TT 54: Transport: Carbon Nanotubes

Time: Wednesday 15:00–18:15 Location: H22

TT 54.1 Wed 15:00 H22

Carbon nanotubes in high magnetic field — •Magdalena Marganska[1], Peter L. Stiller[2], Alois Dirnaichner[2], Daniel R. Schmid[2], Michael Niklas[1], Andreas K. Hüttel[2], Christoph Strunk[2], and Milena Grifoni[1] — [1]Institute for Theoretical Physics, University of Regensburg, 93053 Regensburg, Germany — [2]Institute of Experimental and Applied Physics, University of Regensburg, 93053 Regensburg, Germany

A parallel magnetic field affects strongly the electronic transport through a carbon nanotube (CNT) via its coupling to the orbital degree of freedom. Although such a wire-like system can host neither the fully developed Hofstadter butterflies nor Landau levels, the magnetic field has nevertheless a deep influence on the CNT's spectrum and wave functions. We report here on the results of both theoretical calculations and experimental measurements of a CNT quantum dot. The two experimental results on which we focus are a strong suppression of the conductance by the parallel magnetic field and an unusual evolution of the spectral lines. The unique boundary conditions, which couple the transverse and longitudinal momentum, are responsible both for decreased transmission through the CNT and for the remarkable dependence of the longitudinal momentum on the magnetic field.

TT 54.2 Wed 15:15 H22

Co-sputtered Mo/Re superconducting coplanar resonators compatible with carbon nanotube growth — •Stefan Blien, Peter L. Stiller, Karl Götz, Ondrej Vavra, Thomas Huber, Thomas Mayer, Christoph Strunk, and Andreas K. Hüttel — Institute for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany

Carbon nanotubes are simultaneously prototypical single electron tunneling devices and nano-electromechanical resonators. In particular for "ultraclean" devices, where the nanotube is grown in a last fabrication step over pre-existing chip structures, highly regular quantum spectra and high mechanical quality factors emerge. Targeting optomechanical experiments, a coupling of these devices to on-chip superconducting coplanar waveguide resonators is highly desirable. The conditions for in-situ growth of carbon nanotubes over metal contacts are quite detrimental to most superconductors: the CVD growth process takes place in a hydrogen/methane atmosphere heated up to 900°C. We present data on transmission line resonators fabricated of a co-sputtered molybdenum rhenium alloy that withstand CVD and remain superconducting with critical temperatures up to 8K after growth. Resonant operation at cryogenic temperatures is demonstrated, and the behaviour is highly consistent with a combination of Mattis-Bardeen theory and two-level systems in the substrate.

TT 54.3 Wed 15:30 H22

Franck-Condon physics in a few-electron nanotube quantum dot — Peter L. Stiller, Daniel R. Schmid, Christoph Strunk, and •Andreas K. Hüttel — Institute for Experimental and Applied Physics, Universität Regensburg, Regensburg, Germany

Franck-Condon sidebands in the transport spectroscopy of suspended carbon nanotubes provide a beautiful nano-electromechanical model system where quantized harmonic oscillator behaviour becomes visible. We present measurements on a strongly localized few-electron system ($0 \leq N_{\rm el} \leq 2$), where the coupling of single electron tunneling and vibrational motion arises solely at finite magnetic fields parallel to the carbon nanotube axis. The Franck-Condon parameter g increases with magnetic field and saturates above $B \approx 4$ T. The behaviour of the sidebands dressing the electronic ground and excited quantum state resonances is compared, and tentative models are discussed.

TT 54.4 Wed 15:45 H22

Secondary interference from trigonal warping in clean carbon-nanotubes — Alois Dirnaichner[1,2], •Miriam del Valle[2], Karl Götz[1], Felix Schupp[1], Nicola Paradiso[1], Milena Grifoni[2], Andreas Hüttel[1], and Christoph Strunk[1] — [1]Institute for Experimental and Applied Physics, University of Regensburg — [2]Institute for Theoretical Physics, University of Regensburg

We investigate experimentally and theoretically a Fabry-Perot resonator based on a clean carbon nanotube. The trigonal warping of the Dirac cones away from the charge degeneracy point leads to a superstructure in the interference pattern. This secondary interference results from the presence of the valley degree of freedom. Single wall carbon nanotubes can be classified to be either zigzag, armchair, zigzag-like, or armchair-like. In any armchair case two interferometer channels with different wave vectors exist; specifically in the armchair-like (chiral with finite-$k_\parallel$ Dirac point) nanotube case these two channels additionally mix on reflection at the interferometer ends. The wave vector difference depends on the chiral angle; this way we can use the resulting slow modulation of the average conductance to estimate the chiral angle of the measured nanotube. Measurements on an ultraclean, long and suspended carbon nanotube device at millikelvin temperatures are complemented with tight binding calculations of the transmission for specific chiralities and analytic modelling.

TT 54.5 Wed 16:00 H22

Emerging Kondo screening and many-body Kramers entanglement in a carbon nanotube — •Michael Niklas[1], Sergey Smirnov[1], Davide Mantelli[1], Magdalena Margańska[1], Jean-Pierre Cleuziou[2], and Milena Grifoni[1] — [1]Institute for Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany — [2]Institute Néel, CNRS and Université Grenoble Alpes, BP 166, 38042 Grenoble, France

The entanglement of quantum states is at the heart of the Kondo effect. In its simplest realization, interactions between a localized spin and itinerant electrons give rise to an entangled singlet ground state with no net spin. Carbon nanotubes offer the possibility to study the emergence of this entanglement in a system with orbital and spin degrees of freedom by simply tuning a gate voltage. Here we investigate the magnetospectrum of a carbon nanotube and find the disappearance of some inelastic excitation lines when sweeping the gate voltage from the weak to the strong coupling regime where Kondo behavior is observed. We consider the global $SU(2) \otimes SU(2)$ symmetry associated to the two Kramers channels of a carbon nanotube and find that only excitations involving flips of the Kramers pseudospins are observed in the Kondo regime, revealing that those pseudospins are fully screened by the conduction electrons.

TT 54.6 Wed 16:15 H22

Mode splitting in zig-zag carbon nanotubes — Jhon González[1], Gilles Buchs[2], •Dario Bercioux[3,4], and Andres Ayuela[1,3] — [1]Centro de Física de Materiales (CFM-MPC) Centro Mixto CSIC-UPV/EHU, E-20018 Donostia-San Sebastián, Spain — [2]Centre Suisse d'Electronique et de Microtechnique (CSEM) SA, Rue de l'Observatoire 58, CH-2002 Neuchâtel, Switzerland — [3]Donostia International Physics Center (DIPC), E-20018 Donostia-San Se- bastián, Spain — [4]IKERBASQUE, Basque Foundation of Science, E-48011 Bilbao, Spain

We investigate theoretically the electron scattering properties of defected and free-standing zig-zag single-walled carbon nanotubes. The variation of the chemical potential, realized in the suspended region, produces quasi-bound states, which compete with the ones created by multiple defects [1]. We show that a particular configuration of the tube defects produces a degeneracy lifting in the metallic branches of the nanotube. As a consequence we observe a doubling or splitting of the quasi-bound states. We also observe a particle-hole symmetry breaking due to selection rules associated to the interplay of tube and defects [2]. Our predictions are supported by an experimental case where a partially suspended zig-zag tube shows split quasi-bound states between defects induced by Ar^{+} ions [1] Our results find applications in angular momentum filtering as well as in THz optics. [3].

[1] D. Bercioux *et al.*, Phys. Rev. B **83**, 165439 (2011).
[2] L. Mayrhofer and D. Bercioux, Phys. Rev. B **84**, 115126 (2011).
[3] J. González *et al.*, *submitted.*

15 min. break

Invited Talk TT 54.7 Wed 16:45 H22

Cooling a nanomechanical resonator by electron transport in hybrid devices. — •Gianluca Rastelli, Pascal Stadler, and Wolfgang Belzig — Universität Konstanz, Germany

A still open challenge in nanoelectromechanical systems is the achievement of active cooling using purely electron transport in devices fabricated with bottom-up techniques as, for instance, carbon nanotube quantum dots suspended between two electric nano-contacts. Owing to the interaction between the electrons and the flexural mechanical modes, the electron transport results inelastic. The vibration assisted tunneling processes give rise to a mechanical damping and, for an applied bias-voltage, to a steady non-equilibrium phonon occupation of the resonator. I will discuss these effects for: (i) spin-polarised current between two ferromagnets [1,2] and (ii) sub-gap Andreev current between a superconductor and normal metal [3]. I will show that ground state cooling of the resonator can be achieved for realistic parameters of the system. I will also discuss the signatures of the non-equilibrium state of the resonator in the current-voltage characteristic.

[1] P. Stadler, W. Belzig, and G. Rastelli, PRL **113**, 047201 (2014).
[2] P. Stadler, W. Belzig, and G. Rastelli, PRB **91**, 085432 (2015).
[3] P. Stadler, W. Belzig, and G. Rastelli, arXiv:1511.04858.

TT 54.8 Wed 17:15 H22

Electronic transport in strained, bent and deformed nanotubes in presence of magnetic field — Magdulin Dwedari[1], Eric Kleinherbers[1], Lennart Korsten[1], Thomas Stegmann[1,2], and •Nikodem Szpak[1] — [1]Fakultät für Physik, Universität Duisburg-Essen, Duisburg — [2]Instituto de Ciencias Fisicas, Universidad Nacional Autonoma de Mexico, Cuernavaca

Due to imminent applications in nanoelectronics it is of high interest to better understand the precise conductance properties of various types carbon nanotubes. Since low-energy electronic excitations in graphene behave like massless Dirac fermions the current flow can be approximated semiclassically and used as a guide in the design of conducting nanotube-elements. We compare two alternative approaches to the electronic transport: a) current flows obtained with the non-equillibrium Green's function (NEGF) method from the tight-binding model with local strain and external magnetic field, b) classical trajectories for relativistic point particles moving in a curved surface with pseudo-magnetic and magnetic field. We discuss several setups and effects of special interest: gap engineering in strained nanotubes with parallel magnetic field, magnetic field-effect transistor and current flow paths in bent and deformed nanotubes. We compare results obtained theoretically with numerical simulations.

TT 54.9 Wed 17:30 H22

Electron transport in defective metallic and semiconducting carbon nanotubes — •Fabian Teichert[1,2,4], Andreas Zienert[3], Jörg Schuster[4], and Michael Schreiber[2] — [1]Dresden Center for Computational Materials Science (DCMS), Dresden, Germany — [2]Institute of Physics, Technische Universität Chemnitz, Chemnitz, Germany — [3]Center for Microtechnologies (ZfM), Technische Universität Chemnitz, Chemnitz, Germany — [4]Fraunhofer Institute for Electronic Nano Systems (ENAS), Chemnitz, Germany

The present work describes the transport properties of metallic and semiconducting CNTs with randomly positioned realistic defects, namely mono- and divacancies. The calculations are based on a fast, linearly scaling recursive Green's function formalism, allowing us to treat large systems quantum-mechanically. The electronic structure is described by a density-functional-based tight-binding model.

In [1], transmission spectra of metallic CNTs with many defects are studied comprehensively with a statistical analysis and diameter-dependent localization lengths are extracted. We extend this work to defect mixtures and show that the total localization length can be reduced to the ones of CNTs with one defect type. Based thereon, we show how to estimate or even predict the conductance of CNTs with an arbitrary number of defects of different types. Finally, we focus on defective semiconducting CNTs and show the influence of the structural parameters – the diameter and the chiral angle – on the conductance and the localization length.

[1] F. Teichert et al., NJP **16** (2014) 123026

TT 54.10 Wed 17:45 H22

Shot noise of excited states in a CNT quantum dot — •Daniel Steininger, Nicola Paradiso, Michael Schafberger, Michael Niklas, Milena Grifoni, and Christoph Strunk — University of Regensburg

Shot noise experiments are a fundamental tool for studying the correlation between carriers in mesoscopic devices. The study of fluctuations provides information that is not accessible by current measurements alone. Here we report on simultaneous measurements of shot noise and conductance of carbon nanotube quantum dots. The high sensitivity of our setup (of the order of 10^{-29} A^2/Hz) allows us to observe the change in the shot noise induced by each CNT excited states. The experimental results are discussed in light of a theory accounting for shot noise effects in the sequential tunnelling limit. In addition we investigate the shot noise in regions of the stability diagram with negative differential conductance.

TT 54.11 Wed 18:00 H22

Electronic Transport through surface functionalized noble metal nanoparticles: Studied at the single object level — •Tuhin Shuvra Basu, Simon Diesch, and Elke Scheer — Fachbereich Physik, Universität Konstanz, Universitätsstraße 10, 78457 Konstanz, Germany

Surface functionalized noble metal nanoparticles exhibit strong plasmonic effects which can be tuned by changing the size of the nanoparticle and by altering the surface functionalization. Additionally due to intraband splitting in ultra-small nanoparticles, they often exhibit weak photoluminescence (PL) [1]. The photo-physics of plasmonics and PL effect are not well understood in ensemble measurements. The understanding of the size and surface effect are essentially important from the further integration of these nanoparticles with other nanosystems to utilize their modified optical properties. In this work, we want to address the size effect of these systems especially weakly coupled gold (Au) nanoparticles by tunneling spectroscopy. Differential conductance of individual noble metal nanoparticles with different temperatures (from mK to K order) shows band-structure fluctuations which can effectively provide signature information of the nanoparticles. We discuss our results in terms of correlations between the electron dynamics, size, surface functionalization and temperature.

[1] S. Eustisa, M. A. El-Sayed, Chem. Soc. Rev. **35**, 209 (2006)
[2] J. Zheng, C. Zhou, M. Yua, J. Liua, Nanoscale **4**, 4073 (2012).