Dynamics of Emerging Quasiparticles in Topological Dirac Materials

731. WE-Heraeus-Seminar

11 – 14 October 2020
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

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 731. WE-Heraeus-Seminar:

Topological materials are a focus of current solid-state research. Within a few last years, the family of different topological electronic phases in solids has rapidly grown: the Dirac-and Weyl-semimetal phases have recently been accompanied by the nodal-line, type-II, and multifold topological semimetals, which often have no direct analogues in high-energy physics. Research on these novel phases and on related quantum phenomena provides new strong ties between different branches of physics. On the other hand, potential applications of topological semimetals range from high-speed opto-electronic and spintronic devices to electron superlenses and catalysts. Both, fundamental interests and potential applications, are calling for thorough theoretical and experimental investigations of these novel topological phases. The most interesting properties of and the most intriguing phenomena in these materials are due to their peculiar low-energy band structure, which often reminds the Dirac cone. The elementary excitations, existing in such electronic bands, determine the physics of the topological solid-state phases and are the focus of the current WE-Heraeus-Seminar. The seminar aims to bring together theorists and experimentalists, actively working in the area of topological Dirac materials. The experimental results obtained by (magneto-)optical, photoemission, magnetotransport, and photogalvanic measurements will be confronted with the most recent theoretical achievements in topological condensed-matter physics.

Scientific Organizers:

Prof. Dr. Claudia Felser	MPI Dresden, Germany, E-mail: claudia.felser@cpfs.mpg.de
Prof. Dr. Mark Oliver Goerbig	Université Paris-Sud, France E-mail: mark-oliver.goerbig@u-psud.fr
Dr. Artem Pronin	Universität Stuttgart, Germany, E-mail: artem.pronin@pi1.physik.uni-stuttgart.de

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Registration:

Dirk Guthy-Rahn (Physikzentrum, Bad Honnef)
at the Physikzentrum, reception office
Sunday (16:00 h – 18:00 h)

Door Code:

(Keysymbol) 2 7 3 1 #
For entering the Physikzentrum
during the whole seminar

Program

Sunday, 11 October 2020

16:00 – 18:00	Registration	
17:30 – 18:00	Claudia Felser Mark Oliver Goerbig Artem Pronin	**Welcome and start of the scientific program**
18:00 – 19:00	Carlo Beenakker (Tutorial)	**Chiral magnetic effect in a Weyl superconductor**
19:00	*DINNER* and informal get together	

Monday, 12 October 2020

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Raffaele Resta (Tutorial)	**Geometrical and topological observables**
10:00 – 11:00	Yulin Chen	**tba**
11:00 – 11:20	*COFFEE BREAK*	
11:20 – 12:20	Steffen Wiedmann	**Probing the Fermi surface topology of nodal-line semimetals by means of quantum oscillations**
12:20 – 12:30	Conference Photo (in front of the Physikzentrum/Main entrance)	
12:30 – 14:00	*LUNCH*	

Program

Monday, 12 October 2020

14:00 – 14:45	**Poster flashing**	
14:45 – 16:00	**Posters**	
16:00 – 17:00	Joel Moore	**Nonlinear optical properties of non-magnetic Weyl/Dirac semimetals in and out of equilibrium**
17:00 – 17:20	*COFFEE BREAK*	
17:20 – 18:20	Ece Uykur	**Optical investigations of Weyl semimetals**
18:20 – 19:20	Ana Akrap	**Understanding the ground states of topological systems: a view from infrared spectroscopy**
19:20	*HERAEUS DINNER at the Physikzentrum (cold & warm buffet with complimentary drinks)*	

Program

Tuesday, 13 October 2020

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Adolfo Grushin (Tutorial)	**Symmetry indicators and experimental signatures of amorphous topological insulators**
10:00 – 11:00	Johannes Knolle	**Anomalous quantum oscillations in type II Weyl semimetals and Graphene-$RuCl_3$ heterostructures**
11:00 – 11:20	*COFFEE BREAK*	
11:20 – 12:20	Vladimir Juričić	**Optical conductivity in interacting Dirac and Weyl semimetals**
12:20 – 14:00	*LUNCH*	
14:00 – 15:40	**Posters**	
15:40 – 16:40	Maia Vergniory	**Cluster perturbation theory and topological Hamiltonian: a route to identify topological phases in correlated systems**
16:40 – 17:40	Jennifer Cano	**A moiré superlattice on the surface of a topological insulator**
17:40 – 18:00	*COFFEE BREAK*	
18:00 – 18:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
18:15 – 19:00	Leslie Schoop (Tutorial)	**From chemical bonds to topology**
19:00	*DINNER*	

Program

Wednesday, 14 October 2020

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Yoichi Ando	**Nonreciprocal Transport in a Nodal-Line Semimetal**
10:00 – 11:00	Milan Orlita	**Magneto-optics of electrons in conical bands**
11:00 – 11:40	*COFFEE BREAK*	
11:40 – 12:40	Andrei Pimenov	**Quantized Faraday rotation and band structure in topological insulators**
12:40 – 12:45	Claudia Felser Mark Oliver Goerbig Artem Pronin	**Closing remarks**
12:45	*LUNCH*	

End of the seminar and departure

Posters

01	Tobias Biesner	**Spectroscopic investigations of the Quantum Magnet Averievite under external stimuli**
02	Jihaan Ebad-Allah	**Effect of tuning the interlayer bonding on the optical conductivity of the Nodal-line Semimetal ZrXY**
03	Ansgar Graf (online)	**Geometric properties of SU(N) parametric Hamiltonians**
04	Jonas Kiemle	**Electrical Control of Spin Textures at the Interface Between Graphene and Topological van der Waals Materials**
05	Christine Kuntscher (online)	**Influence of magnetic ordering on the optical response of the antiferromagnetic topological insulator $MnBi_2Te_4$**
06	Jasper Linnartz (online)	**Fermi surface reconstruction and nested (Russian doll) magnetic breakdown in WTe_2**
07	Quentin Marsal (online)	**Topological Weaire-Thorpe model of amorphous matter**
08	Ivan Mohelský	**Landau level spectroscopy of Bi_2Te_3**
09	Claudius Müller (online)	**A quantum oscillation study in the Dirac nodal-line semimetal HfSiS**
10	Daniel Muñoz-Segovia (online)	**Many-body effects in nodal-line semimetals: Correction to the optical conductivity**
11	Sascha Polatkan	**Magneto-Optics of a Weyl Semimetal beyond the Conical Band Approximation: Case Study of TaP**
12	Lukas Powalla	**Gatable current-induced Kerr signal in WTe_2/graphene heterostructures**

Posters Monday

13	Seulki Roh	**Spectroscopic evidence of chiral anomaly in Cd_3As_2**
14	Miguel-Ánge Sánchez-Martínez (online)	**Linear optical conductivity of the chiral multifold semimetal RhSi**
15	Sharareh Sayyad (online)	**Non-Hermitian dynamical topology of driven-dissipative Kitaev chain**
16	Pavlo Sukhachov (online)	**Acoustogalvanic effect in Weyl and Dirac semimetals**
17	Sergueï Tchoumakov (online)	**Chiral anomaly induced Veselago lensing in Weyl semimetals**
18	Jan Wyzula	**Magneto optical spectroscopy of Dirac nodal line semimetal NbAs2**

Abstracts of Lectures

(in chronological order)

Chiral magnetic effect in a Weyl superconductor

Carlo Beenakker

Instituut-Lorentz, Leiden University, Leiden, The Netherlands

The chiral magnetic effect is the appearance of a current along the lines of magnetic flux, due to an imbalance between Weyl fermions of opposite chirality. In a Weyl semimetal this is a dissipative, non-equilibrium current. We will discuss how this current can flow in equilibrium, without dissipation, in the vortex lattice of a Weyl superconductor. The chirality imbalance appears when one of the two chiralities is confined to vortex cores. The confined states are charge-neutral Majorana fermions.

Geometrical and topological observables

Raffaele Resta

Istituto Officina dei Materiali (CNR-IOM), Trieste

Some ground-state intensive observables have a geometrical or even topological nature. Most of them are defined at the independent particle level, in a mean-field sense (Hartree-Fock or Kohn-Sham); in the crystalline case the relevant geometry is the one of the occupied Bloch manifold [1]. The geometrical observables come in two very different classes: those of class (i) only make sense for insulators, and their bulk value is defined modulo 2π (in dimensionless units), while those of class (ii) are defined for both insulators and metals, and are single-valued.

As for class (i), two observables are known: electrical polarization and the "axion" term in magnetoelectric response. In the former case the integrand is a 1-form (the Berry connection, one $\mathbf{k}$-derivative); in the latter case it is a 3-form (three $\mathbf{k}$-derivatives). In mathematical speak both are Chern-Simons forms, and they are integrated over the Brillouin zone. For both observables the modulo 2π ambiguity is fixed only after the termination of the insulating sample is specified. Furthermore in presence of some symmetry only the values zero or π (mod 2π) are allowed: the observable becomes then a topological $\mathbb{Z}_2$ index. A 3d axion-odd insulator is dubbed "strong topological insulator" when the invariant is protected by time-reversal symmetry, and "axion insulator" when it is protected by inversion symmetry [1,2].

The paradigmatic observable in class (ii) is anomalous Hall conductivity (intrinsic term thereof in metals): the integrand is a 2-form (the Berry curvature, two $\mathbf{k}$-derivatives). The observable becomes topological in 2d insulators, yielding a $\mathbb{Z}$ (not $\mathbb{Z}_2$) index: the Chern invariant. Another class (ii) observable, also rooted in a 2-form, is orbital magnetization [1].

Owing to their single-valuedness, the geometrical observables in class (ii) can also be defined locally in coordinate space: they admit therefore a "density", thus allowing to deal with noncrystalline and/or a macroscopically inhomogeneous sample, and even a bounded sample, where there is no $\mathbf{k}$-vector to speak of [3-5]. The Chern invariant admits a local "marker" [6]. The observables in class (i) instead, being multiple valued, do not admit a density. In particular "polarization density" is a nonsensical concept, in sharp contrast with orbital magnetization density (which is well defined) [4,5].

Acknowledgment: Work supported by the ONR Grant N00014-11-1-0145.

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Probing the Fermi surface topology of nodal-line semimetals by means of quantum oscillations

Steffen Wiedmann

High Field Magnet Laboratory (HFML-EMFL) and Institute for Molecules and Materials, Radboud University, Nijmegen, the Netherlands

Nodal-line semimetals (NLSMs) are recent members of the family of topologically nontrivial systems. The band structure of these materials is characterized by the degeneracy of conduction and valence bands along a closed loop in the three-dimensional Brillouin zone [1]. In many cases, they not only represent ideal systems with which to investigate the properties of charge carriers with a linear dispersion relation, they also have the potential to create a platform for research on topological correlated matter [2].

In my contribution, I will introduce and show recent results on quantum oscillatory phenomena that occur in NLSMs in high magnetic fields up to 35 T with the focus on the compound ZrSiS. The Fermi surface topology of these materials is determined by means of de Haas–van Alphen and Shubnikov-de Haas quantum oscillations in a full angle-dependent study. Comparison of our experimental observations with theoretical predictions provides us with a full picture of the electronic ground state [2-4].
In case the magnetic field is applied parallel to the *c*-axis of the crystals, a complex oscillation spectrum evolves above a threshold magnetic field originating from individual electron and hole pockets as well as from magnetic breakdown between them. The magnetic breakdown orbits can be seen as a manifestation of Klein tunneling in momentum space, although in a regime of partial transmission due to a small but finite spin-orbit gap between adjacent pockets. Additional high-frequency quantum oscillations signify magnetic breakdown orbits that encircle the entire Dirac nodal loop. Furthermore, I will show that quantum oscillations in resistivity persist up to high temperatures in ZrSiS that are attributed to Stark interference between orbits of nearly equal masses [4].

The work presented at this Heraeus-Seminar has been carried out in collaboration with J. Ayres and A. Carrington (Bristol University), L. M. Schoop (Princeton University), M. Breitkreiz (Freie Universität Berlin) and C. S. A. Müller, T. Khouri, M. R. van Delft, S. Pezzini, Y.-T. Hsu, and N. E. Hussey (HFML-EMFL).

References

[1] C. Fang *et al.,* Chinese Phys. B **25**, 117106 (2016).
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[3] M. van Delft *et al.,* Phys. Rev. Lett. **121**, 256602 (2018).
[4] C. S. A. Müller *et al.,* Phys. Rev. Research **2**, 023217 (2020).

Nonlinear optical properties of non-magnetic Weyl/Dirac semimetals in and out of equilibrium

Joel E. Moore[1,2*]

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[2] Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA

Weyl semimetals support strong and unusual nonlinear optical responses, both in equilibrium and when driven out of equilibrium by an applied current. This talk starts by reviewing known examples of how topological materials generate new kinds of electrodynamic couplings and effects. We then focus on how topological Weyl and Dirac semimetals can show unique electromagnetic responses; we argue that in linear response the main observable effect [1] solves an old problem via the orbital moment of Bloch electrons, and how in nonlinear optics there should be a new quantized effect [2], for which there is now partial experimental support in RhSi [3]. This nonlinear effect has a natural quantum e^3/h^2 and appears in chiral Weyl semimetals over a finite range of frequencies, with corrections from electron-electron interactions [4]. We close by mentioning how strong nonlinear effects can be induced in Dirac semimetals by an applied current [5].

*Work in collaboration with the authors of papers below

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Optical investigations of Weyl semimetals

E. Uykur[1]

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In recent years, the field of topological materials has been rapidly grown. Many systems have been predicted and experimentally confirmed to host topologically non-trivial bands. The novel phases of (Type-I and Type-II) Dirac and Weyl semimetals, as well as nodal-line, triple-point, multifold semimetals have been proposed (Fig) and experimental evidences have followed up.

While investigating different properties of Weyl semimetals, (magneto-)optical spectroscopy became one of the superior methods in the investigation of the low-energy dynamics of the Dirac/Weyl states and the discussion of the optical signatures of Dirac/Weyl fermions under certain considerations have been established.

In this talk, I will present our recent (magneto)-optical studies on several Weyl semimetals.

Understanding the ground states of topological systems: a view from infrared spectroscopy

A. Akrap[1]

[1]*University of Fribourg, Fribourg, Switzerland*

Nowadays we know of many gapless electronic phases with conical bands, such as graphene, Dirac semimetals, and Weyl semimetals. Their low-energy excitations resemble truly relativistic particles.

To address those excitations, the key is grasping the physics at a milli-electron-volt scale. We access electronic structures at these low energies by combining Landau level spectroscopy, infrared spectroscopy at zero magnetic field, and effective Hamiltonian models.

Because of their inherent low energy scales, our materials are often easy to tune by external parameters–temperature, high pressure and magnetic field, and have rich phase diagrams. I will now illustrate our approach on several Dirac and Weyl semimetals, focusing on $ZrTe_5$.

References

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Symmetry indicators and experimental signatures of amorphous topological insulators

Q. Marsal[1], D. Varjas[2] and Adolfo G. Grushin[1]

[1]Néel Institute, CNRS, Grenoble, France
[2] TU Delft, Delft, Netherlands

Amorphous solids remain outside of the classification and systematic discovery of new topological materials. This is because our interpretation of models and experiments in non-interacting topological matter strongly rely on symmetry, in particular the notion of a space group. Extending topological properties to amorphous topological matter could significantly increase the number of new topological materials, and be a promising route towards cheap scalable topological devices. In this talk I will discuss a possible way to extend the notion of symmetry indicators, which are labels of topology, for a class of amorphous topological models that I will introduce, the topological Weaire-Thorpe models. These indicators are a promising starting point to build a classification scheme. Lastly, I will discuss how recent experiments in amorphous bismuth selenide, in particular transport and photoemission data, are consistent with the presence of a topological Dirac surface state, potentially turning this material into the first amorphous topological insulator ever observed.

References

[1] Q. Marsal, D. Varjas, A. G. Grushin arXiv: 2003.13701
[2] P. Corbae et al. arXiv: 1910.13412

Anomalous Quantum Oscillations in type II Weyl Semimetals and Graphene-$RuCl_3$ Heterostructures

J. Knolle[1]

[1]TQM Technical University Munich, Germany

Correlated Weyl and Dirac materials may show remarkable transport properties in the presence of a strong magnetic fields. Here, we discuss magnetotransport and quantum oscillations in two different systems. First, we show that type-II Weyl semimetals are susceptible to forming magnetic field induced charge density waves (CDW) which leads to anomalous transport signatures. Second, we develop a microscopic theory and provide new experimental data of anomalous quantum oscillations in a $RuCl_3$-Graphene heterostructure. We discuss how the interplay of fractionalized spin excitations and itinerant Dirac electrons can lead to quantum oscillation phenomena beyond the standard Lifshitz-Kosevich paradigm.

Optical conductivity in interacting Dirac and Weyl semimetals

V Juričić[1], B. Roy[2], H. Rostami[1]

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Dirac and Weyl semimetals feature pseudorelativistic linearly dispersing excitations which give rise to universal signatures in optical conductivity. They are stable for weak electron-electron interactions due to a vanishing density of states at the nodal point. At a strong interaction, however, they can undergo a plethora of quantum phase transitions into various insulating and superconducting states. In two dimensions non-Fermi liquid emerging from the underlying quantum critical point lacks sharp quasiparticle excitations, and is thus difficult to probe. I will show that the linear optical conductivity in the collisionless regime can play a pivotal role in this regard [1]. More specifically, a universal suppression of both the inter-band optical conductivity and the Drude peak occurs in such a non-Fermi liquid due to strongly coupled gapless fermionic and bosonic excitations. Furthermore, in a tilted two-dimensional nodal semimetal, this non-Fermi liquid leaves its imprint on the nonlinear Hall conductivity [2]. Finally, in three-dimensional Dirac and Weyl semimetals the long-range Coulomb interaction causes a universal enhancement of the zero-temperature optical conductivity that depends solely on the number of nodal points at the Fermi level [3].

References

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Cluster perturbation theory and topological Hamiltonian: a route to identify topological phases in correlated systems

Maia Vergniory

Donostia International Physics Center, Materials Department, San Sebastian, Spain

Topological quantum chemistry (TQC) framework has provided a complete description of the universal properties of all possible atomic band insulators in all space groups considering the crystalline unitary symmetries. While this formalism filled the gap between the mathematical classification and the practical diagnosis of topological materials, an obvious limitation is that it only applies to weakly interacting systems. It is an open question to which extent this formalism can be generalized to strongly correlated system that can exhibit symmetry protected topological Mott insulators. In this work we address this question by combining cluster perturbation theory and topological Hamiltonians within TQC. This simple formalism will be applied to calculate to the phase diagram of the Hubbard model for a diamond chain. The results are compared to numerically exact calculations from density matrix renormalization group and variational Monte Carlo simulations together with many-body topological invariants.

A moiré superlattice on the surface of a topological insulator

J. Cano[1,2], S. Fang[3], J. Pixley[3] and J. Wilson[3]

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[3] *Department of Physics and Astronomy, Center for Materials Theory, Rutgers University, Piscataway, NJ 08854 USA*

Twisting van der Waals heterostructures to induce correlated many body states provides a novel tuning mechanism in solid state physics. In this work, we theoretically investigate the fate of the surface Dirac cone of a three-dimensional topological insulator subject to a superlattice potential. Using a combination of diagrammatic perturbation theory, lattice model simulations, and ab initio calculations we elucidate the unique aspects of twisting a single Dirac cone with an induced moire potential and the role of the bulk topology on the reconstructed surface band structure. We report a dramatic renormalization of the surface Dirac cone velocity as well as demonstrate a topological obstruction to the formation of isolated minibands. Due to the topological nature of the bulk, surface band gaps cannot open; instead additional satellite Dirac cones emerge, which can be highly anisotropic. We discuss the implications of our findings for future experiments.

References

[1] J. Cano, S. Fang, J. Pixley and J. Wilson, *in prep.*

From chemical bonds to topology

Leslie M. Schoop – Department of Chemistry - Princeton University

In the discipline of chemistry, it is common to have guidelines and heuristics that help to predict how chemical reactions will proceed. We are interested to expand these heuristics to understand electronic properties of inorganic solids. In this talk, I will show how delocalized chemical bonds in certain structural networks allow us to define chemical descriptors that predict topological materials. Using these descriptors, we found a layered, antiferromagnetic van der Waals material with very high mobility. These properties have previously not coexisted in a material that can be mechanically exfoliated. We further implemented our heuristics to discover novel complex topological phases, including magnetic ones, and phases that are in competition with complex structural distortions.

The second part of my talk will focus on the concept of chemical exfoliation. With this method, we can exfoliate materials for which the scotch tape method fails. I will show how we were able to synthesize a new chromium chalcogenide this way, which might be a new 2D magnetic material.

Nonreciprocal Transport in a Nodal-Line Semimetal

Y. Ando[1]

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The van-der-Waals compound $ZrTe_5$ has been a focus of many studies in the recent literature on topological Dirac materials. This compound is peculiar in that it shows a temperature-driven quantum phase transition from a strong 3D topological insulator (TI) phase to a weak 3D TI phase with increasing temperature [1]. At the transition point between these two gapped phases, a gapless semimetallic state marked by a pronounced resistivity peak is realized. By measuring the Shubnikov-de Haas oscillations, we found that this gapless semimetallic state is in fact a nodal-line semimetal having a toroidal Fermi surface. Furthermore, we found an intriguing nonreciprocal transport characterized by a large second-harmonic generation in this semimetallic state.

This work is a collaboration with Y. Wang, H. F. Legg, T. Bömerich, J. Park, A. A. Taskin, and A. Rosch at the University of Cologne. It was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 741121) and was also funded by the German Research Foundation (DFG) under CRC 1238 - 277146847 as well as under Germany's Excellence Strategy - Cluster of Excellence Matter and Light for Quantum Computing (ML4Q) EXC 2004/1 - 390534769.

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Magneto-optics of electrons in conical bands

M. Orlita

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Intriguing analogies to relativistic systems have largely helped to understand the electronic properties of various solid-state systems which largely fit into the emergent class of topological matter. These include, for instance, 2D graphene, surfaces of topological insulators, novel 3D Dirac and Weyl semimetals, Rashba-type semiconductors, or more recently, nodal-line Dirac semimetals or conical bands in more complex manifolds. In this talk, I will discuss how the relativistic-like dispersion of electrons in solids impacts their magneto-optical properties, or in turn, how can magneto-optical spectroscopy visualize the electronic bands in different materials, and in general, contribute to our understanding of physical phenomena related to topological materials. Results obtained on various materials (graphene, Bi_2Se_3, Bi_2Te_3, BiTeI, Cd_3As_2, HgCdTe, TaP, $NbAs_2$...) will be presented as examples [1-8].

References

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Quantized Faraday rotation and band structure in topological insulators

Andrei Pimenov

Vienna University of Technology, Austria

Topological insulators are materials which are insulating in the bulk and which reveal conducting surface states. The electrodynamics of topological insulators is described by modified Maxwell's equations, which contain additional terms that couple an electric field to a magnetization, such that the coupling coefficient is quantized in odd multiples of $e^2/2hc$ per surface. The new term leads to universal values of Faraday rotation angle equal to the fine structure constant $\alpha \approx 1/137$ radian when a linearly polarized terahertz radiation passes through a topological insulator. This regime is obtained in high magnetic field and in the quantum regime.

In weak external magnetic fields the quasi-classical approximation is realized and a series of cyclotron resonances is observed in the terahertz frequency range. From the analysis of these experiments the band structure of topological insulator HgTe can be obtained both for 2D and 3D configurations. Therefore, the magneto-optical technique provide an experimental method to test the band structure calculations of topological insulators based on quantum wells.

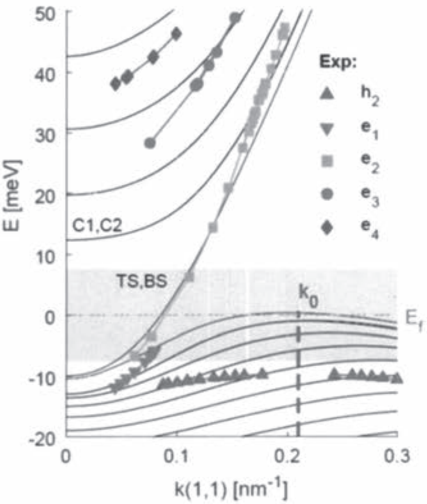

Fig. 1. Band structure of 3D topological insulator along the (1,1) direction obtained from the analysis of the cyclotron resonance. Sample - HgTe film 80 nm thick. Symbols - experimental data, e - electrons, h - holes, solid lines are predictions of the **k·p** model calculated for the charge neutrality point. C1, C2 - spin-degenerate conduction bands, TS, BS -top and bottom surfaces, respectively. For the charge neutrality point the degeneracy of the bands is not lifted.

[1] In cooperation with: J. Gospodaric, V. Dziom, A. Shuvaev, G. V. Astakhov, G. Tkachov, E. M. Hankiewicz, C. Brüne, H. Buhmann, L. W. Molenkamp, N. N. Mikhailov, and Z. D. Kvon.

Abstracts of Posters

(in alphabetical order)

Spectroscopic investigations of the Quantum Magnet Averievite under external stimuli

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The copper oxide Averievite $Cu_5V_2O_{10}(CsCl)$ [1,2] hosts highly frustrated $S = 1/2$ kagome planes connected in 3D by a honeycomb sublattice. Due to the large intra- and interlayer coupling of the magnetic copper ions, the material possesses an antiferromagnetic ground state ($T_N = 24$ K). By substituting Cu ions within the honeycomb lattice by Zn, the kagome planes decouple and the long-range magnetic order is suppressed, glancing at the celebrated quantum spin liquid.

We present a comprehensive magneto-optical study on $Cu_{5-x}Zn_xV_2O_{10}(CsCl)$ for a Zn substitution $x = 0, 0.25, 0.5, 0.75, 1, 1.25$ in a broad range of frequencies from the THz region to the visible range and down to 1.6 K. Comparing our experimental results with the recent band structure calculations, we elaborate the rich electronic structure and the possible magnetic low-energy excitations.

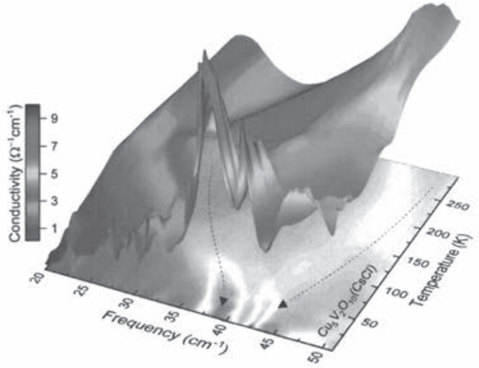

Figure 1: Temperature dependent low-energy excitations of $Cu_5V_2O_{10}(CsCl)$

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Effect of tuning the interlayer bonding on the optical conductivity of the Nodal-line Semimetal Zr*XY*

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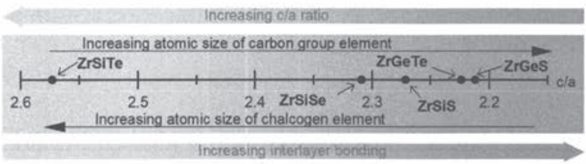
The layered materials Zr*XY* (*X* = Si, Ge and *Y* = S, Se, Te) are currently extensively investigated as nodal-line semimetals with Dirac-like band crossings protected by nonsymmorphic symmetry. We carried out a comparative study on the optical conductivity of Zr*XY* by reflectivity measurements over a broad frequency range combined with density functional theory calculations [1]. The optical conductivity exhibits a distinct U shape, ending at a sharp peak at around 1.25 eV for all studied compounds except for ZrSiTe. The energy position of sharp high-energy peak depends on the interlayer bonding correlated with the c/a ratio, which can be tuned by either chemical or external pressure. For ZrSiTe, another pair of crossing bands appears in the vicinity of the Fermi level, corrugating the nodal-line electronic structure and leading to the observed difference in optical conductivity. Accordingly, we further carried out pressure-dependent infrared spectroscopy, Raman spectroscopy, and x-ray diffraction measurements combined with electronic band structure calculations for ZrSiTe [2,3]. We find indications for two pressure-induced Lifshitz transitions for ZrSiTe with major changes in the Fermi surface topology in the absence of lattice symmetry changes. These electronic phase transitions can be attributed to the enhanced interlayer interaction induced by external pressure.



Scheme illustrating the chemical pressure effect in Zr*XY*.

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Geometric properties of SU(N) parametric Hamiltonians

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SU(N) Hamiltonians depending on parameters are ubiquitous in physics, typical examples being N-band Bloch Hamiltonians or N-level atomic systems. We consider the geometric properties of such Hamiltonians in a unified framework, generalizing the well-known N=2 case. Aiming to avoid energy eigenfunctions, we focus on eigenprojectors and the associated (generalized) Bloch vectors. This leads directly to a new Bloch-vector based expression for the quantum geometric tensor (QGT), which unifies quantum metric and Berry curvature. The Cayley-Hamilton theorem then allows to derive new explicit formulas for the SU(3) and SU(4) Berry curvature. The formalism is especially practical in the case of a symmetric spectrum, where the energy levels/bands occur in pairs of opposite sign, and where a zero-energy state exists for N odd. Our results are broadly applicaple, in particular to lattice models of the Lieb and Kagomé family, topological insulators and superconductors, but also to low-energy effective Hamiltonians as well as qutrits and qudits studied in quantum information.

Electrical Control of Spin Textures at the Interface Between Graphene and Topological van der Waals Materials

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Van der Waals heterostructures comprised of graphene and three-dimensional topological insulators, combining high electron mobilities and nontrivial spin textures, are promising to exert pronounced proximity-induced spin phenomena that can be electrically controlled [1]. Here, we study the interface properties of van der Waals heterostructures by means of optoelectronic spectroscopy. In particular, we investigate the proximity-induced spin-orbit coupling at the interface of graphene and the topological insulator $BiTe_2Se$ which is fabricated by van der Waals epitaxy with a commensurate lattice configuration [2]. To read-out and probe the spin-orbit coupling at the interface, we utilize time-integrated and time-resolved magneto-optic Kerr microscopy and photocurrent spectroscopy [3]. Moreover, we probe the electrically generated spin polarization in field effect devices as a function of Fermi level.

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Influence of magnetic ordering on the optical response of the antiferromagnetic topological insulator $MnBi_2Te_4$

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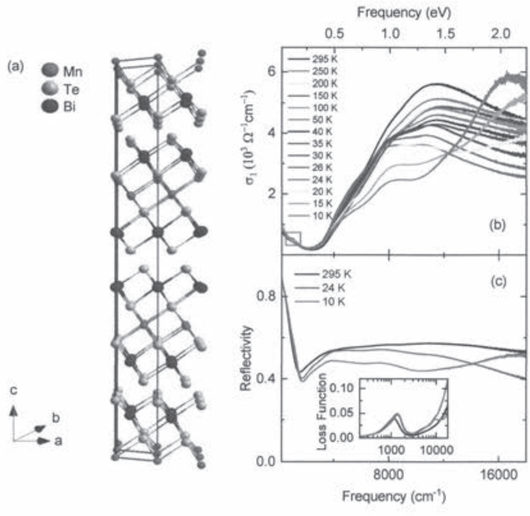
The layered topological insulator $MnBi_2Te_4$ has attracted great interest recently due to its intrinsic antiferromagnetic order, potentially hosting various topological phases [1,2,3]. By temperature-dependent infrared spectroscopy over a broad frequency range, we studied the changes in the optical conductivity of $MnBi_2Te_4$ at the magnetic ordering temperature T_N=24 K. The temperature dependence of several optical parameters reveals an anomaly at the magnetic phase transition, which suggests the correlation between the bulk electronic band structure and the magnetism. We relate our findings to recent reports on the temperature dependence of the electronic band structure of $MnBi_2Te_4$.



(a) Crystal structure of $MnBi_2Te_4$, consisting of Te-Bi-Te-Mn-Te-Bi-Te septuple layers with van der Waals-type interaction along the *c* direction. (b) Optical conductivity σ_1 for all measured temperatures. (c) Reflectivity spectrum for selected temperatures 295, 24, and 10 K together with the corresponding loss function in the inset.

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Fermi surface reconstruction and nested (Russian doll) magnetic breakdown in WTe_2

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The transition metal dichalcogenide WTe_2 in the T_d-phase is a prototypical example of a Weyl type-II semimetal. Despite a large number of quantum oscillation experiments that provided insights on the Fermi surface, its exact topology remains to be determined. We present a systematic magneto-resistance and quantum oscillation study on WTe_2 in high magnetic fields up to 30 T. By measuring the Shubnikov-de Haas oscillation superimposed on a large magneto-resistance, we find four distinct pockets of the Fermi surface, two of them being hole and two electron-like, in agreement with existing DFT calculations. With increasing magnetic field, we observe magnetic breakdown between individual pockets which are identified by the extracted cyclotron masses in agreement with theory. By investigating the angle dependence of the quantum oscillations, magnetic breakdown can be observed in a wide range of tilt angles away from the c-axis suggesting this phenomenon occurs between two (or more) nested electron- and hole-pockets in WTe_2.

Topological Weaire-Thorpe model of amorphous matter

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Amorphous solids remain outside of the classification and systematic discovery of new topological materials, partially due to the lack of realistic models that are analytically tractable. Nevertheless, experiments have recently shown that topological edge states exist in amorphous systems [1]. These states being insensitive to localized defects, and protected by global properties of the material, there is indeed no reason why they should not remain in amorphous matter. Here [2] we introduce the topological Weaire-Thorpe class of models, which are defined on amorphous lattices with fixed coordination number, a realistic feature of covalently bonded amorphous solids [3]. Their short-range properties allow us to analytically predict spectral gaps. Their symmetry under permutation of orbitals allows us to compute analytically topological phase diagrams, which determine quantized observables like circular dichroism, by introducing symmetry indicators for the first time in amorphous systems. These models and our procedures to define invariants are generalizable to higher coordination number and dimensions, opening a route towards a complete classification of amorphous topological states in real space using quasi-local properties.

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Landau level spectroscopy of Bi_2Te_3

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Here we report on Landau level spectroscopy in magnetic fields up to 34 T performed on a thin film of the topological insulator Bi_2Te_3 epitaxially grown on a BaF_2 substrate. The observed response is consistent with the picture of a direct-gap semiconductor in which charge carriers closely resemble massive Dirac particles. The fundamental band gap reaches $E_g = (175 \pm 5)$ meV at low temperatures and it is not located on the trigonal axis, thus displaying either six or twelvefold valley degeneracy. Interestingly, our magneto-optical data do not indicate any band inversion at the direct gap. This suggests that the fundamental band gap is relatively distant from the Γ point where profound inversion exists and gives rise to the relativistic-like surface states of Bi_2Te_3.

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A quantum oscillation study in the Dirac nodal-line semimetal HfSiS

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The semimetal HfSiS belongs to a class of Dirac nodal-line (DNL) materials in which the conduction and valance bands cross (or touch) each other along a closed trajectory inside the Brillouin zone (BZ) in momentum space.
We have performed a de Haas – van Alphen (dHvA) quantum oscillation study of HfSiS in high magnetic fields up to 31 T. For parallel alignment of the magnetic field and the c-axis, we observe quantum oscillations originating from individual electron and hole pockets, as well as oscillations caused by magnetic breakdown (MB) between these pockets. The MB orbits come in a wide variety, ranging from a so-called 'figure-of-eight' orbit to orbits enclosing large areas in the BZ. Contrary to a previous magneto-transport study we are able to fully resolve the large-area enclosing MB orbits. All MB orbits can be seen as a manifestation of Klein tunneling in momentum space, although in a regime of partial, intermediate transmission due to the finite and larger separation between adjacent pockets as compared to the sister compound ZrSiS. Our experimental observations, the strong dependence of the oscillation amplitude on the field angle and the cyclotron masses of the MB orbits, is in good agreement with the theoretical predictions for this novel tunneling phenomenon.

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Many-body effects in nodal-line semimetals: Correction to the optical conductivity

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Long-range Coulomb electron-electron interaction might have important effects on the physical observables in topological semimetals with vanishing density of states at the band touching due to the weak screening. In this talk, I will present our results for the first-order perturbative correction to the optical conductivity in a clean three-dimensional (3D) nodal-line semimetal (NLSM) [1]. Our calculation exploits the analogy between 3D NLSMs and two-dimensional massless Dirac fermions [2], and our result $\sigma_0 C_2 \alpha$ for the correction reflects this parallelism, where σ_0 is the conductivity in the noninteracting limit, $C_2 = (19 - 6\pi)/12 \simeq 0.01$ is an universal numerical coefficient (exactly the same which appears in graphene), and α is the renormalized fine structure constant. Therefore, I will first review the analogous problem of the interaction correction to the optical conductivity in graphene, where there was a long-standing controversy [3-5], but now there is arguably agreement on its solution. I will then discuss the optical conductivity of the 3D interacting NLSMs, highlighting the features introduced by the interactions, and also comparing it to the optical conductivity in graphene and Weyl semimetals. Finally, I will briefly comment on the experimental measurements of the optical conductivity in some NLSMs and how they compare to our result.

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Magneto-Optics of a Weyl Semimetal beyond the Conical Band Approximation: Case Study of TaP

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Landau-level spectroscopy, the optical analysis of electrons in materials subject to a strong magnetic field, is a versatile probe of the electronic band structure and has been successfully used in the identification of novel states of matter such as Dirac electrons, topological materials or Weyl semimetals. The latter arise from a complex interplay between crystal symmetry, spin-orbit interaction, and inverse ordering of electronic bands. Here, we report on unusual Landau-level transitions in the monopnictide TaP that decrease in energy with increasing magnetic field. We show that these transitions arise naturally at intermediate energies in time-reversal-invariant Weyl semimetals where the Weyl nodes are formed by a partially gapped nodal-loop in the band structure. We propose a simple theoretical model for electronic bands in these Weyl materials that captures the collected magneto-optical data to great extent.

Gatable current-induced Kerr signal in WTe_2/graphene heterostructures

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Heterostructures comprised of a spin transport material (e.g. graphene) combined with a spin-generator (e.g. a strong spin-orbit coupled material) are of strong interest for spintronics that is controllable by all-electrical means. Intriguing materials for charge-to-spin conversion are the Weyl semimetals such as WTe_2. The latter has been demonstrated to enable efficient electrical current-based magnetic switching [1]. Thus far, only the in-plane spin texture of graphene/WTe_2 heterostructures has been experimentally investigated using electrical signals [2][3]. Here, we aim to probe the out-of-plane spin texture in such heterostructures with the aid of Kerr microscopy as a spatially resolved optical read-out method. Along these lines, we compare the results of electrical transport measurements, current-induced Kerr microscopy, as well as zero-bias photocurrent measurements, all of which have been performed as a function of back gate voltage on graphene/WTe_2 heterostructure devices. We propose a model based on the gate-dependent current distribution in order to account for the observed behavior.

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Spectroscopic evidence of chiral anomaly in Cd_3As_2

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One of the most exotic phenomena of topological semimetal is the realization of chiral anomaly in condensed matter physics. The chiral anomaly is a charge imbalanced state between two Weyl points with different chiralities. This effect is expected to take place in Dirac and Weyl semimetal when parallel electric field and magnetic field are applied. Here, we present our recent magneto-optical study performed on 3D Dirac semimetal, Cd_3As_2. We observed some signatures under magnetic field which can be explained by the chiral anomaly. Details will be discussed in this presentation.

Linear optical conductivity of the chiral multifold semimetal RhSi

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The 230 space groups, of which only 65 are chiral, describe all possible combinations of non-magnetic crystal symmetries in nature. Materials described by some of these groups host band degeneracies near the Fermi level protected by the corresponding crystal symmetries[1]. The low-energy excitations around these band degeneracies give rise to quasiparticles called multifold fermions, and we refer to the materials hosting them as multifold semimetals. We calculate the linear optical conductivity of *all* chiral multifold fermions using low-energy $\boldsymbol{k}\cdot\boldsymbol{p}$ Hamiltonians[2], and show that its distinctive features can be used as an experimental fingerprint for each type of multifold fermion. We build a generic four-band tight-binding model using the symmetries of the space group 198[3], where RhSi crystallizes. This model is suitable to describe any material in space group 198, and has been used to study the properties of the chiral multifold semimetal CoSi[4]. We obtain the model for RhSi by fitting the tight-binding parameters to first-principles calculations and compare the results with the experimental data. The theoretical curves agree well with the experimental measurements[5] and show that the low-energy conductivity is determined by the threefold degeneracy at the Γ point. Using these results, we conclude that RhSi has a relatively short hot-carrier lifetime, and that the chemical potential sits below the threefold node.

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Non-Hermitian dynamical topology of driven-dissipative Kitaev chain

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We theoretically investigate the non-Hermitian dynamical topology of a driven-dissipative Kitaev chain. For this, we have employed the third quantization formalism [1] to explore signatures of the non-trivial topology in the time-evolution of the entanglement spectra.

We shall first present a concise summary of the underlying physics of the Kitaev chain and clarify the merits of stepping outside the realm of Hermitian physics. We then focus on the driven-dissipative Kitaev chain and explore it's richer phase diagram with gapless, real-line gapped, imaginary-line gapped, and topological phases. We further discuss this system's dynamics from the initial dissipation-less trivial phase to other regions of the phase diagram. We reveal that non-trivial topology is reflected in crossings in the entanglement spectrum for quenches from a trivial to the topological phase. Finally, we shall emphasize that our results are unique to interacting open quantum systems.

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Acoustogalvanic effect in Weyl and Dirac semimetals

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The acoustogalvanic effect in Dirac and Weyl semimetals is proposed. This is a nonlinear mechanism to generate a direct electric current by dynamical strains, e.g., by passing acoustic waves. Unlike the standard acoustoelectric effect, which relies on the sound-induced deformation potential and the corresponding electric field, the acoustogalvanic one originates from the pseudo-electromagnetic fields, which are not subject to screening. Because of the interplay of pseudoelectric and pseudomagnetic fields, the current could show a nontrivial dependence on the direction of sound wave propagation. Being within the experimental reach, the effect can be utilized to probe dynamical deformations and the corresponding pseudo-electromagnetic fields.

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Chiral anomaly induced Veselago lensing in Weyl semimetals

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The description of electron scattering between two media is similar to the refraction of light, where light-rays follow the path of least accumulated optical index. In the late 60's Veselago showed that this optical index can be negative [1], opening new ways for imaging, even below the diffraction limit [2]. A similar situation also occurs in the case of Dirac electrons, in Klein tunneling [3,4]. In this poster we discuss that on the contrary to 2D materials, such as graphene, Veselago lensing can be observed separately for cones of opposite chirality in Weyl semimetals with the help of the chiral anomaly. We study this in the case of two physical phenomena : Friedel oscillations and non-local conductivity. This will allow us to discuss how Veselago lensing occurs in solid-state devices and its extensions to other types of materials.

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Magneto optical spectroscopy of Dirac nodal line semimetal NbAs2

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Transition metal di-pnictides (TMdP) family consist of six materials with formula XPn_2 (X = Ta, Nb, Pn = P, As, Sb) crystallizing in the monoclinic system with the centrosymmetric space group $C_{12/m1}$. According to first-principle calculations, all TMdP materials posses a nodal line region in their band structure, which is gapped, if the spin-orbital coupling is considered. The calculations also suggest that $NbAs_2$, $TaAs_2$, and $NbSb_2$ are nearly compensated semimetals, which makes these materials appealing candidates for optical studies, and in particular, in externally applied magnetic fields.

$NbAs_2$ has been so far explored in a few experiments only. Magneto-resistance studies revealed the presence of several Fermi surfaces, as well as extremely large and strongly anisotropic magnetoresistance. Optical measurements performed at zero magnetic field identified the high anisotropic response in the mid-infrared region depending on the polarization of incident light with respect to crystallographic orientation. Nearly vanishing optical conductivity deduced for light polarized parallel with the b-axis of $NbAs_2$ was interpreted as a signature of a nodal line extend indefinitely through multiple Brillouin zones. At present, the magneto-optical response of $NbAs_2$ has been barely explored, let alone understood, which calls for further investigations.

Here we report on high-field magneto-reflectivity studies of $NbAs_2$ (up to 34T @ 1.6K). These were performed on a set of samples (and their facets with various crystallographic orientation) in order to map the dispersion of the nodal line. We conclude that the observed response can be always understood in terms of two series of electric-dipole-active inter-Landau level excitations. A simplified theoretical approach with relativistic-like corrections is suggested in order to describe the observed magneto-optical response as a function of the angle between the nodal line direction and the wave vector.