Abstract of the talks

* Only author name who gives the presentation is given. Information on collaborators would be given in the presentation.

Shahal Ilani (Weizmann Inst. Sci.)
Imaging interacting electron states in one dimension

Massimo Rontani (CNR NANO)
Carbon nanotubes as excitonic insulators

Fifty years ago Walter Kohn speculated that a zero-gap semiconductor might be unstable against the spontaneous generation of excitons–electron-hole pairs bound together by Coulomb attraction. The reconstructed ground state would then open a gap breaking the symmetry of the underlying lattice, a genuine consequence of electronic correlations.

I will show that this 'excitonic insulator' is realized in zero-gap carbon nanotubes, by presenting results of first-principles calculations performed by means of many-body perturbation theory as well as quantum Monte Carlo [1]. The excitonic order modulates the charge between the two carbon sublattices of the armchair tube, opening an experimentally observable gap which scales as the inverse of the tube radius and weakly depends on the axial magnetic field.

These findings invalidate the common wisdom that the ground state of armchair carbon nanotubes is a Luttinger liquid. I will discuss the physical origin of this conclusion, related to the strong e-h binding in quasi-1D and the almost unscreened long-range interactions in undoped nanotubes. Finally, I will propose independent experimental tests to discriminate between the excitonic insulator and the Luttinger liquid at strong coupling (Mott insulator).

This work is performed together with Daniele Varsano, Sandro Sorella, Davide Sangalli, Matteo Barborini, Stefano Corni, and Elisa Molinari and it is partly supported by EU Centre of Excellence 'MaX–Materials Design at the Exascale' (Grant No. 676598).

[1] D. Varsano, S. Sorella, D. Sangalli, M. Barborini, S. Corni, E. Molinari, M. Rontani, arXiv:1703.09235.

Catalin Pascu Moca (BME)
Wigner crystal phases in confined carbon nanotubes

Electrons interacting through simple Coulomb interaction represent one of the most fundamental interacting quantum system. Apart from dimensionality, the behavior of a Coulomb gas depends on just two parameters: the temperature T, and the strength of the Coulomb interaction relative to the electrons' kinetic energy r_s. At large temperatures electrons form a (almost) classical plasma, the behavior of the gas at low temperatures depends on the specific value of r_s. At large densities corresponding to $r_s \ll 1$, the Coulomb interaction plays a minor role in $D = 3$ dimensions, and Landau's Fermi liquid state emerges as the temperature is lowered. At small densities ($r_s \gg 1$), however, interactions become strong and relevant. In this limit, translational symmetry is broken, electrons localize at low temperatures, and form a Wigner crystal. This picture fails in one dimension, where quantum fluctuations destroy the long ranged charge order, remove the phase transition between the crystalline and the liquid phases, and replace it by a smooth crossover. We present a theoretical analysis of the Wigner crystal states in confined semiconducting carbon nanotubes. We show, using scaling arguments, that the effective exchange interaction has an SU(4) symmetry, and can reach values even as large as $J \sim 100$ K in weakly screened, small diameter nanotubes, close to the Wigner crystal - electron liquid crossover. Modeling the nanotube carefully and analyzing the magnetic structure of the inhomogeneous electron crystal, we recover the experimentally observed 'phase boundaries' of Deshpande and Bockrath [V. V. Deshpande and M. Bockrath, Nature Physics **4**, 314 (2008)].

Nadya Mason (Univ. Illinois)
Mesoscopic transport in topological nanowires

In this talk, I will discuss transport measurements of nanowires formed from two key "topological" materials, Bi_2Se_3 and proximity-coupled InSb. I will describe mesoscopic behavior observed in these materials – such as quantized conductance in proximity-coupled InSb nanowires, and Kondo and Aharonov-Bohm effects in BiSe nanowires – and discuss how these behaviors relate to the unusual properties of the materials.

Joseph Dufouleur (IFW-Dresden)
Transport in quantum confined 3D topological insulators

Dieter Weiss (Univ. Regensburg)
Transport in mesoscopic topological insulators: wires and antidot superlattices made from strained 3D-HgTe

Strained 3D HgTe is a strong topological insulator [1-4] with conducting two-dimensional surface states encasing the bulk, which is insulating if the Fermi level is tuned into the bulk gap. The advantage of exploring 3D HgTe is its very high electron mobility which allows probing of mesoscopic effects. Here we present data obtained from single wires and antidot arrays. In wires we observe the predicted switching of the phase of the Aharonov-Bohm type oscillations with Fermi energy for a magnetic field aligned along the axis of a wire [5]; confirming their topological nature requires, however, a more quantitative analysis. Antidot arrays, on the other hand, can be considered as a network of 1D wires. Here we show first experiments trying to explore superlattice effects in a 3D topological insulator.

Work done in close collaboration with J. Ziegler, H. Maier, D. A. Kozlov, R. Fischer, S. Weishäupl, Z. D. Kvon, N. N. Mikhailov, S. A. Dvoretsky, J. Dufouleur, R. Kozlovsky, C. Gorini, M. H. Liu and Klaus Richter.

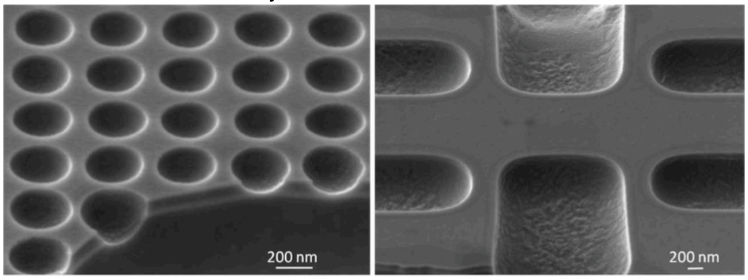

Figure: Antidot lattice (left) and wire geometry with attached potential probes (right) made from strained 3D HgTe films.

[1] L. Fu and C. L. Kane, Phys. Rev. B **76**, 045302 (2007).
[2] C. Brüne et al., Phys. Rev. Lett. **106**, 126803 (2011).
[3] D. A. Kozlov et al., Phys. Rev. Lett. **112**, 196801 (2014).
[4] D. A. Kozlov et al., Phys. Rev. Lett. **116**, 166802 (2016).
[5] J. H. Bardarson, P. W. Brouwer, J. E. Moore, Phys. Rev. Lett. **105**, 156803 (2010).

Peter Krogstrup (Niels Bohr Inst.)
Hybrid materials for topological superconductivity

Hybrid nano-crystals has recently received a lot of attention and has become a key element in many quantum device architectures. This is in particular true in the field of low dimensional topological superconductivity, where semiconductor nanowires with high spin orbit coupling, coupled to a superconducting phase, constitute some of the most promising candidates in the search for materials suitable for quantum information technology [1].

More generally, hybrid epitaxial materials serve as an excellent platform for studying new quantum properties and technologies because they open a reproducible path to new advanced electronic properties.

I will discuss the synthesis, structural and compositional properties hybrid semiconductor-superconductor-ferromagnetic nanowires and other hybrid materials grown in-situ by Molecular Beam Epitaxy [2].

[1] Nayak *et al*. Rev. Mod. Phys. **80**, 1083 (2008).
[2] Krogstrup *et al*. Nature Mater. **14**, 400-406 (2015).

Michael Wimmer (TU Delft)
Majorana fermions in ballistic nanowires

In this talk I will discuss several recent developments in ballistic Majorana nanowire systems, showing how a theoretical and experimental effort has deepened our understanding of these devices. In particular, I will discuss how Andreev-enhanced conductance can be used to probe the disorder in a Majorana device. I will then touch briefly on recent progress in nanowires with epitaxial superconductors, that seem to allow to probe previous predictions of topological conductance quantization. Finally, I will point out the importance of orbital effects to understand experiments in these devices.

Karsten Flensberg (Niels Bohr Inst.)
Majorana wires

Magdalena Marganska (Univ. Regensburg)
Majorana fermions in carbon nanotubes

The possibility of creating Majorana states has been explored theoretically in several solid state systems. The greatest experimental advances have been achieved in semiconducting quantum wires with spin-orbit coupling and in atomic chains of ferromagnetic atoms, both in the proximity of a superconductor. Carbon nanotubes, which are among the cleanest and best understood quasi-1D systems, have also been put forward as potential Majorana hosts in some proposals. One of them, exploiting the nanotube's intrinsic spin-orbit coupling, has inspired our own investigation.

Our carbon nanotubes are semiconducting, have a native spin-orbit splitting, with both the valley mixing and superconducting pairing induced by the contact with a superconductor. We have performed tight-binding numerical calculations and developed an effective model to interpret the results. In this talk I will show how in the experimentally accessible parameter regime some of the extended states of the system become localized and take on Majorana nature. I will also discuss the topological invariants which can be defined in our system and the limits of their applicability.

Gergely Zaránd (BME)
Semi-semiclassical theory of quantum quenches in one dimensional quantum systems

Hartmut Buhmann (Univ. Würzburg)
Quantum spin Hall and quantum anomalous Hall effect

The discovery of the quantum spin Hall (QSH) effect is already ten years old. However, an undisturbed edge channel transport has rarely been reported especially for samples which exceed a few micrometers in size, even though the QSH-states are protected against backscattering by time reversal symmetry. The reasons are manifold but mainly due to the fact that most two-dimensional topological insulators are based on narrow gap semiconductors. Small disturbances and inhomogeneity may already result in potential fluctuations which introduce locally metallic electron or hole puddles destroying the expected perfect quantized conductance.

In this presentation I will shortly review the progress in QHS quantization and discuss aspects of its stability in magnetic field and at elevated temperatures. More intriguingly however are results obtained on magnetically doped quantum wells (QW) of the two-dimensional topological insulator material HgTe. These (Hg,Mn)Te QW samples show a transition into the quantum anomalous Hall (QAH) state at very low magnetic field. An unexpected observation related to this quantized conductance level occurs at high magnetic fields. A $\nu = -1$ to $\nu = +1$ transition for constant carrier density may give first experimental indications of a parity anomaly.

Björn Trauzettel (Univ. Würzburg)
Chiral anomaly in real space from stable fractional charges at the edge of a quantum spin Hall insulator

The chiral anomaly is based on a nonconserved chiral charge and can happen in Dirac fermion systems under the influence of external electromagnetic fields. In this case, the spectral flow leads to a transfer of right- to left-moving excitations or vice versa. The corresponding transfer of chiral particles happens in momentum space. Here we describe an intriguing way to introduce the chiral anomaly into real space. Our system consists of two quantum dots that are formed at the helical edges of a quantum spin Hall insulator by means of magnetic barriers. Such a setup gives rise to fractional charges which we show to be sharp quantum numbers for large barrier strengths. Interestingly, it is possible to map the system onto a quantum spin Hall ring in the presence of a flux pierced through the ring, where the relative angle between the magnetization directions takes the role of the flux. The chiral anomaly in this system is then directly related to the excess occupation of particles in the two quantum dots. This analogy allows us to predict an observable consequence of the chiral anomaly in real space, which is connected to the presence of fractional charges in the very same system.

Jesper Nygård (Niels Bohr Inst.)
Subgap states in hybrid single and double quantum dots based on nanowires

Quantum dots equipped with superconducting leads are excellent model systems for investigating correlation phenonomena with a high degree of tunability [1]. Such hybrid dots can e.g. mimic the behavior of magnetic impurities coupled to quasi-particle reservoirs and chains of multiple dots may lead to engineered topological order and Majorana bound states [2].

Hybrid dots are readily fabricated by contacting e.g. carbon nanotubes or semiconductor nanowires with superconducting electrodes. We focus here on experiments with hybrid single and double quantum dots (QD) formed in N-QD-S devices based on III-V semiconductor nanowires [3]. In the single quantum dot configuration, transport spectroscopy yield Yu-Shiba-Rusinov (YSR) sub-gap excitations [4, 5] that are also revealed when coupling ferromagnetic impurities to a superconducting substrate in STM experiments. In gate controlled dots the sub-gap ground state can be tuned from singlet to doublet versus tuning of the couplings [5].

We proceed to define hybrid double quantum dots and map the sub-gap state behavior versus filling of the two dots. The stability diagrams acquire qualitatively new patterns, reflecting quantum phase transitions in the hybrid quantum dot-superconductor system. In particular the well known honeycomb double dot diagram breaks down in superconducting phase as a result of subgap states. A simple effective model as well as NRG can reproduce most spectroscopic features [6].

We finally discuss the realization of superconducting dots based on nanowires with epitaxially matched superconductor-semiconductor interfaces [7]. Here, Majorana states can be formed at the ends of superconducting islands, e.g. allowing a study of their exponential protection as a function of separation [8].

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[7] P. Krogstrup *et al.*, Nature Mat. **14**, 400 (2015).
[8] S. Albrecht *et al.*, Nature **531**, 206 (2016).

Ramón Aguado (ICMM-CSIC)
Measuring Majorana non-locality and spin structure with a quantum dot

An interacting quantum dot coupled to a superconducting contact is an artificial analogue of a quantum impurity in a superconductor. The physics of such hybrid device is governed by the fermionic parity and spin of the two possible ground states, doublet or singlet (and their corresponding Shiba sub-gap excitations). Here we generalise this paradigmatic model to the case where the superconductor becomes topological. Such a quantum dot-topological superconductor junction can be experimentally realised by e. g. creating quantum dots at the end of epitaxial hybrid semiconductor-superconductor nanowires. We study the hybridisation between Shiba states in the dot and Majoranas in the nanowire and show that specific and measurable spectral features arise from the interplay of these states. Interestingly, these features are enough to fully characterise the spin structure of the Majorana wavefunction, the degree of Majorana non-locality and the Majorana splitting. Apart from a full numerical analysis, all the relevant results are derived from a low-energy effective model, and are given in closed analytical form. We conclude that quantum dots used to perform spectroscopy of a Majorana nanowire are a powerful probe into the quantum structure of Majorana bound states.

Reinhold Egger (Univ. Düsseldorf)
Topological Kondo physics with Majorana fermions

In this talk, I will review the theory of the topological Kondo effect in Majorana devices. When attaching normal-conducting leads to a superconducting island with Majorana zero modes, one can realize an overscreened multi-channel Kondo effect which is manifest in universal conductance features at low temperature. We also consider the case of superconducting leads, where an interesting competition between Kondo screening and superconducting gap opening takes place. The non-Fermi liquid character of the topological Kondo effect here leads to Josephson effects with unconventional phase periodicity corresponding to transfer of charge in units of $2e/3$ between different leads.

Poster Abstract

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Tobias Frank (Univ. Regensburg)
Edge states in spin-orbit enhanced graphene
We show how a realistic combination of spin-orbit coupling parameters in sublattice symmetry broken graphene generates four peculiar edge states in zigzag ribbons. They can be separated into two groups of valley centered and helical type. By comparing these edge modes to the quantum spin Hall state we show that in contrast they generate a net spin current. The calculation of the $\mathbb{Z}_2$ invariant in the intrinsic spin-orbit coupling phase space clarifies the transition from nontrivial to trivial phases and identifies the nature of the four edge state hosting system to be a trivial insulator. The two groups of edge states exhibit different behavior in edge localization, which can be used to generate states in finite sized flakes which are protected against short range scattering.

Andreas Hüttel (Univ. Regensburg)
Not just a quantum box: tuning the shape of an electron in a nanotube with a magnetic field
Transport measurements on single wall carbon nanotubes allow fascinating insights into the interplay of molecular structure and electronic wave functions. Here, we analyze the magnetic field behaviour of quantum states in the limit of a single electron strongly confined to a quantum dot. An axial magnetic field (in the experiment up to 17T) exposes a very distinct behaviour of the two valleys. K' valley states experience an increase of the tunnel coupling at low field, followed by subsequent decoupling. In contrast, K valley states decouple from the leads monotonically.
This phenomenon stems from the unique combination of cylindrical topology and honeycomb atomic lattice. Longitudinal and transversal momentum are coupled, allowing manipulation of the longitudinal electronic wave function via the Aharonov-Bohm phase. At zero field, the nanotube acts similar to a "$\lambda/4$ resonator", where a wave function amplitude is finite near one of the contacts. A large magnetic field restores quantum box behaviour comparable to a "$\lambda/2$ resonator", where the amplitude vanishes on both sides. This is directly reflected in the tunnel rates.
In addition, the magnetic field induces a Franck-Condon vibrational coupling; different electronic states show different behaviour of the vibrational side bands.

Michael Kammermeier (Univ. Regensburg)
Control of spin helix symmetry in semiconductor quantum wells by crystal orientation
As a generalization of previous findings [2,3] on persistent spin states in semiconductor quantum wells, we discover general conditions for the realization of spin-preserving symmetries for 2DEGs with Rashba and Dresselhaus spin-orbit coupling [1]. It is shown that a conserved spin operator can be realized if and only if at least two growth-direction Miller indices agree in modulus. We determine the appropriate requirements on the axial symmetric Rashba and Dresselhaus contributions and discuss the impact of cubic Dresselhaus terms which break this symmetry. We observe that including the latter commonly inhibits a perfect realization of the persistent spin helix symmetry except for two specific directions, i.e., [110] and [111]. Furthermore, by analyzing the spectrum of the spin diffusion equation, we show that besides the cases of perfect spin-preserving symmetries, the spin of the long-lived homogeneous spin state relaxes about a factor 2 faster than for the helical spin state. To support experimental probing, we additionally provide analytical expressions for the weak (anti)localization correction and the characteristic shift of the magnetoconductivity minima which show an imprint of the peculiar symmetry. The later allows for a direct determination of spin-orbit coupling parameters without parameter fitting as recently shown in Ref. [4].
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[2] J. Schliemann, J. Carlos Egues, and Daniel Loss, Phys. Rev. Lett. **90**, 146801 (2003).
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Raphael Kozlovsky (Univ. Regensburg)
Magneto-transport in 3D topological insulator nanowires
We investigate the transport characteristics of 3D topological insulator (3D TI) nanowires in external electric and magnetic fields. The wires host topologically non-trivial surface states wrapped around an insulating bulk and are modelled by surface effective Hamiltonians. A magnetic field along the wire axis leads to Aharonov-Bohm type oscillations of the conductance. Such oscillations have been observed in numerous systems and signal surface transport, though alone cannot prove its topological nature. Furthermore, it is not known how they are affected by the wire specific geometry which is never perfectly tubular as assumed in theoretical models up to now.
We thus focus on two issues: (i) An accurate modelling of surface transport in gated, strained HgTe nanowires, accompanying experimental measurements performed by our collaborators (J. Ziegler & D. Weiss, Uni Regensburg); (ii) A theoretical study of magneto-conductance through shaped (tapered, curved) 3D TI nanowires. In particular, a non-constant radius along the wire direction gives rise to a spatial variation of the enclosed magnetic flux, implying novel quantum transport phenomena.

Lars Milz (Univ. Regensburg)
Topological invariants in carbon nanotubes with superconducting pairing
The symmetries present in a gapped Hamiltonian system determine the types of topological invariants which can be defined for that system. Our case of interest here is a carbon nanotube, which in its normal state is known to possess a non-trivial integer topological invariant, the winding number. Its value determines the number of edge states. When a superconducting pairing is imposed on the nanotube, the symmetry class of the system changes and it is possible to define also a Z_2 Pfaffian topological invariant, exploiting the particle-hole rather than the chiral symmetry. We explore the relationship between the two invariants and their influence on the energy spectrum and eigenstates, in particular the edge modes, of a finite carbon nanotube.

Rin Okuyama (Keio Univ.)
Topological phase transition and edge states in metallic single-wall carbon nanotube
The single-wall carbon nanotube (SWNT) can be regarded as a one-dimensional topological insulator owing to the sublattice symmetry for A and B lattice sites [1]. It is characterized by a $\mathbb{Z}$ topological invariant, winding number, in both the absence (class BDI) and presence (AIII) of magnetic field. We theoretically study the topological phase transition in a metallic SWNT, where a small energy gap is opened by the mixing between σ and π orbitals due to a finite curvature of the tube surface and closed by applying a magnetic field $B = B^* \sim 1\,\mathrm{T}$ parallel to the tube axis [2]. We demonstrate discontinuous changes in the winding number at B^*, which can be observed as a change in the number of edge states via the bulk-edge correspondence. This is confirmed by numerical calculations for finite SWNTs of length $\sim 1\ \mu\mathrm{m}$, using a 1D lattice model to effectively describe the mixing between σ and π orbitals and spin-orbit interaction [3].
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Heng Wang (Univ. Regensburg)
Electron-vibron coupling in finite suspended carbon nanotubes
The remarkable electronic and vibronic properties of suspended carbon nanotubes (CNTs) make them very promising for nanomechanical devices. The strong coupling between single electron tunneling in quantum dots and the mechanical vibration of the suspended CNTs have been observed in several experiments. We provide an analytical investigation of the interaction between the stretching vibrational modes and the electronic degrees of freedom in a finite-length CNT in the helical picture. A parity symmetry and the rotational symmetry of the CNT are used in the derivation to simplify the electron-vibron coupling Hamiltonian. Selection rules, which are dierent for zigzag class and armchair class CNTs, determine which electronic transitions are coupled to distinct vibrational modes.

Johannes Ziegler (Univ. Regensburg)
Aharonov-Bohm type oscillations in topological insulator HgTe nanowires
In topological insulator nanowires, the helical surface states form a conducting cylinder enclosing the bulk. These states give rise to Aharonov-Bohm-type oscillations when a magnetic field is applied along the wire axis [1]. These oscillations, periodic with the flux quantum Φ_0, are predicted to change their phase periodically as a function of the Fermi level E_f. We fabricate nanowires with typical cross sections of 80×150 nm using an optimized wet etching process to maintain the high mobility and mean free path. In our experiments, we found, as expected, h/e periodic oscillations as a function of magnetic flux Φ with alternating maxima and minima as a function of E_f for $\Phi/\Phi_0 = 1/2$ and $\Phi/\Phi_0 = 1$. We compare the resulting periodicity with a simple model and electrostatic simulations.
[1] J.H. Bardarson *et al.*, Phys. Rev. Lett. **105**, 156803 (2010).