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The computational complexity of linear optics

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The purpose of this talk is to explain why linear optics is of interest to computer science, specifically to complexity theory and quantum computing. It is based on work done with Scott Aaronson.
We present evidence that under plausible conjectures, one cannot classically simulate the outputs of linear optical systems, even approximately. As a result, linear optical experiments demonstrate statistical outcomes that cannot be reproduced by any computational device in a reasonable time span, even ones that use a completely different mechanism to produce these outcomes. As such, they give hands-on evidence of quantum supremacy, that quantum phenomena cannot be generally simulated by classical devices.
Computational complexity is concerned broadly with what algorithmic problems can be solved efficiently on a computer. For instance, one can easily multiply two large primes numbers, but there is no known fast algorithm to recover the factors of the product, and factoring 1000-digit numbers remains out of the reach of current hardware. Understanding the quantum nature of the world has led to the invention of new algorithms that exploit the phenomena of superposition and entanglement. One can, for instance, perform different computations in two branches of the wavefunction, then perform an operation that interacts with both branches. Notably, Grover's Algorithm allows searching through a list of size N is c N operations, whereas Shor's algorithm lets one factor numbers efficiently.
While many different physical implementations have been proposed for a quantum computer, any device able to perform a certain set of operations is a universal quantum computer that can do roughly the same computations using the same amount of resources to within a constant factor. Although building a universal quantum computer is still on the horizon, we are able to reason abstractly about what such computers will and will not be able to do. One important goal is to demonstrate what advantages quantum computers have over what is possible classically.
In joint work with Scott Aaronson, we demonstrate quantum advantage using linear optics. Rather than proving taking a problem believed to be classically hard (say, factoring) and coming up with a clever quantum algorithm to solve it, we instead formalize the generic behavior of a quantum system (here, linear optics) and prove that it is hard to simulate classically. So, we are not showing quantum computers to be solving a useful problem, just exhibiting behavior that cannot be mimicked in the classical world without prohibitively much computation.
We formalize as "BosonSampling" a class of optical experiments in which a fixed number of identical pho- tons are produced in different modes, the photons pass through a network of beamsplitters and phaseshifters that mix the modes, and a count is measured of the number of photons emerging in each mode. Of course, different runs of the experiments will produce different counts. We proved that the statistical distribution of counts itself cannot be produced classically, i.e. that no random classical algorithm generates outcomes with the same probabilities, even approximately, under assumptions commonly used in complexity theory.
There are a few reasons linear optics is ideal for this demonstration. First, there is a close relationship between the behavior of identical photons and the permanent, a matrix function that is computationally difficult. This fact is at the heart of out proof. Second, our formalization of linear optics (BosonSampling) is very restrictive, and therefore easy to state and reason about. In particular, the network of beamsplitters and phaseshifters is fixed before the experiment begins, a single operation is applied, and all measurements are done at the end. We do not believe this to allow universal quantum computing. Third, showing that even such a restrictive model lets one do something super-classical shows that little quantumness is needed to get an advantage. In particular, the photons do have any explicit coupling interactions, and only interact statisically by being identical bosons.

Many-Body localization characterized by entanglement and occupations of natural orbitals

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In this talk I will discuss the main features of many-body localization, the interacting version of the Anderson insulator, focussing on the entanglement and the one-particle density matrix in eigenstates and after a global quench. The entanglement of eigenstates have an area law in the localized phase but a volume law in the ergodic phase, with diverging fluctuations at the many-body localization phase transition. The entanglement grows logarithmically after a global quench from a local product state. Similar logarithmic growth is also found in the quantum mutual information. The occupations (eigenvalues) of the one-particle density matrix in eigenstates show a fermi-liquid-like discontinuity, reflecting the presence of local quasiparticles and, in a sense, adiabatic connectivity to the Anderson insulator. This discontinuity is smeared at long times after a global quench, in similar way as the discontinuity in a fermi liquid is smeared by finite temperature.

Fast-slow approximation in the Dicke model

Bastarrachea Magnani, Miguel Angel
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In this work it is shown that the Dicke model has a very approximate second integral of motion, making the system very approximately integrable within a wide range of energies and values of the coupling constant and the detuning between the field and the collective atomic system. This entails that the energy levels of the Dicke model can be labelled with two quantum numbers within this region, and can be computed without numerically diagonalizing the Hamiltonian matrix. The physical origin of this second integral of motion is firmly established throughout the Born-Oppenheimer Approximation (BOA), allowing to determine its range of applicability and opening new venues of research in the Dicke or related models where the same strategy to approximately solve the models' dynamics could be applicable.

Expansion of Bose-Einstein condensates in disorder: Anderson localization and wave chaos

Brezinova, Iva
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Bose-Einstein condensates (BECs) in disordered potentials are an ideal test-bed to investigate the interplay between coherent dynamics one the single-particle level and many-body interactions. A non-interacting BEC released from a harmonic trap into a disorder potential will exhibit Anderson localization due to destructive interference in coherent scattering at the disorder. The persistence of Anderson localization in the presence of pair interactions has remained an open and hotly debated issue. Within the framework of the Gross-Pitaevskii equation (GPE) we show that the condensate function develops wave chaos [1] which we trace back to a fast excitation dynamics using the multi-configurational time-dependent Hartree for bosons method [2]. For the long-time expansion we compare the results obtained from the GPE to a system whose interactions have been switched off after the initial expansion dynamics [3]. We find that the time scale on which differences between the interacting and the non-interacting system begin to emerge exceeds the observation time in current state-of-the art experiments [4] suggesting that these are not yet strongly sensitive to the influence of two-body interactions. Our results, furthermore, suggest that interactions between the particles in the presence of disorder scattering lead to destruction of Anderson localization and incoherent dynamics observable at the microscopic scale while coarse-grained macroscopic observables still might be well reproduced by the GPE [5].

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Particles and pseudo-particles in bosonic field theories

Bruckmann, Falk
(University of Regensburg, Germany)

Semiclassical origins of density functional approximations

Burke, Kieron
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Density functional theory has become a standard approach to electronic structure in chemistry, condensed matter physics, and materials science. Over the past decade, my group has shown that the remarkable success of its very crude approximations is due to their capturing the dominant terms in a very specific semiclassical expansion. I will review this subject and report some of our latest results.

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A spatio-temporal zeta function for transitional turbulence?

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Advances in experimental imaging, computational methods, and dynamical systems theory reveal that the unstable recurrent flows observed in moderate Reynolds number turbulent flows result from close passes to unstable invariant solutions of Navier-Stokes equations. In past decade hundreds of such solutions been computed for a variety of flow geometries, always confined to small computational domains (minimal cells). While the setting is classical, such classical field-theory advances offer new semi-classical approaches to quantum field theory and many-body problems.

Recent work of Gutkin and Osipov on many-particle quantum chaos (in particular, the coupled cats lattice models) suggests a path to determining such solutions on spatially infinite domains. Flows of interest (pipe, channel flows) often come equipped with D continuous spatial symmetries. If the theory is recast as a (D+1)-dimensional space-time theory, the space-time translationally recurrent invariant solutions are (D+1)-tori (and not the 1-dimensional periodic orbits of the traditional periodic orbit theory). Coupled cat map lattice models suggest that symbolic dynamics should likewise be (D+1)-dimensional (rather than a single temporal string of symbols), and that the corresponding zeta functions should be sums over tori, rather than 1-dimensional periodic orbits.

Many-body quantum interference on hypercubes

Dittel, Christoph
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Beyond the regime of distinguishable particles, many-body quantum interferences influence quantum transport in an intricate manner. However, symmetries of the single-particle transformation matrix alleviate this complexity and even allow the analytic formulation of suppression laws, which predict final states to occur with a vanishing probability due to total destructive interference. Here we investigate the symmetries of hypercube graphs and their generalizations with arbitrary identical subgraphs on all vertices. We find that initial many-particle states, which are invariant under self-inverse symmetries of the hypercube, lead to a large number of suppressed final states. The condition for suppression is determined solely by the initial symmetry, while the fraction of suppressed states is given by the number of independent symmetries of the initial state. Our findings reveal new insights into particle statistics for ensembles of indistinguishable bosons and fermions and may represent a first step towards many-particle quantum protocols in higher-dimensional structures.

Many-body Interference in Interacting Nano-junctions

Donarini, Andrea
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Interference, being intimately related to particle wave duality, plays a central role in quantum mechanics. The fingerprints of quantum interference in the transport characteristics of interacting nanojunctions is in the focus of our research [1-4]. I will present results concerning a triangular quantum dot molecule in the single electron tunneling regime which, due its spatial symmetry, has a degenerate many-body spectrum. Interference phenomena are ubiquitous in the stability diagram of this system. They are responsible of the negative differential conductance, the current blocking and super-Poissonian Fano factor which occur at specific values of the bias and gate voltage. Moreover, the interplay of interference and exchange interaction, in the presence of ferromagnetic leads, also allows for an all-electric control of the spin on the system.

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Quantum software for linear photonic simulations

Drummond, Peter
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The search for new quantum computers designed to outperform classical computers is driven by the end of Moore's law and the quantum advantages obtainable. A new generation of application specific quantum computers has shown great promise in providing this quantum leap. One is already commercially available, and now undergoing trials at Google and NASA. This talk will discuss three novel designs being investigated at SUT, with experiments planned at Swinburne and elsewhere.

The largest quantum computer in the world is the Stanford/Tokyo Ising machine. But can it really outperform classical computers at NP-hard optimization? We discuss the physics of this novel device, and how it is theoretically modelled. An alternative hardware model is the XY machine, which uses a different type of photonic interaction, and with experiments at the Weizmann Institute in Israel. Preliminary theory at SUT of a novel parametric XY machine will be given.

It is important to have quantum computers that provide both computational advantages and verifiable results. Boson sampling photonic networks are promising examples, with experiments in Oxford, Vienna, Rome and Queensland. These are closely related to #P hard problems, which are more challenging still. We have developed both a quantum simulation of a boson sampling quantum computer, and analytic results. This gives signatures that verify the computational output.

Finally, the emulation of the quantum decay of a relativistic scalar field from a metastable state ("false vacuum decay") is a fundamental idea in quantum field theory and cosmology. We propose that this can be simulated using an ultra-cold spinor Bose gas. This will demonstrate that an exponentially complex, high energy theoretical model can be solved on a table-top quantum computer. Movies of our simulations of the planned SUT laboratory demonstration will be given.

Genuine quantum many-body interference in fock space: coherent backscattering and many-body spin echo

Engl, Thomas
(Massey University, New Zealand Institute for Advanced Study, Auckland, New Zealand)

Semiclassical approaches by means of Gutzwiller's propagator or trace formula establish a connection between a quantum system and its classical counterpart by describing quantum coherent effects as interference between classical paths. In single particle systems these semiclassical techniques are well established and have been used to describe and predict universal interference effects like coherent backscattering and weak localization.
Transfering these methods into the realm of interacting many-body systems enables us to predict genuine many-body interference effects that lie beyond mean field theories. One is the analog of coherent backscattering in Fock space which is a coherent enhancement of the return probability for many-body states. It implies that quantum interference gives rise to a systematic deviation from full thermalization that is generally assumed to take in for mesoscopic interacting many-body systems. Another example is many-body spin echo characterized by an increase of the return probability echoing an intermediate sudden spin-flip. It is independent of the interaction strength within a large regime of parameters showing that the well known Hahn (spin) echo cannot be fully destroyed by interactions.

Mechanisms of enhancement of many-body delocalization

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I will discuss recent ideas on mechanisms of many-body delocalization, including spectral diffusion [1] and "cold-hot" interactions in a continuum [2].

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Bose-Einstein condensates in time-dependent optical lattice

Guéry-Odelin, David
(University Paul Sabatier, Toulouse, France)

We present a few experiments performed with rubidium-87 Bose-Einstein condensates in optical lattices. Our setup provides the possibility to change rapidly both the phase and the amplitude of the optical lattice. We have used these possibilities (i) to study the traversal time of a wavepacket through the tunnel barriers of the optical lattice, (ii) to realize micron-size Mach-Zehnder interferometers and (iii) to investigate the dynamics of condensate in phase modulated lattices in various regimes.

We will report on the measurement of the time required for a wave packet to tunnel through the potential barriers of an optical lattice. The experiment is carried out by loading adiabatically a Bose-Einstein condensate into a 1D optical lattice. A sudden displacement of the lattice by a few tens of nm excites the micromotion of the dipole mode. We then directly observe in momentum space the splitting of the wave packet at the turning points of the oscillatory motion. In contrast with the methods explored in other fields to deduce the tunnel traversal time, we choose parameters so that roughly half the wave packet tunnels through the barrier. Using both the quasi-isochronism of oscillations in the lattice and the packet that has not tunneled as a reference, we infer precisely the duration of the tunneling process and measure the delay between the reflected and the tunneled packets for various initial displacements. The tunnel barriers act therefore as beam splitters. Using such atomic beam splitter twice, we realize a chain of coherent micron-size Mach-Zehnder interferometers at the exit of which we get essentially a wave packet with a negative momentum, a result opposite to the prediction of classical physics. \\

The dynamics of Bose-Einstein condensates in phase modulated optical lattices is very rich. One can distinguish different regimes depending on the relative time scales of the frequency of modulation and that of the tunneling rate. For large modulation frequency, the periodic potentiel has its strength simply renormalized. We demonstrate how this feature can be used to tune the lattice properties in a very controlled manner. In the opposite limit, the physics is dominated by the tunneling rate renormalization and the emergence of a phase order in space for which the neighbouring wells have opposite phases, referred to as staggered states. The new phase appears from a dynamical instability. We will report on our experimental results in these two different regimes.

Landau quantized graphene in a photon cavity - signatures of superradiance

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In his pioneer work [1] Dicke studied a closed non-dissipative system of N identical two-level atoms interacting with one single radiation mode via dipole interaction. Due to the collective character of the light-matter interaction in this system Dicke [1] found that the atomic ensemble "super-radiates" spontaneously with an intensity proportional to N^2 rather than N as one would expect for incoherent spontaneous decay.

In the thermodynamic limit this model system can exhibit a second-order classical as well as quantum phase transition from a normal state into a superradiant state with broken parity symmetry, macroscopic photonic occupation and the potential to superradiate [2, 3] as a consequence of the collective character of this state.

The Dicke model neglects quadratic terms of the cavity vector potential which naturally emerge from minimal coupling in systems with parabolic dispersion and which suppress the existence of a superradiant phase (no-go theorems) [4, 5] in most cases.

Due to the linear energy dispersion close to the Dirac points graphene seems to be an ideal candidate for theoretical but also experimental investigations on collective light-matter interaction effects. The controversially discussed [6, 7, 8] question about the existence of a Dicke-type superradiant phase and connected phenomena due to photon-induced cyclotron transitions opens a challenging subfield of research in graphene.

In this context we consider Landau-quantized monolayer graphene exposed to an electromagnetic cavity mode. Due to the large degeneracy and Dirac-type characteristics of the Landau-level spectrum graphene is meant to show collective excitation effects under the influence of the additional radiation field in a resonant strong light-matter-coupling regime [6].

We find a distinct indication of the existence of a superradiant phase in graphene within a path integral approach where the full many-body Hamiltonian of Landau-quantized graphene is considered. Furthermore our results are confirmed by a realistic tight-binding simulation.

Additionally we follow the technique presented in Ref. [8], where the authors derive a generalized Dicke Hamiltonian from the full Landau-quantized many-body Hamiltonian claiming dynamically generated quadratic terms which then again lead to a no-go theorem. Contradictory, our investigations on this method do confirm our preceding results and also indicate the existence of a superradiant phase in graphene.

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Generalized Lieb-Liniger model for cold atoms with finite-range interactions

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Ultracold atoms confined in optical lattices can serve as a versatile tool for the purpose of quantum simulations. For short-range interatomic interactions, the dynamics of cold bosons system in a quasi-one-dimensional trap can be well described using Lieb-Liniger model. Here we discuss the corrections arising from the finite range of the interactions. We derive the modified pseudopotential for the system, which turns out to have universal form. The dynamics of the many-body system can then be described using generalized Lieb-Liniger model. In the dilute limit, it can again be reduced to the standard Lieb-Liniger Hamiltonian, but with an effective coupling constant which can strongly differ from the zero-range approximation. We provide predictions for the parameter range where such effect can be experimentally observed.

Spin-chain inspired symmetry and many-particle interference

Keil, Robert
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Symmetries are a key concept to categorize our description of physical systems. They are at the core of many textbook models governing phenomena from the single-particle level (e.g., rotational symmetry for the hydrogen atom) up to the macroscopic regime (e.g., translational invariance for the band model of solids). Surprisingly, comparably little is known in the domain of few indistinguishable particles, a domain which contains a lot of interesting physics due to interference effects arising from the exchange symmetry of the particles [1, 2].

There are a few known cases of how the elastic scattering of identical particles can be affected by symmetries in the scattering material [3-5]. In each case, the symmetry enforces a complete destructive interference for a certain set of output configurations. This set can be analytically identified via so-called suppression laws.
In this talk, I will briefly review the field and then focus on one particular symmetry, which is inspired by spin chains: Initially designed for the purpose of perfect single-excitation transfer [6], arrays of nearest-neighbour coupled sites with a tailored symmetric distribution of the coupling rate also exhibit interesting properies on the many-particle level: Highly regular interference patterns arise for a parity-symmetric excitation of these systems, as it has been demonstrated via proof-of-principle experiments for two photons in optical waveguides [7, 8]. I will show how this behaviour can be understood more systematically and formulate a general suppression law for this type of symmetry. Finally, I will present the latest status of our ongoing experiment, with which we aim to demonstrate this suppression for up to four particles [9].
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Statistical physics of time-periodic systems

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Einstein-Podolsky-Rosen entanglement of narrow-band photons from cold atoms

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The gedankenexperiment proposed by Einstein-Podolsky-Rosen (EPR) in 1935 involves a pair of particles that are entangled in their positions and momenta. The position-momentum-like continuous variable EPR entanglement was initially explored by using quadrature-phase amplitudes of two-mode squeezed states. Genuine EPR position-momentum entanglement of photon pairs, essential for quantum imaging and quantum metrology, was demonstrated later by spontaneous parametric down-conversion (SPDC) photons. Since SPDC photons have very large bandwidth (~ THz), they are not suitable for atom-photon interaction, which typically require ~ MHz bandwidth. While narrowband entangled photons can be generated via cavity-enhanced SPDC, the optical cavity necessary for bandwidth narrowing

completely removes EPR position-momentum entanglement between the photons.
In this work, we report, to the best of our knowledge, the first experimental demonstration of EPR position-momentum entanglement of narrowband photon pairs by using spontaneous four-wave mixing in a cold atom ensemble [1]. We explicitly demonstrate position-momentum entanglement, with the help of quantum ghost imaging and interference effects, between the narrowband photons by showing that the photon pairs violate the separability criterion. We further demonstrate continuous-variable EPR steering by using the EPR position-momentum entangled narrowband photons. We also show in experiment that it is possible to vary the degree of position-momentum entanglement between the two photons by introducing a distinguishability element at the source. Our new source of EPR-entangled narrow-band photons is expected to play an essential role in spatially multiplexed quantum information processing, such as, storage of quantum correlated images, quantum interface involving hyper-entangled photons, etc.

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Treating many-body quantum systems by means of classical mechanics

Kolovsky, Andrey
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Many-body physics of identical particles is commonly believed to be a sovereign territory of Quantum Mechanics. The aim of this talk is to show that it is actually not the case and one gets useful insights into a quantum many-body system by using the theory of nonlinear dynamical systems. In the talk I shall focus on one paradigmatic model of many-body quantum physics - the Bose-Hubbard model, which, in particular, describes interacting ultracold Bose atoms in an optical lattice. After a preliminary, purely quantum analysis of the system we introduce a classical counterpart of the Bose-Hubbard model and its governing equations of motion. We analyze these equations for the problem of Bloch oscillations of cold atoms where a number of experimental results are available. We compare the results obtained by using pure classical arguments with those obtained quantum-mechanically, and with those observed in the laboratory experiment.

Experimenting with distinguishability in few-photon interference

Kolthammer, Steve
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Optical fields provide a unique opportunity to study quantum interference with non-interacting particles in the lab. When two single photons are fed into an interferometer, the output distribution depends on the degree to which the photons are indistinguishable. When more particles are involved, the concept of distinguishability becomes significantly richer. We have studied the interference of three independent photons with full experimental control over the distinguishability of the particles (PRL in press, arXiv:1609.09804). This relationship does not generally reduce to pairwise distinguishabilities and has clear consequences for scattering outcomes. For example, we are able to manipulate three-particle correlations in the detected photon positions while keeping one- and two-particle correlations unchanged. I will highlight some experimental advances that enabled this work, including a novel chip-integrated array of photon sources (Optica 4, 90 2017). I'll discuss prospects for studying larger ensembles of photons and speculate about implications for non-universal optical quantum computation.

Coherence and dissipation in photosynthetic energy transfer

Kramer, Tobias
(Zuse Institute Berlin, Berlin, Germany)

Photosynthetic systems operate at the classical-quantum borderline, where both, coherence and dissipation, influence the energy transfer [1]. I discuss the interpretation and prediction of time-resolved spectroscopy data of photosynthetic complexes based on the efficient and accurate "Hierarchical equation of motion (HEOM)" method. Differences to classical rate equations and more approximate treatments are discussed.

The HEOM method is particularly suitable for simulating open quantum dynamics on massively parallel processors [2] and has been generalized to different forms of system-environment couplings. A ready-to-run GPU implementation is available at https://nanohub.org/tools/gpuheompop

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Hanbury Brown and Twiss noise correlations in a topological superconductor beam splitter

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We study Hanbury-Brown and Twiss current cross-correlations in a three-terminal junction where a central topological superconductor (TS) nanowire, bearing a Majorana bound state at its end, is connected to two normal leads. Relying on a non-perturbative Green function formalism, our calculations allow us to provide analytical expressions for the currents and their correlations at subgap voltages, while also giving exact numerical results valid for arbitrary external bias. We show that when the normal leads are biased at voltages V1 and V2 smaller than the gap, the sign of the current cross-correlations is given by -sgn(V1 V2). In particular, this leads to positive cross-correlations for opposite voltages, a behavior in stark contrast with the one of a standard superconductor, which provides a direct evidence of the presence of the Majorana zero-mode at the edge of the TS. We further extend our results, varying the length of the nanowire (leading to an overlap of the Majorana bound states) as well as its chemical potential (driving it away from half-filling), introducing a new form of the TS nanowire Green function, generalized to those cases. In the case of opposite bias voltages, sgn(V1 V2) = -1, driving the TS wire through the topological transition leads to a sign change of the current cross-correlations, providing yet another signature of the physics of the Majorana bound state.

Bloch oscillations in the absence of a lattice

Meinert, Florian
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In our experiments, we have studied the dynamics of correlated quantum many-body systems with particular focus on ultracold bosons confined to one-dimensional geometry [1-3]. Very recently, we have investigated the quantum motion of an impurity atom that is immersed in the strongly interacting Bose liquid and is subject to an external force. We find that the momentum distribution of the impurity exhibits characteristic Bragg reflections at the edge of an emergent Brillouin zone. While Bragg reflections are typically associated with lattice structures, in our strongly correlated quantum liquid they result from the interplay of short-range crystalline order and kinematic constraints on the many-body scattering processes in the one- dimensional system. As a consequence, the impurity exhibits periodic dynamics that we interpret as Bloch oscillations, which arise even though the quantum liquid is translationally invariant. Our observations are supported by large-scale numerical simulations.

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Symmetrical quasi-classical model for classical molecular dynamics simulations of electronically non-adiabatic processes

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A recently described symmetrical windowing methodology [J. Phys. Chem. A 117, 7190 (2013)] for quasi-classical (SQC) trajectory simulations has been applied to the Meyer-Miller (MM) [J. Chem. Phys. 70, 3214 (1979)] model for the electronic degrees of freedom in electronically non-adiabatic dynamics. The approach treats nuclear and electronic degrees of freedom (DOF) equivalently (i.e., by classical mechanics, thereby retaining the simplicity of standard molecular dynamics), and provides "quantization" of the electronic states through the symmetrical quasi-classical (SQC) windowing model. The approach is seen to be capable of treating extreme regimes of strong and weak coupling between the electronic states, as well as accurately describing coherence effects in the electronic DOF (including the de-coherence of such effects caused by coupling to the nuclear DOF). A survey of recent applications to a variety of problems is presented to illustrate the performance of the approach. Also described is a newly developed variation on the original SQC model (found universally superior to the original) and a general extension of it to obtain the full electronic density matrix (at no additional cost/complexity). It has also been pointed out that even though the MM classical vibronic Hamiltonian generates ‘Ehrenfest dynamics’, when this is processed via the SQC windowing methodology detailed balance is described correctly.

Quantum fluctuation relations for generalized Gibbs ensembles

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The non-equilibrium dynamics of a strongly-correlated quantum system is one of the most fascinating problems in physics, with open questions regarding when and how thermalization occurs and what the equilibrium state is like. Unusual phenomena are observed when the system exhibits conserved quantities that constrain its evolution in phase space, invalidating the predictions of standard quantum thermodynamics. We have derived generalized versions of the quantum Jarzynski equality and the Tasaki-Crooks relation for these systems, and provide numerical simulations showing that these novel QFRs can be tested with available technology in trapped ion setups. Our results pave the way for a deeper understanding of the role of conserved quantities in non-equilibrium processes, and will help guide ongoing developments of nanoscopic quantum machines that aim at extracting work from quantum as well as thermal fluctuations.

Quantum-classical correspondence: experimental aspects

Oberthaler, Markus
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I will summarized the experimental results obtained over the last years on finite size coupled and

interacting Bose fields. I will touch on the generation and characterization of entanglement, the exploration of the quantum dynamics close to a classical unstable fixed point and beyond. Finally I will also present the results on a driven many-particle system, where the dynamics of the quantum noise reveals the emergence of stable and unstable fixed points predicted by the Poincare-Birkhoff theorem.

Efficient quantum transport in disordered interacting many-body networks

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The coherent transport of n fermions in disordered networks of l single-particle states connected by k-body interactions is studied. These networks are modeled by embedded Gaussian random matrix ensemble (EGE). The conductance bandwidth and the ensemble-averaged total current attain their maximal values if the system is highly filled $n \sim l-1$ and $k \sim n/2$. For the cases k=1 and k=n the bandwidth is minimal. We show that for all parameters the transport is enhanced significantly whenever centrosymmetric embedded Gaussian ensemble (csEGE) are considered. In this case the transmission shows numerous resonances of perfect transport. Analyzing the transmission by spectral decomposition, we find that centrosymmetry induces strong correlations and enhances the extrema of the distributions. This suppresses destructive interference effects in the system and thus causes backscattering-free transmission resonances that enhance the overall transport. The distribution of the total current for the csEGE has a very large dominating peak for $n=l-1$, close to the highest observed currents.

Coherent multidimensional action spectroscopy: in operando touch of quantum dynamics

Pullerits, Tõnu
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Recently we have developed a new direction in coherent spectroscopy where the multidimensional spectra are obtained by using incoherent “action” signals like fluorescence or photocurrent. Particularly the photocurrent detected spectroscopy relates the coherent signals directly to the relevant “action” of the device – the current. In this way the coherent measurement directly “touches” the transport processes in the material and the dynamics, coherent and/or dissipative, can be related to the functioning of the devices.

Many-body semiclassics for interacting bosons: Weyl law, trace formula and quantum phase transitions in the Lieb-Liniger model

Richter, Klaus
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A major objective of the semiclassical approach to interacting many-body systems is to combine the information of its two possible classical limits, namely a classical system of particles and a classical field theory, into an unified framework a la Gutzwiller, providing a picture of many-body interference based on coherent sums over classical solutions. Following this direction we will discuss recent progress in the semiclassical analysis of many-body quantum interference for a benchmark example of integrable quantum field theory, the Lieb-Liniger model, describing interacting bosons on a ring. We show that in the limit of high excitations its spectrum can be understood by means of suitable generalizations of the Weyl expansion for the smooth part, and a Berry-Tabor-like trace formula for the oscillatory part, revealing a spectral shell structure in terms of many-body periodic orbits. In the second part of the talk, we will show how the classical limit of the Lieb-Liniger model in the complentary limit of large particle number, given by a nonlinear Schroedinger equation, admits as well an analysis as an integrable classical system, now near its ground state. This enables the description of a sequence of quantum phase transitions arising for increasing attractive interaction, along with an understanding of numerical results for the spreading of information around crriticallity.

Emergent eigenstate solution to quantum dynamics far from equilibrium

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The quantum dynamics of interacting many-body systems has become a unique venue for the realization of novel states of matter. In this talk, we will discuss how it can lead to the generation of time-evolving states that are eigenstates of emergent local Hamiltonians, not trivially related to the ones dictating the time evolution. We study geometric quenches in interacting fermionic and bosonic systems in one-dimensional lattices, and provide examples of experimentally relevant time-evolving states [1,2] that are either ground states or highly excited eigenstates of emergent local Hamiltonians [3].

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Coherent backscattering in the Fock space of ultracold bosonic atoms

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Coherent backscattering refers to a robust constructive quantum (or wave) interference phenomenon between backscattered classical (or ray) paths and their time-reversed counterparts, which arises in complex disordered or chaotic systems upon some configurational or energetic average. We present numerical evidence for the occurrence of this interference phenomenon in the Fock space of a small disordered Bose-Hubbard system. In this many-body space, coherent backscattering can most conveniently be observed in time evolution processes that start from a Fock state of the Bose-Hubbard system, where it manifests itself in an enhanced detection probability of this initial state as compared to other Fock states with comparable total energy. We argue that coherent backscattering in Fock space can be experimentally measured with ultracold bosonic atoms in optical lattices, using state-of-the-art single-site detection techniques as well as synthetic gauge fields in order to break time-reversal symmetry within the lattice and thereby destroy coherent backscattering.

Nonequilibrium quantum dynamics of ultracold systems: interplay of interference, interactions and nonlinearity

Schmelcher, Peter
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We explore the quantum dynamics out of equilibrium for ultracold quantum gases ran- ging from the correlated quantum dynamics in optical lattices to beyond mean-field beha- viour of solitons and collisionally coupled correlated species. Our approach is the multi- layer multi-configuration time-dependent Hartree method for bosons (ML-MCTDHB) that represents a powerful ab initio method for the investigation of the non-equilibrium quantum dynamics of single and multi-species bosonic systems in traps and optical lattices. Firstly we demonstrate in a ‘bottom-up approach’ the correlated many-particle effects in the collective breathing dynamics for few- to many-boson systems in a harmonic trap. Many-body proces- ses in black and grey matter-wave solitons are explored thereby demonstrating that quantum fluctuations limit the lifetime of the soliton contrast, which increases with increasing soliton velocity. For atomic ensembles in optical lattices we explore the interaction quench indu- ced multimode dynamics leading to the emergence of density-wave tunneling, breathing and cradle-like processes. An avoided-crossing in the respective frequency spectrum provides to a beating dynamics for selective modes. A particular far from equilibrium system is then stu- died at hand of the correlated quantum dynamics of a single atom collisionally coupled to a finite bosonic reservoir. In the last part of the presentation we provide some selective aspects of our recent investigations on atom-ion hybrid systems using the same methodology. First the ground state properties of ultracold trapped bosons with an immersed ionic impurity are discussed. Subsequently the capture dynamics of ultracold atoms in the presence of the impurity ion is explored.

Does classical physics emerge from unitary evolution of a complex enough quantum system?

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The evolution of an isolated quantum system is unitary. This is simple to probe for small systems consisting of few non-interacting particles. But what happens if the system becomes large and its constituents interact? In general, one will not be able to follow the evolution of the complex many body eigenstates. In this talk I present experimental evidence that classical physics properties emerge from the unitary evolution in an isolated many body quantum system.
Ultra-cold quantum gases are an ideal system to probe many body quantum physics and the related quantum fields. Interfering two quantum-gases allows to study the coherence between the two quantum fields and the full distribution functions and correlation functions give insight into the many body states and their evolution.
In our experiments we study how the coherence created between the two isolated one-dimensional quantum gases by coherent splitting slowly degrades by coupling to the many internal degrees of freedom available [1]. We find that a one-dimensional quantum system relaxes to a pre-thermalized quasi steady state [2] which emerges through a light cone like spreading of 'de-coherence' [3]. The pre-thermalized state is described by a generalized Gibbs ensemble [4] represented in a classical density matrix. By engineering the modes of the 1d system we demonstrate many body quantum revivals. Furthermore we point to two distinct ways for further relaxation towards a final state that appears indistinguishable from a thermally relaxed state. The system looks like two classically separated objects. This demonstrates in an experiment how aspects of classical physics emerge from unitary evolution of a complex enough quantum system.
We conjecture that our experiments points to a universal way through which relaxation in isolated many body quantum systems proceeds if the low energy dynamics is dominated by scrambling of the eigenmodes of long lived excitations (quasi particles) [5].
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Implementation and certification of Boson Sampling with integrated photonics

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Integrated photonic circuits have a strong potential to perform quantum information processing [1, 2]. 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 [3]. Boson sampling is a computational task hard for classical computers, but efficiently solvable via bosonic interference in a specialized quantum computer. We report several experiments of boson sampling

implemented with integrated quantum photonics.
The evolution of bosons undergoing arbitrary linear unitary transformations quickly becomes hard to predict using classical computers as we increase the number of particles and modes. Photons propagating in a multiport interferometer naturally solve this so-called boson sampling problem, thereby motivating the development of technologies that enable precise control of multiphoton interference in large interferometers. We adopted, novel three-dimensional manufacturing techniques to achieve simultaneous control of all the parameters describing an arbitrary interferometer [4]. We implement a small instance of the boson sampling problem by studying three-photon interference in a 13-mode integrated interferometer, confirming the quantum-mechanical predictions. Scaled-up versions of this set-up are a promising way to demonstrate the computational advantage of quantum systems over classical computers [4,5]. Furthermore we report a new variation of this task, scattershot boson sampling, which leads to an exponential increase in speed of the quantum device, using a larger number of photon sources based on parametric down-conversion [6]. This is achieved by having multiple heralded single photons being sent, shot by shot, into different random input ports of the interferometer. Finally we will discuss the development of integrated architecture with three-dimensional geometries [7,8].

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Quantum de Moivre-Laplace theorem for noninteracting indistinguishable particles in random networks

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The De Moivre-Laplace theorem applied to a Galton board says that probability distribution of N balls over output bins takes a Gaussian form as N->oo. A quantum version of the theorem for N noninteracting indistinguishable bosons (fermions) in a unitary M-mode network is discovered: the average probability distribution of particles over bins in a random network converges to a Gaussian law as N->oo, where their quantum statistics enters through the particle density N/M. The quantum De Moivre-Laplace theorem applies to an arbitrary partition of output modes into small number of bins and, moreover, for a given network with averaging over allowed input configurations. For N>>1 the Gaussian law is a good approximation for an exact probability distribution over bins in a network without symmetries. In the thermodynamic limit N->oo a finite difference in probability in a random network between indistinguishable bosons, fermions, and distinguishable particles is possible only at a non-vanishing particle density and occurs for a singular binning of output events.

Single-particle interference and two-particle collisions

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Electronic analogues of optical interferometers, like the Mach-Zehnder interferometer, can be realized with the help of edge states in the Quantum Hall regime taking the role of wave guides and quantum point contacts figuring as beam splitters. In the last decade, also single-electron sources, which can coherently and in a controlled way inject particles into these electronic setups, have been developed.
In this talk, I will present theoretical predictions for different effects that occur when injecting single particles into an electronic interferometer and when creating "collisions" between several particles within the setup.
When well-separated, single particles (electrons or holes) are emitted from a singleparticle source into an interferometer, such that they can traverse either its upper or its lower path, Aharonov-Bohm oscillations are observed in the charge current at the interferometer output. These oscillations decay when the interferometer imbalance is increased with respect to the single-particle coherence length. The resulting visibility suppression is predicted to be a tool to detect the single-particle coherence length, which turns out to be equal to the width of the single-particle wave-packets [1].
By placing a second single-particle source in one of the interferometer arms and conveniently synchronizing it with respect to the first one [2], controlled particle "collisions" can occur in certain parts of the interferometer. While the particles of the second source would not show interference effects on their own, they can however influence the previously discussed oscillations in the detected charge by exchange interaction. This "coherent interference suppression" can be understood in terms of which-path detection due to collisions between particles. It is thus a signature of twoparticle effects in the current, which is confirmed by equivalent observations in the charge current noise [3]. At the same time, it can be understood as an averaging effect of oscillations in the energy- (or time-)resolved charge current spectrum (similar to what would be a channelled spectrum in optics).
The interpretation in terms of multi-particle effects however breaks down when considering energy currents in addition to charge currents [3]: Which-path information that would seemingly be accessible from the energy current does not lead to an interference suppression. At the same time, a particle picture would lead to an apparent separation of energy and charge of the particles.

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The physics and quantum computational supremacy of multi-photon correlation interference with single-photon states of arbitrary distinguishability

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Multi-photon interference based on correlated measurements is a fundamental phenomenon in atomic, molecular and optical physics with numerous applications in quantum information processing, quantum metrology, and imaging.

This talk will present a compact full description of multi-photon correlation measurements in polarization and/or time of arbitrary order N in passive linear interferometers with input single-photon pure states with arbitrary degree of distinguishability [1]. Our results describe general multi-photon correlation landscapes for an arbitrary number of input single photons and arbitrary interferometers. In particular, two different schemes are used to demonstrate, respectively, arbitrary-order quantum beat interference and 100% visibility entanglement correlations even for input photons distinguishable in their frequencies [1].

Multi-photon interference in arbitrary N-photon interferometers is also described in the case of measurements non resolving any of the inner photonic degrees of freedom for input photon states with arbitrary distinguishability [1,2].

We also give evidence even for non-identical photons of the tremendous computational power of multi-photon quantum interference at the heart of the complexity of multi-photon correlation sampling at the output of random linear interferometers [3]. In particular, we address the task of MultiBoson Correlation Sampling (MBCS) from the probability distribution associated with polarization- and time-resolved detections at the output of random linear optical networks [3,4,5]. We show that the MBCS problem is fundamentally hard to solve classically even for nonidentical input photons, regardless of the color of the photons, making it also very appealing from an experimental point of view. These results fully manifest the quantum computational supremacy inherent to the fundamental nature of quantum interference.

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Non-linear Schrödinger approach to mean field games

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Mean field games theory is a rather recent research area, at the frontier between applied mathematics, social sciences and physics. It was initiated a decade ago by Pierre-Louis Lions and Jean-Michel Lasry as a tool to model certain social phenomena involving a significant number of actors - through a game theory approach - while maintaining a reasonable level of simplicity thanks to the concept of mean-field imported from physics.

In this presentation, after a general introduction to mean field game, I will show that there is a formal, but deep, link between an important class of these models and the nonlinear Schrödinger (or Gross-Pitaevskii) equation familiar to physicists. This link makes it possible to develop a deeper understanding of the behavior of Mean Field Games. A specific example will be treated in details and will demonstrate how various concepts developed by physicists while studying the non-linear Schrödinger equation can be used with profit in the context of Mean Field Game

The quantum design of photosynthesis

Van Grondelle, Rienk
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In photosynthesis absorbed sun light produces collective excitations (excitons) that form a coherent superposition of electronic and vibrational states of the individual pigments. Two-dimensional (2D) electronic spectroscopy allows a visualization of how these coherences are involved in the primary processes of energy and charge transfer. Based on quantitative modeling we identify the exciton-vibrational coherences observed in 2D photon echo of the photosystem II reaction center (PSII-RC). We find that the vibrations resonant with the exciton splittings can modify the delocalization of the exciton states and produce additional states, thus promoting directed energy transfer and allowing a switch between the two charge separation pathways. We conclude that the coincidence of the frequencies of the most intense vibrations with the splittings within the manifold of exciton and charge-transfer states in the PSII-RC is not occurring by chance, but reflects a fundamental principle of how energy conversion in photosynthesis was optimized.

Correlations as tools for characterisation

Walschaers, Mattia
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Correlation functions are ubiquitous in quantum statistical mechanics because they allow for a full description of many-particle quantum states. However, theoretically or experimentally obtaining all the relevant high-order correlations is often unfeasible. Therefore, in this contribution, we discuss characterisation schemes which use only low-order correlations.

First, we focus on many-particle interference effects which arise due to the particles' indistinguishability. This physical phenomenon lies at the heart of boson sampling and its fine details are notoriously intractable. We combine random matrix theory with the correlations of different pairs of output detectors to probe statistical signature of these interference processes.

In the second part, we study the use of quadrature correlations to explore non-Gaussian quantum states of light in the continuous variable regime. In concreto, we treat multimode Gaussian states from which a photon is subtracted, and show that truncated correlation functions are fruitful to differentiate these states from statistical mixtures of Gaussian states.

Periodic Orbits in Quantum Many-Body Systems

Waltner, Daniel
(University of Duisburg-Essen, Physical Faculty, AG Guhr, Duisburg, Germany)

Classical periodic orbits on the one side and the quantum energy spectrum on the other are related by trace formulae in semiclassical theories. In the past, there has been huge interest in obtaining periodic orbit spectra for one-particle quantum systems (e.g. for the hydrogen atom in a strong magnetic field). Therefore, the Fourier transformation of the trace formula was compared with the periodic orbits calculated by the classical equations of motion. In this talk, I demonstrate how to generalize this comparison to a many-particle system considering a kicked spin chain with nearest neighbor Ising coupling and on-site kicked magnetic field. Here, we face the problem that the dimension of the quantum Hilbert space and the number of periodic orbits is too large to apply the conventional methods for the single-particle case. We derive a trace formula for that system. Furthermore, we show how to overcome the problem arising from the large Hilbert space dimension by a duality relation and identify dominant contributions to the quantum spectrum arising from collective classical motion of the spins.

Multiple scattering of interacting bosons in random potentials

Wellens, Thomas
(University of Freiburg, Physikalisches Institut, Quantum Optics and Statistics, Freiburg, Germany)

In this talk, I will give an overview of our works on multiple scattering of interacting bosons in random media. Starting first with the non-interacting case, the effects of coherent backscattering and weak localization are introduced as the main interference corrections to diffusive transport in weak disorder. Then, I will extend the underlying theoretical concepts (ladder and crossed diagrams) to the case of many interacting particles (beyond the mean field approximation), and derive nonlinear transport equations which finally characterize the effect of weak interactions on diffusive transport and coherent backscattering. In particular, it is shown that interactions induce thermalization of the single-particle energies and profoundly change the coherent backscattering interference contrast.

Atomtronics: Computing With Neutral Atoms

Wimberger, Sandro
(Parma University, DiFeST, Physics Department, Parma, Italy)

State-of-the-art experiments with ultra-cold atoms offer a unique setting for quantum simulation of interacting many-body systems. The high degree of controllability, the novel detection possibilities and the extreme physical parameter regimes that can be reached in these "artificial solids" provide a complementary set-up as compared with natural condensed-matter systems. We review recent advances in technology and discuss the progress in the implementation of structures and currents consisting of a single atom to a few million atoms, covering the crossover from microscopic to macroscopic matter. New forms of atomic transport, including materials with negative differential resistivity, driven by many-body quantum correlation effects have already been realized in the laboratory. The current control by "external voltages" is the basic ingredient of atomtronic transistors still to be implemented. This opens many frontiers for the design of new quantum matter and the use of atomtronics in scalable integrated quantum networks as future technological platforms.