Advances in open systems and fundamental tests of quantum mechanics

684. WE-Heraeus-Seminar

December 2 - 5, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 684. WE-Heraeus-Seminar:

Quantum mechanics has shown unprecedented success as a physical theory, providing astonishing accurate predictions, but at the same time it has forced upon us a new perspective on the description of physical reality.

While Schrödinger's equation applies to the dynamics of an isolated closed system, the treatment of an open system setting appeared as an essential ingredient in the very formulation and understanding of the theory since its very beginning. Indeed, the very formulation of a measurement process, allowing to extract information on the state of the system of interest, depends on the analysis of its interaction with an external system, typically with very different features, such as being macroscopic or in a specially prepared initial state. The search for a more realistic treatment of the measurement process as the result of the interaction between two systems, ultimately to be both described by quantum mechanics, has led to important improvements in the formulation of quantum theory. A basic motivation for the consideration of open quantum systems rests on the conceptually unfeasible, and experimentally often too inaccurate, idealization of a perfect shielding of the system of interest from the external environment. The development of the formalism of open quantum systems has also led to a deeper understanding of the very structure and features of quantum mechanics. In particular it sets the framework in which any experiment testing the foundations of quantum mechanics or willing to discriminate between quantum mechanics and alternative theories has to be considered.

This seminar aims at reporting about recent results in the foundations of open quantum systems and its connection with the most advanced experiments testing the basic features of quantum mechanics, from the microscopic to the macroscopic regime.

Scientific Organizers:

Prof. Bassano Vacchini	Università degli Studi di Milano, Italy E-mail: Bassano.Vacchini@mi.infn.it
Prof. Heinz-Peter Breuer	Universität Freiburg, Germany E-mail: breuer@physik.uni-freiburg.de
Prof. Angelo Bassi	University of Trieste, Italy E-mail: bassi@ts.infn.it

Program

Program

Sunday, December 2, 2018

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER and get-together*	
20:00 – 21:00	Domenico Giulini	**Gravity and quantum mechanics**

Monday, December 3, 2018

08:00	*BREAKFAST*	
09:30 – 09:45	Scientific organizers	**Opening**
09:45 – 10:30	Florian Marquardt	**Topological effects in cavity optomechanics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Nicolas Gisin	**From quantum foundations to applications and back**
11:45 – 12:30	Fabio Sciarrino	**Experimental tests on quantum causality**
12:30 – 12:40	**Conference Photo** (in the front of the lecture hall)	
12:40	*LUNCH*	

Program

Monday, December 3, 2018

14:30 – 15:15	Markus Arndt	**Advances in matter-wave experiments with biomolecular nanomatter**
15:15 – 16:00	Klaus Hornberger	**Testing rotational quantum mechanics with levitated nanoparticles**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:00	Andrea Smirne	**Quantum coherence and non-classicality in quantum Markovian processes**
17:00-17:30	Francesco Ciccarello	**Quantum thermodynamics and collision models: ab initio analysis in a matter-light system**
17:30 – 19:30	**Poster Session**	
19:30	*DINNER*	

Program

Tuesday, December 4, 2018

08:00	*BREAKFAST*	
09:00 – 09 :45	Susana Huelga	**Are there non-trivial quantum effects in Biology? A discussion on light harvesting processes from an open quantum system perspective**
09:45 – 10:30	Mauro Paternostro	**Operational Markov condition for quantum processes**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Francesco Buscemi	**The role of statistical comparison theory in the study of open quantum systems**
11:45 – 12:30	Dariusz Chruscinski	**Divisibility and information flow for non-invertible dynamical maps**
12:30	*LUNCH*	
14:30 – 15:15	Jyrki Piilo	**Full control of dephasing dynamics — complex quantum networks**
15:15 – 16:00	Roberta Zambrini	**Non-classical, synchronization and thermodynamic effects in extended open quantum systems**
16:00 – 16:30	*COFFEE BREAK*	

Tuesday, December 4, 2018

16:30 – 17:15	Irene Burghardt	**Non-Markovian dynamics in molecular aggregates: coherence and decoherence in structured environments**
17:15 – 17:45	Manuel Gessner	**Detecting system-environment correlations without accessing the environment**
17:45 – 18:15	Luca Ferialdi	**Qubit entanglement generation by Gaussian non-Markovian dynamics**

19:00 *HERAEUS DINNER*
(social event with cold & warm buffet with complimentary drinks)

Program

Wednesday, December 5, 2018

08:00	*BREAKFAST*	
09:00 – 09 45	Markus Aspelmeyer	**Experiments with optomechanical systems**
09 :45 – 10:30	Hendrik Ulbricht	**Levitated optomechanics experiments towards testing fundamental physics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Tobias Schätz	**Time-resolved observation of thermalization in an isolated quantum system and accessing measures of its non-Markovianity**
11:45– 12:15	Sandro Donadi	**Testing collapse models: a theory perspective**
12:15 – 12:45	Matteo Carlesso	**Non-interferometric diagnostics of collapse models**
12:45 – 13:15	Scientific organizers	**Poster prize award** **Closing**
13:15	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Thursday morning

Posters

Posters

Georg Enzian	**Observation of Brillouin optomechanical strong coupling with an 11 GHz mechanical mode**
Sergey Filippov	**Collisional model with correlated environment in the matrix product form**
Ivan Galinskiy	**Towards heralded single-phonon state generation of an ultracoherent nanomechanical resonator**
Rodrigo Gómez	**Study of the role of system-environment correlations in quantum open system dynamics**
André Großardt	**Semiclassical gravity – faster than light?**
Karen Hovhannisyan	**Defining and generating current in open quantum systems**
Muhammad Javed	**The dynamics of quantum correlations in mixed classical environments**
Andreas Ketterer	**Characterizing multipartite entanglement with moments of random correlations**
Deepak Khurana	**Experimental emulation and control of quantum non-Markovian dynamics**
Theodora Kolioni	**The transmission of quantum information of an open quantum system interacting with a quantum scalar field**
Seid Koudia	**Process estimation in qubit systems in the presence of noise**
Thao P. Le	**System-environment correlations in (strong) quantum Darwinism**
Valentin Link	**Stochastic Feshbach projection for open quantum systems**

Posters

Kimmo Luoma	**Parametrization and optimization of Gaussian non-Markovian unravelings for open quantum dynamics**
Gonzalo Manzano	**Squeezed thermal reservoir as a generalized equilibrium reservoir**
Marta M. Marchese	**Dissipative collapse model in optomechanical systems**
Stephanie Matern	**Memory effects in a simple metal**
Hannah McAleese	**How fat is your quantum cat?**
Conor McConnell	**Electron counting statistics for non-additive environments**
M. Tahir Naseem	**Thermodynamic consistency of the optomechanical master equation**
Marco Pezzutto	**An out-of-equilibrium non-Markovian quantum heat engine**
Carlos Pineda	**Divisibility of qubit channels**
Graeme Pleasance	**Exact non-Markovian dynamics of an open quantum system using a chain representation of the environment**
Andrey Rakhubovsky	**Pulsed optomechanical CV transducer based on geometric phase effect**
Ricardo Román-Ancheyta	**Collectively-enhanced thermalization via multi-qubit collisions**
Björn Schrinski	**Macroscopicity of arbitrary quantum superposition experiments**

Posters

Benjamin Stickler	**Orientational decoherence, diffusion, and thermalization of quantum rigid rotors**
Dario Tamascelli	**Efficient simulation of finite-temperature open quantum systems**
Santiago Tarragó Vélez	**Towards an optomechanical bell test with room temperature phonons**
Gabriel Teixeira Landi	**Information transport in quantum non-equilibrium steady-states**
Christian Ventura-Velázquez	**Robust optomechanical cooling with a phase sequence**
Frederik vom Ende	**Markovian reachability taken to the limit in controlled dissipative quantum systems**
Xiansong Xu	**Many-body open quantum systems beyond Lindblad master equations**
Dmitry Zhdanov	**Friction as a consistent quantum-mechanical concept**
Yujun Zheng	**Non-Markovian decoherence dynamics in nonequilibrium environments**

Abstracts of Talks

(in chronological order)

Gravity and Quantum Mechanics

D. Giulini[1,2]

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[2] ZARM, Bremen, Germany

According to General Relativity, the interaction of gravitational fields with matter is ruled by Einstein's Equivalence Principle (EEP). According to this principle, matter couples to gravity in a *universal* fashion through the geometry of space-time, the universality being expressed by the requirement that all matter components "see" the *same* geometry. This prescription, which requires the matter's dynamical law to be specified in a form compatible with the requirements of Special Relativity, does not obviously apply to Galilean invariant Quantum Mechanics (QM). This poses the theoretical problem of how to derive the matter-gravity couplings for systems described by QM, the clarification of which becomes important in, e.g., proposed "quantum tests of the equivalence principle". In my talk I shall review the current status of EEP and then turn to some aspects of the "coupling-problem" just outlined.

Topological effects in cavity optomechanics

Florian Marquardt[1,2]

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[2] *Institut für Theoretische Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 7, 91058 Erlangen, Germany*

Optomechanics, the interaction between light and vibrations, can be used to engineer topological transport of both photons and phonons. In this talk, I will describe our theoretical ideas in this field. There are two options: (i) One explicitly breaks time-reversal invariance with the help of the optomechanical interaction and a suitably engineered light field, creating a Chern insulator. (ii) Time-reversal invariance is preserved, but a suitably designed phononic crystal gives rise to helical edge channels. Time permitting, I will also explain our recent work on dynamical gauge fields in optomechanical arrays, where the effective magnetic field acting on photons becomes a dynamical degree of freedom.

References

[1] V. Peano, C. Brendel, M. Schmidt, and F. Marquardt, "Topological Phases of Sound and Light," Phys. Rev. X **5**, 031011 (2015)

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From quantum foundations to applications and back

Nicolas Gisin
Group of Applied Physics, University of Geneva, Switzerland

Quantum information science emerged from studies on the foundations of quantum physics. I'll illustrate this, starting from Bell inequalities and the Ekert protocol for Quantum Key Distribution (QKD), to continuing to Device-Independent Quantum Information Processing (DIQIP). But the story doesn't stop here. Quantum information science, in turn, feeds back into the foundations, asking questions like, e.g., "how does non-locality manifest in quantum networks" and "how to mitigate the detection loophole for DIQIP". More broadly, new ways of addressing old questions emerge, for example new ways to tackle the quantum measurement problem (i.e. How could an apparatus made out of ordinary matter not obey the superposition principle just because of a sticker saying "measurement apparatus") and to ask what is "macroscopic quantumness", both conceptually and experimentally [1].
This is a beautiful and timely illustration of physics with applied physics and foundations nourishing each other, as it should always be.

References

[1] N. Gisin and F. Fröwis, Philosophical Transactions of the Royal Society A **376**, 2017.0326 (2018)

Experimental tests on quantum causality

Fabio Sciarrino

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The fields of quantum non-locality, in physics, and causal discovery, in machine learning, both face the problem of deciding whether observed data are compatible with a presumed causal relationship between the variables. Bell's theorem shows that quantum mechanical correlations can violate the causal constraints imposed on any classical explanation of experiments performed by space-like separated parties, the phenomenon of non-locality. Recently, it has been realized that many of the concepts and tools from the field of causal inference, such as Bayesian networks, are useful not only to reinterpret known results but most importantly to provide generalizations of Bell's theorem. We will report several experiments aimed at developing a deep understanding of the departure between classical and quantum causality by starting from elementary but fundamental causal structures [1-5].

References

[1] G. Carvacho, F. Andreoli, L. Santodonato, M. Bentivegna, R. Chaves, F. Sciarrino. "Experimental violation of local causality in a quantum network", *Nature Communications* **8**, 14775 (2017).

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[3] F. Andreoli, G. Carvacho, L. Santodonato, M. Bentivegna, R. Chaves, F. Sciarrino, "Experimental bilocality violation without shared reference frames", *Phys. Rev. A* **95**, 062315 (2017).

[4] R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, F. Sciarrino, "Quantum violation of an instrumental test", *Nature Physics* (2017). doi:10.1038/s41567-017-0008-5.

[5] E. Polino, I. Agresti, D. Poderini, G. Carvacho, G. Milani, G. Barreto Lemos, R.Chaves, F Sciarrino, "Device independent certification of a quantum delayed choice experiment", arXiv:1806.00211.

Advances in matter-wave experiments with biomolecular nanomatter

Markus Arndt

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Matter-wave interferometry with biological nanomatter [1, 2] explores the frontier between quantum physics, biochemistry, nanotechnology, asking how quantum-delocalization influences biological function and if biology can provide natural nanotechnology for quantum experiments [3]. We ask what needs to be done to prepare and detect intact neutral polypeptide and protein beams and why this is relevant? Which tools are so and universal and serve as coherent matter-wave beam splitters for a multitude of molecules?

Answers to these questions open the path for quantum interference as a metrological tool, where the emerging density fringe pattern serves as a nanoruler that can be read with high precision and a force sensitivity < 10^{-26} N. Optical phase and photo-depletion beam splitters allow us addressing a plethora of organic particles in a universal way. This enables measurements of electronic [4], optical [5-7] and magnetic [8] molecular properties. We will discuss the diffraction of antibiotics, quantum assisted metrology on vitamins and interference of polypeptides.

Our experiments in the Vienna Quantum Nanophysics Group are performed in close collaboration with the Synthetic Chemistry Group around Marcel Mayor and Valentin Köhler (University of Basel) as well as the Quantum Theory Group around Klaus Hornberger and Benjamin Stickler (University of Duisburg Essen).

References

1. M. Arndt, *De Broglie's meter stick: Making measurements with matter waves,* **Phys. Today 67, 30 (2014).**
2. J. Schätti et al., *Bio-inspired neutral nanoparticle beams,* **(2018).**
3. J. Schätti et al., *Tailoring the volatility and stability of oligopeptides,* **J. Mass Spectrom. 52, 550 (2017).**
4. L. Mairhofer et al., *Quantum-Assisted Metrology of Neutral Vitamins in the Gas Phase,* **Angew. Chem. Int. Ed. 56, 10947 (2017).**
5. S. Eibenberger, X. Cheng, J.P. Cotter, and M. Arndt, *Absolute absorption cross sections from photon recoil in a matter-wave interferometer,* **Phys. Rev. Lett. 112, 250402 (2014).**
6. J. Rodewald et al., *New avenues for matter-wave-enhanced spectroscopy,* **Appl. Phys. B 123, (2016).**
7. C. Brand et al., *Conformer-selection by matter-wave interference,* **Phys. Rev. Lett. accepted, (2018).**
8. L. Mairhofer, S. Eibenberger, A. Shayeghi, and M. Arndt, *A Quantum Ruler for Magnetic Deflectometry,* **Entropy 20, 516 (2018).**

Testing rotational quantum mechanics with levitated nanoparticles

B. A. Stickler[1], B. Papendell[1], S. Kuhn[2], J. Millen[3], M. Arndt[1] and K. Hornberger[1]

[1]*University of Duisburg-Essen, Germany*
[2]*University of Vienna, Austria*
[3]*King's College London, UK*

This talk will discuss the physics of optically levitated nanoparticles, focussing on objects whose rotation and alignment can be optically addressed. I will review the experimental status regarding rotational control [1,2], and present the prospects of cavity cooling the ro-translational state of motion into the quantum regime [3]. The treatment of environmental effects such as orientational decoherence and rotational friction will be outlined [4,5], as well as the impact of spontaneous collapse models on rotational dynamics [6]. Based on this, I will propose an experiment creating and probing a macroscopic superposition of different orientation states [7]. It is based on the phenomenon of orientational quantum revivals, a complete recurrence of the initial orientation of a particle due to the quantization of angular momentum.

References

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Quantum coherence and non-classicality in quantum Markovian processes

A. Smirne[1], D. Egloff[1], M.G. Díaz[2], M.B. Plenio[1], and S.F. Huelga[1]

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Quantum coherence is a basic trait of quantum mechanics, but the presence of coherences in the quantum description of a certain phenomenon does not rule out by itself an alternative classical description of the same phenomenon [1]. One can think, for example, of the intense debate about the possible role of quantum coherence to enhance the efficiency of certain biological processes [2,3]. In this talk, I will discuss definite criteria to determine when and to what extent quantum coherence is unambiguously related with non-classicality. Starting from the quantum description of a physical system undergoing sequential measurements of one observable, a general property of classical stochastic processes, namely the fulfillment of the Kolmogorov conditions [4], is exploited to discriminate the resulting multi-time statistics from the statistics of any classical process. In this way, one can prove [5] that a Markovian multi-time statistics obtained from repeated measurements of a nondegenerate observable cannot be accounted for by means of a classical process if and only if the dynamics generates coherences (with respect to the measured observable) and subsequently turns them into populations. The interaction of the measured system with the environment is taken into account, so that the system is treated as an open quantum system [4], and the notion of Markovianity refers to the fulfillment of the quantum regression theorem. Furthermore, I will show with simple counterexamples that a direct connection between quantum coherence and non-classicality is generally absent if the process is non-Markovian, so that one can even have a fully non-classical statistics, despite there being no coherence of the measured observable in the quantum state of the system at any moment.

References

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[2] G.S. Engel, et al, Nature **446**, 782 (2007)
[3] A.W. Chin, J. Prior, R. Rosenbach, F. Caycedo-Soler, S.F. Huelga and M.B. Plenio, Nat. Phys. **9**, 113 (2013)
[4] H.-P. Breuer and F. Petruccione, *The Theory of Open Quantum Systems* (Oxford University Press, New York, 2002)
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Quantum thermodynamics and collision models: ab initio analysis in a matter-light system

Francesco Ciccarello [1,2]

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A collision model (CM; aka "repeated interactions model") is a simple theoretical framework assuming a bath made out of a large collections of subunits ('ancillas') with which a system S 'collides' one at a time. These days, CMs are apparently becoming a routine theoretical tool in the hot field of quantum thermodynamics [1,2], a major advantadge being indeed that they allow to keep track of the environmental degrees of freedom thus enabling calculations of quantities such as heat fluxes [3,4]. Although well-defined, to what extent CMs are effective to describe *natural* system-bath dynamics is generally unclear (while it is well-known that they describe engineered dynamics such as micromasers). From a thermodynamical viepoint, for instance, a CM Hamiltonian is intrinsically time-dependent, an indesirable feature for a system-bath microscopic model and that was indeed shown to necessarily entail the presence of an external work [5].

Here, we consider a popular quantum-optics model featuring an emitter S that is RWA-coupled to a white-noise bosonic bath: one of the few known (if not the only) natural system-bath dynamics fully describable by a suitably-constructed CM in a certain picture [6]. We critically analyze from a thermodynamical viewpoint some of the distinctive features of this quantum optical CM and compare them to standard assumptions in the quantum thermodynamics literature. We tackle issues such as: justifying that the bath starts in a product of single-ancilla thermal states, pinpointing the physical origin of the external work stemming from the time-dependent nature of the Hamiltonian, clarifying how such time dependance does not conflict with the fact that the system and bath jointly form an isolated system [7].

References

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Are there non-trivial quantum effects in Biology? A discussion on light harvesting processes from an open quantum system perspective

Susana F. Huelga[1]

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Quantum biology is an emerging field of research that concerns itself with the experimental and theoretical exploration of non-trivial quantum phenomena in biological systems (See references below for recent reviews on the subject).

We will present an overview aimed to bring out fundamental assumptions and questions in the field, using light harvesting as a prototypical biological process. We will identify basic design principles and develop a key underlying theme -- the dynamics of quantum dynamical networks in the presence of an environment and the fruitful interplay that the two may enter. A fundamental element in the discussion is the formulation of a microscopic model able to explain the observed persisting oscillatory features in the spectral response of different pigment-protein complexes (PPC) at ambient temperatures. Along delocalized electronic excitations, we argue that quantum coherent interactions with near-resonant vibrations are instrumental for explaining long lived coherence and may contribute to light-harvesting performance. Experimental results on both natural and artificial systems will be shown to be in qualitative agreement with this vibronic model which could therefore provide an archetypical framework for the field. However, the accurate simulation of the dynamics and the spectral response of actual PPCs is formidable. We discuss the prospects of going beyond the state of the art and the possible roadmap in order to provide further insight on the persistence (or the absence) of coherence effects in biological environments.

S. F. Huelga and M.B. Plenio, Contemp. Phys. **54**, 181 (2013)
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Operational Markov condition for quantum processes

M. Paternostro[1]

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I will discuss a necessary and sufficient condition for a quantum process to be Markovian which coincides with the classical one in the relevant limit. Such condition unifies all previously known definitions for quantum Markov processes by accounting for all potentially detectable memory effects. I will then derive a family of measures of non-Markovianity with clear operational interpretations, such as the size of the memory required to simulate a process, or the experimental falsifiability of a Markovian hypothesis.

References

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The Role of Statistical Comparison Theory in the Study of Open Quantum Systems

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The theory of statistical comparison was formulated [1] in order to extend the theory of majorization to objects beyond probability distributions, like multivariate statistical models and stochastic transitions, and has played an important role in mathematical statistics ever since [2]. In this talk, after reviewing the basic ideas of statistical comparison, with an emphasis on their operational character, I will discuss various generalizations to quantum theory. In particular, I will argue that quantum statistical comparison, with its notion of "information order", provides a natural framework to study the information flows in open quantum system dynamics. Recent results in this direction will be discussed [3,4,5,6,7].

References

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Divisibility and information flow for non-invertible dynamical maps

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We analyze the relation between CP-divisibility and the lack of information backflow for an arbitrary - not necessarily invertible - dynamical map [1,2]. It is well known that CP-divisibility always implies lack of information backflow. Moreover, these two notions are equivalent for invertible maps. It is shown that for a map which is not invertible the lack of information backflow always implies the existence of completely positive (CP) propagator which, however, needs not be trace-preserving [2]. Interestingly, for a class of image non-increasing dynamical maps this propagator becomes trace-preserving as well and hence the lack of information backflow implies CP-divisibility. This result sheds new light into the structure of the time-local generators giving rise to CP-divisible evolutions. We show that if the map is not invertible then positivity of dissipation/decoherence rates is no longer necessary for CP-divisibility.

References

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[2] D. Chruscinski, A. Rivas, and E. Størmer, Phys. Rev. Lett. **121**, 080407 (2018).

Full control of dephasing dynamics — complex quantum networks

J. Piilo

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Engineering, controlling, and simulating quantum dynamics is a strenuous task. However, these techniques are crucial to develop quantum technologies, preserve quantum properties, and engineer decoherence. Earlier results have demonstrated reservoir engineering, construction of a quantum simulator for Markovian open systems, and controlled transition from Markovian to non-Markovian regime. Dephasing is an ubiquitous mechanism to degrade the performance of quantum computers. However, all-purpose quantum simulator for generic dephasing is still missing. Here, we demonstrate full experimental control of dephasing allowing us to implement arbitrary decoherence dynamics of a qubit [1]. As examples, we use a photon to simulate the dynamics of a qubit coupled to an Ising chain in a transverse field and also demonstrate a simulation of nonpositive dynamical map. Our platform opens the possibility to simulate dephasing of any physical system and study fundamental questions on open quantum systems.

Following another line of research, we explore possibilities of using complex quantum networks of harmonic oscillators for reservoir engineering and quantum probing purposes [2,3] - including a possibility for their experimental realization with an optical multimode set-up [4].

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Non-classical, synchronization and thermodynamic effects in extended open quantum systems

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Extended quantum systems composed of several units, eventually in architectures of increasing complexity, can display different forms of dissipation into the environment. Each unit can suffer the effects of an independent external perturbation homogeneous or not, or dissipation can be correlated. In this talk, different non-classical [1], synchronization [2] and thermodynamics [3] effects, induced by dissipation in extended systems, will be discussed.

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Non-Markovian Dynamics in Molecular Aggregates: Coherence and Decoherence in Structured Environments

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Even though biological and material systems often appear like a paradigm of the transition to the classical world, quantum effects in these high-dimensional, structured systems, are strikingly manifest in functional features, especially involving transport and photoexcitation. In this talk, we present examples from realistic quantum dynamical studies of exciton migration in organic polymer materials [1] and light absorption of heme proteins [2], both of which highlight the transient persistence of quantum coherence in molecular aggregates. In both types of systems, electronic delocalization, trapping phenomena, and coherent dynamics induced by strong electron-phonon correlations are prominent features, preceding the onset of decoherence and effective classicality. In this context, unitary system-plus-bath dynamics in many dimensions [1-3] is contrasted with non-Markovian reduced dynamics approaches [4] and reduced-dimensional effective-mode descriptions [4-6] that are closely related to time-dependent density-matrix-renormalization-group (t-DMRG) methods.

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Detecting system-environment correlations without accessing the environment

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Initial correlations between system and environment can significantly influence the dynamics of open quantum systems. Certain types of correlations can further lead to a quantum advantage in quantum information protocols. In this talk we present a method that allows to reveal discord-type correlations between system and environment by exploiting their dynamical effect on the reduced dynamics [1,2]. The method relies on local operations on the open system only and is therefore applicable to situations where the environment is completely inaccessible or even unknown.

In this talk we provide an overview of the progress on this topic over the last years [3,4]. We present experimental realizations ranging from single ions [5] and photons [6,7] up to chains of 42 ions [8]. We further discuss theoretical applications of the method as a local probe in a complex environment [9].

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Qubit Entanglement generation by Gaussian non-Markovian dynamics

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We consider two qubits interacting with a common bosonic bath, but not directly between themselves. We derive the (bipartite) entanglement generation conditions for Gaussian non-Markovian dynamical maps [1] and show that they are similar as in the Markovian regime; however, they depend on different physical coefficients and hold on different time scales. Indeed, for small times, in the non-Markovian regime entanglement is possibly generated on a shorter time scale (proportional to t^2) than in the Markovian one (proportional to t) [2]. Moreover, although the singular coupling limit of non-Markovian dynamics yields Markovian ones [3], we show that the same limit does not lead from non-Markovian entanglement generation conditions to Markovian ones. Also, the entanglement generation conditions do not depend on the initial time for non-Markovian open dynamics resulting from couplings to bosonic Gaussian baths, while they may depend on time for open dynamics originated by couplings to classical, stochastic Gaussian environments.

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Time-resolved observation of thermalization in an isolated quantum system and accessing measures of its non-Markovianity

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Starting from which size can a closed quantum system feature thermailization, how can we reveal the related microscopic dynamics at its timescales?

We want to discuss our experimental study [1] based on linear chains of trapped ions using two different isotopes of magnesium to realize a single s pin with tunable coupling to a resizable bosonic environment. By that we extend our trapped-ion system including its engineered phonon environment up to relevant Hilbert space dimensions. We measure time averages and fluctuations of spin observables and exploit an effective dimension to study their dependence on the size of the system. We find time averages of spin observables becoming indistinguishable from microcanonical ensemble averages, and amplitudes of time fluctuations decaying as we increase the effective system size. Simultaneously, we monitor the coherent dynamics, revealing the importance of initial and transient time scales by direct observation of the evolution towards thermal equilibrium. We interpret this behaviour as the emergence of statistical mechanics in a near-perfectly-isolated quantum system, despite its seemingly small size.

In general, trapped-ion are well suited to study quantum dynamics at a fundamental level, featuring unique control in preparation, manipulation, and detection of electronic and motional degrees of freedom. Their Coulomb interaction of long range permits tuning from weak to strong coupling to the environment and controlling non-linear contributions. Additionally, systems can be scaled bottom up to the mesoscopic size of interest to investigate many-body physics.

We aim to discuss future prospects, such as, generating a multitude of initial conditions, choosing different system and environment states, and preparing initial correlations. The system allows measuring a variety of observables. Applying those techniques, we can study the measures of non-Markovianity [2].

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Testing collapse models: a theory perspective

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Collapse models [1,2] are phenomenological models, proposed to solve the measurement problem. In these models, the Schrödinger equation is modified adding non-linear and stochastic terms which describe the collapse of the wave function in space. The dynamics is built in such a way that the deviations from the linear Schrödinger dynamics are very small for microscopic systems (e.g. particles and atoms) while they become more and more relevant when the system's size increases, explaining the quantum to classical transition.

Collapse models do different predictions compared to Quantum Mechanics, hence they can be tested. The predictions depend on new phenomenological parameters and a large class of experiments have been already considered to set bounds on these parameters.

In this talk, I will give an introduction to the most relevant collapse models and their main properties. Then, I will show how the study of the X-rays radiation emission from Germanium can be used to set relevant bounds on the free parameters of the models [3].

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Non-interferometric diagnostics of collapse models

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Collapse models represent one of the possible solutions for the quantum-to-classical transition. They coherently solve the measurement problem without incurring in paradoxes, as the Copenhagen interpretation of quantum mechanics does. The Continuous Spontaneous Localization (CSL) model [1] is the most studied among the collapse models, and it represents a valid alternative to standard quantum mechanics. Since the model is phenomenological, the value of its parameters can be identified only through experimental investigations. Here, we present the non-interferometric techniques [2-4] that can be used to inquire CSL, and collapse models in general. Applications of this method are shown for several experiments [5-7], which strongly bound the collapse parameters. We will introduce several proposals though to cover the still unexplored region of the parameter space [8-9].

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Abstracts of Posters

(in alphabetical order)

Mixing-induced quantum non-Markovianity and information flow

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Mixing dynamical maps describing open quantum systems can lead from Markovian to non-Markovian processes. Being surprising and counter-intuitive, this result has been used as argument against characterization of non-Markovianity in terms of information exchange. Here, we demonstrate that, quite the contrary, mixing can be understood in a natural way which is fully consistent with existing theories of memory effects. In particular, we show how mixing-induced non-Markovianity can be interpreted in terms of the distinguishability of quantum states, system-environment correlations and the information flow between system and environment.

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Dynamics of quantum heat engines: A comprehensive analysis

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We consider a Carnot-like cycle in which the working substance is a single two-level system. In the cycle, the system experiences two adiabatic evolutions via an optomechanical interaction and thermalizes to the heat baths through the "collision model" Hamiltonian in two strokes.

Utilizing optomechanical interaction, we have a moving object in adiabatic strokes which resembles the piston in classical heat engines. Besides, the thermalization of the system occurs via colliding the bath particles which is close to the classical version of thermalization.

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Quantum Optimal Control for Mixed State Squeezing

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Accurate state preparation, a key requirement for quantum technology, is often carried out with external controls. In order to obtain maximum performance, the pulse shape of the controls can be derived using optimal control theory, by minimizing a suitable performance measure. Care needs to be taken when defining the performance measure for non-pure target states. Visualizing the open system dynamics on the Bloch sphere, we construct an optimization functional that seeks to independently match Bloch vector angle and length of the target state. We employ the ensuing optimization framework to maximize squeezing of an optomechanical oscillator at finite temperature and find that shaping the cavity drives can significantly speed up squeezed state preparation.

Collision model for heat transport through a two-qubit system

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We investigate a collision model for the heat flow between two baths which are separated by a two-qubit system. Each environment couples to one part of the system. The baths consist of sequences of qubits in thermal states which interact only once with the system (Markovian dynamics).
As expected the heat flow depends on the coupling strength between the system qubits and between the system and the baths as well as on the temperature difference. We find that the steady state of the evolution can be entangled.
By introducing memory effects in the environments we can extend the model to a generally non-Markovian one. This leads to effective temperatures (the temperature "seen" by the system) which can be different from the actual bath temperatures. Numerical results show, that the steady state entanglement is affected by the non-Markovian environments.

Classicalization of a bosonic quantum field

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We present a Markovian master equation describing the classicalization of a nonrelativistic bosonic quantum field, based on the simultaneous generalized measurement of its canonical variables. Using the phase space representation, we study the dynamics of the purity decay for a superposition of coherent states, and show that in the classical limit a Boltzmann-type equation describes the time evolution of the Wigner functional of the field.

How to deduce master equations from expectation values: Application to nonconservative forces via quantum reservoir engineering

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Realistic models of quantum systems must include dissipative interactions with an environment, which may be of various natures. A difficulty of constructing master equations for the density matrix lies in fundamental limitations of the current paradigm for modeling open system dynamics: First, the combined system and bath are assumed to evolve unitarily; second, the environmental degrees of freedom are traced out by making a number of approximations. This procedure neither guarantees that the resultant master equation can reproduce the observations characterizing phenomenon of interest nor that the equations have a desired mathematical structure (such as positivity of the density matrix). To overcome these fundamental limitations, a new paradigm of *Operational Dynamical Modeling (ODM)* [1, 2] has been put forth, enabling the generation of models directly from expectation values: To derive master equations, ODM needs two inputs: observed data recast in the form of Ehrenfest relations and a specified mathematical structure of the equation of motion. As an outcome, ODM guarantees that the resulting equations of motion have the desired physical structure to reproduce the supplied dynamical observations. As an application of ODM, a systematic approach is given for engineering dissipative environments that steer quantum wave packets along desired trajectories [3]. The methodology is demonstrated with several illustrative examples: environment-assisted tunneling, trapping, effective mass assignment, and pseudorelativistic behavior. Nonconservative stochastic forces do not inevitably lead to decoherence — we show that purity can be well preserved. These findings highlight the flexibility offered by nonequilibrium open quantum dynamics.

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Fundamental limits in detecting localisation effects

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Advances in the control of quantum mechanical systems have seen experiments place larger objects in quantum mechanical states. Yet quantum correlations are absent from the classical physics which emerges at the macroscopic scale. Collapse models propose a non-deterministic mechanism which suppress quantum effects in macroscopic objects while having negligible impact on microscopic systems [1]. Localisation of a test particle due to collapse models causes additional spreading of the particle's wavefunction. We explore the attainable precision for such localisation rates when a free particle is allowed to evolve, with particular focus around the parameters of the proposed MAQRO mission [2]. As well as the preparation of thermal states we consider the potential impact of generating mechanical squeezing.

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Linear-and-quadratic bosonic reservoir engineering

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Reservoir engineering is a powerful tool that enables the robust preparation of pure quantum states in noisy environments. In the context of bosonic systems, it has been successfully employed for the stabilization of squeezed and entangled states in trapped atoms [1] and ions [2, 3], circuit quantum electrodynamics [4] and opto/electro- mechanics [5]. However, despite the success, bosonic reservoir engineering is currently limited by the linear character of the evolution, which restricts the set of target states to Gaussian ones.

We present a dissipative scheme for the unconditional preparation of pure non-Gaussian states of a target system. The target mode is coupled both linearly and quadratically to an auxiliary damped mode, which acts as an engineered reservoir. We show that any pure state that can be prepared unconditionally, i.e. without requiring initialization, is either (i) a cubic phase state, namely a state given by the action of a non-Gaussian (cubic) unitary on a squeezed vacuum or (ii) a (squeezed and displaced) finite superposition of Fock states. State (i) plays a fundamental role in continuous variable quantum computation, where it allows the realization of any arbitrary unitary operation. Class (ii) represents a novel family of bosonic states that encompasses both (displaced) single Fock states and Schrodinger-cat-like states. We show how to stabilize these states in an optomechanical cavity that is parametrically coupled to both the mechanical displacement and the displacement squared. The mechanical resonator is prepared in the desired state by driving the cavity with multiple coherent drives and adjusting their relative strengths and phases. This scheme enables the unconditional preparation of several nonclassical states of a macroscopic object.

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Quantum Mechanics with Compactified Extra Dimensions

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This work is an investigation of how the presence of additional, space-like dimensions would affect quantum mechanical models of atoms. The main part is focused on the effect of extra spatial dimensions on the stability and energy spectrum of the non-relativistic hydrogen atom with a potential defined by Gauss' law. The case of one extra dimension, with a potential proportional to 1/|x|^2 is examined in detail. The additional spatial dimension is considered to be either infinite or curled-up in a circle of radius R. In both cases, there exists a critical value for the effective charge below which the energy spectrum is bounded from below and unbounded otherwise. When the energy spectrum is bounded from below, as a consequence of the compactification, new negative energy eigenstates appear: if R is smaller than a quarter of the Bohr radius (giving us a constraint on models involving one extra dimension), the corresponding Hamiltonian possesses an infinite number of bound states with a minimal energy extending at least to the ground state of the hydrogen atom. Furthermore, the energy spectrum of the hydrogen atom in a space with one extra compactified dimension is calculated numerically by using Hamiltonian diagonalization techniques.

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Slow dynamics and thermodynamics of open quantum systems

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We develop a perturbation theory of quantum (and classical) master equations with slowly varying parameters, applicable to systems which are externally controlled on a time scale much longer than their characteristic relaxation time. We apply this technique to the analysis of finite-time isothermal processes in which, differently from quasistatic transformations, the state of the system is not able to continuously relax to the equilibrium ensemble. Our approach allows one to formally evaluate perturbations up to arbitrary order to the work and heat exchange associated with an arbitrary process. Within first order in the perturbation expansion, we identify a general formula for the efficiency at maximum power of a finite-time Carnot engine. We also clarify under which assumptions and in which limit one can recover previous phenomenological results as, for example, the Curzon-Ahlborn efficiency [1].

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Thermodynamics of quantum trajectories in the presence of coherent feedback

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Large Deviation Theory is a theoretical framework developed around the 50s for studying the asymptotic behavior of probability distributions in the limit of large samples and the statistics of rare events [1,2]. Recently, it was shown that LDT can be advantageously used in open quantum systems theory to explore the statistics of quantum trajectories, leading to a new viewpoint according to which different emission regimes of driven quantum emitters are interpreted as different thermodynamic phases [3,4]. Very recently, LDT has been extended to open dynamics conditioned by measurement-based feedback [5]. It is known, however, that feedback can also occur unitarily, hence without spoiling quantum coherence (coherent feedback) [6]. Here, we apply LDT to a paradigmatic open dynamics subject to coherent feedback: a V-level atom coupled to the one-dimensional field of a single-end waveguide, a setup recently proposed [7] to experimentally test some predictions of the emerging field of chiral quantum optics [8]. Here, the waveguide end serves as a perfect mirror providing a coherent feedback mechanism, whose associated relevant parameter is the phase shift acquired by a photon to travel between the emitter and mirror. We find that tuning this phase shift can significantly affect fluctuations in photo-count statistics. Depending on the phase shift, the system can exhibit: (i) an unstable, highly intermittent dynamics - which is interpreted through LDT as a first-order phase transition (coexistence) between an active and an inactive thermodynamic phase [5], (ii) an intermediate, low-emitting dynamics with limited fluctuations or (iii) a stable dynamics featuring zero emission and low fluctuations [9].

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Entropy production and asymptotic factorization via thermalization: a collisional model approach

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The Markovian evolution of an open quantum system is characterized by a positive entropy production, while the global entropy gets redistributed between the system and the environment degrees of freedom. Starting from these premises, we analyze the entropy variation of an open quantum system in terms of two distinct relations: the Clausius inequality, that provides an intrinsic bound for the entropy variation in terms of the heat absorbed by the system, and an extrinsic inequality, which instead relates the former to the corresponding entropy increment of the environment. By modeling the thermalization process with a Markovian collisional model, we compare and discuss the two bounds, showing that the latter is asymptotically saturated in the limit of large interaction time. In this regime not only the reduced density matrix of the system reaches an equilibrium configuration, but it also factorizes from the environment degrees of freedom. This last result is proven analytically when the system-bath coupling is sufficiently strong and through numerical analysis in the weak-coupling regime.

Fundamental limits on quantum dynamics based on entropy change

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It is well known in the realm of quantum mechanics and information theory that the entropy is non-decreasing for the class of unital physical processes. However, in general, the entropy does not exhibit monotonic behavior. This has restricted the use of entropy change in characterizing evolution processes. Recently, a lower bound on the entropy change was provided in the work of Buscemi, Das, and Wilde [Phys. Rev. A 93(6), 062314 (2016)]. We explore the limit that this bound places on the physical evolution of a quantum system and discuss how these limits can be used as witnesses to characterize quantum dynamics. In particular, we derive a lower limit on the rate of entropy change for memoryless quantum dynamics, and we argue that it provides a witness of non-unitality. This limit on the rate of entropy change leads to definitions of several witnesses for testing memory effects in quantum dynamics. Furthermore, from the aforementioned lower bound on entropy change, we obtain a measure of non-unitarity for unital evolutions.

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A model of calorimetric measurements in an open quantum system.

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I will present a theoretical study of a planned experiment by Pekola et al [1]. The aim of the experiment is to measure quanta of energy emitted or absorbed by a driven qubit by measuring temperature changes of its environment. In conjunction with performing an initial and final measurement on the energy of the qubit, it is possible to assign a value on the work performed on the qubit.

Theoretically, the model consists of a driven qubit in contact with a finite size electron reservoir, the calorimeter initially in equilibrium with an infinite phonon bath. Under weak coupling assumptions the evolution of the qubit-calorimeter system can be modelled as a stochastic jump process for the temperature of the calorimeter and the state of the qubit [2].

I present numerical and analytical studies of the temperature behavior of the qubit for two regimes of the drive: 1. the strength of the drive is much larger than the qubit-calorimeter coupling [3] and 2. the strength of the drive is much smaller than the level spacing of the qubit. Asymptotically in the duration of the drive, for both regimes it is possible to derive a Fokker-Planck equation for the temperature. We compare the regimes and keeping the assumptions for regime 2 met, we identify the region of parameters for which regime 1 is valid.

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Observation of Brillouin optomechanical strong coupling with an 11 GHz mechanical mode

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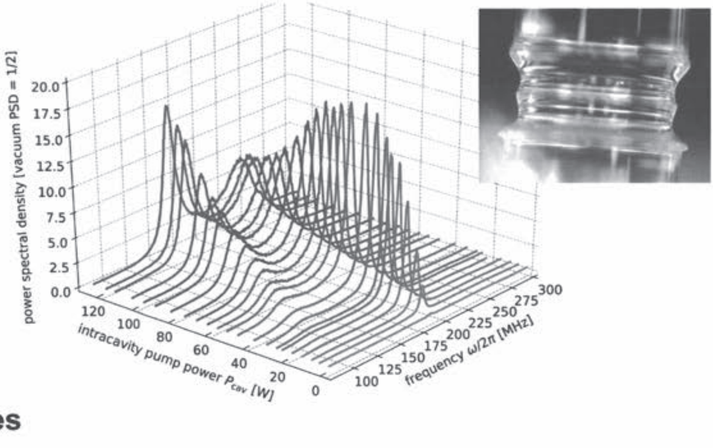
Achieving optomechanical strong coupling with high-frequency phonons provides a rich avenue for quantum technology development including quantum state-transfer, memory, and transduction, as well as enabling several fundamental studies of macroscopic phononic degrees-of-freedom. Reaching such coupling with GHz mechanical modes however has proved challenging, with a prominent hindrance being material- and surface-induced-optical absorption in silicon. Here, we circumvent these challenges and report the observation of optomechanical strong coupling to a high frequency (11 GHz) mechanical mode of a fused silica microresonator via the electrostrictive Brillouin interaction. Using an optical heterodyne detection scheme, the anti-Stokes light backscattered from the resonator is measured and normal-mode splitting and an avoided crossing are observed in the recorded spectra, providing unambiguous signatures of strong coupling. The optomechanical coupling rate reaches values as high as $G/2\pi$=39 MHz through the use of an auxiliary pump resonance, where the coupling dominates both the optical ($\kappa/2\pi$=3 MHz) and the mechanical ($\gamma_m/2\pi$=21 MHz) amplitude decay rates. Our findings provide a promising new fully integrated approach for optical quantum control using light and sound.



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Collisional model with correlated environment in the matrix product form

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Collisional model describes an open quantum system interacting sequentially with subenvironments. If all the subenvironments are initially identical and there are no correlations among them, then the system dynamics is Markovian in the stroboscopic limit [1]. However, if the environment is in the correlated state, then such correlations naturally affect system dynamics and can make it strictly non-Markovian [2]. Divisibility property of collisional models is analyzed in [3]. In present report, we consider a particular form of correlations in the environment, namely, the environment is in the matrix product state (MPS). We develop Nakajima-Zwanzig projective techniques for such a case and derive the corresponding master equation. The memory kernel is expressed through matrices defining MPS. The considered model is able to describe spin transport in carbon chains [4].

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Towards heralded single-phonon state generation of an ultracoherent nanomechanical resonator

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Here we present our progress towards heralded single phonon generation [1] in a membrane-in-the-middle optomechanical system. We show ground state cooling of a soft-clamped membrane resonator [2], as well as spectral filtering and detection of the relevant mechanical sidebands. The high detection efficiency of our system, as demonstrated by strong ponderomotive squeezing of light, lends itself ideal for tomography of the mechanical state.

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Study of the role of system-environment correlations in quantum open system dynamics

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We study system-environment correlations and entanglement in an exactly solvable model of a quantum open system. We discuss the relation between the dynamics of correlations and the parameters describing the open system, such as the spectral density of the environment, decay rate, detuning, etc. We distinguish the cases when the system behaves Markovian and Non-Markovian, and investigate how this affects the dynamics of system-environment correlations.

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Semiclassical gravity – faster than light?

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The lack of experimental evidence for the quantisation of the gravitational field, combined with the fact that such evidence appears to be easier to obtain [1] than Planck scale effects, has fuelled the idea that gravity might be fundamentally semiclassical [2]. The main objection to this approach is the alleged possibility of superluminal signals through the gravitational field of entangled quantum states, resulting in causal inconsistencies [2-5]. I will have a closer look at common assertions and discuss their limitations and possible loopholes, showing that – although the possibility of faster than light signals is a serious concern – arguments that semiclassical gravity would necessarily be in conflict with causality are, at this stage, still inconclusive.

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Defining and generating current in open quantum systems

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Defining current in open quantum systems can be problematic: No general description exists for the current of operators not conserved by the system-environment interaction. We fill this gap by deriving a general formula for probability current on an arbitrary graph, universally applicable to any system-environment interaction. We furthermore provide a representation of the average current, whereby the operator is first measured weakly, then strongly. When the dynamics is of Lindblad form, we derive an explicit formula for the current. We exemplify our theory by analysing a simple Smoluchowski-Feynman-type ratchet, operating deep in the quantum regime. Consisting of only two interacting particles, each moving on a three-site ring, the ratchet displays several novel quantum effects, such as tunnelling-induced current inversion, which we relate to the onset of quantum contextuality in the system, and steady-state entanglement generation in the presence of arbitrarily hot environment. The role of spatial symmetry in current generation is also studied.

The Dynamics of Quantum Correlations in Mixed Classical Environments

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We present a comparative study of the dynamics of entanglement and quantum discord in a bipartite system in the presence of mixed classical noises. In particular, the joint effects of three different types of classical noises, namely, random telegraphic noise (RTN), Ornstein–Uhlenbeck noise (OU), and static noise, are studied by combining them in two different ways. In each case, one marginal system is coupled with random telegraphic noise, and the other marginal system is coupled with either OU or static noise. We make a comparison between the behaviors of both correlations in the two setups. In the weak coupling regime, the qualitative behavior of entanglement is unaffected by switching the coupling of only one marginal system from OU to static noise, and vice versa. However, the behavior of quantum discord strongly depends on whether it is coupled with OU or static noise. On the other hand, in the strong coupling regime, the static noise is more fatal to the survival of both correlations as compared to the other two noises.

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Characterizing multipartite entanglement with moments of random correlations

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The trustworthy detection of multipartite entanglement usually requires a number of judiciously chosen local quantum measurements which are aligned with respect to a previously shared common reference frame. If such a reference frame is not available one has to develop alternative detection strategies which do not rely on a specific choice of the local measurement bases. One possibility in this direction is to perform a number of local measurements with settings distributed uniformly at random and to resort to statistical tools in order to draw conclusions about the entanglement properties of the underlying states. In this work we follow such a treatment and show that an improved detection of multipartite entanglement is possible by combining moments of different order. To do so, we make use of unitary designs which link entanglement criteria based on moments to ordinary reference-frame independent ones involving a number of fixed measurement settings. The strengths of our methods are illustrated in various cases starting with two qubits and followed by more involved multipartite scenarios. In particular, we also discuss the possibility to discriminate different classes of multipartite entangled states within our approach.

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Experimental emulation and control of quantum non-Markovian dynamics

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The inevitable presence of environment surrounding the quantum system leading to decoherence is the major hurdle in fault-tolerant implementation of quantum technologies. Many rescue techniques like error correction strategies [1], dynamical decoupling [2], etc., are developed to counter the detrimental effect of the decoherence. However, these techniques must be quantitatively benchmarked to ensure their robustness against various kinds of environments encountered in realistic experimental scenarios. One way to achieve this task is by engineering artificial environments since natural environments are generally beyond experimental control. Such methods developed from benchmarking perspectives [3] till now have mainly concentrated on engineering environments which lead to Markovian or memoryless dynamics. In general, it is crucial to take into account the strong environmental memory effects, characteristic of quantum non-Markovian dynamics.

In this work, we experimentally emulate the non-Markovian dynamics of a pure dephasing spin-boson model at zero temperature. Specifically, we use a randomized set of external radio-frequency fields to engineer a desired Ohmic noise power-spectrum to effectively realize a non-Markovian environment for a single NMR qubit. The information back-flow characteristic to the non-Markovianity is captured in the non-monotonicity of decoherence function [4] and von Neumann entropy of the system. Using such emulated non-Markovian environments, we experimentally show the inefficiency of Carr-Purcell-Meiboom-Gill dynamical decoupling sequence [5] to inhibit the loss of coherence. Finally, we design an optimized dynamical decoupling sequence which utilizes the information back-flow to maximize coherence protection for non-Markovian environments.

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The transmission of quantum information of an open quantum system interacting with a quantum scalar field

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In this work, using the quantum Brownian motion model, we study the transmission of information between two separated harmonic oscillators, that interacting via a massless quantum scalar field. We calculate the exact solutions to the open system dynamics. We demonstrate that the Markovian approximation fails in this system. We explore the interplay between characteristic non-Markovian phenomena, such as memory effects and quantum correlations, and the quantum phenomena of superposition and entanglement.

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Process estimation in qubit systems in the presence of noise

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We address quantum decision theory as a convenient framework to analyze process discrimination and estimation in qubit systems. On the one hand, we employ Bayes strategy to find the optimal measurement scheme that allows to discriminate with minimum error probability whether or not a qubit system has been affected by a given unitary perturbation. On the other hand, we use Neyman-Pearson strategy to find the ultimate bound posed by quantum mechanics for the detection of the minimum parameter of the qubit perturbation, where the optimal POVM and the best probing states for estimation are determined in the presence of different kinds of noise.

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System-environment correlations in (strong) Quantum Darwinism

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Realistic systems are constantly interacting with their surrounding environments. Decoherence theory successfully describes how quantum systems lose their internal coherence, but it does not explain another aspect of objectivity: redundancy of information. In (strong) quantum Darwinism [1, 2] and spectrum broadcast structure [3], the environment cannot be ignored—the correlations between the system and environment play a crucial role in determining the objectivity of the system.

Here, we describe strong quantum Darwinism [2] which formalises our intuition that objectivity requires classical correlations and vanishing quantum correlations. We examine an example where strong quantum Darwinism is required over traditional quantum Darwinism: a two-level system strongly interacting with an N-level environment [4]. Finally, we prove that strong quantum Darwinism and strong independence is equivalent to spectrum broadcast structure. This bridges the gap between the different tools used to study objectivity—quantum information theory, state structure and geometry.

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Stochastic Feshbach Projection for Open Quantum Systems

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We introduce a stochastic projection formalism for quantum dynamics in bosonic or spin environments [1]. The Schrödinger equation in coherent state representation with respect to the environmental degrees of freedom can be reformulated by employing a Feshbach partitioning technique [2]. In this picture the reduced state of the system is obtained as a stochastic average over pure state trajectories. The corresponding stochastic Schrödinger equations include an explicit memory integral. In the case of harmonic environments and linear coupling the approach gives a new form of the established non-Markovian quantum state diffusion stochastic Schrödinger equation [3]. Utilizing spin coherent states, the evolution equation for spin environments resembles the bosonic case with, however, a non-Gaussian average for the reduced state unraveling.

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Parametrization and optimization of Gaussian non-Markovian

unravelings for open quantum dynamics.

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We derive a family of Gaussian non-Markovian stochastic Schrödinger equations for the dynamics of open quantum systems. The different unravelings correspond to different choices of squeezed coherent states, reflecting different measurement schemes on the environment. Consequently, we areable to give a single shot measurement interpretation for the stochastic states and microscopic expressions for the noise correlations of the Gaussian process. By construction, the reduced dynamics of the open system does not depend on the squeezing parameters. They determine the non-Hermitian Gaussian correlation, a wide range of which are compatible with the Markov limit. We demonstrate the versatility of our results for quantum information tasks in the non-Markovian regime. In particular, by optimizing the squeezing parameters, we can tailor unravelings for improving entanglement bounds or for environment-assisted entanglement protection.

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Squeezed thermal reservoir as a generalized equilibrium reservoir

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We explore the perspective of considering the squeezed thermal reservoir as an equilibrium reservoir in a generalized Gibbs ensemble with two noncommuting conserved quantities: energy and second-order moments asymmetry. We outline the main properties of such a reservoir in terms of the exchange of energy, both heat and work, and entropy, giving some key examples to clarify its physical interpretation. This allows for a correct and insightful interpretation of all thermodynamic features of the squeezed thermal reservoir, which can be extended as well to other similar nonthermal reservoirs. This characterization includes reversibility, work extraction, and the first and second laws of thermodynamics [1].

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Dissipative Collapse Model in optomechanical systems

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Collapse models [1] provide a universal dynamical equation which applies to both small and large-scale systems, to explain the quantum-to-classical transition. These models assume that the collapse of the wave function is a physical process, which happens at a random time in space. Collapse Models are able to explain the absence of superposition at macroscopic scale while they give the same predictions of Quantum Mechanics for microscopic systems. The dynamics is described by a non-linear stochastic Schrödinger equation, which leads to a master equation in the Lindblad form. A drawback of these models is that they do not preserve energy, for this reason a dissipative extension has been proposed [2]. We can think of the collapse effect as the action of a real physical field at finite temperature, then the energy gain or loss by the system has just been exchanged with the noise field and the principle of energy conservation can be re-established.

This poster will be about the characterisation of an optomechanical cavity in which we include the effect due to the dissipative extension of the collapse model [3]. It is useful to introduce the Density Noise Spectrum (DNS) function through which we can get information about the mirror in the cavity. So far it has been analysed the steady state case [4] and our aim is to explore the DNS in the time domain: we will compare the dynamics between three cases, such as the simply open optomechanical system, the case including the standard Collapse effect and finally the dissipative extension of CSL. Exploring the time evolution dynamics is interesting in order to gain more information for a better characterisation and a deeper understanding of the phenomena.

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Memory effects in a simple metal

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We study the full time evolution of a nuclear spin coupled to itinerant electrons through the hyperfine interaction, with a particular focus on memory effects leading to a non-Markovian behaviour. We show that even a noninteracting electron system causes a notable memory effect due to the restriction of fluctuations by the Fermi surface. The resulting short time dynamics of the nuclear spin is dominated by a logarithmic, temperature independent decay before crossing over to the standard, thermally induced exponential decay. But even at the longer time scales the initial non-Markovian decay causes a systematic reduction of the decay amplitude that should be detectable.

Our approach is based on an expansion of the exact Nakashima-Zwanzig equation in the hyperfine coupling constant, set up to preserve the analytical structure of the memory kernel that causes the non-Markovian behaviour.

Our results are analytical and describe the full time range from the novel non-Markovian contributions to the well-known exponential decay expressions.

How Fat is Your Quantum Cat?

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Schrödinger's famous thought experiment, involving a cat that is simultaneously dead and alive, illustrates the counterintuitive nature of quantum mechanics. We know that microscopic objects such as photons and electrons can be in a superposition of two states at once but in this work, we aim to find out if it is possible to generate a quantum superposition in a macroscopic system.

We studied an isolated optomechanical system with a macroscopic mirror [1] using a measure of macroscopic quantumness based on phase space [2]. After homodyne detection, it was found that at certain times and positions the mirror was macroscopically quantum and its state had a high value of fidelity with a Schrödinger cat state. A "membrane-in-the-middle" system with a quadratic interaction term between the cavity and the mechanical mode was also considered [3]. We were able to find macroscopically quantum states but the fidelity with cat states was low.

We moved on to study the effect of noise on the linear system. The evolution of the system is taken to be Markovian and to solve the master equation for the system, we use the quantum unravelling method [4]. This involves splitting the time period into small time steps. At each time step, either the system evolves as normal with a time evolution operator or a photon is leaked into the environment. This decay occurs randomly. The solution of the master equation is found by repeating this process many times and averaging over the results. As expected, noise has a detrimental effect; the higher the cavity damping rate, the lower the macroscopic quantumness of the mirror.

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Electron Counting Statistics for Non-Additive Environments

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Molecular electronics is a rapidly developing field focussed on modelling and constructing electronic circuits using molecules as the structural basis. In such systems, it is often the case that the system of interest may couple to multiple environments. For example, we consider here a model comprised of a double quantum dot (or molecule) coupled strongly to a phonon bath and weakly to two electronic leads. The strong coupling to phonons suggests that it should not be valid to consider the phonon and electronic environments simply as acting additively, as would be the case if both were weakly coupled to the dot system (or in the infinite lead bias regime[1]). Instead, making use of the reaction co-ordinate framework [2,3] we incorporate strong phonon coupling within an enlarged system Hamiltonian. This allows us to derive a form of the lead coupling that accounts properly for the strong coupling between the double quantum dot system and the phonons. Applying counting statistics techniques[4,5] we track electron flow between the double quantum dot and the electronic leads, revealing strong non-additive effects in the current, noise and Fano factor when examining the finite bias regime.

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Thermodynamic consistency of the optomechanical master equation

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We investigate the thermodynamic consistency of the master equation description of heat transport through an optomechanical system attached to two heat baths, one optical and one mechanical. We employ three different master equations to describe this scenario: (i) The standard master equation used in optomechanics, where each bath acts only on the resonator that it is physically connected to; (ii) the so-called dressed-state master equation, where the mechanical bath acts on the global system; and (iii) what we call the global master equation, where both baths are treated non-locally and affect both the optical and mechanical subsystems. Our main contribution is to demonstrate that, under certain conditions including when the optomechanical coupling strength is weak, the second law of thermodynamics is violated by the first two of these pictures. In order to have a thermodynamically consistent description of an optomechanical system, therefore, one has to employ a global description of the effect of the baths on the system.

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An out-of-equilibrium non-Markovian Quantum Heat Engine

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We study the finite-time thermodynamics of a heat engine operating an Otto cycle whose working medium is a quantum harmonic oscillator. Hot and cold environments are modelled via a collections of spin-1/2 particles. The work strokes of the cycle are implemented via parametric changes of the frequency of the harmonic oscillator, while heat exchanges result from collisional dynamics with the environments that may allow for memory effects.

The scope of our study is twofold: on the one hand, we investigate work transformations of controlled yet variable duration, spanning the whole range from an infinitely slow (and thus adiabatic) transformations, to the opposite extreme of a sudden quench. On the other hand, by including intra-environment interactions, we allow for the emergence of memory effects and thus non-Markovianity in the dynamics of the engine. We investigate numerically the behaviour of the engine and its performance in the two cross-overs from adiabaticity to sudden quench, and from Markovianity to non-Markovianity.

We find that the efficiency of the device always decreases as we approach the sudden-quench regime, and the quantification of an optimal time at which the power output is maximum. Intra-environment interactions, in turn, seem to have no effect on the long-time engine performance. However, they affect the transient of the evolution of the engine by seemingly lowering the efficiency of the heat-transfer process – at least in the case when the both the engine and the environment particles are initialized in a thermal state. In no case we observe a performance exceeding the classical bounds. We do observe however a strong connection between non-Markovianity and the coherences in the initial engine state. Finally, the analysis of the behaviour of the machine at different temperatures allowed us to single out the parameter regime in which it behaves as a refrigerator rather then a thermal engine.

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Divisibility of qubit channels

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The concept of divisibility of dynamical maps is used to introduce an analogous concept for quantum channels by analyzing the simulability of channels by means of dynamical maps. In particular, this question is addressed for Lindblad divisible, completely positive divisible and positive divisible dynamical maps and the corresponding L-divisible, CP-divisible and P-divisible subsets of channels [1]. We visualized for the case of qubit channels and discuss the general inclusion relations among divisibility sets. Finally, we show some equivalences for qubit channels, in particular we show that there are channels that are CP-indivisible and markovian in the sense of infinitesimal divisibility in positive maps. To this end we study the conditions of L-divisibility for channels, especially the case of channels with negative eigenvalues. Furthermore we show that transitions among every two divisibility sets are allowed, and present some examples. Finally we show that every divisible but not infinitesimal divisible qubit channel (in positive maps) is entanglement-breaking.

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Exact non-Markovian dynamics of an open quantum system using a chain representation of the environment

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A theoretical framework is developed to study the dynamics of an open quantum system in a setting where the environment – assumed to comprise a continuous bath of bosonic modes – is mapped onto a 1D tight-binding chain [1,2]. It is shown that the exact system-environment dynamics can be formulated in terms of Heisenberg operator equations that describe the coupling of the system degrees of freedom to a set of damped discrete chain modes. From this result, we determine that the combined evolution of the system-plus-discrete modes is provided in terms of a master equation of Gorini-Kossakowski-Sudarshan-Lindblad form. Hence, the original non-Markovian problem can be fully amended to a quantum Markov (white noise) process by enlarging the open system to include the nearest chain modes which have flat coupling to the remaining bath field. Ultimately our approach generalises the exact, nonperturbative result of the pseudomode method [3] to cases involving multiple excitation of the reservoir with a Lorentzian-type spectrum.

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Pulsed Optomechanical CV Transducer Based on Geometric Phase Effect

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We propose a transducer that uses a sequence of pulsed quantum nondemolition (QND) interactions of the two modes of radiation with a mechanical oscillator to effectively induce a QND coupling between the modes. The properly engineered sequence of interactions drives the mechanical oscillator around a closed path in a phase space and thereby allows to trace the mechanical mode out of the interaction of the radiation modes, leaving the latter coupled. Importantly, the coupling can be achieved regardless of the temperature of the noisy mechanical mode.

Collectively-enhanced thermalization via multi-qubit collisions

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We investigate the evolution of a target qubit caused by its multiple random collisions with N-qubit clusters. Depending on the cluster state, the evolution of the target qubit may correspond to its effective interaction with a thermal bath, a coherent (laser) drive, or a squeezed bath. In cases where the target qubit relaxes to a thermal state its dynamics can exhibit a quantum advantage, whereby the target-qubit temperature can be scaled up proportionally to N^2 and the thermalization time can be shortened by a similar factor, provided the appropriate coherence in the cluster is prepared by non-thermal means. We dub these effects quantum super-thermalization due to its analogies to super-radiance.

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Macroscopicity of arbitrary quantum superposition experiments

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We discuss a macroscopicity measure [1] that quantifies how empirical evidence gathered in an experiment falsifies macrorealistic modifications of quantum mechanics. So far, a quantitative assessment of the macroscopicity has only been formulated for interference experiments. We extend this by providing a general scheme based on Bayesian hypothesis testing of the underlying parameter space that characterizes the macrorealistic modifications. We apply this scheme to assess the macroscopicity reached in recent experiments showing different kinds of quantum phenomena: Squeezed collective spin states [2], Leggett-Garg-tests [3] and the entanglement between micromechanical oscillators [4,5].

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Orientational decoherence, diffusion, and thermalization of quantum rigid rotors

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Motivated by recent progress in levitated optomechanics with aspherical nanoscale objects, we present the Markovian quantum master equation of an arbitrarily shaped rigid rotor revolving in a homogeneous background gas [1]. Since such a nanoparticle barely revolves during a single collision, this master equation describes orientational decoherence [2], quantum angular momentum diffusion [3], as well as rotational thermalization towards a Gibbs-like steady state. We derive the decoherence rate and the rotational friction and diffusion tensors in terms of the microscopic scattering amplitudes and solve the master equation numerically for the linear and planar rotor. In addition, we show that if the particle rotates multiple times during the scattering process, collisions with gas atoms lead to the decoherence of an intial superposition of angular momentum eigenstates and to the re-orientation of the angular momentum vector. We calculate the ensuing rotational decoherence rates [4] and obtain excellent agreement with recent experiments with nitrogen superrotors [5].

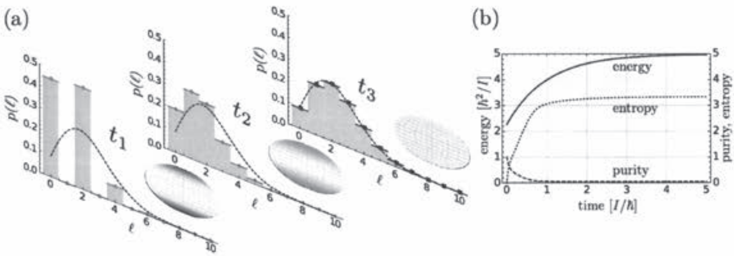

Fig. 1: (a) The rotation state of a quantum rigid rotor immersed in a homogeneous background gas first decoheres and then thermalizes with the environment. (b) Rotational energy, von Neumann entropy, and purity as a function of time. Figure taken from Ref. [1].

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Efficient simulation of finite-temperature open quantum systems

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Abstract

Chain-mapping techniques have proven to be a powerful tool for the simulation of open-quantum- system dynamics. When finite-temperature environments are considered, however, such techniques suffer from an unfavorable algorithmic scaling with the temperature. In this work we prove that this difficulty can be overcome by exploiting the equivalence between an open quantum system interacting with a bosonic bath at finite temperature and the same system interacting with a second bosonic bath at zero temperature. This approach provides a polynomial improvement over existing state-of-the-art chain-mapping techniques and paves the way to numerically-exact and certifiable simulation of complex open quantum systems at finite temperature.

Towards an optomechanical Bell test with room temperature phonons

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Since they were originally published in 1964, Bell and Bell-type inequalities revolutionized the way of thinking about fundamental tests of quantum mechanics. Bell's theorem shows that there are experiments in which theories with local hidden variables predict different results as those of quantum mechanics, providing a way to experimentally distinguish between the two [1]. Bell tests have been done with photons originating from atomic cascades [2], from parametric down conversion sources [3], and more recently with NV centers in diamond [4] and mechanical oscillators near absolute zero temperature [5]. I will be presenting our work towards performing a Bell test with room temperature phonons using ultra-fast lasers and time-correlated single photon Raman spectroscopy.

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Information transport in quantum non-equilibrium steady-states

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(Dated: October 10, 2018)

Non-equilibrium steady-states are characterized by the existence of macroscopic heat currents flowing between two or more reservoirs. However, the existence of these currents also implies that information is constantly being transmitted from one reservoir to the other. In this letter we address the transport of information in the context of quantum non-equilibrium steady states. We first show how the ability of the excitations to transfer information can be quantified by the conditional mutual information (CMI), a more general measure of tripartite correlations. We then apply this to an exactly soluble model allowing for both ballistic and diffusive behavior. Our approach allows us to compute the CMI for arbitrary sizes and thus find the scaling rules connecting information transport and diffusivity. Finally, we discuss how this new perspective in the characterization of non-equilibrium systems may be applied to understand the issue of local equilibration in non-equilibrium states.

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Robust optomechanical cooling with a phase sequence

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We studied a strongly-driven optomechanical system in the red-detuned case. There, we use linearized quantum Langevin equations for the annihilation operators of the cavity and the mechanical oscillator. The equations obtained resemble those found for the probability amplitudes of a driven qubit without losses. We use this link to propose a quantum control technique for the optomechanical system: a composite driving sequence with appropriately-chosen phases[1] and a constant power. In the qubit, the composite sequence produces robust population inversion and in our system we obtained a robust optomechanical cooling, even in the presence of losses[2].

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Markovian Reachability Taken to the Limit in Controlled Dissipative Quantum Systems

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Which quantum states can be reached by coherently controlling n-level quantum systems coupled to a thermal bath in a switchable Markovian way?
For this challenging problem class, we combine recent extensions of majorization techniques and Lie-geometrical control theory to give inclusion relations deduced from dissipative actions on diagonal forms of quantum states and their unitary orbits. The inclusions hold for temperatures $0<T\leq\infty$, while exact bounds exist for $T=0$. One furthermore can structure the whole class of normal Lindblad generators in terms of reachability given full unitary control. These techniques may also be useful in view of related thermalization problems.

Many-body open quantum systems beyond Lindblad master equations

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Many-body systems present a rich phenomenology which can be significantly altered when they are in contact with an environment. In order to study such set-ups, a number of approximations are usually performed, either concerning the system, the environment, or both. A typical approach for large quantum interacting systems is to use master equations which are local, Markovian, and in Lindblad form. Here, we present an implementation of the Redfield master equation using matrix product states and operators. We show that this allows us to explore parameter regimes of the many-body quantum system and the environment which could not be probed with previous approaches based on local Lindblad master equations. The accuracy of our results has also been verified with the numerical exact thermofield-based chain-mapping approach.

Friction as a consistent quantum-mechanical concept

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Friction (a velocity-only dependent force resisting the relative motion of objects) is ubiquitous in macroscopic world: from igniting matches to accelerating/decelerating a car. However, starting with pioneering work of Goran Lindblad [1], all attempts to introduce friction into quantum world have failed (except for free Brownian motion case [2]). Recently we proved that a quantum analog of friction (understood as a phenomenological completely positive Markovian translation-invariant model of dissipation) is in odds with the detailed balance in the thermodynamic limit [3]. Note, however, that this result applies only to point particles.

Here we consider quantum systems with internal states non-adiabatically coupled to translation dynamics. A toy example is the quantum damped harmonic oscillator with internal stretching mode shown in Fig. 1. For such systems, we derive general quantum master equation which phenomenologically accounts for the frictional effect of a uniform zero temperature environment [4]. Conjectures regarding the finite temperature case are also formulated.

The results are important for efficient simulations of complex molecular dynamics and quantum reservoir engineering applications.

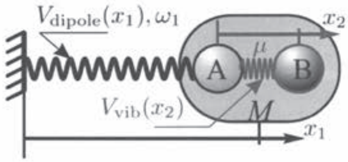

Fig. 1. *The ball-and-spring model of a quantum damped harmonic oscillator (e.g., a diatomic molecule in a dipole trap). We prove that quantum friction acting on the molecule as a whole must also dump an internal stretching mode.*

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Non-Markovian decoherence dynamics in nonequilibrium environments

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We theoretically investigate the non-Markovian dynamical decoherence of a quantum system coupled to nonequilibrium environments with nonstationary statistical properties. We show the time evolution of the decoherence factor in real-imaginary space to study the environment-induced energy renormalization and backaction of coherence which are associated with the unitary and nonunitary parts of the quantum master equation, respectively. It is also shown that the nonequilibrium decoherence dynamics displays a transition between Markovian and non-Markovian and the transition boundary depends on the environmental parameters. The results are helpful for further understanding non-Markovian dynamics and coherence backaction on an open quantum system from environments.

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