Synthetic dimensions and Topological frequency conversion in strongly driven quantum systems

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When a small quantum system is subject to multiple periodic drives, it may realize multidimensional topological phases. In my talk, I will explain how to make such constructions, and show how a spin-1/2 particle driven by two elliptically-polarized light beams could realize the Bernevig-Hughes-Zhang model of 2 topological insulators. The observable consequence of such construction is quantized pumping of energy between the two drive sources. If time allows I will also discuss how to use memory in order to impose boundary conditions in photon-induced synthetic dimensions, such as the ones giving rise to the topological pumping effect.

Floquet insulators: topological engineering by driving

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Out of equilibrium systems open new possibilities to observe novel phenomena. In recent years the topic has been revitalized due to the development of new ideas and theoretical concepts as well as the exquisite control reached experimentally in different systems (like graphene, superconducting quits, cold atoms and photonics crystals, for instance).

A particular area of research is the study of how the presence of (periodic) time dependent potentials can induce topological properties in an otherwise topologically trivial material. These systems are called Floquet topological insulators and, similar to ordinary topological insulators (TI), present a bulk gap in their (quasi-) energy spectrum and chiral states at their edges/surfaces or at the interfaces with other materials.

In this talk I will discuss some examples on different systems (graphene, Tis, TMDC, Josephson junctions) in the presence of circularly polarized laser radiation where we characterized the bulk topological properties and a hierarchy of chiral states that appear at the border or around defects and adatoms. We also evaluate the effect of this edge states on charge transport and show how they lead to a Hall signal. This in turns, calls for a discussion on the relation between topological invariants of the Floquet bands and physical observables.

Quantum transport and interactions in Majorana nanowires

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The possibility to induce topological superconductivity (TS) in semiconducting nanowires is opening new avenues for research in quantum transport. Present technologies could allow to explore transport in all type of hybrid structures including TS wires in either two terminal or multiterminal geometries. This situation claims for a flexible theoretical framework going beyond idealized models but still simple to account analytically for transport through subgap and continuum states in these devices. On the other hand, the role of interactions in actual experiments for detecting Majorana bound states (MBS) continues to be an important open issue.

In this presentation I shall review work done in collaboration with different groups along these lines. I shall first present an approach that we have recently introduced [1] to analyze transport in hybrid TS junctions based on a tunnel Hamiltonian description. Using this approach we have obtained analytical results for conductance, noise and supercurrent in hybrid junctions of arbitrary transparency. I shall also discuss recent results [2] on transport in multi-terminal junctions including both TS and (non-topological) S leads which demonstrate the possibility to test the spin of the MBSs through supercurrent measurements. Finally, I shall discuss the effect of interactions mediated by the electrostatic environment of the nanowires which may lead to zero energy pinning of the MBSs even in the absence of topological protection [3].

[1] "Low energy transport theory of Majorana wire junctions", A. Zazunov, R. Egger and A. Levy Yeyati, Phys. Rev. B 94, 014502 (2016).
[2] "Josephson effect in multiterminal topological junctions", A. Zazunov, R. Egger, M. Alvarado and A. Levy Yeyati, Phys. Rev. B 96, 024516 (2017).
[3] "Zero-energy pinning from interactions in Majorana wires", F. Dominguez, J. Cayao, P. San-Jose, R. Aguado, A. Levy Yeyati and E. Prada, npj Quantum Materials 2, 13 (2017).

Fractional Spin and Josephson Effect in Time-Reversal-Invariant Topological Superconductors

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Time-reversal-invariant topological superconducting (TRITOPS) wires are known to host a fractional spin 1/4 at their ends. In this talks we show how this fractional spin affects the Josephson current in a TRITOPS-quantum dot-TRITOPS Josephson junction, describing the wire in a model that can be tuned between a topological and a nontopological phase.
The equilibrium Josephson current of the full model is computed by continuous-time Quantum Monte Carlo simulations and, to help the interpretation of the results, an effective low-energy theory will be presented.

We show that in the topological phase, the 0-to-π transition is quenched via formation of a spin singlet fromthe quantum-dot spin and the fractional spins associated with the two adjacent topological superconductors.

From topological band-insulators to topological Kondo-insulators in one dimension

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Topological insulators are a recently discovered class of materials that fall outside the framework of Landau's paradigm, where phases of matter are classified according to the symmetries which are spontaneously broken. Instead, topological insulators must be classified according to the topology of its electronic ground state wavefunction.

Our present understanding of topological phases is largely limited to non-interacting systems, where the so-called topological band theory or the scattering-matrix approach can be applied. Taking into account the effects of interactions among electrons constitutes a difficult challenge, and developing a unified theoretical description of strongly interacting topological phases is still an open issue. In that respect, model Hamiltonians (e.g., the Hubbard model) play an important role in helping to develop an intuitive understanding and to predict the properties of interacting topological matter.
In this talk, I will focus on the so-called topological Kondo insulators, materials characterized by the interplay of the topology of its band structure and strong interactions. I will explain recent results obtained using theoretical toy models proposed to describe a 1D topological Kondo insulator: the "p-wave" 1D Kondo Heisenberg model and the sp-ladder Hubbard model. Using a combination of Abelian bosonization and the density matrix renormalization group (DMRG), we have been able to characterize the ground state properties of the system in the strongly-interacting regime. A careful analysis of the topologically-protected edge-states, charge and spin excitation gaps, and non-local string order parameter, allows us to conclude that the ground state is in the Haldane phase universality class, a paradigmatic phase typically associated to the antiferromagnetic S=1 Heisenberg chain, which displays non-vanishing string order and fractionalized S=1/2 end-states. Our results allow to make an interesting and unexpected connection between non-interacting and strongly-interacting topological phases.

[1] A. M. Lobos, A. O. Dobry, and V. Galitski, Phys. Rev. X 5, 021017 (2015).
[2] A. Mezio, A. M. Lobos, A. O. Dobry, and C. J. Gazza, Phys. Rev. B 92, 205128 (2015)
[3] F. T. Lisandrini, A. M. Lobos, A. O. Dobry, and C. J. Gazza, Papers in Physics 8, 080005 (2016).
[4] F. T. Lisandrini, A. M. Lobos, A. O. Dobry, and C. J. Gazza, Phys. Rev. B 96, 075124 (2017)

Topological quantum phase transition between two Fermi liquid ground states through a non-Fermi liquid in a generalized Anderson impurity model

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Quantum phase transitions build up one of the scenarios for the emergence of non-Fermi liquid (NFL) behavior in electronic systems, driven by the strong competence between quantum fluctuations of the two distinct phases close to the critical point. In this work, we solve a S=1 Anderson impurity model with single-ion anisotropy D, coupled to two degenerate conduction bands, using the numerical renormalization group. At a critical anisotropy Dc > 0, we find a quantum phase transition between two regular Fermi liquid phases: for D < Dc the impurity is Kondo screened, while, for D > Dc. the impurity magnetic degree of freedom is quenched by the anisotropy. Surprisingly, the Fermi liquids are separated by a NFL region, whose behavior corresponds to a two-channel Kondo effect, as we have been able to characterize it through an analysis of entropy and electrical conductance. In addition, the two Fermi liquids are differentiated topologically by the value that the integral I_L, related with Luttinger theorem, takes in each one of them: I_L = 0 for D < Dc and the non-trivial I_L = pi/2 for D > Dc.

Chiral and degenerate phases in the kagome antiferromagnet

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The study of topological phases has been of great interest in the last years. At the center of these studies has been the kagome antiferromagnet. Numerous models have been proposed in the quest for topological exotic phases, including XXZ anisotropy, further neighbour couplings and antisymmetric interactions. In some regions of antiferromagnetic parameters, at the boundaries of classically chiral phases, recent studies suggest the emergence of chiral spin liquid quantum phases. In this work, we contribute to this topic inspecting the low temperature behaviour of these regions in the classical model. We enhance the chirality of the system adding Dzyaloshinskii-Moriya interactions and an external magnetic field. The competition of these interactions gives rise to a rich phase diagram, with different spontaneously broken symmetry phases. Most notably, for a significant region of parameter space the system acquires, by a spontaneously symmetry breaking, a net chirality. We close with comments for future work on quantum systems.

New observations on no n-abelian quantum Hall states

Adiel Stern

Weizman Institute

Majorana based quantum computation

Felix von Oppen

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Topological quantum chemistry

Andrei Bernevig

Princeton University

The past decade's apparent success in predicting and experimentally discovering distinct classes of topological insulators (TIs) and semimetals masks a fundamental shortcoming: out of 200,000 stoichiometric compounds extant in material databases, only several hundred of them are topologi- cally nontrivial. Are TIs that esoteric, or does this reflect a fundamental problem with the current piecemeal approach to finding them? To address this, we propose a new and complete electronic band theory that highlights the link between topology and local chemical bonding, and combines this with the conventional band theory of electrons. Topological Quantum Chemistry is a descrip- tion of the universal global properties of all possible band structures and materials, comprised of a graph theoretical description of momentum space and a dual group theoretical description in real space. We classify the possible band structures for all 230 crystal symmetry groups that arise from local atomic orbitals, and show which are topologically nontrivial. We show how our topological band theory sheds new light on known TIs, and demonstrate the power of our method to predict a plethora of new TIs.

Topology of the Fermi surface wavefunctions and magnetic oscillations in metals

Leonid Glazman

Yale University

In the traditional Fermiology, the size and shape of the Fermi surface in a metal is often deduced from the period of magnetic oscillations of transport or thermodynamic characteristics, *e.g.*, from the de Haas – van Alphen effect. We find that the intercept g of the infinite-field asymptote of the oscillations yields information about the topology of the Fermi surface wave functions. The topological invariance of g originates from the symmetry of extremal orbits, which depends not only on the space group but also on the field orientation with respect to the crystal axes. The wavefunctions fall into 10 distinct classes stemming from the crystalline symmetry; transitions between the classes occur via magnetic breakdown

"Geometrodynamics of electrons in crystals under deformation"

Qian Niu

Texas University

Semiclassical dynamics of Bloch electrons in a slowly varying deforming crystal is developed in the geometric language of a lattice bundle. Berry curvatures and gradients of energy are introduced in terms of lattice covariant derivatives, with connections given by the gradient and rate of strain. A number of physical effects are discussed: an effective post-Newtonian gravity, polarization induced by spatial gradient of strain, orbital magnetization induced by strain rate, and transverse electron viscosity.

Thermo- and magnetoelectric effects in superconducting nanostructures with spin-dependent fields.

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Spin-dependent fields acting on superconductivity lead to intriguing phenomena. Under equilibrium conditions these phenomena are attributed to the singlet-triplet conversion of the superconducting condensate [1]. In this talk I first discuss the effect of spin-orbit coupling (SOC) and exchange fields on the properties of hybrid superconducting structures. I distinguish between intrinsic and extrinsic SOC and predict non-dissipative Spin-Hall, Anomalous-Hall, Edelstein and Spin-Galvanic effects in analogy to normal systems with different types of SOC [2-4]. These predictions open new opportunities for the development of low-dissipation magneto-electronics.

In the second part of the talk, I will focus on charge and heat currents in superconducting structures with ferromagnetic insulators (FI).

The spin-splitting of the BCS density of the states induced in the superconductor leads to striking phenomena which I will illustrate by briefly discussing few examples [5]:

(i) a huge thermoelectric effect in a N-FI-S structure, (ii) the occurrence of a thermophase in S-FI-S structures, (iii) the possibility of using FI-S in high sensitive detectors and thermometers [6], and (iv) a heat valve based on a ferromagnetic Josephson junction [8].

[1] F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Rev. Mod. Phys. 77, 1321, 77 (2005).
[2] F.S. Bergeret and I. V. Tokatly, Phys. Rev. Lett. 110, 117003 (2013), and Phys. Rev. B 89, 134517 (2014).
[3] F.S. Bergeret and I. V. Tokatly, Phys. Rev. B 94, 180502 (R) (2016)
[4] F. Konschelle, F. S. Bergeret and I. V. Tokatly, *Physical Review B* 92.12 (2015): 125443.

Weyl Semimetals and beyond!

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Topology a mathematical concept became recently a hot topic in condensed matter physics and materials science. One important criteria for the identification of the topological material is in the language of chemistry the inert pair effect of the s-electrons in heavy elements and the symmetry of the crystal structure [1]. Beside of Weyl and Dirac new fermions can be identified compounds via linear and quadratic 3-, 6- and 8- band crossings stabilized by space group symmetries [2]. Binary phoshides are the ideal material class for a systematic study of Dirac and Weyl physics. Weyl points, a new class of topological phases was also predicted in NbP, NbAs. TaP, MoP and WP2. [3-7]. In NbP micro-wires we have observed the chiral anomaly [8]. NbP has served as a model system for the gravitational anomaly in astrophysics [9] and WP2 for a hydrodynamic flow of electrons [10]. MoP and WP2 show exceptional properties such as high conductivity (higher than copper), high mobilties and a high magneto-resistance effect. With thermal and magnetoelectric transport experiments, a transition from a hydrodynamic electron fluid below 15 K into a conventional metallic state at higher temperatures is observed. The hydrodynamic regime is characterized by a viscosity-induced dependence of the electrical resistivity on the square of the channel width that coincides with as strong violation of the Wiedemann-Franz law. In magnetic materials the Berry curvature and the classical AHE helps to identify interesting candidates. Magnetic Heusler compounds were already identified as Weyl semimetals such as Co2YZ [12-16] and in Mn3Sn [17,18].

The Anomalous Hall angle helps to identify even materials in which a QAHE should be possible in thin films.

[1] B Bradlyn et al., Nature 547 298, (2017)arXiv:1703.02050
[2] B. Bradlyn, et al., Science 353, aaf5037A (2016).
[3] C. Shekhar, et al., Nature Physics 11, 645 (2015)
[4] Z. K. Liu, et al., Nature Materials 15, 27 (2016)
[5] L. Yang, et al., Nature Physics 11, 728 (2015)
[6] C. Shekhar, et al. preprint arXiv:1703.03736
[7] N. Kumar, et al., Nature Com. accepted, preprint arXiv:1703.04527
[8] A. C. Niemann et al., Sci. Rep. 7 43394 (2017)
[9] J Gooth et al., Nature 547 324, (2017) arXiv:1703.03736
[10] J. Gooth et al. preprint arXiv: 1706.05925
[11] Wang et al., Physical review letters 117, 236401 (2016)
[12] Kübler and Felser, Europhys. Lett. 114, 47005 (2016)
[13] Chang et al., Scientific Reports 6, 38839 (2016)
[14] Kübler and Felser, EPL 108 (2014) 67001 (2014)
[15] Nayak, et al., Science Advances 2 e1501870 (2016)
[16] Nakatsuji, Kiyohara and Higo, Nature 527 212 (2015)

Exotic phenomena in Tellurium under pressure

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Elemental tellurium is a semiconductor with a relatively small band gap of around 320meV. It naturally occurs in a trigonal crystal structure with spirals of Te atoms ordered in a hexagonal lattice. Several non-trivial topological phases have been proposed to occur in this material under the application of modest hydrostatic pressure. These include a topologically insulating and several Weyl semi-metal phases. We have performed resistivity measurements under pressure and small magnetic fields on high-quality tellurium single crystals. Our results give first experimental evidence of the material being in the closest vicinity to an insulator-to-metal transition of the Lifshitz type at over 20kbar. Moreover, we find an anomaly in the low temperature range, which might be related to the unique camel-back shaped band structure of tellurium.

Topological Physics in HgTe-based Quantum Devices

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Suitably structured HgTe is a topological insulator in both 2- (a quantum well wider than some 6.3 nm) and 3 (an epilayer grown under tensile strain) dimensions.

The material has favorable properties for quantum transport studies, i.e. a good mobility and a complete absence of bulk carriers, which allowed us to demonstrate variety of novel transport effects.

One aspect of these studies is topological superconductivity, which can be achieved by inducing superconductivity in the topological surface states of these materials. Special emphasis will be given to recent results on the ac Josephson effect. We will present data on Shapiro step behavior that is a very strong indication for the presence of a gapless Andreev mode in our Josephson junctions, both in 2- and in 3-dimensional structure. An additional and very direct evidence for the presence of a zero mode is our observation of Josephson radiation at an energy equal to half the superconducting gap.

Controlling the strain of the HgTe layers strain opens up yet another line a research. We have recently optimized MBE growth of so-called virtual substrates ((Cd,Zn)Te superlattices as a buffer on a GaAs substrate), that allow us to vary the strain from 0.4% tensile to 1.5% compressive. While tensile strain turns 3-dimensional HgTe into a narrow gap insulator, compressive strain turns the material into a topological (Weyl) semimetal, exhibiting clear signs of the Adler-Bell-Jackiw anomaly in its magnetoresistance. In quantum wells, compressive strain allows inverted energy gaps up to 60 meV.

Phase transitions in a mixed Landau level system

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In two-dimensional electron systems exposed to a strong magnetic field, interactions give rise to a rich set of phases. These include emergent Fermi surfaces, topological and nematic phases as well as insulating states. In traditional GaAs based 2D electron systems, it has been apparent that the orbital index of the partially filled level plays a crucial role for the competition among these phases, but a systematic study is hampered by the lack of any suitable means to tune the orbital index of the partially filled level at total fixed filling. Here we resort to ZnO 2D electron systems to overcome this limitation. This material system offers larger spin susceptibility and smaller kinetic energies, while simultaneously providing exceptional quality so that these states induced by fragile interactions can develop. Our studies unveil a complex, partly unexpected cascade of transitions between all of these phases as levels with different orbital index are forced to swap.

Chiral domain walls and magnetic anti-skyrmions

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Over the past few years there have been remarkable discoveries in spin-based phenomena that rely on *spin-orbit coupling* that could spur the development of advanced magnetic memory devices[1-3]. These include the formation of *chiral* spin textures in the form of Néel domain walls and topological spin textures – skyrmions - that are stabilized by a Dzyaloshinskii-Moriya exchange interaction. The Dzyaloshinskii-Moriya exchange interaction is derived from broken symmetries and spin-orbit interactions at interfaces or within the bulk of materials. Recently we have discovered magnetic *antiskyrmions* in a tetragonal Heusler compound, $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$, using Lorentz transmission electron microscopy[4]. The antiskyrmions are stable over a wide range of temperature and magnetic field. In thin films of the related compound Mn_2RhSn we find evidence of anti-skyrmions from variable temperature magnetic force microscopy. The stability of anti-skyrmions strongly depends on the thickness of the slab in which they are formed. Finally, we compare the properties of antiskyrmions with those of skyrmions and chiral domain walls and their possible use in Racetrack Memory[2,3].

1 Parkin, S. S. P. & Yang, S.-H. Memory on the Racetrack. *Nat. Nano.* **10**, 195-198, (2015).
2 Yang, S.-H., Ryu, K.-S. & Parkin, S. S. P. Domain-wall velocities of up to 750 ms^{-1} driven by exchange-coupling torque in synthetic antiferromagnets. *Nat. Nano.* **10**, 221-226, (2015).
3 Garg, C., Yang, S.-H., Phung, T., Pushp, A. & Parkin, S. S. P. Dramatic influence of curvature of nanowire on chiral domain wall velocity. *Sci. Adv.* **3**, e1602804, (2017).
4 Nayak, A. K. *et al.* Magnetic antiskyrmions above room temperature in tetragonal Heusler materials. *Nature* **548**, 561-566, (2017).