WILHELM UND ELSE HERAEUS-STIFTUNG

553. WE-Heraeus-Seminar

Discrete and Analogue Quantum Simulators

February 10th – 12th, 2014
at the Physikzentrum Bad Honnef (Germany)

Subject to alterations!

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. To German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Aims and Scope of the 553. WE-Heraeus Seminar:

We intend to bring together leading scientists working in the field of quantum simulation, who make use of either analogue or discrete simulation methods. Analogue simulators find natural applications in the investigation of quantum systems ruled by continuous time Hamiltonians. On the other hand, it was theoretically shown that quantum simulators based on discrete time operations can also provide an excellent approximation for continuous time systems. In recent years, both analogue and discrete simulation methods have been receiving significant attention from theory to develop new strategies and algorithms, while experimental advances with atoms, ions, and photons allow for the investigation of nontrivial problems, which are otherwise intractable using classical computers.

Scientific Organization:

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Introduction

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Program

Program

Sunday, February 9, 2014

17:00 – 21:00	Registration	
from 18:00	*BUFFET DINNER* / Informal get together	

Monday, February 10, 2014

07:30	*BREAKFAST*	
08:40 – 08:45	Dieter Meschede Andrea Alberti Reinhard Werner	**Welcome and opening**
08:45 – 09:00	Ernst Dreisigacker	**About the Wilhelm and Else Heraeus Foundation**
09:00 – 09:45	Martin Zwierlein	**Strongly Interacting fermi gases in and out of equilibrium**
09:45 – 10:30	Jens Eisert	**Dynamical analogue quantum simulators**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Fabio Sciarrino	**3D-quantum integrated optical simulation**
11:45 – 12:30	Philipp Preiss	**Quantum walks of strongly interacting bosons**
12:30 – 12:40	**Conference Photo** (in front of the Physikzentrum)	
12:40	*LUNCH*	

Program

Monday, February 10, 2014

14:00 – 14:45	Fernando Brandao	**Preparing Gibbs states on quantum computers**
14:45 – 15:30	Christina Kraus	**Quantum simulation at finite temperature in an optical lattice clock**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Stefan Kuhr	**Towards single-site-resolved detection of fermions in an optical lattice**
16:45 – 17:30	Carlo Sias	**A one-dimensional liquid of fermions with tunable spin**
18:00 – 19:00	Rudolf Gross **(evening talk)**	**Superconducting hybrid quantum circuits**
19:00	*DINNER*	

Program

Tuesday, February 11, 2014

08:00	*BREAKFAST*	
09:00 – 09:45	Rainer Blatt	**Quantum simulations with trapped ions**
09:45 – 10:30	Klaus Sengstock	**Quantum gas simulators**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Barbara Terhal	**Space-Time Circuit-to-Hamiltonian construction and its applications**
11:45 – 12:30	Andrew White	**Photonic quantum simulation**
12:30	*LUNCH*	
14:00 – 14:30	Marco Koschorreck (α)	**Universal spin dynamics in two-dimensional Fermi gases**
14:30 – 15:00	Gheorghe Sorin Paraoanu (α)	**Simulation of motional averaging with a superconducting circuit**
15:00 – 15:30	Thomas Schulte-Herbrüggen (α)	**Quantum simulation via applied systems theory**
15:30 – 16:00	*BREAK*	
16:00 – 16:45	Tobias Osborne	**Quantum Yang-Mills theory on the lattice and tensor network states**
16:45 – 18:00	**Poster flash talks (β)**	
18:00 – 19:00	**Poster session**	
19:00	*HERAEUS DINNER* *(cold & warm buffet, free beverages)* **& poster awards**	

Program

Wednesday, February 12, 2014

08:00	*BREAKFAST*	
09:00 – 09:45	Mark Rudner	**Topological bands in periodically-driven systems**
09:45 – 10:30	Alexander Szameit	**Photonic floquet topological insulators**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Pablo Arrighi	**Quantum walks for relativistic particles**
11:45 – 12:30	Yoav Lahini	**Quantum walks of interacting particles**
12:30 – 12:45	Dieter Meschede Andrea Alberti Reinhard Werner	**Final remarks**
12:45	*LUNCH*	

***End of the seminar** and FAREWELL COFFEE / Lab tours (γ)*

(α) Contributed talk session.

(β) Young researchers have the opportunity to present their own results with a flash presentation of about 2/3 minutes.

(γ) We offer lab tours of University of Bonn's laboratories. You are kindly invited to contact us if you are interested.

Posters

Posters

Sascha Agne	**Signal-to-noise ratio for single atom detection with microcavities**
Andrea Alberti	**Electric quantum walks with individual atoms**
Murtaza Ali Khan	**Nanometric surface probing with ultra-cold atoms**
Alexander Baust	**Superconducting resonator systems for quantum simulations**
Marco Bentivegna	**Experimental boson sampling with integrated photonic circuits**
Stefan Brakhane	**2D discrete quantum simulator**
Christopher Cedzich	**Quantum walks in electric fields**
Myung-Hoon Chung	**Tensor network states for fermion lattice models**
Simon Cornish	**Towards quantum simulation with ultracold molecules**
Guanxiang Du	**Imaging of microwave fields with quantum atomic vapors**
Terry Farrelly	**Quantum computing and particle physics in discrete spacetime**
Mathis Friesdorf	**Emergence of coherence and the dynamics of quantum phase transitions**
Holger Frydrych	**Constructing Pauli pulse schemes for quantum simulation**
Maximilian Genske	**Doublons and Holons in perodically driven Mott insulators**
Bahareh Ghannad Dezfouli	**Adiabatic tracking of many-body dynamics**
Markus Gräfe	**High-Order Single-Photon W-states for random number generation**
Christopher Grossert	**Simulation of relativistic wave equation predictions with ultracold atoms in an optical lattice**
Anna Hambitzer	**Quantum Simulations with circuit QED**
René Heilmann	**Realization of Hadamard and Pauli-X gate for polarization encoded qubits on chip**
Kotbi Lakhdar	**The quantum hall effect within the notion of Peer Cooper**

Posters

Karla Loida	**Ultracold bosons in optical lattices subjected to a periodic perturbation**
Anna Marchant	**Towards the creation of ground-state ultracold RbCs molecules for quantum simulation**
Michael Marthaler	**Fundamental quantum physics with superconducting qubits**
Oliver Marty	**Quantifying entanglement with simple measurements**
Maria Moreno Cardoner	**Exotic quantum magnetism with spin F=1 ultracold gases in optical lattices**
Armando Perez-Leija	**Reconstruction of Wigner functions using Glauber-Fock photonic lattices**
Tim Richardt	**Nonlinear PT-symmetric photonic graphene**
Carsten Robens	**Rigorous violations of the Leggett Garg inequality using quantum walks of single atoms**
Tomas Rybar	**Memory requirements for general reversible qubit stream processors**
Hamed Saberi	**Quantum simulation with kagome photon lattices**
Malte Schlosser	**Experimental demonstration of more than 100 individually addressable qubits for quantum simulation and quantum computation**
Ameneh Sheikhan	**Relaxation dynamics of a Fermi gas in an optical superlattice**
Simon Stützer	**Optical supersymmetry: A fundamental approach to a new kind of mode converters**
Nikodem Szpak	**Quantum simulation of relativistic fields interacting with artificial gravity in 2D bichromatic optical lattices**
Bernard van Heck	**Thermal conductance as a probe of topological order in a hybrid semiconductor-superconductor system emulating the Higgs model**
Martin Weides	**Towards scalable superconducting quantum bits for analog quantum simulation**

Contributed Talks

Marco Koschorreck	**Universal spin dynamics in two-dimensional Fermi gases**
Gheorghe Sorin Paraoanu	**Simulation of motional averaging with a superconducting circuit**
Thomas Schulte-Herbrüggen	**Quantum simulation via applied systems theory**

Abstracts of Lectures

(in chronological order)

Strongly Interacting Fermi Gases in and out of Equilibrium

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Ultracold atomic Fermi gases near Feshbach resonances have emerged as a unique platform to study the many-body physics of strongly interacting fermions in and out of equilibrium. Precise experimental data allow the validation of theoretical models for other strongly interacting fermionic systems, such as high-temperature superconductors, neutron stars or the quark-gluon plasma of the early universe. Concerning equilibrium properties, we obtained the equation of state of the Unitary Fermi gas with high precision [1]. Our method does not rely on any theoretical input, a fitting procedure or an external thermometer. It allowed us to directly observe the superfluid lambda transition of the gas in its thermodynamic properties such as the specific heat. The superfluid transition temperature is 17% of the Fermi temperature, the record for known fermionic superfluids.

In regards to non-equilibrium properties, we were recently able to directly imprint long-lived solitary waves into the fermionic superfluid [2]. As the interactions are tuned from the regime of Bose–Einstein condensation of tightly bound molecules towards the Bardeen–Cooper–Schrieffer limit of long-range Cooper pairs, the waves' effective mass increases dramatically, to more than 200 times their bare mass. This mass enhancement is more than 50 times larger than the theoretically predicted value for planar solitons. Our most recent experiments reveal the microscopic nature of the observed solitary waves. Our work provides a benchmark for theories of non-equilibrium dynamics of strongly interacting fermions.

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[2] Tarik Yefsah, Ariel T. Sommer, Mark J.H. Ku, Lawrence W. Cheuk, Wenjie Ji, Waseem S. Bakr, Martin W. Zwierlein, Nature **499**, 426-430 (2013)

Dynamical analogue quantum simulators

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Complex quantum systems out of equilibrium are at the basis of a number of long-standing questions in physics. This talk will be concerned on the one hand with recent progress on understanding how quantum many-body systems out of equilibrium eventually come to rest, thermalise and cross phase transitions, on the other hand with dynamical analogue quantum simulations using cold atoms [1–4]. If time allows, I will in an outlook discuss the question of certification of quantum simulators, and will how this problem also arises in other related settings, such as in Boson samplers [5, 6].

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[1] S. Braun, M. Friesdorf, S. S. Hodgman, M. Schreiber, J. P. Ronzheimer, A. Riera, M. del Rey, I. Bloch, J. Eisert, U. Schneider, in preparation (2014).
[2] M. Kliesch, M. Kastoryano, C. Gogolin, A. Riera, J. Eisert, arXiv:1309:0816.
[3] S. Trotzky, Y.-A. Chen, A. Flesch, I. P. McCulloch, U. Schollwoeck, J. Eisert, I. Bloch, Nature Physics 8, 325 (2012).
[4] A. Riera, C. Gogolin, M. Kliesch, J. Eisert, n preparation (2014).
[5] C. Gogolin, M. Kliesch, L. Aolita, J. Eisert, in preparation (2014) and arXiv:1306.3995.
[6] S. Aaronson, A. Arkhipov, arXiv:1309.7460.

3D-Quantum Integrated Optical Simulation

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Integrated photonic circuits have a strong potential to perform quantum information processing. Indeed, the ability to manipulate quantum states of light by integrated devices may open new perspectives both for fundamental tests of quantum mechanics and for novel technological applications. Within this framework we have developed a directional coupler, fabricated by femtosecond laser waveguide writing, acting as an integrated beam splitter able to support polarization-encoded qubits [1]. As following step we addressed the implementation of quantum walk. For the first time, we investigated how the particle statistics, either bosonic or fermionic, influences a two-particle discrete quantum walk [2]. As following step we have exploited this technology to simulate the evolution for disordered quantum systems observing how the particle statistics influences Anderson localization [3]. Finally we will discuss the perspectives of optical quantum simulation: the implementation of the boson sampling to demonstrate the computational capability of quantum systems and the development of integrated architecture with three-dimensional geometries [4]. We report the experimental observation of three-photon interference in an integrated three-port directional coupler realized by ultrafast laser writing. By exploiting the capability of this technique to produce three-dimensional structures, we realized and tested in the quantum regime a three-port beam splitter, namely a tritter, which allowed us to observe bosonic coalescence of three photons [5]. These results open new important perspectives in many areas of quantum information, such as fundamental tests of quantum mechanics with increasing number of photons, quantum state engineering and quantum simulation.

References

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Quantum Walks of Strongly Interacting Bosons

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Microscopy techniques for ultracold quantum gases offer the opportunity to characterize complex bosonic many- body states on a single-particle level. With a novel single-site addressing scheme, we are now able to study the most elemental building blocks of such strongly correlated systems. We initialize Fock states of few bosons in an optical lattice with high fidelity and follow their dynamics in one dimension. Focussing on free quantum walks of two atoms, we directly observe the crossover from bunching to anti-bunching as the bosons fermionize in the presence of strong repulsive interactions. Our work gives access to interaction effects in the simplest possible setting and allows the assembly of many-body states one particle at a time.

Preparing Gibbs States on Quantum Computers

Fernando Brandao
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In this talk I will discuss a new quantum algorithm for preparing Gibbs states on a quantum computer. The algorithm is fundamentally different from the quantum Metropolis algorithm, being closely related to the well-known Davies generators from open quantum systems theory. I will then discuss the efficiency of the algorithm and argue that it runs quickly whenever the Gibbs state is clustering (has decaying correlations). The talk is based on joint work with Michael Kastoryano.

Quantum simulation at finite temperature in an optical lattice clock

Christina Kraus
Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences and Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria

This project is in collaboration with the Strontium team (X. Zhang, M. Bishof, S. Bromley, A. M. Rey and Jun Ye) at JILA.

Quantum simulation of fermionic many-body systems is complicated by the lack of efficient cooling schemes that would allow to reach the temperature regime where many interesting quantum mechanical effects arise. One important class of such systems are SU(N) spin models that are expected to describe transition metal oxides, heavy fermion materials or spin liquid phases. In search to overcome the notorious cooling problem we propose the possibility to use an optical lattice clock based on Alkaline Earth atoms operated at μK temperature as a finite temperature quantum simulator of two-orbital SU(N) physics, and explain how the SU(N) physics can be probed in a Ramsey-type experiment.

Towards single-site-resolved detection of fermions in an optical lattice

Stefan Kuhr

University of Strathclyde, Glasgow, United Kingdom

Ultracold atoms in optical lattices have become a tool to simulate and test fundamental concepts of condensed matter physics, in particular to simulate electrons in solid crystals. Recent experiments with single-site resolution of single atoms at individual lattice sites have resulted in the direct observation of quantum phase transitions, such as the superfluid to Mott insulator transition for bosonic particles [1], and, e.g. single-site addressing [2] and the quantum dynamics of spin-impurities [3].

However, an experimental proof of single-site-resolved detection of correlated phases of ultracold fermions in a lattice is still missing. I will report on our current progress to realise single-site resolved, in-situ imaging and manipulation of strongly correlated fermionic ^{40}K in an optical lattice. Such a system would be an ideal environment to simulate the Fermi-Hubbard Hamiltonian, allowing for the direct observation and characterisation of, e.g., temperature, spin-structure, or entropy distribution of quantum phases such as fermionic Mott insulators, Band insulators or Néel antiferromagnets.

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[2] C. Weitenberg, M. Endres, J. F. Sherson, M. Cheneau, P. Schauß, T. Fukuhara, I.Bloch, S. Kuhr, *Single-spin addressing in an atomic Mott insulator*, Nature **471**, 319 (2011).

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A one-dimensional liquid of Fermions with tunable spin

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Correlations in physical systems with spin degree of freedom are at the heart of several fundamental phenomena, ranging from magnetism to superconductivity. In general, the effects of correlations depend strongly on the dimensionality of the system. A striking example are fermions confined in one dimension, whose small-energy excitations have a collective nature - a phenomenon that cannot be described by a quasiparticle treatment and has counterintuitive effects such as the separation of spin and charge excitations.

We report on the realization of multi-component one-dimensional liquids of ultracold ^{173}Yb fermions. These two-electron atoms are characterized by a large nuclear spin and highly-symmetric atom-atom interactions, which result in the possibility of performing quantum simulations of systems with intrinsic SU(N) symmetry. In one dimension, repulsive interactions between atoms in different nuclear spin states cause static and dynamic properties of the system to significantly depart from those of an ideal Fermi gas, in accordance with the Luttinger theory for a 1D liquid of spin-1/2 interacting fermions. Much stronger deviations are measured when the fermionic liquid is prepared in more than 2 internal states. This work provides the first experimental study of Luttinger physics with repulsive spinful atoms and the first realization of multi-component Luttinger liquids with tunable SU(N) symmetry.

References

[1] G. Pagano et al., Nature Physics, in press.

Superconducting Hybrid Quantum Circuits*

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The combination of superconducting microwave cavities with superconducting, mechanical or magnetic nanosystems leads to the fascinating field of superconducting hybrid quantum systems, allowing the study of a rich variety of interesting phenomena. In ***circuit-QED systems***, the strong and ultra-strong coupling regime, where the coupling rate between superconducting qubits and the cavity reaches a considerable fraction of the cavity transition frequency [1], can be achieved, allowing for the study of physics beyond the Jaynes-Cummings model. Superconducting circuit-QED systems are also promising for the realization of analog quantum simulators. A particular example is the simulation of Bose-Hubbard-type dynamics in chains of coupled nonlinear superconducting resonators [2]. The implementation of flexible simulators requires tunable resonator nonlinearities and inter-resonator coupling strengths. To this end, switchable and tunable coupling between transmission line resonators mediated by superconducting qubits [3] or RF-SQUIDs [4] is promising.

In ***circuit nano-electromechanics***, the parametric coupling of electromagnetic and mechanical degrees of freedom gives rise to a host of phenomena such as quantum-limited displacement measurements, sideband cooling or amplification of mechanical motion. Likewise, this interaction provides mechanically mediated functionality for the processing of electromagnetic signals. By coupling a superconducting coplanar-waveguide (CPW) resonator to a silicon nitride based nanomechanical oscillator [5,6], we demonstrate both electromagnetically induced transparency (EMIT) and absorption (EMIA). Using EMIT, we realize all-microwave field-controlled tunable slowing and advancing of microwave signals, with millisecond distortion-free delay and negligible losses [5].

Superconducting-magnetic circuit QED systems have been realized by coupling the ferrimagnetic insulator $Y_3Fe_5O_{12}$ (YIG) to a superconducting CPW microwave resonator. The strong coupling regime between YIG and the microwave cavity has been reached [7], allowing for the coherent exchange of the quantized excitations (magnons and photons) in such hybrid quantum systems.

*This work is supported by the German Research Foundation via SFB 631, the Excellence Initiative via the Nanosystems Initiative Munich (NIM), and the EU projects CCQED and PROMISCE.

References

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Quantum Simulations with Trapped Ions

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In this talk, the basic tool box of the Innsbruck quantum computer based on a string of trapped Ca^+ ions will be reviewed. The quantum toolbox is applied to carry out both analog and digital quantum simulations. In this talk the basic simulation procedure will be presented and its application will be discussed for a variety of spin Hamiltonians. Including a carefully controlled dissipation mechanism, the toolbox allows for the quantum simulation of systems, especially for Ising-type spin models and for open quantum systems. A string of ions is used to implement a string of spins that interact by means of quantum gate operations and the dynamical evolution of a spin system can be simulated. With an additional ancilla ion which is coupled to the environment, open system behavior is simulated in a well-controlled way. Thus, entangled states, such as Bell and GHZ states can be generated by dissipative processes and can be used as part of the quantum simulator. Recent experimental results on the simulation of propagating spin waves and of competing coherent and dissipative processes will be discussed.

Quantum gas simulators

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Space-Time Circuit-to-Hamiltonian Construction and Its Applications

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The circuit-to-Hamiltonian construction translates dynamics (a quantum circuit and its output) into statics (the groundstate of a circuit Hamiltonian) by explicitly defining a quantum register for a clock. The standard Feynman- Kitaev construction uses one global clock for all qubits while we consider a different construction in which a clock is assigned to each interacting qubit. This makes it possible to capture the spatio-temporal structure of the original quantum circuit into features of the circuit Hamiltonian. The construction is inspired by the original two-dimensional interacting fermionic model in [1]. We prove that for one-dimensional quantum circuits the gap of the circuit Hamiltonian is appropriately lower-bounded, partially using results on mixing times of Markov chains, so that the applications of this construction for QMA (and partially for quantum adiabatic computation) go through. For one-dimensional quantum circuits, the dynamics generated by the circuit Hamiltonian corresponds to diffusion of a string around the torus. Our results can be found in [2].

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Photonic Quantum Simulation

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In principle, quantum mechanics can exactly describe any system of quantum particlesfrom single electrons to unwieldy proteinsbut in practice this is impossible for even moderately interesting systems as the number of equations grows exponentially with the number of particles.

A well known example is the fundamental problem faced in quantum chemistry, calculating molecular properties such as total energy of the molecule. In principle this is done by by solving the Schrdinger equation; in practice the computational resources required increase exponentially with the number of atoms involved and so approximations become necessary. Recognising this, in 1982 Richard Feynman suggested using quantum components for such calculations. It wasn't until the 1990's than a quantum algorithm was proposed where the computational resources increased only polynomially in the problem size, and experimental implementations are even more recent, e.g. a photonic quantum computer was used in 2010 to obtaining the energiesat up to 47 bits of precisionof the hydrogen molecule, H_2 [1].

Here we examine the state of play in photonic quantum simulation, highlighting the difference between wave-mechanics simulations, which can be done with single photons or classical light, and quantum-mechanics simulations, which require multiple photons. Along the way we look at phenomena and problems from biology, chemistry, computer science, and physics, including zitterbewegung, enhanced quantum transport, quantum chemistry, and topological phases. We discuss the latest advances in photon technology, notably sources [2], detectors, and nonlinear interactions, and the implications for large-scale implementations in the near to medium term, e.g. in the Boson-Sampling problem [3].

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Quantum Yang-Mills theory on the lattice and tensor network states

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In this talk we pursue a description of the ground-state of lattice gauge theory in terms of a tensor network state. We work with pure gauge theory in the hamiltonian formalism on the lattice and study the locally gauge invariant sector of Hilbert space. We develop a toolkit to describe states in this sector, exploiting parallel transport operations and block-spin averaging operations to construct hierarchical tensor networks for pure gauge theory on the lattice. The continuum limit of our ground-state ansatz is also be discussed, and is connected to the removal of the lattice regulator. Connections to discrete quantum simulation will be emphasised. This talk is intended as a high-level overview of an ongoing programme.

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Topological Bands in Periodically-Driven Systems

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Recent work on topological materials has revealed a wide variety of intriguing phenomena that may arise when particles move in "non-trivial" bands. Advances in experimental capabilities for controlling electronic, atomic, and optical systems raise the possibility that analogous phenomena may be generated dynamically in driven systems. In this talk I will discuss how systems with discrete time translation symmetry offer an exciting platform for studying topological phenomena analogous to those familiar from non-driven systems. For example, analogues of the complete periodic table of topological classes for non-interacting systems can be realized in driven systems[1]. Going beyond this paradigm, I will also show that the differences between discrete and continuous time systems reveal entirely new robust phenomena, which can *only* occur in driven systems. In particular, a two dimensional driven system in which all "Floquet bands" have Chern number zero may still host robust chiral edge modes[2]. I will explain how this occurs, and what it means, and give some outlook on recent and proposed experiments on these so-called Floquet topological insulators[3].

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Photonic Floquet Topological Insulators

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We present the experimental demonstration of topological insulators (TIs) [1] where the propagating field is electromagnetic (in this case, visible light), rather than electronic. In solid-state TIs, topological protection is achieved by virtue of the Kramers degeneracy, which does not apply to photons (since they are bosons). Therefore, another mechanism is required. Theoretical proposals for achieving photonic TIs have included: aperiodic coupled resonator arrays; coupled optical cavities; birefringent metamaterials; and temporally modulated photonic crystal slabs. Our system, which is quite distinct from the previously proposed structures, is composed of an array of evanescently-coupled helical waveguides arranged in a honeycomb lattice. In this system, light diffracts according to the Schrödinger equation, where the time coordinate is replaced by the distance of propagation, and the waveguides act as potential wells. The helicity of the waveguides induces a fictitious, time-varying electric field, and the structure thus becomes equivalent to a Floquet TI [2]. The resulting 2+1-dimensional "photonic lattice" exhibits topologically protected edge states, and we demonstrate their presence and probe their properties experimentally.

We will show a number of consequences of topological protection, such total absence of backscattering at sharp corners, and scatter-free propagation around edge defects. Our setting can potentially allow for the study of mean-field interactions (through optical nonlinearity), and the effects of highly tunable disorder in TIs. Photonic TIs have been suggested for a number of applications, including highly robust optical delay lines, on-chip optical diodes, and spin-cloaked photon sources.

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Quantum Walks for Relativistic particles

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Quantum Walks are providing a new language for modelling quantum physical phenomena, whether for the sake of quantum simulation, or as toy models. For instance, the Diracequation can be modelled as a quantum walk, with the quantum walk being: discrete in time and space (i.e. a unitary evolution of the wave-function of a particle on a lattice); homogeneous (i.e. translationinvariant and time-independent), and causal (i.e. information propagates at a bounded speed, in a strict sense). This quantum walk model was proposed independently by Succi and Benzi, Bialynicki-Birula and Meyer: we rederive it in a simple way in all dimensions and for the Bargmann–Wigner equations in general. We then prove that for any time t, the model converges to the continuous solution of the Dirac equation at time t, i.e. the probability of observing a discrepancy between the model and the solution is an O(epsilon^2), with epsilon the discretization step. Finally, we present a general approach to decoupling of Quantum Walks, i.e. a procedure to obtain an evolution law for each scalar component of the QW, in such a way that it does not depend on the other components. In particular, the method is applied to show the relation between the Dirac (or Weyl) Quantum Walk in three space dimensions with (or without) mass term, and the Klein-Gordon (or wave) equation.

Quantum Walks of Interacting Particles

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I will discuss implementations of quantum walks of ultra-cold atoms on optical lattices and of photons on photonic lattices, and their potential for quantum simulations and quantum information processing.

Abstracts of Contributed talks

(in alphabetical order)

Universal spin dynamics in two-dimensional Fermi gases

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Studying transport in low-dimensional nanostructures has a long and rich history because of its non-trivial features and its relevance for electronic devices. The most common case, charge transport, has great technological implications and determines the currentvoltage characteristics of a device. With the development of the field of spintronics, however, spin transport has also moved into the focus of the research interest. Spin transport has unique properties, setting it aside from charge transport: first, the transport of spin polarization is not protected by momentum conservation and is greatly affected by scattering. Therefore, the question arises: what is the limiting case of the spin transport coefficients when interactions reach the maximum value allowed by quantum mechanics? Second, unlike charge currents (which lead to charge separation and the buildup of an electrical field, counteracting the current), spin accumulation does not induce a counteracting force.

Fermionic quantum gases allow the study of spin transport from first principles because interactions can be precisely tailored and the dynamics is on directly observable timescales. In particular, at unitarity, spin transport is dictated by diffusion and the spin diffusivity is expected to reach a universal, quantum-limited value on the order of the reduced Planck constant divided by the particle mass. Here, we study a two-dimensional Fermi gas after a quench into a metastable, transversely polarized state [1]. Using the spin-echo technique, for strong interactions, we measure the lowest transverse spin diffusion constant of 0.006 $\hbar/m$ so far. For weak interactions, we observe a collective transverse spin-wave mode that exhibits mode softening when approaching the strongly interacting regime.

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Simulation of motional averaging with a superconducting circuit

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Superconducting circuits offer a very attractive platform for the realization of quantum simulations, due to the availability of strong coupling between circuit elements, tunability, and scalability. I will give a brief review of a number of recent proposals and experimental achievements, then I will discuss our own realization of the so-called motional averaging/narrowing effect [1] using a circuit QED experimental setup.

Our circuit consisting of a capacitively-shunted charge qubit (a transmon) embedded in a superconducting waveguide resonator. Two microwave fields are applied to the system: one, at the frequency of the resonator, is used for measurement, while the other, around the Larmor frequency of the qubit, is used to drive the qubit. In addition, the qubit frequency is modulated by a random telegraph noise with externally-controlled amplitude and characteristic jumping frequency. Surprisingly, by adding noise in this way a new, "motional averaged" spectral line is formed with a linewidth smaller than the amplitude of the random modulation. We have also succeeded in driving Rabi oscillations on the motional averaged line, demonstrating the formation of hybrid states of the transmon and modulation field, with transitions that can be coherently driven.

When modulating the system sinusoidally, we observe a rich spectral structure, resembling a Landau-Zener interference pattern. However, direct Landau-Zener transitions are prohibited in our system by the fact that the frequency of the modulation is much smaller than the energy level separation. We show that in this case the transitions occur through the absorption of photons from the driving field; we call this process photon-assisted Landau-Zener effect.

For the values of the fields used in our experiment we show that, in a rotating frame, the system reaches the ultrastrong coupling regime. Our setup can also be seen as the simulation of the effect of coupling an externally-controlled fluctuation to a qubit. We anticipate that the experimental demonstration of motional averaging presented in this work will provide a novel route to improving the dephasing times of existing superconducting qubits.

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Quantum Simulation via Applied Systems Theory

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Quantum simulation with coherent and incoherent degrees of control is analysed in the unified picture of quantum systems theory:

First, we answer the question which quantum system can simulate another system in terms of the repective dynamic system Lie algebras. We give a plethora of illustrative concrete examples ranging from finite spin chains [1], fermionic systems [2] to recent developments on infinite-dimensional systems such as n two-level systems (n spins) interacting with one mode of the electromagnetic field in a cavity. The latter includes a time-dependent version of the Jaynes-Cummings model [3].

Then, with the system algebras at hand, it is easy to derive reachable sets for closed systems and open Markovian ones from the geometry of Lie groups [1, 2] and Lie semigroups [4].

Finally, we give a further outlook on quantum simulation in open systems. We show how adding simplest bang-bang switchable noise on a single qubit to unitary control suffices to make an n-qubit system so powerful that any n-qubit target state can be reached from any n-qubit initial state [5]. This may serve as an easy-to-come-by alternative to the more complicated set-ups of quantum simulators employing measurement-based feed-back schemes with resettable ancillas [6, 7]. – Likewise, time-dependent noise modulation is shown to improve noise-assisted exciton transfer in realistic models of the light-harvesting FMO complex in photobiochemistry.

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Abstracts of Posters

(in alphabetical order)

Signal-to-Noise Ratio for Single Atom Detection with Microcavities

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The poster summarises my master thesis, which is turned into a Phys Rev A paper at the moment.
The realisation of a real-time microwave-cavity single atom detector is an important prerequisite for a proposed cluster state quantum computer architecture [1], which can be used as a simulator. A proof of principle experiment for optical cavities was conducted in the 90's in Kimble's group [2] and the critical signal-to-noise ratio (SNR) in those setups was optimised in 2008 [3]. The microwave regime, on the other hand, is interesting in many ways but also introduces difficulties. The comparison of the SNR in optical and microwave setups sheds new light on the steady state and real-time operation of such nondestructive single atom detectors, which is a big step forward for the control of single quanta. The theoretical method (rate equations) employed to solve the governing master equation is useful for a wide variety of related cavity quantum electrodynamics problems.

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Electric Quantum Walks with Individual Atoms

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We have experimentally realized electric quantum walks, which mimic the effect of an electric field on a charged particle in a lattice. We use individual neutral atoms in a 1D optical lattice, which can be accelerated with radiofrequency precision to simulate a homogeneous external force. Starting from a textbook implementation of discrete time quantum walks, we introduce an extra operation (acceleration for a finite time) in each step to implement the effect of the field. The recorded dynamics of such a quantum particle exhibits features closely related to Bloch oscillations and interband tunneling. In particular, we explore the regime of strong fields, demonstrating contrasting quantum behaviors: quantum resonances vs. dynamical localization depending on whether the accumulated Bloch phase is a rational or irrational fraction of 2π.

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Nanometric surface probing with ultra-cold atoms

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We intend explore the possibilities offered by Ultra-cold atoms as nano metric surface probes. The interaction between a neutral atom and the surface of a dielectric or a conductor is a subject of research around which are concentrated many experimental and theoretical efforts in recent years. The reasons are varied. On the one hand it is a fundamental problem of QED, which has open conceptual and experimental aspects, such as e.g. the role of thermal fluctuations of the electromagnetic field produced by the surface. On the other hand, the interest is also motivated by the possibility of technological applications for advanced sensors. Finally, the systematic study of these forces is a crucial step for the derivation of new limits on hypothetical forces in non-Newtonian short distance.

The experimental project at LENS is concerned with the realization of an apparatus for laser cooling of atoms and their manipulation at sub-micrometric distances from a nano-structured surface that allows for rapid replacement of the test surfaces.

Superconducting resonator systems for quantum simulations

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During the last decade, tremendous progress has been made towards quantum computation with superconducting circuits. Nevertheless, the requirements for a scalable universal quantum information processor are still beyond state-of-the-art technology. In contrast, recent proposals for analog quantum simulations are based on present-day-performance of superconducting circuits. A particular example is the simulation of a Bose-Hubbard-type dynamics in chains of coupled nonlinear superconducting resonators. In order to make such a simulator as flexible as possible, the resonator nonlinearities and the coupling strengths between two adjacent resonators should be tunable. Here, we present important experimental progress on the toolbox required for this purpose. In particular, we discuss switchable and tunable coupling between two transmission line resonators mediated by a superconducting flux qubit [1] or RF-SQUID [2]. Our results allow one to analyze this coupling in frequency and time domain.

This work is supported by the German Research Foundation through SFB 631, the German Excellence Initiative through NIM, Spanish MINECO FIS2009-12773, FIS2011-25167, FIS2012-36673-C03-02; UPV/EHU UFI 11/55; Basque Government IT472-10 and EU projects CCQED, PROMISCE and SCALE-QIT.

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Experimental boson sampling with integrated photonic circuits

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The evolution of non-interacting bosons through a linear transformation acting on their Fock state is strongly believed to be hard to compute [1]. This is commonly known as the Boson Sampling problem, and has recently got a lot of attention as the first possible way to demonstrate the superior computational power of quantum devices over classical ones [2–5]. However, this very complexity makes the certification of the correct functioning of Boson Sampling devices a non-trivial problem, at least in the hard-computational regime [6]. We report the experimental implementation of a three-photon Boson Sampling experiment [2], which make use of femtosecond laser-written waveguides integrated on a glass chip. We also experimentally address the problem of validating the results in a computationally efficient way [7].

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2D Discrete Quantum Simulator

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Recent advances in the detection and coherent manipulation of neutral atoms in single sites of optical lattices pave the way to simulate complex physical phenomena where information is can be extracted from the position of the atoms in the lattice [1].

Spin-dependent transport via precise polarization control of laser beams in a one-dimensional lattice has been used to show discrete quantum walks [2]. Generalizing this scheme to two dimensions will allow us to, for instance, simulate artificial magnetic fields and Dirac cones using discrete time and space operations.

Our planned apparatus features a square 2D state-dependent optical lattice with a novel polarization synthesis allowing us to independent transport along the two orthogonal directions. An in-house designed state-of-the-art diffraction-limited high-numerical-aperture imaging system (NA = 0.92) will enable us to detect and address atom up to the level of single lattice-sites by means of highly-focused steering laser beams.

We present the current status of the experiment including the assembly of a high-optical-access dodecagonal glass cell with minimal bifrefringence and the objective.

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Quantum Walks in Electric Fields

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We study one-dimensional quantum walks in a homogenous electric field, which correspond to discrete time standard walks where after each step a phase depending linearly on position is applied. We show that the propagation properties of the system depend sensitively on the value of the electric field Φ. (1) When $\Phi/(2\pi) = n/m$ is an irreducible fraction, there is a revival after m or $2m$ steps, which is exponentially sharp in m. This is followed by a ballistic expansion. (2) When Φ has very good rational approximations, as provided by continued fractions, there is a hierarchy of time scales, each coming with a sharper revival and an arbitrarily large ballistic excursion. (3) In the very irrational case we find Anderson localization, i.e., a complete system of discrete, exponentially decaying eigenfunctions. We conjecture that this holds with probability one for random fields.

Tensor Network States for Fermion Lattice Models

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When a fermion lattice model is written as a sum of local Hamiltonians and furthermore it has a translational symmetry, the infinite time-evolving block decimation [1] is a powerful method for finding correlation functions. It is important to choose a tensor network state for the model in the infinite time-evolving block decimation. In the spirit of the infinite time-evolving block decimation, we propose a method for obtaining the ground-state energy and the wave function for two-dimensional quantum many-fermion systems, especially the Hubbard model.

In fact, we report a ground state solution for the two-dimensional fermionic Hubbard model, which is obtained by a numerical variational method. Two ingredients in this approach are tensor network states of Fig. 1 and the infinite time-evolving block decimation. While we easily handle the horizontal hopping in the Hamiltonian, we proceed further to see the fermion exchange effects by the vertical hopping. By requiring no blowing-up and no shrinking-down for the ground state [2], we successively determine the ground state energy per site as a function of the chemical potential and the horizontal lattice length. We find the dimensional crossover from one-dimension to two-dimension by observing the behavior of the ground state energy along with the horizontal lattice length [3].

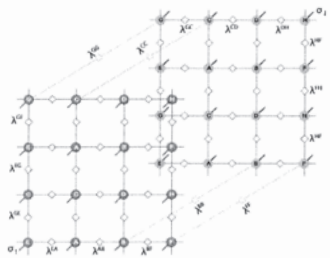

FIG. 1. A diagrammatic representation of a coefficient in front of an orthonormal basis of $|\sigma_0 \cdots \sigma_{N-1}\sigma_N \cdots \sigma_{2N-1}\rangle$. The closed circles represent eight tensors: A, B, C, D, E, F, G, and H; these tensors are among the $2L$ six-index tensors. The open diamonds represent the Schmidt coefficients λ assigned to each bond. We neglect to draw any spin bonds except the four lines between the spin-up and the spin-down layers. Nevertheless, it should be understood that there are spin bonds between all spin-up and spin-down tensors.

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Towards quantum simulation with ultracold molecules

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Ultracold and quantum degenerate mixtures of two or more atomic species open up many new research avenues, including the formation of ultracold heteronuclear ground-state molecules possessing a permanent electric dipole moment [1]. The anisotropic, long range dipole-dipole interactions between such molecules offer many potential applications, including novel schemes for quantum simulation. We report our progress on two experiments to create ultracold molecules for quantum simulation. The first uses ultracold mixtures of Rb and Cs [2], where weakly bound RbCs molecules are created using magneto-association on a Feshbach resonance. We are currently exploring routes to transfer these molecules to the rovibronic ground state. The second experiment aims to produce ground state CsYb molecules. Here the extra valence electron in ytterbium means that CsYb will have both an electric dipole moment and a magnetic moment in the ground state. This additional degree of freedom makes it possible to explore interesting phenomena such as spin dependent interactions in lattices [3]. We report our recent observation of a dual-species Cs-Yb magneto-optical trap and our plans to produce molecules.

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Imaging of microwave fields with quantum atomic vapors

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Imaging of the microwave (mw) spatial distribution of monolithic microwave integrated circuits (MMIC) are an essential step to diagnose the circuit design, defect inspection. We demonstrated that ultracold atoms can be used to image the near fields from mw waveguides on an atom chip [1], where mw field drives Rabi oscillations on atomic hyperfine transitions that can be detected via state-selective absorption imaging. From a practical point of view, simple atomic vapors instead would be more attractive, at room temperature or moderately heated. Recently, we have applied this technique to characterize the mw field distribution of a microfabricated vapor cell seated in a mw cavity, a central part of an atomic clock [2]. We also imaged the population lifetime T_1 of the ground states and coherence time T_2 using Ramsey interferometry. This technique is frequency tunable, non-invasive and calibrated by nature, which offers sub-wavelength resolution (100 micrometer in atomic vapor), high precision (mw B-field of 10^{-8} Tesla).

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Quantum Computing and Particle Physics in Discrete Spacetime

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We look at quantum systems in discrete spacetime that evolve in a causal fashion, meaning that over every timestep information can only travel a finite distance. This is a discrete spacetime analogue of a finite speed of light.

First, we discuss the result of [1] for a massless single particle with a two dimensional extra degree of freedom: in the continuum limit it obeys the Weyl equation, provided that we perform a simple relabeling of the coordinate axes or demand rotational symmetry in the continuum limit. It is surprising that this occurs regardless of the specific details of the evolution: it would be natural to assume that discrete evolutions giving rise to relativistic dynamics in the continuum limit would be very special cases.

Second, we discuss the results of [2] for fermionic systems. We see that any causal (possibly interacting) evolution of fermions in discrete spacetime can also be viewed as the causal evolution of a lattice of qubits, meaning these systems can be viewed as quantum cellular automata. A consequence of this is that the dynamics of causal fermions in discrete spacetime can be very efficiently simulated on a quantum computer in a natural way.

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Emergence of coherence and the dynamics of quantum phase transitions

We investigate the dynamical emergence of coherence when crossing the Mott to superfluid quantum phase transition in the precisely controllable setup of ultracold atoms, experimentally addressing long-standing questions on the dynamics of quantum phase transitions. For one-dimensional systems, we find perfect agreement between experimental observations and numerical simulations of homogeneous systems, thus performing a certified analogue quantum simulation. For intermediate quench velocities, we observe a power-law behaviour of the coherence length, reminiscent of the Kibble-Zurek mechanism. Contrary to what the latter suggests, we find a complex behaviour, yielding exponents that strongly depend on the final interaction strength in the superfluid. By using the full power of the quantum simulation, we also explore the emergence of coherence in higher dimensions as well as for negative temperatures. We connect our findings with insights into the propagation of quasiparticles and close-to-adiabatic quantum evolutions.

M. Friesdorf presenting joint work with S. Braun, S. S. Hodgman, M. Schreiber, J. P. Ronzheimer, A. Riera, M. del Rey, I. Bloch, J. Eisert, and U. Schneider

Constructing Pauli pulse schemes for quantum simulation

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Dynamical decoupling is a powerful technique to suppress errors in quantum systems originating from environmental couplings or from unwanted interparticle interactions [1]. However, it can also be used to selectively decouple or weaken specific couplings in a quantum system [2], making it suitable for purposes of approximate quantum simulation. We present a simple and easy-to-use general method to construct such selective decoupling schemes on qubit and qudit networks by means of (generalized) Pauli operations. Some examples are presented, demonstrating the use of our method and the resulting pulse schemes.

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Doublons and Holons in perodically driven Mott insulators

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Periodically driven systems can lead to a directed motion of particles. We investigate this ratchet effect for a bosonic Mott insulator where both a staggered hopping and a staggered local potential vary periodically in time. If driving frequencies are smaller than the interaction strength and the density of excitations is small, one obtains effectively a one-particle quantum ratchet describing the motion of doubly occupied sites (doublons) and empty sites (holons). Such a simple quantum machine can be used to manipulate the excitations of the Mott insulator. For suitably chosen parameters, for example, holons and doublons move in opposite direction. To investigate whether the periodic driving can be used to move particles 'uphill", i.e., against an external force, we study the influence of a linear potential $-Fx$. For long times, transport is only possible when the driving frequency ω and the external force F are commensurate, $nF = m\omega$, with $n, m \in \mathcal{Z}$.

Adiabatic tracking of many-body dynamics

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Quantum simulators employ well-controlled quantum systems for simulating complex quantum matter. Nonadiabatic transitions to unwanted states are a major source of error in controlling quantum dynamics of many-body systems. For few-particle systems, supplementing the system with an additional Berry Hamiltonian that perfectly restores the adibaticity seems an experimentally feasible scenario since the Berry interactions can be emulated easily. However, this ceases to be the case for large-scale many-body systems where the Berry Hamiltonian can neither be easily inferred in an explicit form nor be implemented in an experiment. Based on the recent proposal by Opatrny and Moelmer [1] we propose a simple approach for suppression on demand of the nonadiabatic transitions in large-scale many-body systems. We illustrate the applicability of our method in the context of one-dimensional spin chain models and their possible engineering for realization of well-controlled quantum simulators.

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High-Order Single-Photon W-states for Random Number Generation

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In our work, we experimentally realize high order W-states by forcing single photons to exist in a uniform coherent superposition of N spatial optical modes within a multi-port integrated system, that is, $|\mathrm{W}_N\rangle = (1/\sqrt{N}) \sum_{n=1}^{N} \mathrm{e}^{i\phi_n} \hat{a}_n^\dagger |0\rangle$. Here, $\hat{a}_n^\dagger$ denotes the bosonic creation operator in mode n, and ϕ_n represents an arbitrary relative phase. Interestingly, in the generated W-states, a single photon will emerge from any of the N output ports of a multi-port optical system with exactly the same probability. Based on that fact we have additionally developed a scheme for the generation of genuine random bits, which is of great importance nowadays [1–4]. The authenticity of the random numbers is validated by applying the fifteen statistical tests suggested by National Institute of Standard Technology (NIST) [5].

We present two different approaches, based on evanescently coupled waveguides [6], which lead to single-photon W-states having an arbitrary high, even and odd, number of entangled modes (see Fig. 1 (a) & (b)). The waveguide structures are fabricated by the femto-second laser writing technique [6–9]. Single-photon states were produced by coupling one of the twin-photons, emerging from a BiB_3O_6 crystal in a spontaneous parametric down-conversion configuration [10], into the waveguide structures.
In order to guarantee that only one photon was involved at every measurement, the absence of photon coincidences at the output of all waveguides was verified during the process. Since single-photon W-states are a coherent superposition of multiple single-photon states their coherent nature (i. e. a fixed phase relation between the single-photon states) can be examined by means of optical multi-port interferometers. This was experimentally confirmed for both waveguide systems (straight array & integrated beamsplitters - see Fig. 1 (a) & (b)).
As a direct application, we exploit the intrinsic uncertainty of the produced W-states $|\mathrm{W}_8\rangle$ for the generation of genuine random numbers. In that vein, by utilizing $N = 8$ output channels and performing M measurements, the maximal presentable number is $N^M = 8^M$. To evaluate the statistical randomness of the bit sequences we applied the standard statistical test suite for random number generators provided by NIST [5] to an arbitrarily chosen bit sequence. The sequence passes all tests which clearly verifies the true randomness.

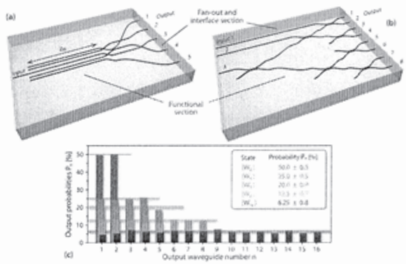

Figure 1. (a) Integrated waveguide structure to generate the $|\mathrm{W}_5\rangle$. (b) Cascade of integrated beam splitters to generate $|\mathrm{W}_{2,4,8}\rangle$ by choosing the input 1, 2, 3, respectively. To share a single photon among 16 guides, a similar structure was used. (c) Experimentally obtained output probabilities for the generated W-states.

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Simulation of relativistic wave equation predictions with ultracold atoms in an optical lattice

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In the area of solid state physics, it has been demonstrated that electrons in graphene can behave as relativistic particles, although the electron velocity is orders of magnitude below the speed of light [1]. Here we report a proof-of-principle quantum simulation of relativistic wave equation predictions with an atomic ^{87}Rb Bose-Einstein condensate in an optical lattice. We observe the analog of Klein-Tunneling [2] and describe an experiment demonstrating both negative refraction and Veselago lensing with an atomic Bose-Einstein condensate in a variable optical lattice. Our experiment is based on rubidium atoms in a Fourier-synthesized lattice potential consisting of an optical standing wave with spatial periodicity $\lambda/2$, where λ denotes the laser wavelength, and a higher spatial harmonic with lambda $\lambda/4$ spatial periodicity. In theoretical work it has recently been shown that the dynamics of atoms in the bichromatic lattice near the crossing between the first two excited bands can be formally described using a one-dimensional Dirac-like wave equation [3]. For the future, we expect that ultracold atoms in variably shaped optical lattices allow quantum simulations of a wide range of effects of both linear and nonlinear Dirac-dynamics.

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Quantum Simulations with circuit QED

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To simulate an interesting but not well understood quantum system by using a controllable quantum system in a lab has been fascinating physicists for a while. More recently, experimental work has been done toward simulations of complex quantum dynamics mostly with cold atoms and trapped ions.

On our poster, we will explore the potential of the newest player on the field: circuit quantum electrodynamics. Superconducting quantum circuits are well suited for quantum simulations due to their flexibility, scalability, and controllability. We will briefly present our current efforts to implement quantum simulations, in particular dynamics in Bose-Hubbard models in superconducting quantum circuits.

Realization of Hadamard and Pauli-X gate for polarization encoded qubits on chip

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The implementation of quantum operations in photonic devices plays a central role towards quantum computing, as light is a logical choice when low decoherence and stability is of interest [1]. It turned out that three-dimensional waveguide architectures fabricated using the femtosecond laser-writing approach [2] are particularly useful for polarization-encoded on-chip quantum optics [3]. However, the problem of modulating polarization states in laser-written structures remained so far unsolved.

In our work, we demonstrate an arbitrary waveplate operation on chip including Hadamard and Pauli-X gate operation for polarization encoded qubits. To this end, we employing particular line defects close to the waveguide [4], which enables a direct tuning of the birefringence in laser-written waveguides.

When such a waveguide is prone to a defect's stress field (see Fig.1(a)), an artificial birefringence is induced in this guide, which results in a reorientation of the optical axis as a function of the relative position of the two guides. As the relative position (in distance and angle) can be tuned with high precision, strong tilting of the birefringent axis can be implemented at will. This allows arbitrary desired wave plate operations on the light that propagates in the waveguide exposed to the stress field which was characterized utilizing classical laser light in the first step (see Fig.1(b)). By adjusting the length of the defect along the waveguide, the retardation between ordinary and extraordinary field components is precisely tunable including half wave plate and quarter wave plate operations (see Fig.1(c)).

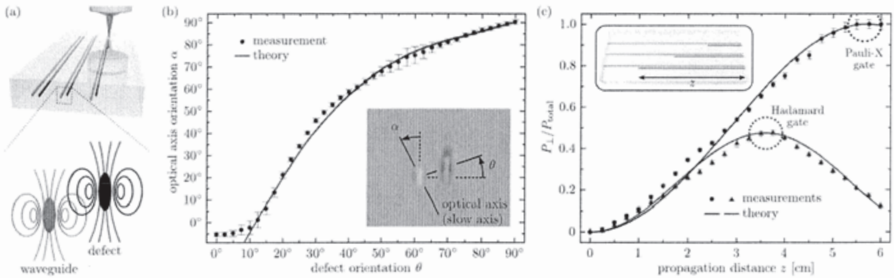

FIG. 1. (a) Sketch of the writing setting and cross section of the waveguide arrangement where an additional stress field induces a reorientation α of the waveguide's optical axis. Experimental data from classical caracterization for (b) α depending on the defect's orientation and (c) for the perpendicular transmission (H or V polarization) as a function of the interaction length between defect and waveguide for $\alpha = 45°$ (black dots) or 22.5° (red triangles).

Using our novel approach, we implemented Hadamard and Pauli-X operations in the single photon regime. Using single photon pairs generated by a standard type I SPDC source one photon heralds its sibling passing the photonic gate. The resulting state is measured by collecting the outputs of a polarizing beam splitter for different bases determined by adapted half-wave and quarter-wave plates. The resulting gate fidelities $\mathcal{F}_{\mathrm{Had}}^{|\mathrm{H}\rangle,\,\mathrm{V}\rangle} = 0.999(5)$ and $\mathcal{F}_{\mathrm{PX}}^{\mathrm{H}\rangle,\,\mathrm{V}\rangle} = 0.992(7)$ underline the precise performance of a Hadamard and a Pauli-X operation, which constitutes a benchmark for a full manipulation of polarization-encoded qubits on-chip.

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The Quantum Hall Effect within the notion of Peer Cooper

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Abstract :

In this paper,we are interested in the study of the two-dimensional quantum mechanics of electrons in a magnetic field using the polar coordinate system(particles in a uniform magnetic field),Results were obtained concerning the definition of the orbital angular momentum of two-dimensional particle and its projection and statistics related to these particles.

On the other hand, we look for the fractional quantum Hall effect from the concept of electron pairs using the notion of Peer Cooper.*We determine the wave functions for the exact fundamental theory :the wave functions of two pair of electron is not other than the 'Laughlin'wave function but with two electrons in a near multiplicative hypergeometric function.*

The merit of this work is not only to calculate the wave function, but in showing that the energy and the correlation function of this state are proportional to the distance between the electrons , Moreover ,we show the wave function that we find by the notion of peer cooper can be exactely expressed in terms of correlation functions of local vortex operator in the Conformal Field Theory.

Cold atom simulator of exotic spin models

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Quantum magnetism has long formed a major branch of condensed matter theory. Despite intense research in this field during the last decades, many questions remain open. Cold atoms in optical lattices constitute an alternative approach in order to explore phenomena related to quantum magnetism. Anti-ferromagnetic spin chains have already been realized in these systems where the spin is mapped onto the atomic site occupation [1]. Most theoretical proposals to date relay, however, on decoding the spin degree of freedom in internal atomic electronic states [2]. In terms of quantum simulators, due to the properties of the involved scattering lengths, such schemes have their limitations since they normally support continuous symmetries and thereby typically result in integrable models. We propose a new system in which a plethora of different non-integrable spin models can be realized. More precisely, motivated by recent experiments [3] on preparing bosonic atoms on the first excited bands of an optical lattice, we demonstrate how effective spin models emerge when the spin is described by the orbital degree of freedom present on excited bands. Contrary to using spinor atoms, here the effective spin models are non-integrable and by considering bosonic atoms the system surprisingly favours anti-ferromagnetic order. While the method is very versatile, we here focus on the realization of the spin-1/2 anti-ferromagnetic XYZ Heisenberg chain in an external field [4]. We map out the phase diagram and also discuss how to address the spin degrees of freedom using techniques from trapped ion physics.

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Ultracold bosons in optical lattices subjected to a periodic perturbation

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In recent years ultracold atomic gases in optical lattices have developed into a powerful tool to mimick condensed matter phenomena. The unique control and tunability of parameters has enabled the engineering of sophisticated quantum systems. In particular with the experimental realization of effectively strong and tunable interactions between atoms the area of strongly correlated systems has entered the focus of interest. In these systems, the emergent phenomena are governed by the interplay of a macroscopic number of atoms. Theoretically, atomic gases in optical lattices are described by various kinds of Hubbard models. These models are widely employed for the description of solids, where they are only rough approximations. However, Hubbard models may be cleanly realized in cold atom systems. Even more exciting are these atomic gases as one finally gains access to the dynamics of many-body theory. These dynamics are of fundamental interest but so far little understood. One example is the time evolution of the propagation of correlation.

We study non-equilibrium situations in the one dimensional Bose-Hubbard model which are governed by the interplay of local interaction and kinetic processes. The Bose-Hubbard model exhibits a phase transition between a Mott insulating and a superfluid phase. We probe the Mott insulating phase in one dimension by applying a periodic perturbation. This periodic driving can experimentally easily be implemented by adding an additional laser wave incommensurate with the underlying optical lattice. We study how the system responds using an approximative approach based on fermionic quasiparticles.

Towards the creation of ground-state ultracold RbCs molecules for quantum simulation

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Ultracold and quantum degenerate mixtures of two or more atomic species open up many new research avenues, including the formation of ultracold heteronuclear ground-state molecules possessing a permanent electric dipole moment [1]. The anisotropic, long range dipole-dipole interactions between such molecules offer many potential applications, including novel schemes for quantum information processing [2] and simulation [3]. Our goal is to create ultracold ground-state RbCs molecules using magneto-association on a Feshbach resonance followed by optical transfer to the rovibronic ground state [4–6]. Here we present our recent results on the formation of both ultracold Cs_2 Feshbach molecules from a Cs Bose-Einstein condensate and ultracold ^{87}RbCs Feshbach molecules from a Rb-Cs atomic mixture. For ^{87}RbCs we discuss the magneto-association scheme, which is complicated by the large background interspecies scattering length, and outline our progress towards the optical transfer to the ground state using stimulated Raman adiabatic passage (STIRAP).

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Fundamental quantum physics with superconducting qubits

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In recent years the coherence time of superconducting qubits has improved significantly. But not only the single qubit properties have improved, it is also possible to couple many qubits with minimal additional noise by indirect interaction via a superconducting transmission-line resonator. Tuning in and out of resonance allows controlling the couplings between the qubits. Since the coupling of superconducting qubit to a resonator is much stronger than that of an atom to an optical cavity, these systems give us access to new parameter regimes of interaction between effective two-level systems and the radiation field. This can already now be used to study fundamental physics in systems with single or few qubits. With a single superconducting charge qubit it is possible to create an effective single atom laser. Using the specific properties of this device we showed that it is possible to create highly squeezed photon distributions [1]. Using the possibility to couple qubit and resonator in a highly nonlinear fashion, via a SQUID, we showed that multi-stabilities similar to an optical micro-maser can be created [2]. With a more simple structure, a superconducting resonator shunted by a voltage biased Josephson junction, we showed that it is possible to generate pairs of photons [4]. While there is strong coupling between qubit and electromagnetic resonator mode, a solid state qubit is in general also less coherent than a natural atom. We showed that qubits with poor coherence properties can be used to create an inversionless laser [3]. Beyond single qubit experiments, it is now crucial to scale up to larger systems. In a recent work we demonstrated the resonant coupling of up to eight superconducting qubits to a superconducting resonator [5] (see fig. 1).

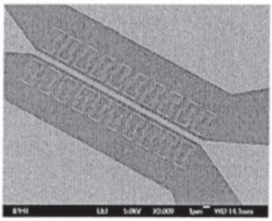

FIG. 1. Twenty superconducting flux qubits, coupled to a superconducting transmission-line resonator.

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Quantifying entanglement with simple measurements

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Entanglement is a resource for quantum informational tasks and a benchmark for the classical simulability of many-body systems (by DMRG or similar methods), which is typically hard at quantum phase transitions and in non-equilibrium situations such as, e.g., sudden quenches. Quantum simulators may address these and other facets of entanglement experimentally in a well controlled manner. Thus, arguably, it will be of interest to quantify entanglement based on accessible measurements [1–5]. Ideally, such measurements are simple and cheap, e.g., less time-consuming and with a better scaling with the system size than full state tomography, and robust against noise, like spontaneous emission, dephasing and non-adiabaticity, temperature and statistical errors. We report on how the bipartite entanglement (as quantified by the logarithmic negativity) can be lower bounded based on a few already available observables. The bounds do not depend on any assumptions on the system but only on the measured data. We demonstrate the feasibility by numerical simulations of a chain of trapped ions simulating a system which is approximately given by a transverse field Ising model with algebraically decaying couplings [6]. We report on results for ground states across quantum phase transitions and sudden quenches under this Hamiltonian. The necessary optimization may be formulated as a semidefinite program [2]. We further discuss how the optimization may be completely avoided at the hand of two examples: Lower bounds for the ground state of the Ising model may be directly obtained from a sequence of Bell measurements and numerical calculations suggest that such measurements are optimal. Secondly, we show how other entanglement measures like, e.g., the best separable approximation may be bound from below directly using scattering experiments from samples consisting of large numbers of qubits [4, 5]. Again, the required data, here the measurement of the structure factor, is simple to obtain and the bounds do not rely on any assumptions on the system.

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Exotic quantum magnetism with spin F=1 ultracold gases in optical lattices

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The high degree of tunability and experimental control achieved in cold gases convert them into promising candidates for simulating and understanding quantum many-body phenomena. Particularly appealing is the study of quantum magnetism by using cold atoms loaded into optical lattices. For a very deep lattice, where tunneling is strongly suppressed and particles become localized at each lattice site, these systems can effectively realize spin models.

On the other hand, the quest for realistic models that can support a topological spin liquid (or other forms of exotic magnetism) is at the frontier of current research, due to its connection with high-Tc superconductivity and the fractional quantum Hall effect. The spin S=1 Heisenberg model in a triangular lattice in presence of a uniaxial magnetic field has been suggested as one of the simple models that could support a spin liquid ground state in some region of its phase diagram. However, the available theoretical methods to describe its phases are scarce and rely mostly on numerical or variational approaches.

We present here our studies on this model by using the Cluster Mean-Field approach [1] and compare the results with other methods as the Gutzwiller mean-field ansatz or the exact diagonalization of a small plaquette. The CMF is a combined method that divides the lattice into finite size clusters which are treated in a full quantum way by exact diagonalization and which are coupled by a mean-field approach. It represents a step forward compared to the Gutzwiller ansatz, since it includes quantum correlations at the cluster level. By using this method, we obtain the complete phase diagram and search for a signature of local disorder in the lattice, necessary for a spin liquid state.

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Reconstruction of Wigner functions using Glauber-Fock photonic lattices

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Photonic lattices can serve as an ideal environment where one can directly generate and observe a wide range of physical processes. In this regard, Glauber-Fock photonic lattices have been used in the past to classically emulate coherent and displaced Fock states using classical light. The classical realization of these displaced oscillator eigenstates was performed by establishing a correspondence between the number state $|n\rangle$ and classical light launched into the n-th waveguide of an array where the coupling coeffcients obey a square root law distribution between nearest neighbors, that is, $C_{k,k+1} = \sqrt{n+1}$, [1]. In this contribution we endow such glauber-Fock photonic lattices with an alternating positive and negative coupling coefficients , $C_{k,k+1} = (-1)^{n+1}\sqrt{n+1}$ [2]. It is shown that specific wave-packets traveling through these optical arrangements give rise to superposition of Wigner functions [3] and characteristics functions corresponding to coherent and displaced number states. Then, by monitoring light propagation along z, in two different waveguide lattices, one can isolate Wigner functions corresponding to such states. In general, the propagation of the modal optical fields in these semi-infnite Glauber-Fock oscillator lattices is governed by the following set of coupled equations:

$$\begin{aligned} i\frac{dE_0}{dZ} - \lambda E_1 &= 0 \\ i\frac{dE_n}{dZ} + \lambda(-1)^n \left(\sqrt{n+1}E_{n+1} + \sqrt{n}E_{n-1}\right) &= 0 \end{aligned} \tag{1}$$

In this case one can show that the evolution operator is given by:

$$U(Z) = \frac{1}{2}\left(D(\lambda z) + D^{\dagger}(\lambda z) - i\left[D(\lambda z) - D^{\dagger}(\lambda z)\right](-1)^n\right), \tag{2}$$

where $D(\lambda z) = \exp\left(iz\left(a + a^{\dagger}\right)\right)$ is the Glauber displacement operator [4], and $(-1)^n$ is also an operator. From this equation we can identify the Wigner operator $W(z) = D(z)(-1)^n$. Therefore, the field distribution at waveguide n for any input excitation $|\psi(0)\rangle$ will be described by

$$E_n(z) = \langle n|\, U(z)\, |\psi(0)\rangle\,, \tag{3}$$

Consider, for instance, the initial field profile corresponding to a coherent state, $|\psi(0)\rangle = |\alpha\rangle$, i.e., $E_n(0) = \exp(-\alpha^2/2)\alpha^n/\sqrt{n!}$, where α represents a complex constant. In this case, the input field distribution will evolve to a superposition

$$E_n(z) = \frac{1}{2}\left(\langle n\,|\lambda + z\rangle + \langle n\,|\lambda - z\rangle - i\,\langle n\,|z - \lambda\rangle + i\,\langle n\,|-z-\lambda\rangle\right) \tag{4}$$

Hence, if we launch the same initial field distribution into another array having a negative λ parameter yields to

$$E_n(z) = \frac{1}{2}\left(\langle n\,|-\lambda + z\rangle + \langle n\,|-\lambda - z\rangle - i\,\langle n\,|-z - \lambda\rangle + i\,\langle n\,|z-\lambda\rangle\right) \tag{5}$$

Finally, by interfering these two fields we obtain $W(\lambda z) = \langle n\,|z - \lambda\rangle$, i.e., we can generate the Wigner function corresponding to a coherent state. Following this same procedure we can emulate any Wigner funcion for oscillator eigenstates.

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Nonlinear $\mathcal{PT}$-symmetric photonic graphene

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In the framework of non-dissipative quantum systems, Hermiticity is usually a requirement to the Hamiltonian, since it ensures a real spectrum and hence the conservation of energy. However, Bender et al. [1, 2] have shown that the postulation of only local parity-time ($\mathcal{PT}$) symmetry extends the class of Hamiltonians that obey the law of energy conservation. Although $\mathcal{PT}$-symmetric quantum theory violates the no-communication theorem and therefore may be ruled out as a fundamental theory [5], it contains very interesting structures (e.g. excitations with tachyon dynamics [3], sharp transitions between transport regimes) and, most importantly, it is accessible through simulations by photonic lattices. In our work, we analyze a particular $\mathcal{PT}$-symmetric system: *nonlinear photonic graphene*, a lattice of coupled waveguides in honeycomb geometry [4]. The dynamics in this highly complex system is described by a set of nonlinear tight-binding Schrödinger equations

$$\mathrm{i}\frac{\partial\psi_a}{\partial z}(z) = \left(\mathrm{i}\gamma_a + \sigma\,|\psi_a(z)|^2\right)\,\psi_a(z) + \sum_{b\in N_a} c_{ab}\psi_b(z), \quad c_{ab}, \sigma, \gamma_a \in \mathbb{R}.$$

Here $\psi_a(z)$ is the field amplitude of lattice site a at propagation distance z, N_a is the index set of neighbours of site a and c_{ab} are the coupling constants to the neighboring sites. The quantities γ_a and σ describe the on-site gain/loss amplitude and the acting Kerr nonlinearity, respectively. We analyze various questions in this highly non-trivial system: Do solitary solutions exist and, if yes, which properties they possess? Do such solitons interact? Does modulational instability exist in this system?

In Fig. 1 we give a short overview on our results. Fig. 1a shows the band structure of $\mathcal{PT}$-symmetric photonic graphene . Clearly, the typical Dirac cones of graphene (that show an approximately linear dispersion) are replaced by hyperbolic bands at which the dispersion is hyperbolic. Interestingly, at $E = 0$ the slope of the dispersion diverges on a contour shown in Fig. 1b, giving rise to tachyonic behavior. We find solitary solutions in such a system for both, focusing and defocusing nonlinearity. An example of such an entity (with focusing nonlinearity) is shown in the inset of Fig. 1a, where the intensity envelope os plotted over the honeycomb lattice.

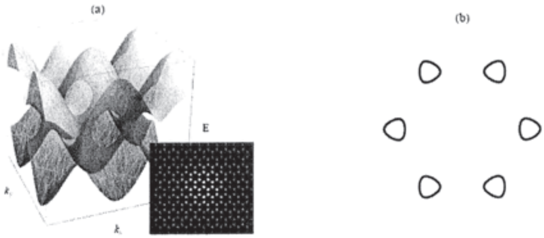

FIG. 1. (a) The band structure of linear $\mathcal{PT}$-symmetric graphene. The inset image shows the field amplitude of a solitary solution for focusing nonlinearity. (b) Contours of the bands at $E = 0$. Excitations that are localized in momentum space around the drawn regions show tachyonic behavior.

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Rigorous violations of the Leggett Garg inequality using quantum walks of single atoms

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(Dated: January 28, 2014)

Given the assumptions of *Macroscopic Realism* (MR) and *Noninvasive Measurability* (NIM), Leggett and Garg derived an inequality in their original work [1] which is capable of ruling out macroscopic realism by falsability. The Leggett Garg inequality can furthermore be used to determine the 'quantumness" of a system, given one accepts quantum mechanics as the only alternative theory to macroscopic realism.

We report on our recent results testing the Leggett Garg inequality for quantum walks with single atoms. Our implementation to measure a violation of the Leggett Garg inequality follows closely the original proposed measurement scheme, by making use of an ideal negative measurement. This measurement is employed by our state dependent optical lattice. The strongest recorded violation of the Leggett Garg inequality violates the inequality by $21\,\sigma$. Furthermore we studied how an initially decoherence free quantum system that violates the Leggett Garg inequality gradually transitions into a classical system that fulfills the LG inequality by increasing the decoherence in a controlled fashion.

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Memory requirements for general reversible qubit stream processors

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We show that the index of a one dimensional reversible quantum cellular automaton, which is in addition also ausal, equals to the minimal memory overhead needed to construct this automaton as a strictly forgetful memory hannel[1]. Furthermore we develop bounds on the neighborhood scheme of a translational invariant automaton, iven its index and prove that these bounds are optimal. We also derive bounds on the neighborhood of the inverse ransformation, up to trivial shifts of the chain. We connect the structure of "forgetting" of the memory channel to 3rattelli diagrams of inclusions of algebras. So far it is not clear whether every such diagram represents a strictly orgetful memory channel.

Consider a device processing quantum information in the following sense: presented with a stream of input qubit ystems it will output a stream of output qubits. We call this a *causal process* if, for any step number t, the probability f any outcome which can be determined on the outputs up to t is independent of the later inputs. That is, if no lifference between two given input streams can be detected by measurements on inputs up to t, the same will be rue for the outputs. There are two basic ways of describing such a system: one is in terms of its input-output ransformation alone. That is, we consider the system completely specified if we can determine the probability for ny outcome of an arbitrary measurement on the outputs, given the joint state of all the inputs. The second way of lescribing such a system is in terms of its inner workings. Typically the processing is done by a system with, say, inite quantum memory, and reading in an additional input, or sending a qubit to the output are operations explicitly lescribed by unitary operations. These two points of view are complementary to each other, and while it is usually asy to pass from the description of the internal circuitry to the input-output transformation, the "inverse problem", ometimes called the "system identification problem" can in general be very hard.

We describe a complete solution of the inverse problem for the special case of reversible processes. That is, we equire the existence of a second causal process, so that the concatenation with the given process is equal to a time hift. It turns out that this reversibility forces the process to be a locality preserving automorphism of the quasi-local lgebra, in other words a *quantum cellular automaton* [2]. A key result of our theory is that the minimal Hilbert space limension required for the memory of a circuit implementation of the process is equal to the *index* of the automaton, s introduced in [3].

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Quantum simulation with kagome photon lattices

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The energy spectra and photon transfer dynamics of kagome arrays is explored by virtue of a projected-entangled pair state (PEPS) ansatz to the many-photon wavefunction. Photons from a microwave source are injected into one of the twelve cavities of the unit kagome and are able to hop into other cavities with a hopping strength that can be tuned experimentally. The competition between the field energy and the hopping rate decides the phase diagram of the model. We demonstrate how the latter two-dimensional version of the powerful tensor network formalism provides a flexible numerical benchmark for addressing such a challenging two-dimensional model. We present results for the energy spectra as well as two-point correlation functions of such a cavity lattice and compare them to those from the brute force exact diagonalization of the model. The correlation functions associated with the propagation of single-photon and two-photonic excitations reveal intriguing interference patterns which might be understood from the symmetry features of the kagome topology. Possible avenues of utilizing such arrays for quantum simulation of correlated matter are being discussed [1].

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Experimental demonstration of more than 100 individually addressable qubits for quantum simulation and quantum computation

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Efficient quantum simulation and quantum information processing requires scalable architectures that guarantee the allocation of large-scale qubit resources. Optical dipole potentials such as arrays of focused laser beams provide flexible geometries for the synchronous investigation of multiple atomic quantum systems with a high degree of decoupling from the environment. In our work, we focus on the implementation of multi-site geometries based on microfabricated optical elements. This approach allows us to develop flexible, integrable and scalable configurations of multi-site focused beam traps for the storage and manipulation of single-atom qubits and their interactions [1].

We give an overview on the investigation of ^{85}Rb atoms in two-dimensional arrays of well over 100 individually addressable dipole traps featuring trap sizes and a tunable site-separation in the single micrometer regime. Advanced schemes for atom number resolved detection with high efficiency and reliability allow us to probe single atoms stored in the microtrap array. For single atom preparation we utilize light assisted collisions to improve loading efficiencies thus eliminating multi-atom events. We experimentally demonstrate single-atom quantum registers with more than 100 occupied sites, single-site resolved addressing of single atom quantum states in a reconfigurable fashion and discuss progress in introducing Rydberg based interactions in our setup.

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Relaxation dynamics of a Fermi gas in an optical superlattice

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The question of how a closed quantum system out of equilibrium evolves and relaxes, is still not well understood. A specific setting of coherent quantum dynamics can be provided by quenches when one starts from the ground state of an initial Hamiltonian and suddenly changes the Hamiltonian's parameter. After this change the system is highly excited with respect to the new Hamiltonian and evolves in time.

Ultracold quantum gases in optical lattice are good candidate to study such non-equilibrium situations since these gases are approximately isolated from their environment.

Here we study a three dimensional Fermi gas initially loaded into a periodic double well potential along one dimension. The superlattice enables us to prepare the initial state with fermions only occupying even wells. Afterwards the superlattice potential is suddeenly removed the time evolution of the local density imbalance between two neighboring wells is probed. The experimental results are compared to the numerical studies based on the exact diagonalization of the Hamiltonian in the continuum.

Optical supersymmetry: A fundamental approach to a new kind of mode converters

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Abstract: In our work we transfer the concept of supersymmetry (SUSY) to optics and systematically design a new class of optical structures. Key features arising from supersymmetry are used to control the flow of light for mode division multiplexing applications.

Encoding information on a given chanel is one of the central problems of high capacity optical transmission systems. In addition to wavelength division, polarization, and angular momentum multiplexing as well as multilevel modulation, and coherent detection, mode-division multiplexing (MDM) provides a promising platform for increasing the capacity of optical links. While using the individual modes in waveguides one of the outstanding challenges in MDM structures is a robust procedure for selectively populating and extracting specific modes in such integrated networks.

In the optical domain, supersymmetric partners with different dielectric shapes (see Fig.1 (a,c)) share identical properties. With the exception of the fundamental mode, each guided mode of the original multimode lattice has a counterpart in the partner lattice with exactely the same energy or effective index (see Fig.1 (b)). The light propagation is discretized and the corresponding state vector $\mathbf{A}$ is govern by the following evolution equation along the longitudinal coordinate z:

$$-i\frac{\mathrm{d}}{\mathrm{d}z}\mathbf{A} = \mathcal{H}\mathbf{A} \tag{1}$$

Here, $\mathbf{A} = (a_1, ..., a_N)^T$, where a_k describes the complex modal field amplitude in the k^{th} channel, N is the number of lattice sites involved, and the $N \times N$ matrix $\mathcal{H}$ is the Hamiltonian of the system whose elements are given by $\mathcal{H}_{m,n} = (\delta_{m-1,n} + \delta_{m+1,n})C_n + \delta_{n,m}\beta_n$. In the latter expression, β_n denotes the propagation constant of channel n, and C_n represents the coupling strength between adjacent lattice sites. The eigenvalue problem $\mathcal{H}\mathbf{A} = \lambda\mathbf{A}$ associated with Eq. (1) can in turn be used to construct a superpartner lattice [1].

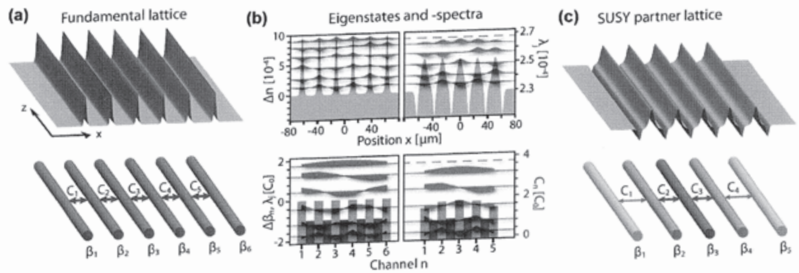

Fig. 1. Supersymmetry in photonic lattices. (a) Continuous refractive index profile (upper row) and discrete representation (lower row) of an array arrangement of evenly spaced, identical waveguides and (c) its superpartner structure. (b) Bound modes of these two systems. Their vertical position indicates the corresponding eigenvalues.

In our work, we demonstrate how supersymmetric partners can be utilized for multiplexing/demultiplexing different modes of highly multimoded systems. To that end, we use direct-written multicore photonic lattices with appropriate index profiles in fused silica (see Fig.1 (b)). While exploiting the unique advantage to directly observe the evolution dynamics by means of fluorescence microscopy [2] our results are general and other fabrication approaches can also be pursued.

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Quantum simulation of relativistic fields interacting with artificial gravity in 2D optical lattices

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We present our latest results on the possibilities of quantum simulation of relativistic fields in 2-dimensional optical lattices. Geometry and relative strength of the laser beams define the properties of the effective quantum field and set the mass-gap of its ground-state excitations (particles and antiparticles). Local static or time-dependent amplitude and/or phase modulations can then introduce effective curved geometry and gravitational potential. The last can be used for simulation of gravitational lensing or interaction with strong gravitational waves – beyond the range of any current direct experiments.

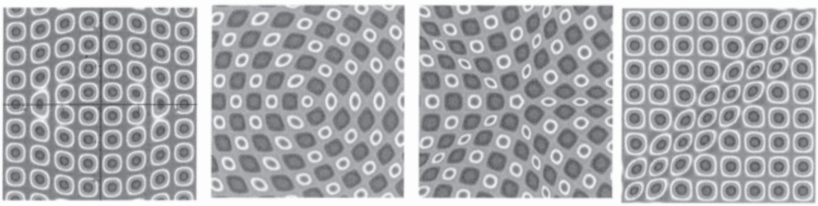

FIG. 1. Optical lattices with dislocations (a), disclinations (b-c) and dynamical small perturbations (d).

Thermal conductance as a probe of topological order in a hybrid semiconductor-superconductor system emulating the Higgs model

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The order parameter in a conventional superconductor can be subject to quantum fluctuations in the form of 2π phase slips. We consider the effect that these quantum phase slips have on a helical quantum wire proximity coupled to the superconductor. At low energies the system is effectively described by a Majorana chain minimally coupled to a dynamical Z_2 gauge field, an example of a matter-coupled lattice gauge theory. Quantum phase slips lift the ground state degeneracy associated with unpaired Majorana edge modes, without breaking fermionic parity. In terms of the lattice gauge theory, the change in ground state degeneracy can be understood as a Higgs transition from a confined to a deconfined phase. We identify the quantization of thermal conductance at the phase transition as a robust experimental feature of the system, which survives the presence of a dynamical gauge field. Our calculation indicates that thermal transport due to the matter degrees of freedom can serve as an experimental probe for quantum phase transitions in matter-coupled gauge theories.

Towards scalable superconducting quantum bits for analog quantum simulation

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The experimental implementation of analog quantum simulation of manybody Hamiltonians requires scalable and well-controllable qubits as building blocks. Superconducting quantum devices are a leading candidate for quantum information processing and analog quantum simulations. These artificially made superconducting loops composed of planar thin films forming Josephson tunnel junctions, inductors and capacitors behave as quantum few-level systems. In contrast to the case of natural atoms or molecules, such systems allow for very large couplings between the electromagnetic field and the effective dipole moment of a few-level artificial atom that even remains frequency-tunable during operation. A wide range of quantum experiments, such as violation of Bell's inequality [1], few-qubit algorithms [2, 3], or implementation of a quantum metamaterial [4] have been demonstrated using these circuits.

However, the materials used for their linear and non-linear circuit elements set a limit on the best achievable coherence times and are increasingly researched. For the linear elements such as capacitors and inductors, resonators showing single photon quality factors up to 1 million depending on aspect ratio and surface treatment [5]. Mixed-material, lumped element resonators allow to systematically locate and extract residual losses [6]. Combining high quality resonators with ultra-small tunnel junction superconducting qubits of increased coherence can be obtained [7]. Josephson junctions, acting as non-linear elements and providing the qubit's anharmonicity, are known to suffer from detrimental interaction with two-level-systems in the amorphous tunnel oxide. These residual states can absorb energy and interfere with the qubit state, resulting in shorter coherence times. Epitaxial tunnel barriers -having fewer defect states than conventional amorphous barriers -were developed and implemented in qubits [8].

At Karlsruhe, the fabrication of superconducting circuits for analog quantum simulation was started recently. Frequency tunable qubits of the *transmon*-type have been realize in a microstrip geometry using aluminum sputter technology. We will present data for the first generation of qubits, and discuss improvement strategies towards scalable, tunable, long-lived qubits for superconducting analog quantum simulators.

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