ETH zürich

QUANTUM CENTER

General Meeting Abstract Booklet

July 5 to 7, 2023

Schwägalp, Säntis

Photo on the front page: Alexander Eichler

Welcome to the General Meeting of the Quantum Center

We are delighted to welcome the members of the Quantum Center and their groups to join us for three days of talks, posters, discussions, and networking at the Schwägalp. The program features a wide range of science talks from various research fields across the Quantum Center community, including invited talks by Wenchao Xu, Mickaël Perrin and Markus Reiher, as well as a keynote talk by Markus Müller. More scientific results will be presented on 34 posters, and the two best posters will be honoured with the Quantum Center Poster Prize.

We are pleased to have you here at the foot of Säntis, and we look forward to an engaging and productive event.

With best wishes,
Francesca Bay, Eva-Corinna Fritz, Kate Stephens, Philipp Kammerlander and Andreas Wallraff

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11:00		Giulia Mazzola	Christoph Adam	11:00
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Detailed Program and Abstracts

Program of Wednesday, July 5

12:00 - 14:00	Arrival, Light Lunch and Posters up
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15:45 - 16:15	Coffee break
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16:15 - 16:45	Bhaskar Ghawri, Transport at Nanoscale Interfaces Laboratory, Perrin group, Empa Thermoelectricity in twisted bilayer graphene
16:45 - 17:15	Javier del Pino, Quantum Condensed Matter Theory, Zilberberg group, D-PHYS Dynamical Gauge Fields with Bosonic Codes in Nonlinear Resonators
17:15 - 17:45	Poster Flash
17:45 - 19:30	Poster Session with Apéro
19:30	Dinner at Schwägalp

14:30 - 15:15 | Markus Reiher

Prospects of Quantum Computing for Molecular Science

Department of Chemistry and Applied Bioscience, ETH Zürich, 8093 Zürich, Switzerland

Many problems in molecular science and condensed-phase systems, which are both governed by the dynamics of electrons and atomic nuclei, demand an explicit quantum mechanical description. In such quantum problems, the representation of wave functions grows exponentially with system size, which poses a severe restriction on traditional approaches. However, such quantum problems should naturally benefit from digital quantum simulation on a number of logical qubits, as this would scale only linearly with system size. In recent years, we have considered quantum computing applications in molecular biology, catalysis, and physical chemistry in general, with a focus on how and where to establish a quantum advantage in these areas [1-5]. In my talk, I will elaborate on the potential benefits of quantum computing in these application areas, especially when compared to state-of-the-art traditional approaches.

[1] A. Baiardi, M. Christandl, M. Reiher, "Quantum Computing for Molecular Biology", *ChemBioChem* (2023) https://doi.org/10.1002/cbic.202300120

[2] H. Liu, G. H. Low, D. S. Steiger, T. Haener, M. Reiher, M. Troyer, "Prospects of Quantum Computing for Molecular Sciences", *Materials Theory* 6, 11 (2022).

[3] V. von Burg, G. H. Low, T. Haener, D. S. Steiger, M. Reiher, M. Roetteler, M. Troyer, "Quantum computing enhanced computational catalysis", *Phys. Rev. Research* 3, 033055 (2021).

[4] P. J. Ollitrault, A. Baiardi, M. Reiher, I. Tavernelli, "Hardware Efficient Quantum Algorithms for Vibrational Structure Calculations", *Chem. Sci.* 11, 6842 (2020),

[5] M. Reiher, N. Wiebe, K. M. Svore, D. Wecker, M. Troyer, "Elucidating reaction mechanisms on quantum computers", *PNAS* 114, 7555 (2017).

15:15 - 15:45 | Uwe von Lüpke

A phonon-phonon beam-splitter in circuit quantum acoustodynamics

Uwe von Lüpke[1,2], Ines C. Rodrigues[1,2], Yu Yang[1,2], Matteo Fadel[1,2], Yiwen Chu[1,2]

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In recent years, remarkable progress has been made towards encoding and processing quantum information in the large Hilbert space of bosonic modes. Mechanical resonators are of great interest for this purpose, since they confine many high quality factor modes into a small volume and can be easily integrated with many different quantum systems. An important yet challenging task is to create direct interactions between different mechanical modes. Here we demonstrate an in-situ tunable beam-splitter-type interaction between several mechanical modes of a high-overtone bulk acoustic wave resonator. The engineered interaction is mediated by a parametrically driven superconducting transmon qubit, and we show that it can be tailored to couple pairs or triplets of phononic modes. Furthermore, we use this interaction to demonstrate the Hong-Ou-Mandel effect between phonons. Our results lay the foundations for using phononic systems as quantum memories and platforms for quantum simulations.

16:15 - 16:45 | Bhaskar Ghawri

Thermoelectricity in twisted bilayer graphene

B. Ghawri[1*], S. Bhowmik[2], P. Singhamahapatra[1], M. Garg[2], S. Mandal[1], A. Jayaraman[1], R. Soni[2], N. Leconte[6], S. Appalakondaiah[6], M. Pandey[2], D. Lee[6,7], K. Watanabe[4], T. Taniguchi[5], H. R. Krishnamurthy[1], M. Jain[1], S. Banerjee[1], J. Jung[6,7], U. Chandni[2], A. Ghosh[1,3]

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*Present affiliation – Transport at Nanoscale Interfaces Laboratory, Empa, Swiss Federal Laboratories for Materials Science and Technology, 8600 Dübendorf, Switzerland
[2]Department of Instrumentation and applied physics, Indian Institute of Science, Bangalore-12, India
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[4]Research Center for Functional Materials, National Institute for Materials Science, Namiki 1-1, Tsukuba, Ibaraki 305-0044, Japan
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[6]Department of Physics, University of Seoul, Seoul, Korea
[7]Department of Smart Cities, University of Seoul, Seoul, Korea

The flatbands formed in moiré systems with twisted bilayer graphene (tBLG) have emerged as an ideal platform for studying many novel concepts of condensed matter physics due to the enhanced interaction effects. It not only causes superconductivity, Mott insulating states, and quantum anomalous Hall effect close to the magic angle ($\theta \sim 1.1^0$), but also unconventional metallic states that are claimed to exhibit non-Fermi liquid (NFL) excitations. However, unlike superconductivity and correlation-induced gap in the density of states, unambiguous signatures of NFL effects in such metals remain experimentally elusive. In the first part of the talk, we report on both resistivity and thermopower measurements in tBLG for a range of twist angle between $\theta \sim 1.0^0$-1.7^0 [1]. We observe an emergent violation of the semiclassical Mott relation (MR) in the form of excess thermopower close to half-filling for $\theta \sim 1.6^0$ that vanishes for $\theta \sim 2^0$. The combination of non-trivial electrical transport and violation of MR provides strong evidence of NFL physics intrinsic to tBLG. Further, most of the observed correlated phases occur when the density is at/or near an integer number of carriers per moiré unit cell and the demonstration of ordered states at fractional moiré band fillings at zero applied magnetic field remains challenging. In the second part of the talk, we demonstrate the appearance of novel states at half-integer moiré band fillings in tBLG devices proximitized by a layer of tungsten diselenide [2]. Our results pointed towards the emergence of a spin or charge density wave ground state in tBLG in the zero-magnetic-field limit.

[1] Ghawri B.*, Mahapatra, P.S.*, Garg, M*, Mandal, S., Bhowmik, S., Jayaraman, A., Soni, R., Watanabe, K., Taniguchi, T., Krishnamurthy, H.R., Jain M., Banerjee, S., Chandni, U., Ghosh, A., "Breakdown of semiclassical description of thermoelectricity in near-magic angle twisted bilayer graphene", *Nat. Commun.* 13, 1522 (2022).
[2] Bhowmik, S., Ghawri, B., Leconte, N., Appalakondaiah, S., Pandey, M., Mahapatra, P.S., Lee, D., Watanabe, K., Taniguchi, T., Jung, J., Ghosh A., Chandni, U., "Broken-symmetry states at half-integer band fillings in twisted bilayer graphene", *Nat. Phys.* 18, 639–643 (2022).

16:45 - 17:15 | Javier del Pino

Dynamical Gauge Fields with Bosonic Codes in Nonlinear Resonators

Javier del Pino[1], Oded Zilberberg[2]

[1]Institute for Theoretical Physics, ETH Zürich, 8093 Zürich, Switzerland
[2]Department of Physics, University of Konstanz, 78464 Konstanz, Germany

Dynamical gauge theories are crucial for understanding particle interactions mediated by gauge bosons. However, they are challenging to simulate using classical methods. The idea of a quantum simulator has led to research efforts to use low-energy, engineered quantum devices to replicate high-energy physics phenomena [1]. A promising approach in quantum computation is to introduce quantum error correction, which involves extending the original Hilbert space and endowing it with local symmetries that define the code space. However, qubit-based QEC is challenging due to vast physical resource overheads and scalability issues. Bosonic codes offer a solution that exploits multi-particle redundancy in bosons.

In this talk, I will showcase the potential of bosonic codes in simulating dynamical gauge fields [2]. Our approach involves encoding both matter and dynamical gauge fields in a network of resonators that are coupled through three-wave mixing nonlinearity. By operating the gauge resonators as Schrödinger Cat states, we establish a mapping to a Z2 dynamical lattice gauge theory. Our research explores the optimal conditions that enable the system to maintain the required gauge symmetries. Our results demonstrate the potential of realizing high-energy models using bosonic codes.

[1] E. Altman et al., "Quantum Simulators: Architectures and Opportunities", *PRX Quantum* **2**, 017003 (2021).
[2] Javier del Pino, Oded Zilberberg, "Dynamical Gauge Fields with Bosonic Codes", *Phys. Rev. Lett.* **130**, 171901 (2023).

17:15 - 17:45

Poster Flash

Everyone who brings a poster gets the chance to flash the content of it on one slide in one minute time. This is to give everyone an overview for the poster session afterwards.

Program of Thursday, July 6

	Chair: Andrei Militaru
08:45 - 09:30	Invited Talk: Wenchao Xu, Experimental Quantum Engineering, D-PHYS Quantum science with Rydberg atom arrays: a review and future
09:30 - 10:00	Ilan Bouquet, Integrated Systems Laboratory, Luisier group, D-ITET 3D Simulation of p-type double quantum dot FinFET with k·p Hamiltonian
10:00 - 10:30	Coffee break
	Chair: Lucy Hale
10:30 - 11:00	Panagiotis Christodoulou, Quantum Optics, Esslinger/Donner group, D-PHYS Spin- and momentum-correlated atom pairs mediated by photon exchange
11:00 - 11:30	Giulia Mazzola, Quantum Information Theory, Renner group, D-PHYS Black hole paradoxes and entanglement measures
11:30 - 12:00	Guy Matmon, Photon Science Division, Aeppli Group, PSI Big light, small devices: accelerator-based light sources for quantum technology
12:00 - 13:30	Lunch
	Chair: Qian Ding
13:30 - 14:00	Eric Bonvin, Photonics Laboratory, Novotny group, D-ITET State Expansion in a Hybrid RF–Optical Trap
14:00 - 14:30	Max Ruckriegel, The Ensslin Nanophysics Group, Ensslin/Ihn group, D-PHYS Hybrid circuit QED with graphene quantum dots
14:30 - 15:00	Group Picture & Coffee break
	Chair: Andreas Wallraff
15:00 – 16:00	Keynote Talk: Markus Müller, RWTH Aachen University and Forschungszentrum Jülich, Germany Fault-Tolerant Quantum Computing: Progress and Perspectives
16:00 - 17:30	Free Time and Hike
17:30 – 17:45	First Cable Car to Säntis
18:00 – 18:15	Second (and last) Cable Car to Säntis
18:30 - 22:00	Conference Dinner at Säntis (https://saentisbahn.ch/essen-trinken/restaurant-saentisgipfel)

Abstracts of Thursday, July 6

08:45 - 09:30 | Wenchao Xu

Quantum science with Rydberg atom arrays: a review and future

Institute for Quantum Electronics, Department of Physics, ETH Zurich, 8093 Zürich, Switzerland

Quantum science promises great potential to revolutionize our current technologies. Arrays of individual atoms trapped in optical tweezers have emerged as an attractive architecture for quantum computation and simulation. This architecture has demonstrated great advantages in scalability, and programmability over the array configurations. Controllable inter-atomic interactions are achieved via the Rydberg states of atoms, which facilitate two-qubit gate operations and to simulate quantum many-body systems.

In this talk, I will first do a brief review on this architecture and the rapid progress during the past few years. I will also point out several challenges and ongoing effort at this moment. Then I will outline my proposed approach at ETH, which aims for building a novel architecture for quantum computation/simulation with dual type dual-element atom arrays. I expect this architecture can mitigate some long-standing challenges, including individual addressability and rapid non-demolish selective detection.

09:30 - 10:00 | Ilan Bouquet

3D Simulation of p-type double quantum dot FinFET with k·p Hamiltonian

Ilan Bouquet, Qian Ding, Andreas Schenk, Mathieu Luisier

Integrated Systems Laboratory ETH Zurich CH-8092 Zurich, Switzerland

We are building a quantum transport (QT) framework for the simulation and optimization of silicon FinFETs capable of hosting electron and hole spin qubits. A home-made QT solver [1] based on effective mass approximation (EMA) and the 6x6 k·p method is employed for the investigation of electrostatically induced double quantum dots (DQD) and their transport properties. Simulation on a reduced 3D structure could reproduce the expected major heavy-hole character of the DQD. Following Luttinger's paper [2], the magnetic field contribution to the k·p Hamiltonian could be implemented to our QT tool. Simulation results display the different mixing of the spin orbitals forming the DQD when in-plane and out-of- plane magnetic fields are applied. Post-processing of the QT simulation outputs will enable the computation of essential device metrics such as g-factor, Lamor/Rabi frequencies, and exchange coupling constant. Non-ideal factors will be introduced (e.g., surface roughness, impurities, interface defects) and tested against different fabrication features to identify the best design options (e.g., crystallographic and magnetic orientations, fin shapes, contact electrodes).

[1] M. Luisier, A. Schenk, W. Fichtner, "Quantum transport in two- and three- dimensional nanoscale transistors: Coupled mode effects in the nonequilibrium Green's function formalism", *J. Appl. Phys.* **100**, 043713, (2006).
[2] J. M. Luttinger, "Quantum Theory of Cyclotron Resonance in Semiconductors: General Theory", *Phys. Rev.* **102**, 1030 (1956).

10:30 - 11:00 | Panagiotis Christodoulou

Spin- and momentum-correlated atom pairs mediated by photon exchange

P. Christodoulou, F. Finger, R. Rosa-Medina, N. Reiter, T. Donner, and T. Esslinger

Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland

An atomic Bose-Einstein condensate (BEC) inside a high-finesse optical cavity is well-suited for simulating models and exploring phase transitions relevant for Quantum Optics [1] or Many-body Physics [2]. Here, we use an ^{87}Rb spinor BEC inside an optical cavity to engineer atom pair correlations both in the internal (spin) and external (momentum) degree of freedom [3]. The underlying mechanism enhances quantum fluctuations via a superradiant photon-exchange process that includes the vacuum mode of the optical cavity, and has intrinsically many similarities with the parametric down-conversion process in Nonlinear Optics. We characterize the produced state by studying the pair statistics and measuring inter-spin correlations in momentum space. Our observation of coherent many-body oscillations involving well-defined momentum modes offers promising prospects for quantum-enhanced interferometry using entangled matter waves.

[1] K. Baumann, C. Guerlin, F. Brennecke, T. Esslinger, "Dicke quantum phase transition with a superfluid gas in an optical cavity", *Nature* 464, 1301 (2010).
[2] R. Landig, L. Hruby, N. Dogra, M. Landini, R. Mottl, T. Donner, T. Esslinger, "Quantum phases from competing short- and long-range interactions in an optical lattice", *Nature* 532, 476-479 (2016).
[3] F. Finger, R. Rosa-Medina, N. Reiter, P. Christodoulou, T. Donner, T. Esslinger, "Spin-and momentum-correlated atom pairs mediated by photon exchange", *arXiv:* 2303.11326v1 (2023).

11:00 - 11:30 | Giulia Mazzola

Black hole paradoxes and entanglement measures

QIT group, ETH Zürich

A major discovery by Hawking was that the interplay between general relativity and quantum theory leads to the prediction that black holes must radiate. In Hawking's original calculation, however, the black hole radiation was found to be of thermal character, resulting in a mixed state that describes the radiation once the black hole has fully evaporated. This conclusion appears to contradict the reversibility of time evolution in quantum theory, which predicts a pure final state of the radiation, thereby giving rise to the famous black hole information puzzle.

In this talk, I will introduce the black hole information paradox and explain how the geometric structure of black holes motivates the definition of novel measures of correlation and entanglement. Such quantities are fundamental in the field of quantum information theory and, in turn, may help us in resolving black hole paradoxes and gaining a deeper understanding of the interplay between general relativity and quantum theory.

[Based on joint work with David Sutter and Renato Renner]

11:30 - 12:00 | Guy Matmon

Big light, small devices: accelerator-based light sources for quantum technology

Guy Matmon[1], Aidan McConnell[1], Maël Clémence[1], Jakub Vonka[1], Jamie Bragg[2], Taylor Stock[2], Neil Curson[2], Bill Bedrini[1], Simon Gerber[1], Gabriel Aeppli[1,3,4]

[1]Photon Science Division, Paul Scherrer Institut
[2]London Centre for Nanotechnology, University College, London
[3]Department of Physics & Quantum Center, ETHZ
[5]Institute of Physics, EPFL

Accelerator-based light sources such as synchrotrons and free electron lasers are mostly associated with biological and pharmaceutical applications on one hand, and with studying phases of matter in solid-state physics on the other. I will talk about how we utilize these sources to develop and study structures that can be used, or are indeed already used, for quantum technology applications. At the Swiss Light Source, we used synchrotron infrared radiation for spectroscopy and characterization of electronuclear states of rare earths in insulators [1], and x-ray beam lines for probing donors and devices in real space [2-4] as well as band structure in reciprocal space; at the x-ray free electron laser SwissFEL, we are developing the capability to read out quantum many-body states in the Fourier domain and at the infrared free electron laser FELIX in the Netherlands we coherently control the Rydberg states of donors in semiconductor devices [5-7]. The flexibility and diversity of these large facilities make them an invaluable tool in the basic science and development stage of (solid state) quantum technologies.

[1] A. Beckert et al., "Precise determination of the low-energy electronuclear Hamiltonian of LiY1-xHoxF4", *Phys. Rev. B* **106**, 115119 (2022), https://doi.org/10.1103/PhysRevB.106.115119
[2] N. D'Anna et al., "Non-destructive x-ray imaging of patterned delta-layer devices in silicon", *Adv. Elec. Mat.* **202201212** (2023), https://doi.org/10.1002/aelm.202201212
[3] M. Holler et al., "High-resolution non-destructive three-dimensional imaging of integrated circuits", *Nature* **543**, 402 (2017), https://doi.org/10.1038/nature21698
[4] M. Holler et al., "Three-dimensional imaging of integrated circuits with macro- to nanoscale zoom", *Nat. Electron.* **2**, 464 (2019), https://doi.org/10.1038/s41928-019-0309-z
[5] P.T. Greenland et al., "Coherent control of Rydberg states in silicon", *Nature* **465**, 1057 (2010), http://dx.doi.org/10.1038/nature09112
[6] K. L. Litvinenko et al., "Coherent creation and destruction of orbital wavepackets in Si:P with electrical and optical read-out", *Nat. Commun.* **6**, 6549 (2015), https://doi.org/10.1038/ncomms7549
[7] S. Chick et al., "Coherent superpositions of three states for phosphorous donors in silicon prepared using THz radiation", *Nat. Commun.* **8**, 16038 (2017), https://doi.org/10.1038/ncomms16038

13:30 - 14:00 | Eric Bonvin

State Expansion in a Hybrid RF–Optical Trap

Eric Bonvin, Louisiane Devaud, Martin Frimmer, Lukas Novotny

Photonics Laboratory, ETH Zürich, 8093 Zürich, Switzerland

Optically levitated nanoparticles offer a high degree of control over the motion of a particle, allowing us to cool the center-of-mass motion of a relatively massive object (~femtogram) to its quantum ground state [1, 2]. This makes them excellent candidates for probing macroscopic models of quantum mechanics. The next step in this endeavor is to coherently expand the wavefunction of a particle from its zero-point motion (typically 10^{-12}m) to a dimension comparable to the diameter of the particle (typically 10^{-7}m). However, optical traps are poorly suited for this task, since the photon recoil caused by the high laser intensities induces significant decoherence, preventing the observation of quantum dynamics.

The addition of a radio-frequency Paul trap [3, 4] provides a solution in the form of secondary trapping potential with no measurement-induced decoherence. We describe our hybrid Paul-optical trap, which consists of an optical trap paired with a high-optical access Paul trap [5], allowing us to trap the same particle at the same point in space with two different methods.

By repeatedly "dropping" a particle from the optical trap into the Paul trap for varying durations, we show that we can grow the size of the (classical) state of this oscillator. In the future, we plan to apply this experimental technique to a ground-state-cooled particle for testing macroscopic quantum mechanics.

[1] L. Magrini et al., "Real-time optimal quantum control of mechanical motion at room temperature", *Nature* 595 (7867): 373–77 (2021).
[2] F. Tebbenjohanns et al., "Quantum control of a nanoparticle optically levitated in cryogenic free space", *Nature* 595 (7867): 378–82 (2021).
[3] G. Conangla et al., "Extending Vacuum Trapping to Absorbing Objects with Hybrid Paul-Optical Traps", *Nano Lett.* 20 (8): 6018–23 (2020).
[4] D. Bykov et al., "Hybrid electro-optical trap for experiments with levitated particles in vacuum", *Rev. Sci. Instrum.* 93 (7): 07320 (2022).
[5] J.-S. Chen et al., "Sympathetic Ground State Cooling and Time-Dilation Shifts in an $^{27}Al^{+}$ Optical Clock", *Phys. Rev. Lett.* 118 (5): 053002 (2017).

14:00 - 14:30 | Max Ruckriegel

Hybrid circuit QED with graphene quantum dots

Max J. Ruckriegel[1], Lisa M. Gächter[1], David Kealhofer[1], Chuyao Tong[1], Rebekka Garreis[1], Benedikt Kratochwil[1], Kenji Watanabe[2], Takashi Taniguchi[2], Mohsen Bahramipanah[1], Andreas Wallraff[1], Thomas Ihn[1], Klaus Ensslin[1], Wister Wei Huang[1]

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[2]National Institute for Material Science, 1-1 Namiki, Tsukuba 305-0044, Japan

Graphene is an increasingly promising host material for spins because its naturally low nuclear spin density and its weak spin-orbit coupling promise long coherence times. A tunable bandgap in bilayer graphene allows to electrostatically define quantum dots (QD) with well controlled ambipolar operation in the single hole or electron regime. Even though the technology is still new, notable advances towards spin qubits in graphene have been made, including the better understanding of individual quantum states [1,2] as well as the demonstration of important primitives such as Pauli spin and valley blockade [3]. Long spin (valley) relaxation times of up to 50 ms (500 ms) have been measured recently with Elzerman readout using a nearby quantum dot as a charge detector [4,5]. It is expected that faster charge sensing with higher fidelity can be achieved by dispersively coupling charge carriers in a double QD to microwave photons in a superconducting resonator [6,7].

Here we report on progress towards integrating graphene QD devices with on-chip superconducting microwave resonators in a hybrid circuit QED architecture. We outline our main advances in design and fabrication of graphene-based hybrid devices and show first proof-of-principle measurements of dispersive charge sensing with microwave resonators.

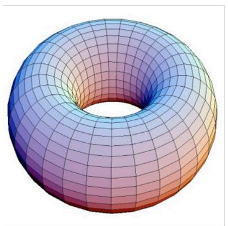
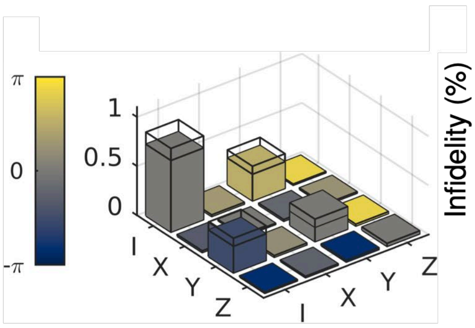
[1] A. Kurzmann et al., “Excited States in Bilayer Graphene Quantum Dots“, *Phys. Rev. Lett.* **123**, 026803 (2019).
[2] C. Tong et al., “Tunable Valley Splitting and Bipolar Operation in Graphene Quantum Dots“, *Nano Lett.* **21** (2), 1068-1073 (2021).
[3] C. Tong et al., “Pauli Blockade of Tunable Two-Electron Spin and Valley States in Graphene Quantum Dots“, *Phys. Rev. Lett.* **128**, 067702 (2022).
[4] L. M. Gächter, R. Garreis et al., “Single-Shot Spin Readout in Graphene Quantum Dots“, *PRX Quantum* 3, 020343 (2022).
[5] C. Tong, R. Garreis et al., *in preparation* (2023).
[6] G. Zheng at al., “Rapid gate-based spin read-out in silicon using an on-chip resonator“, *Nat. Nanotechnol.* **14**, 742–746 (2019).
[7] F. Borjans et al., “Spin Digitizer for High-Fidelity Readout of a Cavity-Coupled Silicon Triple Quantum Dot“, *Phys. Rev. Appl.* **15**, 044052 (2021).

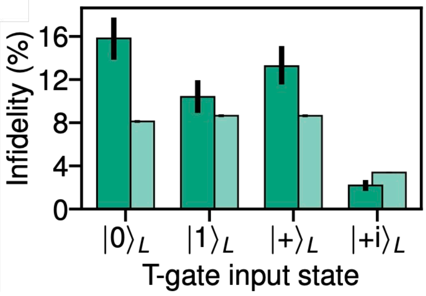
15:00 - 16:00 | Markus Müller

Fault-Tolerant Quantum Computing: Progress and Perspectives

RWTH Aachen University and Forschungszentrum Jülich, Germany

Quantum computers hold the promise to efficiently solve some computationally hard problems, for which efficient solutions are intractable on classical computers. Unfortunately, unavoidable noise limits the capabilities of current noisy intermediate-scale quantum (NISQ) devices. In my talk, I will first introduce basic concepts of topological quantum error correction codes, which allow one to protect quantum information during storage and processing. I will discuss recent theory work and collaborative experimental breakthroughs towards fault-tolerant quantum error correction on various physical platforms. This includes the first realisations of repeated, high-performance quantum error-correction cycles on topological error correcting codes with superconducting qubits, and the first execution of universal and fault-tolerant logical quantum gates with trapped ions. Furthermore, I will highlight alternative explorative approaches towards robust quantum processors, based e.g. on quantum machine-learning based concepts, and outline some promising pathways to scale up current systems towards scalable, error-corrected quantum processors.



Program of Friday, July 7

	Chair: Simon Gerber
08:45 - 09:30	Invited Talk: Mickaël Perrin, Transport at Nanoscale Interfaces Laboratory, Empa Contacting bottom-up synthesized graphene nanoribbons for electronic device applications
09:30 - 10:00	Thea Budde, High Performance Computational Physics, Marinkovic group, D-PHYS Simulating Gauge Theories: Bridging Classical and Quantum Simulations
10:00 - 10:30	Coffee break
	Chair: William Legrand
10:30 - 11:00	Alexa Herter, Quantum Optoelectronics, Faist group, D-PHYS Revisiting Fermi's two-atom problem
11:00 - 11:30	Christoph Adam, The Ensslin Nanophysics Group, Ensslin/Ihn group, D-PHYS Entropy of a quantum dot in bilayer graphene
11:30 - 12:00	Alex Gomez Salvador, Theoretical Physics, Demler group, D-PHYS Unleashing Multidimensional Spectroscopy in Strongly-Correlated Systems
12:00 – 13:30	Lunch
	Chair: Ramona Wolf
13:30 – 14:00	Simon Storz, Quantum Device Lab, Wallraff group, D-PHYS Non-locality meets quantum computing
14:00 - 14:30	Shreyans Jain, Trapped Ion Quantum Information, Home group, D-PHYS Scalable arrays of micro-fabricated Penning traps for quantum computation and simulation
14:30 - 15:00	Vincent Dumont, Spin Physics, Degen group, D-PHYS Towards Observation of Quantum Radiation Force Noise
15:00 - 15:30	Poster Prize Announcement & Concluding Remarks

08:45 - 09:30 | Mickaël Perrin

Contacting bottom-up synthesized graphene nanoribbons for electronic device applications

Mickaël L. Perrin[1,2], Jian Zhang[1], Wenhao Huang[1,3], Liu Qian[4], Oliver Braun[1,3], Gabriela Borin Barin[5], Jan Overbeck[1,3], Michael Stiefel[1], David I. Indolese[3], Rimah Darawish[5], Roman Furrer[1], Antonis Olziersky[6], Abdalghani Daaoub[7], Guido Gandus[2], Klaus Müllen[8], Ivan Shorubalko[1], Daniele Passerone[5], Mathieu Luisier[2], Kenji Watanabe[9], Takashi Taniguchi[9], Sara Sangtarash[7], Christian Schönenberger[3], Hatef Sadeghi[7], Pascal Ruffieux[5], Jin Zhang[4], Roman Fasel[5], Michel Calame[1,3,10]

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Atomically-precise graphene nanoribbons (GNRs) have attracted significant interest from researchers worldwide, as they constitute an emerging class of quantum-designed materials of which the properties are tailored by controlling their width and edge structure during chemical synthesis [1-4]. These remarkable properties include a largely tunable bandgap [1], spin polarized edge states [2] and topologically-protected states [4]. The major challenges toward their exploitation in quantum device applications include the reliable contacting single GNRs and the preservation of their intrinsic physical properties upon device integration [5].

In this talk, I'll present an overview of our recent efforts in the fabrication and characterization of nanoelectronics devices with GNRs as active material. To contact the GNRs, we have developed several multi-gate device architectures based on different electrodes geometries and materials. While the majority of our devices are based on graphene as electrode material [6], we have demonstrated the contacting of single GNRs using single-walled carbon nanotubes (SWNT) electrodes. Here, we observe well-defined quantum transport phenomena, including Coulomb blockade, excited states, and Franck-Condon blockade [7]. In addition, we have developed a strategy to contact h-BN encapsulated GNRs using metallic edge contacts for improving contact and reducing device footprint [8].

These technological advances pave the way for the integration of GNRs into quantum devices for exploring and exploiting their remarkable physical properties. Moreover, an appealing property is the persistence of quantum effects to near room temperature [9], offering promising prospect for quantum technologies at non-cryogenic temperatures.

[1] J. Cai et al., "Atomically precise bottom-up fabrication of graphene nanoribbons", *Nature* 466, 470-473 (2010).
[2] P. Ruffieux et al., "On-surface Synthesis of Graphene Nanoribbons with Zigzag Edge Topology", *Nature* 531, 489 (2016).
[3] Z. Chen et al., "Graphene Nanoribbons: On-surface Synthesis and Integration into Electronic Devices", *Adv. Mater.* 32, 2001893 (2020).
[4] O. Gröning et al., "Engineering of robust topological quantum phases in graphene nanoribbons", *Nature*. 560, 209–213 (2018).
[5] H. Wang et al., "Graphene nanoribbons for quantum electronics", *Nat. Rev. Phys.* 3, 791-802 (2021).
[6] J. Zhang et al., "Tunable quantum dots from atomically precise graphene nanoribbons using a multi-gate architecture", *Adv. Electr. Mater.* 9, 2201204 (2022).
[7] J. Zhang et al., "Contacting individual graphene nanoribbons using carbon nanotube electrodes", *Nature Electronics*, in press.
[8] W. Huang et al., "Edge Contacts to Atomically Precise Graphene Nanoribbons". Under review.
[9] J. Zhang et al., "Near room-temperature quantum dot transistors from atomically-precise graphene nanoribbons". Under review.

09:30 - 10:00 | Thea Budde

Simulating Gauge Theories: Bridging Classical and Quantum Simulations

Thea Budde, Marina Kristć Marinković, Joao C. Pinto Barros

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Simulating gauge theories is one of the promising applications of quantum simulators. In the near term, lower dimensional gauge theories such as the Schwinger model (1+1-dimensional Quantum Electrodynamics) are primary targets. Experimental realizations are becoming increasingly more sophisticated, calling for independent verification using classical algorithms. This is challenging due to issues like preserving Gauss' law and solving notorious fermion sign problems. Recent progress has been made with the new Monte Carlo cluster algorithm for the 1+1-dimensional quantum link model. In this talk, I will discuss this new approach, possible extensions to other theories, and how the developed algorithm can help guide and validate quantum simulations of gauge theories.

10:30 - 11:00 | Alexa Herter

Revisiting Fermi's two-atom problem

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During the development of the quantum theory of light, Fermi studied the propagation of light in vacuum with two atoms probing the electromagnetic field [1]. He investigated the correlation of the atoms caused by the exchange of a photon and concluded: The atoms will show purely causal correlations arising only after the time of flight of the photon has passed. However, following theoretical studies revealed correlations occurring already before the atoms could have exchanged a photon. As we know today, these non-causal correlations are induced by the ground state fluctuations of light. Recently we presented an experiment simulating Fermi's two-atom problem by ultra-short laser pulses interacting with the ground state of light, where we demonstrated vacuum-induce correlations in the non-causal regime [2].

However, effects typically related to vacuum fluctuations, such as spontaneous emission or the Lamb shift, cannot be caused purely by the ground state of light. A second effect – the so-called radiation reaction – is crucial for a conclusive quantum description of light-atom interaction. Though separating the contribution of radiation reaction and vacuum fluctuations was so far limited to the theoretical discussions [3].

Now we want to explain, why the correlations in our experiment are related only to vacuum fluctuations. At the same time, we show how a slight modification of the detection scheme allows to observe the correlations arising from the radiation reaction [4]. The latter are of purely causal nature and therefore relate to the initial picture described by Fermi [1].

[1] E. Fermi, "Quantum Theory of Radiation", *Rev. of Mod. Phys.* **4** (1932).
[2] F. F. Settembrini, et al., "Detection of quantum-vacuum field correlations outside the light cone", *Nature Com.* **13** (2022).
[3] J. Dalibard, J. Dupont-Roc, C. Cohen-Tannoudji, "Vacuum fluctuations and radiation reaction: identification of their respective contributions", *J. Physique* **43** (1982).
[4] F. Lindel, et al., "How to Separately Probe Vacuum Field Fluctuations and Source Radiation in Space and Time", *arXiv preprint* (2023), https://arxiv.org/abs/2305.06387

11:00 - 11:30 | Christoph Adam

Entropy of a quantum dot in bilayer graphene

C. Adam[1], H. Duprez[1], A. Yglesias[1], N. Lehmann[1], K. Watanabe[2], T. Taniguchi[3], T. Ihn[1], and K. Ensslin[1]

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Bilayer graphene quantum dots are a promising platform for implementing qubits utilizing the spin or valley degree of freedom of confined charge carriers [1]. Their excitation spectrum deviates significantly from quantum dots in other material systems [2] and deserves further investigation.

We measure the entropy of a quantum dot in bilayer graphene by using a thermodynamic Maxwell relation [3] allowing us to study the degeneracies of the charge ground states in the dot. For the first charge state our results are in good agreement with previous work. However, for the second charge state we observe that it is non-degenerate, contrary to the expected threefold spin degeneracy observed in other experiments [2].

The device is fabricated in a material stack consisting of bilayer graphene encapsulated in hexagonal boron nitride. A global graphite bottom gate in conjunction with two layers of top gates enable us to form a one-dimensional channel (split gates) wherein we isolate a quantum dot. Its charge occupation number and coupling to the surrounding reservoirs is highly tuneable by the finger gates. Modulating the temperature of the reservoir by driving a current through it (Joule heating) and measuring the response in the charge occupation number of the dot with a charge detector allows us to extract the degeneracy of the charge state present in the quantum dot.

Our results show that entropy measurements are an important addition to the tool set used to study quantum states in highly correlated systems paving the way for more sophisticated experiments involving exotic states in mesoscopic devices.

[1] R. Garreis et al., "Long-lived valley states in bilayer graphene quantum dots", *arXiv preprint* (2023).
[2] A. Kurzmann et al., "Excited states in bilayer graphene quantum dots", *Phys. Rev. Lett.* 123, 026803 (2019).
[3] N. Hartman et al., "Direct entropy measurement in a mesoscopic quantum system", *Nature Phys.* 14, 1083-1086 (2018).

11:30 - 12:00 | Alex Gomez Salvador

Unleashing Multidimensional Spectroscopy in Strongly-Correlated Systems

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Understanding strongly-correlated systems relies on accessing higher-order correlations and the necessity of disentangling responses that extend beyond the limitations of linear response-based techniques. While traditional methods such as optical reflectivity measurements, X-ray diffraction, and neutron scattering have been extensively employed, they often fall short in providing unambiguous answers to the pressing questions within the scientific community.

In this talk, we will delve into the emerging field of multidimensional spectroscopy in condensed matter as a powerful tool for studying strongly-correlated systems. By building upon the foundation of linear response techniques, multidimensional spectroscopy offers an enhanced approach capable of overcoming some of its limitations. Among others, it enables us to disentangle different types of disorder, estimate the strength of nonlinearities, and independently determine dephasing and decaying times.

The recent development of picosecond long pulses has opened up new possibilities for applying this technique to the terahertz scale, which is ubiquitous in condensed matter systems and of special importance in High Tc superconductors. This advancement provides a unique opportunity to study the intricate dynamics and properties of these systems, potentially shedding light on the underlying mechanisms that govern their physics.

[1] S. Mukamel, "Principles of Nonlinear Spectroscopy".
[2] S. T. Cundiff, S. Mukamel, "Optical multidimensional coherent spectroscopy", *Phys. Today* 66(7):44–49 (2013).

13:30 - 14:00 | Simon Storz

Non-locality meets quantum computing

Simon Storz[1], Josua Schär[1], Anatoly Kulikov[1], Paul Magnard[1], Philipp Kurpiers[1], Janis Lütolf[1], Theo Walter[1], Adrian Copetudo[1], Kevin Reuer[1], Abdulkadir Akin[1], Jean-Claude Besse[1], Mihai Gabureac[1], Graham J. Norris[1], Andrés Rosario[1], Ferran Martin[2], José Martinez[2], Waldimar Amaya[2], Morgan W. Mitchell[3,4], Carlos Abellan[2], Jean-Daniel Bancal[5], Nicolas Sangouard[5], Baptiste Royer[6,7], Alexandre Blais[6,8], Andreas Wallraff[1]

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One of the astounding features of quantum physics is that it contradicts our intuitive understanding of local causality, the principle asserting that an event at one location cannot instantaneously influence an event at a distant location without some intermediary force or particle. Quantum physics does not follow this principle, as shown by empirical evidence from Bell test experiments. Here, we present a loophole-free Bell test with superconducting circuits, the first such experiment on a platform that is considered a prime contender for building scalable quantum computing systems [1]. Enabled by a unique setup, we successfully entangled two superconducting circuit devices positioned 30 meters apart using a cryogenically cooled quantum link. We measured a violation of Bell's inequality (CHSH S-value) of 2.0747+-0.0033 with an exceptionally high statistical significance. Our work enables the use of non-locality as a resource for quantum communication and distributed quantum computing protocols with superconducting circuits.

[1] Storz et al., "Loophole-free Bell inequality violation with superconducting circuits", *Nature* **617**, 265–270 (2023).

14:00 - 14:30 | Shreyans Jain

Scalable arrays of micro-fabricated Penning traps for quantum computation and simulation

Shreyans Jain, Tobias Sägesser, Pavel Hrmo, Daniel Kienzler, Jonathan Home

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Scaling up trapped-ion quantum information processors to a useful number of qubits presents a significant challenge. The conventional approach of using linear radio-frequency (r.f.) traps to confine 1-d strings of ions in a single potential well has limitations in terms of scalability. To some extent the Quantum CCD architecture seeks to address this issue by linking multiple trapping zones through dynamic operations like splitting and shuttling within a quasi-2-d arrangement. True large-scale 2-d r.f. trap-arrays must overcome technical issues such as on-chip r.f. power dissipation and r.f.-induced micromotion of ions throughout the trap area. By replacing the r.f.

drive with a strong magnetic field, we here realise a micro-fabricated surface-electrode trap that allows for flexible arrangement of trap sites holding a single ion each. On the path to trap hundreds of ions on a single chip, we demonstrate and characterise the control and operation of the apparatus using a single beryllium ion. Cooling the ion to the 3-d ground state of motion we observe exceptionally low motional heating rates, potentially resulting from the absence of r.f. fields. Further we demonstrate three-dimensional transport of an ion across and perpendicular to the trap chip, an operation not possible in r.f. traps. We find that the transport results in negligible motional excitation and apply this to sense electric-field noise emanating from the electrode surfaces along all three axes over 3-d space. These initial measurements hold promise towards the realisation of a new platform for scalable quantum computing with dynamically reconfigurable ions.

14:30 - 15:00 | Vincent Dumont

Towards Observation of Quantum Radiation Force Noise

Vincent Dumont[1,2], Jiaxing Ma[1], Tommy Clark[1], Simon Bernard[1], Jack Sankey[1]

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[2]Laboratory for Solid State Physics, ETH Zürich, Zürich, Switzerland

A photon, the quantum of light, can impart a momentum kick once it reflects off an object, an effect which was predicted by Kepler in 1619. However, the force exerted by a photon is very small, making it hard to detect, even for laser beams which contain many of these photons. Moreover, the quantization of light leads to quantum fluctuations in optical power, the so-called shot noise, which imparts a fluctuating force when the photons are randomly reflected – the quantum radiation force noise. While this fluctuating force is incredibly small and even harder to detect than the mean force, it is still predicted to limit the precision of the next generation of force sensors. In this talk, I will present the work I have done during my PhD toward demonstrating this quantum effect, at room temperature and on a macroscopic scale "trampoline" mechanical sensor. This work can be a steppingstone toward using this quantum noise as a resource, for example, to produce broadband "squeezed light". Finally, I will present an initial proposal for my postdoctoral research, in the field of "magnetic resonance force microscopy" -- a nano-scale version of magnetic resonance imaging -- where we plan to use novel mechanical sensors and show that their force sensing abilities are limited by the quantum fluctuations of light.

Posters

Please find below the list of posters presented at the General Meeting. The two best presented posters will be honoured with a poster prize.

No.	Authors	Title	Group
P1	J. P. Unsleber, H. Liu, L. Talirz, T. Weymuth, M. Mörchen, A. Grofe, D. Wecker, C. J. Stein, A. Panyala, B. Peng, K. Kowalski, M. Troyer, M. Reiher	High-Throughput Ab Initio Reaction Mechanism Exploration in the Cloud with Automated Multi-Reference Validation	Theoretical Chemistry - Reiher Research Group, D-CHAB
P2	J. Piotrowski, J. Vijayan, D. Windey, K. Weber, L. Novotny	Cavity Optomechanics with multiple Levitated Particles	Photonics Laboratory, D-ITET
P3	M. L. Palm, C. Ding, W. S. Huxter, T. Taniguchi, K. Watanabe, C. L. Degen	Observation of current whirlpools in graphene at room temperature	Spin Physics, D-PHYS
P4	Z. Zhang, J. Arunseangroj, S. Wang, W. Xu	New scheme for quantum operation with dual-type atom array	Experimental Quantum Engineering, D-PHYS
P5	A. Ferk, A. Ricci, B. de Neeve, C. Axline, C. Mordini, M. Marti, M. Müller, M. Nydegger, M. Stadler, V. Negnevitsky	Control System for Scalable Trapped Ion Quantum Computing	Trapped Ion Quantum Information, D-PHYS
P6	L. Graziotto, J. Enkner, F. Appugliese, G.L. Paravicini-Bagliani, M. Beck, C. Reichl, W. Wegscheider, G. Scalari, C. Ciuti, J. Faist	Modifying the quantum Hall effect via cavity vacuum fields	Quantum Optoelectronics, D-PHYS
P7	E. Jöchl, L. Hale, F. Helmrich, M. Barra-Burrillo, L. E. Hueso, R. Hillenbrand, M. Beck, J. Faist, G. Scalari	Ultrastrong light matter interaction at the single element level	Quantum Optoelectronics, D-PHYS
P8	L. Segner, J. Komijani, J. C. Pinto Barros, M. Marinkovic	Generalized Simulated Tempering Approach to Topological Freezing in Lattice Gauge Theories	High Performance Computational Physics, D-PHYS
P9	J. C. Pinto Barros, M. K. Marinkovic	Exploring Quantum Scars in Simple Lattice Gauge Theories	High Performance Computational Physics, D-PHYS
P10	S. Shan, J. Huang, S. Papadopoulos, R. Khelifa, T. Taniguchi, K Watanabe, L. Wang, L. Novotny	Overbias photon emission from light-emitting devices based on monolayer transition metal dichalcogenides	Photonics Laboratory, D-ITET
P11	F. Liu, Z. Meng, L. Wang, W. Han, K. Wen, C. Gao, P. Wang, C. Chin, J. Zhang	Atomic Bose-Einstein condensate in twisted-bilayer optical lattices	Experimental Quantum Engineering, D-PHYS

P12	L. Parato, M. Caselle	Thermodynamics of the 3d gauge Ising model	High Performance Computational Physics, D-PHYS
P13	F. Swiadek, R. Shillito, P. Magnard, Q. Ficheux, A. Remm, G. J. Norris, A. Blais, S. Krinner, A. Wallraff	Enhanced Dispersive Readout of a Transmon Qubit	Quantum Device Lab, D-PHYS
P14	C. Scarato, C. Hellings, K. Hanke, A. Remm, S. Lazar, D. Colao Zanuz, M. Kerschbaum, N. Lacroix, J. Herrmann, F. Swiadek, G. J. Norris, M. Bahrami Panah, A. Flasby, C. Eichler, A. Wallraff	Robust hardware-efficient implementation of a continuous two-qubit gate set for transmon qubits	Quantum Device Lab, D-PHYS
P15	Y. Wu, W. Huang	Fabricating Quantum Dot in Planar Ge/SiGe Quantum Well	The Ensslin Nanophysics Group, D-PHYS
P16	W. Legrand, H. Wang, R. Schlitz, P. Gambardella	Materials and platform for a magnonic qubit	Magnetism and Interface Physics, D-MATL
P17	N. D'Anna, D. Ferreira Sanchez, G. Matmon, J. Bragg, P. C. Constantinou, T.J. Z. Stock, S. Fearn, S. R. Schofield, N. J. Curson, M. Bartkowiak, Y. Soh, D. Grolimund, S. Gerber, G. Aeppli	Non-destructive X-ray imaging of patterned delta-layer devices in silicon	Quantum Photon Science, PSI
P18	L. Amato, M. Grimm, M. Müller	Highly coherent cluster excitations in doped rare-earth insulator	Condensed Matter Theory, PSI
P19	M. Gächter, Z. Zhu, A.-S. Walter, K. Viebahn, T. Esslinger	Probing boundaries in interacting topological systems	Quantum Optics, D-PHYS
P20	Q. Ding, A. Schenk, M. Luisier	TCAD-based Simulation of Hole Spin Qubits in 5-Gate Si FinFETs: Rabi Frequency and Charge Noise	Nano-TCAD, D-ITET
P21	N. Lacroix, L. Hofele, A. Remm, S. Lazar, C. Hellings, F. Swiadek, D. Colao-Zanuz Alexander Flasby, M. Bahrami Panah, G. J. Norris, A. Wallraff, S. Krinner	Fast Flux-Activated Leakage Reduction for Superconducting Quantum Circuits	Quantum Device Lab, D-PHYS
P22	Y. Zhao, A. Leuch, O. Zilberberg, A. Štrkalj	Electron optics with pn junctions in two-dimensional inverted-band systems	Quantum Engineered Systems, D-PHYS
P23	F. Marijanovic, Y. Qu, E. Demler	SSH Bipolaron	Theoretical Physics, D-PHYS

P24	H. Doeleman, T. Schatteburg, M. Drimmer, R. Benevides, Y. Chu	Brillouin optomechanics in the quantum ground state	Hybrid Quantum Systems, D-PHYS
P25	A. Militaru, M. Rossi, N. C. Zambon, M. Frimmer, L. Novotny	A hybrid Paul-optical trap compatible with a cryogenic environment	Photonics Laboratory, D-ITET
P26	F. Vivanco, T. Chen, D. Wang, F. Liu, L. Fernandez, P. Koopmann, F. Bennati Weis, L. Zhang, Z. Zhang, J. Arunseangroj, S. Wang, W. Xu	Dual-type dual element array for quantum computation and simulation	Experimental Quantum Engineering, D-PHYS
P27	F. van Veen, O. Braun, M. Stiefel, G. Blasi, G. Borin Barin, P. Ruffieux, G. Haack, R. Fasel, H. van der Zant, M. Calame, M. Perrin	Thermoelectric properties of graphene nanoribbon films	Quantum Devices, D-ITET
P28	A. Vishwakarma, S. Kovarik, R. Schlitz, D. Ruckert, P. Gambardella, S. Stepanow	Spin resonance of two asymmetrically driven and coupled quantum spins on surfaces	Magnetism and Interface Physics, D-MATL
P29	G. Tomassi, N. Meyer, R. Quidant	Towards the dark evolution of levitated nanoparticles in 1D double-well potentials	Nanophotonic Systems Laboratory, D-MAVT
P30	A. Gandon, P. Ollitrault, I. Tavernelli	Accessing excited state properties in the electronic structure problem with near-term quantum devices.	High Performance Computational Physics, D-PHYS; IBM Quantum, IBM Research - Zurich
P31	R. Andrei, E. Demler	Subgap photoexcitation of carriers in AF Mott insulators: theory and applications	Theoretical Physics, D-PHYS
P32	J. Stefaniak, D. Dreon, A. Baumgärtner, X. Li, S. Hertlein, T. Esslinger, T. Donner	Self-oscillating atomic pump in a dissipative atom cavity system	Quantum Optics, D-PHYS
P33	A. Morelle, P. Tomic, S. P. Ramanandan, A. Fontcuberta i Morral, T. Ihn, K. Ensslin	Quantum coherent hole transport in selective area grown Ge nanowires	The Ensslin Nanophysics Group, D-PHYS; Laboratory of Semiconductor Materials, EPFL

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