formed by the connecting topological insulator nanoribbon bridge. After exceeding the critical current, we observe an enhanced conductance, which we attribute to the remaining proximitized regions directly underneath the superconducting electrodes. The transport studies are complemented by measurements in a magnetic field. As it can be unambiguously shown that the topological insulator nanoribbon becomes superconducting due to the proximity effect, it renders an essential step towards the realization of Majorana fermion based qbits.

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Flux periodic oscillations in topological insulator GeTe nanowires

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The presence of spin–orbit coupling in combination with the superconducting proximity effect makes the topological insulating nanowires very attractive for applications in the field of topological quantum computation. Our investigations showed that distinct phase-coherent phenomena can be observed in GeTe nanowire structures. From universal conductance fluctuations measured on GeTe nanowires with Au contacts, a phase-coherence length of about 280 nm at 0.5 K is determined. The distinct phase-coherence is confirmed by the observation of Aharonov–Bohm type oscillations for parallel magnetic fields. The occurrence of these magnetic flux-periodic oscillations is originated by the formation of a tubular hole accumulation layer. For Nb/GeTe-nanowire/Nb Josephson junctions, a critical current of 0.2 μA at 0.4 K is measured. By applying a perpendicular magnetic field, the critical current decreases monotonously with increasing field; whereas in a parallel field, the critical current oscillates with a period of the magnetic flux quantum confirming the presence of a tubular hole channel.

Transversality-Enforced Tight-Binding Model for 3D Photonic Crystals aided by Topological Quantum Chemistry

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Tight-binding (TB) models can accurately predict the band structure and topology of crystalline systems. They have been heavily used in solid-state physics due to their versatility and low computational cost. It is quite straightforward to build an accurate TB model of any crystalline system using the crystal's maximally localized Wannier functions (WF) as a basis [1, 2]. Unfortunately, in 3D photonic crystals (PhCs), the transversality condition of Maxwell's equations precludes the construction of a basis of maximally localized WF via usual techniques [2]. In this work, we show how to overcome this problem by using topological quantum chemistry which will allow us to express the band structure of the PhC as a difference of elementary band representations (EBRs). This can be achieved by the introduction of a set of auxiliary modes, as recently proposed by *Soljačić et. al.* [3], which regularize the Γ-point obstruction arising from transversality constraint of the Maxwell equations. The decomposition into EBRs allows us to isolate a set of pseudo-orbitals that permit us to construct an accurate transversality-enforced TB model that matches the dispersion, symmetry content, and topology of the 3D PhC under study. Moreover, we show how to introduce the effects of a gyrotropic bias in the framework [4], modeled via non-minimal coupling to a static magnetic field. Our work provides the first systematic method to analytically model the photonic bands of the lowest transverse modes over the entire Brillouin zone via a transversality-enforced TB model.

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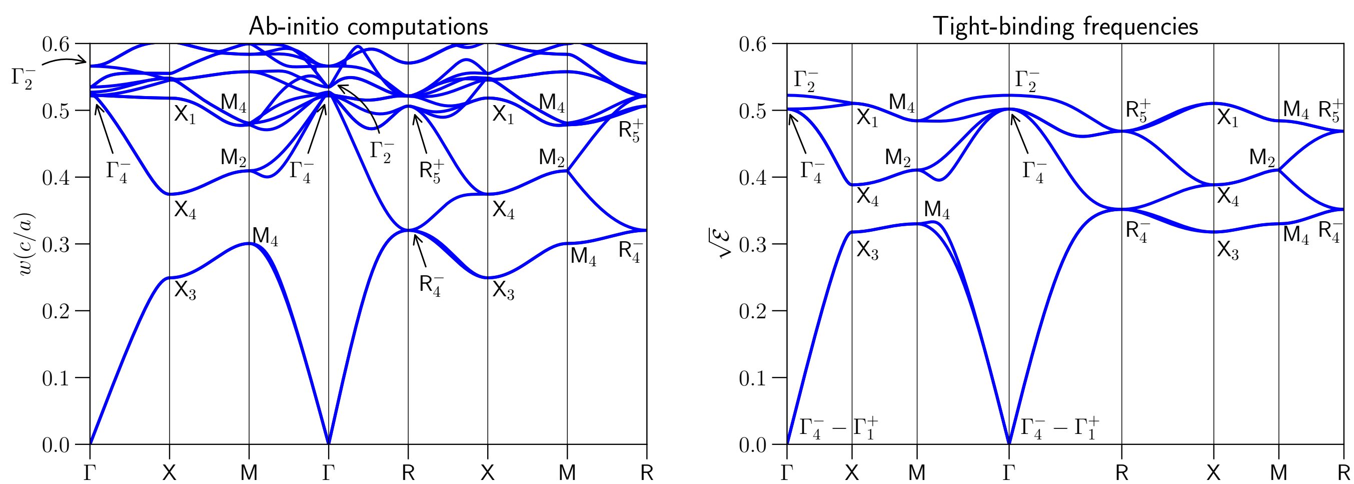

Emergent phenomena in bilayer artificial spin ices

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Spin ice crystals resemble water ice in the sense that geometrical frustration prevents all magnetic dipole pairs to achieve the lowest energy state, yielding residual entropy at zero Kelvin. They are also recognised to provide the first example of fractionalisation in three dimensions (3D): under specific conditions, magnetic dipoles fractionalise into isolated magnetic effective charges interacting by means of a Coulombic potential. In the last years, artificial spin ices (ASI's) have appeared in distinct geometries, enabling to control geometrical frustration effects in these frameworks. In a typical square ASI, magnetic nanoislands are arranged according to respect its underlying geometry throughout the system. Similarly to their 3D analogues, ASI's dipoles also fractionalize into magnetic monopoles whose effective interaction comprises Coulombic augmented by a linearly confining potential. The latter represents the string tension binding monopoles into pairs. However, such a tension may be tuned, for example, by stretching the arrangement: in rectangular geometries tension gets lower, eventually vanishing at a specific aspect ratio. In this case, magnetic monopoles are free to move producing an effective magnetic current. Here, we shall present a study concerning bilayer ASI systems. Besides the appearance of monopoles and their joining strings, there are also the effective interaction between the layers and their specific configurations. As a whole, dipoles in an ASI layer interact with their analogues of the another layer resembling van der Walls potential. Whenever coming into account, magnetic monopoles (and their strings) from a layer couple to those comprised in the another layer according to a n exponentially decaying term. In addition, twisting one layer with respect to another yields minima potential at certain angles. The scenery may be faced as a kind of magnetic molecules framework, in which molecular formation and clustering have their magnetic analogues.

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Dirac fermions with topological mass disorder

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Disorder is a central concept in the field of topological phases, e.g topological responses are negatively defined by robustness to disorder, topological phases can be induced by disorder and disorder leads to Anderson (anti-)localization transitions that depend on topology. We reconsider the phase diagram of Dirac fermions with topological mass disorder using short-ranged impurities instead of sampling the disorder from a normal distribution. The phase diagram is numerically evaluated within an effective lattice Hamiltonian based on the Haldane model. The phases are identified with the quantum geometric tensor that is used to extract the anomalous Hall conductivity as well as a localization length. In accordance with the established theory on class D systems, we observe that the disorder generates a rich phase diagram which can tune between a trivial band insulator to a Chern insulator, to a thermal metal and to an Anderson insulator. However, we find that the structure of the phase diagram can be changed by the distribution of disorder, i.e impurities versus a normal distribution, giving rise to new kinds of critical points. We also find hints of a cross-over between the thermal metal phase and a metallic phase which has a non-critical density of states and is associated with a non-zero intrinsic anomalous Hall conductivity. Possible realizations of our model are discussed, with a special emphasis placed on the amorphous Kitaev model of a $\mathbb{Z}_2$ quantum spin liquid.

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New magnetic topological materials from high-throughput search

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The search for new topologically non-trivial materials, both paramagnetic and magnetic, has been revolutionized by the formalism of topological quantum chemistry, which maps the symmetry of bands to topological properties. Building upon previous research, we conducted a high-throughput search for topological magnetic materials on 521 new, experimentally reported commensurate magnetic structures from MAGNDATA, doubling the number of available materials on the Topological Magnetic Materials database. For each material, we performed first-principle electronic calculations and diagnosed the topology as a function of the Hubbard U parameter. Our high-throughput calculation led us to the prediction of 244 previously overlooked experimentally relevant topologically non-trivial materials, which represent 46.83% of the newly analyzed materials. We present five remarkable examples of these materials, each showcasing a different topological phase: CaMnSi, a narrow gap axion insulator, Mn_2AlB_2, which exhibits a nodal line semimetal to topological insulator transition, UAsS a 5f-orbital Weyl semimetal, $FeCr_2S_4$, a symmetry-enforced semimetal with double Weyls and spin-polarised surface states, and $CsMnF_4$, a material presenting a new type of quasi-symmetry protected closed nodal surface.

Amorphous Kramers-Weyl semimetals

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While nearly half of all crystals exhibit topological properties [1], little is known about topology in amorphous materials. In this study, we developed a model of amorphous chiral Kramers-Weyl semimetals [2], where widely used topological markers such as the Bott index or the local Chern [3] marker are trivially zero due to time-reversal symmetry. We thus proposed an alternative way to characterize the survival of Weyl fermions in strongly disordered systems. Our results indicate that Nielsen-Ninomyia's doubling theorem [4], which states that Weyl fermions must come in pairs of opposite chiralities on a periodic lattice, also holds in the absence of long-range lattice order.

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