# TT 2: Nanotubes, Nanoribbons and Graphene

Time: Monday 9:30–13:15 Location: H22

TT 2.1 Mon 9:30 H22

**Magnetic field control of the Franck-Condon coupling of few-electron quantum states** — Peter L. Stiller, Daniel R. Schmid, Alois Dirnaichner, and •Andreas K. Hüttel — Institute for Experimental and Applied Physics, Universität Regensburg, Regensburg, Germany

The longitudinal vibration of a suspended carbon nanotube has been observed many times in low temperature transport spectra via distinct harmonic Franck-Condon sidebands. Typically, strong Franck-Condon coupling has been attributed to disorder-induced or deliberately targetted charge localization. Here, we present the observation of a strong, tunable coupling in an ultra-clean carbon nanotube with $N = 1$ or $N = 2$ electrons in the conduction band. The clean transport spectrum allows a tentative identification of the electronic base quantum states according to their valley quantum number. Interestingly, the Franck-Condon coupling strength $g$, as extracted from our data, both depends on the magnetic field and on the precise electronic quantum states participating in transport. While spin-dependent Franck-Condon phenomena have already been observed, our results clearly point towards a valley-dependent origin. As possible cause of this phenomenon, reshaping of the electronic wavefunction envelope by the magnetic field is discussed. A simple calculation demonstrates that variations of $g$ as observed in the experiment can be reproduced by the theory, paving the way towards more realistic and detailed quantum-mechanical modelling.

TT 2.2 Mon 9:45 H22

**Transparent low-temperature contacts to $MoS_2$ microtubes** — •Robin T. K. Schock[1], Jonathan Neuwald[1], Matthias Kronseder[1], Simon Reinhardt[1], Luka Pirker[2], Maja Remškar[2], and Andreas K. Hüttel[1] — [1]Institute for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany — [2]Solid State Physics Department, Institute Jožef Stefan,1000 Ljubljana, Slovenia

Even though synthesis procedures of transition metal dichalcogenide (TMDC) based nanotubes have been established for many years, the quantum transport properties remain largely unexplored to date. First low-temperature transort spectroscopy results clearly show Coulomb blockage at 300 mK [1]. However, the contact material still remains a limiting factor due to the Fermi level pinning near the conduction band. Recently, for planar $MoS_2$ materials [2], the use of bismuth improved room-temperature contact resistances drastically. Here we present first transport measurements on $MoS_2$ microtubes with bismuth contacts at millikelvin temperatures. Our $MoS_2$ tubes are grown via a chemical transport reaction, yielding diameters down to 7 nm and lengths up to several millimeters. After transfering the tubes onto a $Si/SiO_2$ substrate, contacts are deposited using electron beam lithography. The resulting devices show Coulomb blockade, with in many cases, a transition from transparent conduction into a band gap. Disorder, compared with previous scandium-based devices, is significantly reduced.

[1] S. Reinhardt *et al.*, Phys. Stat. Sol. RRL **13**, 1900251 (2019)
[2] P. C. Shen *et al.*, Nature 593, **211** (2021).

TT 2.3 Mon 10:00 H22

**Topological transitions in dc+ac-driven superconductor nanotubes** — •Vladimir M. Fomin[1] and Oleksandr V. Dobrovolskiy[2] — [1]Institute for Integrative Nanosciences, Leibniz IFW Dresden, 01069 Dresden — [2]Superconductivity and Spintronics Laboratory, Nanomagnetism and Magnonics, Faculty of Physics, University of Vienna, 1090 Vienna

A complex interplay of the patterns of superconducting screening currents with the 3D geometry unveils a plethora of emerging effects in the dynamics of topological defects in curved 3D superconductor nanoarchitectures [1]. We discuss topological transitions in the dynamics of vortices and slips of the phase of the order parameter in open superconductor nanotubes under a modulated dc+ac transport current [2]. Relying upon the time-dependent Ginzburg-Landau equation, we reveal two voltage dynamics regimes. The first regime with a pronounced first harmonic in the FFT spectrum of the induced voltage occurs when the dominant area of the open tube is in the superconducting or normal state. The second regime entails a rich FFT spectrum of the induced voltage because of the complex interplay between the dynamics of vortices/phase slips and the screening currents. Our findings represent novel dynamical states in superconductor open nanotubes, in particular, paraxial and azimuthal phase-slip regions, their branching and coexistence with vortices, and allow for their control by superimposed dc+ac current stimuli.

[1] V. M. Fomin, O. V. Dobrovolskiy, Appl. Phys. Lett. **120**, 090501 (2022)
[2] V. M. Fomin, R. O. Rezaev, O. V. Dobrovolskiy, Scientific Reports **12**, accepted (2022)

TT 2.4 Mon 10:15 H22

**Graphene nanomembranes as valleytronic devices** — •Nikodem Szpak[1], Walter Ortiz[2,3], and Thomas Stegmann[3] — [1]Fakultät für Physik, Universität Duibsurg-Essen, Duisburg, Germany — [2]Instituto de Investigacion en Ciencias Basicas y Aplicadas, Universidad Autonoma del Estado de Morelos, Cuernavaca, Mexico — [3]Instituto de Ciencias Fisicas, Universidad Nacional Autonoma de Mexico, Cuernavaca, Mexico

We investigate the electronic transport in graphene nanoelectromechanical resonators (GrNEMS), known also as graphene nanodrums or nanomembranes. We demonstrate that these devices, despite small values of strain, between 0.1 and 1%, can be used as efficient and robust valley polarizers and filters. Their working principle is based on the pseudomagnetic field generated by the strain of the graphene membrane. They work for ballistic electron beams as well as for strongly dispersed ones and can be also used as electron beam collimators due to the focusing effect of the pseudomagnetic field. We show additionally that the current flow can be estimated by semiclassical trajectories which represent a computationally efficient tool for predicting the functionality of the devices.

[1] W. Ortiz, N. Szpak, T. Stegmann, arXiv:2202.01739 (2022), submitted

TT 2.5 Mon 10:30 H22

**Quantum interference in graphene by dynamic strain** — •Christian Glasenapp, Pai Zhao, Marta Prada, Lars Tiemann, and Robert h. Blick — Center for Hybrid Nanostructures, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

We exploit surface acoustic waves (SAW) as a time-dependent strain wave that propagates through graphene [1] and study its influence on the weak localization (WL) phenomenon at 4 Kelvin. WL is a quantum interference effect that occurs due to the wave nature of charge carriers. In the case of graphene, it can be characterized by inelastic scattering and elastic inter- and intravalley scattering [2]. We fabricated interdigital transducers (IDTs) on a piezoelectric $LiNbO_3$ substrate, which can be actuated by a radiofrequency (RF) signal to generate a SAW. A large sheet of CVD-grown monolayer graphene was transferred onto the substrate and a Hall bar was patterned in the path of the SAW. In low-field magnetotransport measurements without SAW we observe a well-defined WL effect. When we launch a SAW that strains the graphene layer, WL becomes progressively suppressed with increasing SAW intensity. In this presentation we will show how SAW-induced dynamic strain affects the scattering mechanisms of WL.

[1] P. Zhao et al., Appl. Phys. Lett. 116, 103102 (2020)
[2] E. McCann et al., Phys. Phys. Lett. 97, 146805 (2006)

TT 2.6 Mon 10:45 H22

**Tunable geometric phase in graphene quantum dots with spin-orbit coupling** — •Dario Bercioux[1,2], Diego Frustaglia[3], and Alessandro De Martino[4] — [1]Donostia International Physics Center (DIPC), Manuel de Lardizbal 4, E-20018 San Sebastián, Spain — [2]IKERBASQUE, Basque Foundation for Science, Euskadi Plaza, 5, 48009 Bilbao, Spain — [3]Departamento de Física Aplicada II, Universidad de Sevilla, E-41012 Sevilla, Spain — [4]Department of Mathematics, City, University of London, London EC1V 0HB, United Kingdom

We show how chiral states in circular graphene $pn$ junctions subject to normal magnetic fields and strong proximitized spin-orbit coupling can mimic those of propagating spin carriers in semiconducting quantum rings. We derive the effective one-dimensional Hamiltonian governing the spin dynamics of the zero-mode and calculate the associated geometric phase. We find that for a given polarity of the junction, it exists a special point in parameter space where the spin is fully polarized along the radial direction in the graphene plane. We further propose a quantum-Hall interferometer where these features can be readily identified.

TT 2.7 Mon 11:00 H22

**Effective short distance interacting Hamiltonians for higher Landau levels in graphene** — •Nikolaos Stefanidis[1] and Inti Sodemann[2,1] — [1]Max-Planck Institute for the Physics of Complex Systems, D-01187 Dresden, Germany — [2]Institut für Theoretische Physik, Universität Leipzig, D-04103 Leipzig, Germany

We study the many body problem in graphene in the quantum Hall regime. Although dominated by Coulomb interactions, short range corrections can select among the degenerate ground states. For the $N = 0$ Landau level (LL) their importance has been demonstrated [1,2] and recent work[3] suggests that this remains true in the $N = 1$ LL . In this talk, we will present results on effective Hamiltonians with $N \neq 0$. We analyse the point group symmetries of graphene and find the Hamiltonians dictated by those.

[1] M. Kharitonov, Phys. Rev. B 85, 155439 (2012)
[2] I. Sodemann, A. H. MacDonald, Phys. Rev. Lett. 112, 126804 (2014)
[3] Fangyuan Yang et al., Phys. Rev. Lett. 126, 156802 (2021)

TT 2.8 Mon 11:15 H22

**Massless Dirac fermions with time-dependent magnetic barriers** — •Nico Leumer[1] and Wolfgang Häusler[2] — [1]IPCMS, CNRS, University of Strasbourg, France — [2]University of Augsburg, Germany

Potential barriers controlled by gate electrodes, as common for 2D-electron gases, are inefficient to guide graphene carriers, due to the Klein tunneling phenomenon. One well known way out consists in using inhomogeneous magnetic fields [1]. However, when considering temporal variations, fundamental differences arise between electric and magnetic fields. While to good approximation the former can be treated on its own, time dependent magnetic fields always will induce electric fields of comparable strengths, according to Maxwell's equations. Following Ref. [2] we report on the complete analytical solution for transmission through a weakly, $\omega$-periodically modulated magnetic barrier, homogeneous along the $y$-direction, accounting for side bands that appear at energies $E \pm \omega$ in first order perturbation theory. Inherently, magnetic fields generalize the scattering problem to two dimensions. We find that sideband transport requires the static barrier to be permeable, while momentum conservation imposes new, independent conditions for complete reflection.

[1] A. De Martino, L. Dell'Anna, R. Egger, PRL 98, 066802 (2007)
[2] M. Büttiker, R. Landauer, PRL 49, 1739 (1982)

**15 min. break**

TT 2.9 Mon 11:45 H22

**Measuring correlated phases in encapsulated bilayer graphene via graphite contacts** — •Isabell Weimer, Anna Seiler, and Thomas Weitz — 1st Physical Institute, Faculty of Physics, University of Göttingen, Friedrich-Hund-Platz 1, Göttingen 37077, Germany

Encapsulation of graphene in hexagonal Boron Nitride (hBN) as well as the addition of graphite top and bottom gates to the sample have been central to a lot of the research done on graphene in the recent years. This has allowed the observation of multiple new correlated phases including Stoner metals [1-3], correlated insulators [1] and superconductivity [2] at large electric fields in trigonal warped bilayer graphene.

The extent to which the phase space of Bernal bilayer graphene can be even further explored is amongst other parameters limited by the maximum electric field and thus by the maximum values of gate voltages that can be applied to the sample without breaking through the dielectric. With the aim of increasing these maximum voltages, we have explored the method of using graphite contacts to contact bilayer graphene flakes within van-der-Waals heterostructures [1]. Using graphite contacts instead of commonly used 1D edge contacts [4] removes the necessity to etch into the hBN flakes, which had previously been a limiting factor for the applied electric fields.

[1] A. M. Seiler et al., arXiv:2111.06413 (2021)
[2] H.Zhou et al., Science 375, 774 (2022)
[3] S. C. de la Barrera et al., arXiv:2110.13907 (2021)
[4] L.Wang et al., Science 342, 614 (2013)

TT 2.10 Mon 12:00 H22

**Mapping electrostatically tunable bands in twisted double bilayer graphene in magnetic fields** — •Yulia Maximenko[1,2], Marlou Slot[1,3], Sungmin Kim[1,2], Daniel Walkup[1], Evgheni Strelcov[1], En-Min Shih[1,3], Dilek Yildiz[1,2], Steven Blankenship[1], Kenji Watanabe[4], Takashi Taniguchi[4], Yafis Barlas[5], Paul Haney[1], Nikolai Zhitenev[1], Fereshte Ghahari[6], and Joseph Stroscio[1] — [1]NIST MD USA — [2]U of Maryland USA — [3]Georgetown U DC USA — [4]NIMS Tsukuba Japan — [5]U of Nevada-Reno NV USA — [6]George Mason U VA USA

After the first demonstration of superconductivity in magic-angle twisted bilayer graphene (MATBG), 2D moiré superlattices proved to be valuable systems for band engineering and studying correlated quantum phases. An imposed periodic potential can drive a crystal into a flat-band phase facilitating strong electron-electron interactions. In MATBG, flat bands appear only at a few precise values of the twist angle. In contrast, small-angle twisted double bilayer graphene (TDBG) can be tuned in and out of the correlated regime using electrostatic fields in a continuous range of twist angles. Local probe studies are key to avoid the common complication of angle disorder. Here we employ scanning tunneling microscopy and electrostatic gating to study TDBG with atomic spatial and high energy resolution in magnetic fields up to 15 T. We observe Landau quantization and map out the TDBG band structure in response to the applied electric field. We use theoretical modeling of the effects of displacement fields, Berry curvature, and magnetic fields to support our experimental findings.

TT 2.11 Mon 12:15 H22

**Novel correlated phases near the van Hove singularity in Bernal bilayer graphene** — •Anna Seiler[1], Fan Zhang[2], and Thomas Weitz[1] — [1]1st Physical Institute, Faculty of Physics, University of Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany — [2]Department of Physics, University of Texas at Dallas, Richardson, TX, 75080, USA

Diverging density of states offers a unique opportunity to explore a wide variety of correlated phases in low dimensional systems. Graphene few-layers can host electric-field controlled Lifshitz transitions and concomitant van-Hove-singularities in the density of states. Here, we present the observation of experimental signatures consistent with various interaction-driven phases in trigonally warped Bernal bilayer graphene including the fractional metals of Stoner type (1-3). More prominently, we have found a Chern-insulating phase that emerges at finite densities in between two Lifshitz transitions and even survives at zero magnetic field (1). This phase is consistent with a topologically nontrivial Wigner-Hall crystalline phase, i.e., an electron crystal with a quantized Hall conductance as originally proposed at finite magnetic fields in 1989 (4). Evidently, our discovery shows that the reproducible, tunable, and simple Bernal bilayer graphene is a fertile ground for exploring new, rich, and intricating many-body physics.

[1] A. M. Seiler et al., arXiv:2111.06413 (2021)
[2] H. Zhou et al., Science 375, 774 (2022)
[3] S. C. de la Barrera et al., arXiv:2110.13907413 (2021)
[4] Z. Tešanović, F. Axel, B. I. Halperin, Phys. Rev. B 39, 8525 (1989)

TT 2.12 Mon 12:30 H22

**Towards quantum transport mesaurements on encapsulated rhombohedrally stacked multilayer graphene** — •Monica Kolek Martinez de Azagra and Thomas Weitz — 1. Physikalische Institut, Georg August Universität Göttingen

In the recent past flat band multilayer graphene systems have become an experimental playground to explore a plethora of highly correlated many body phenomena such as superconductivity, topological insulators and ferromagnetic phases. However, so far the broad range of phenomena across the different systems, i.e., bilayer, twisted bilayer and rhombohedral trilayer graphene, still hold open questions to the origins and physical limitations of these phenomena. To further investigate these phenomena, we prepare high quality encapsulated multilayer graphene samples, using a variety of techniques such as Raman spectroscopy, scanning near field microscopy, atomic force microscopy and the dry transfer method with the goal to study these samples through magneto quantum transport measurements in the milli Kelvin regime.

TT 2.13 Mon 12:45 H22

**Effective mass measurements near electric field controlled Lifshitz transitions in trigonally warped bilayer graphene** — •Martin Statz[1], Anna Seiler[1], Francesca Falorsi[1], Jonas Pöhls[1], Kenji Watanabe[2], Takashi Taniguchi[3], and R. Thomas

Weitz[1] — [1]Univ. of Göttingen, Göttingen, Germany — [2]Research Cent. for Funct. Mater., Tsukuba, Japan — [3]Int. Cent. for Mater. Nanoarchitectonics, Tsukuba, Japan

Various spontaneous symmetry broken phases such as Stoner ferromagnetism, spin-polarized superconductivity, a quantum anomalous Hall octet and a topologically non-trivial Wigner-Hall crystal phase have recently been reported in bilayer graphene (BLG). Since these interaction-driven phenomena are dictated by the ratio of the Coulomb and kinetic energy of carriers, they can be promoted by the formation of flat bands and a divergent density of states (DoS) near Lifshitz transitions (LT). Trigonally warped BLG at low vertical displacement fields (D-field) and carrier densities ($\sim 10^{11}$ cm$^{-2}$) displays one centre and three off-centre Dirac cones in each valley and therefore offers a rich playground for correlated phases (CP) by inducing charge density and D-field driven LT. Insights on the renormalized bandstr. and eff. masses of carriers near such LT will foster a deeper understanding of the formation of these CP. Here, we report on our status on eff. mass measurements via $T$-dep. (1.9-25 K) Shubnikov-de Haas osc. in the vicinity of charge density and D-field driven LT in trigonally warped BLG. To minimize effects from pot. disorder, we encapsulate BLG in hex. boron-nitride and employ graphite contacts and graphite gates.

TT 2.14 Mon 13:00 H22

**Ising superconductivity induced from valley symmetry breaking in twisted trilayer graphene** — •Tobias Stauber[1] and Jose Gonzalez[2] — [1]Instituto de Ciencia de Materiales de Madrid, CSIC — [2]Instituto de Estructura de la Materia, CSIC

We show that the e-e interaction induces a strong breakdown of valley symmetry in twisted trilayer graphene, just before the superconducting instability develops in the hole-doped material. We analyze this effect by means of an atomistic self-consistent Hartree-Fock approximation, which is a sensible approach as the Fock part becomes crucial to capture the breakdown of symmetry. This effect allows us to reproduce the experimental observation of the Hall density, including the reset at 2-hole doping. Moreover, the breakdown of valley symmetry has important consequences for the superconductivity, as it implies a reduction of symmetry down to the C3 group. This leads to spin-splitting with respect to the two different valleys, suggesting Ising superconductivity and leading to a Paul-violation with a factor 2-3 as seen in experiments [1]. We also find spin-layer locking which might explain the strong-coupling limit of superconductivity seen in general moiré-samples. We stress that the breakdown of symmetry down to C3 and subsequent spin-valley and spin-layer locking may be shared by other materials with valley symmetry breaking.

[1] J. González and T. Stauber, arXiv:2110.11294