Symposium Characterization and control of complex quantum systems (SYQS)

jointly organized by
the Quantum Optics and Photonics Division (Q),
the Atomic Physics Division (A),
the Molecular Physics Division (MO),
the Theoretical and Mathematical Physics Division (MP),
the Mass Spectrometry Division (MS), and
the Working Group 'Young DPG' (AGjDPG)

Andreas Buchleitner
Physikalisches Institut
Albert-Ludwigs-Universität Freiburg
Hermann-Herder-Str. 3
79104 Freiburg
a.buchleitner@physik.uni-freiburg.de

Irene Burghardt
Institut für Physikalische u.
Theoretische Chemie
Goethe-Universität
Max-von-Laue-Str. 7
60438 Frankfurt
burghardt@chemie.uni-frankfurt.de

Sebastian Heupts
Institut für Theoretische Physik
Universität Heidelberg
Philosophenweg 16
D-69120 Heidelberg
Heupts@jdpg.de

What is 'complex'? A question which stimulates a panoply of often quite diverse associations and answers. While in condensed matter and also macromolecular physics we are used to be forced into effective descriptions of large, multi-component, interacting quantum systems, complexity is '(re-)constructed' in modern quantum optical experiments. In learning how 'complexity' emerges from strongly coupling few degrees of freedom (or particles), we start to contemplate how to control complex systems, and learn to distinguish what is just complicated from what is truly complex. The present symposium collects expertise and perspectives from very diverse fields - photonics, quantum information, molecular dynamics, quantum control, quantum many body physics, open/disordered quantum systems - which all share the interest in getting a better grasp of complexity. In particular, the event aims at making the current state of debate attractive and accessible for students and young researchers. For this purpose, an innovative format will blend a tutorial talk and dedicated questions & answer slots with invited and contributed talks, to foster questions and (constructive) intellectual controversy.

Overview of Invited Talks and Sessions

(Lecture room: Audimax)

Invited Talks

SYQS 1.1	Fri	10:30–11:15	Audimax	**Tutorial Complex Systems: From Classical to Quantum, from Single to Many Particle Problems** — •Klaus Richter
SYQS 1.2	Fri	11:30–12:00	Audimax	**Multiphoton random walks: Experimental Boson Sampling on a photonic chip** — •Ian Walmsley, Justin Spring, Ben Metcalf, Peter Humphreys, Steve Kolthammer, Xianmin Jin, Animesh Datta, James Gates, Peter Smith
SYQS 2.1	Fri	14:00–14:30	Audimax	**Charge transfer and quantum coherence in solar cells and artificial light harvesting systems** — •Christoph Lienau
SYQS 2.6	Fri	15:30–16:00	Audimax	**Feedback control: from Maxwell's demon to quantum phase transitions** — •Tobias Brandes
SYQS 3.4	Fri	17:15–17:45	Audimax	**Multi-photon dynamics in complex integrated structures** — •Fabio Sciarrino
SYQS 3.5	Fri	17:45–18:15	Audimax	**Complexity and many-boson coherence** — •Malte Tichy

Sessions

SYQS 1.1–1.4	Fri	10:30–12:30	Audimax	**Characterization and control of complex quantum systems I**
SYQS 2.1–2.6	Fri	14:00–16:00	Audimax	**Characterization and control of complex quantum systems II**
SYQS 3.1–3.5	Fri	16:30–18:30	Audimax	**Characterization and control of complex quantum systems III**

SYQS 1: Characterization and control of complex quantum systems I

Time: Friday 10:30–12:30 Location: Audimax

Invited Talk SYQS 1.1 Fri 10:30 Audimax
Tutorial Complex Systems: From Classical to Quantum, from Single to Many Particle Problems — •Klaus Richter — Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany

There does not exist a common notion of what defines a complex (quantum) system; depending on context and community perception of complex behavior varies a lot. I will first review aspects and characteristics of complexity in classical systems, where it has been originally considered, pointing out analogies between complex phenomena in simple low-dimensional settings and emergent complexity from interactions in the many-body case. Thereby I will put forward the notion that complex behaviour is linked to discontinuities. In the second part of the lecture I will discuss implications for complex quantum systems.

Questions & answers (11:15 - 11:30)

Invited Talk SYQS 1.2 Fri 11:30 Audimax
Multiphoton random walks: Experimental Boson Sampling on a photonic chip — •Ian Walmsley[1], Justin Spring[1], Ben Metcalf[1], Peter Humphreys[1], Steve Kolthammer[1], Xianmin Jin[1], Animesh Datta[1], James Gates[2], and Peter Smith[2] — [1]University of Oxford, Department of Physics, Clarendon Laboratory, Parks Rd. Oxford, OX2 3PU, UK — [2]Optoelectronics Research Center, University of Southampton, SO17 1BJ, UK

Photonics provides a feasible platform for implementing many quantum information protocols, with the opportunity to realise quantum enhancements to technologies from sensing to computation. For instance, ideal universal quantum computers may be exponentially more efficiently than classical machines for certain classes of problems. Nonetheless, the formidable challenges in building such a device motivate the search for and demonstration of alternative problems that still promise a quantum speedup. Quantum boson sampling (QBS) provides such an example. We have constructed a photonic quantum boson sampling machine (QBSM) to sample the output distribution resulting from the nonclassical interference of photons in an integrated photonic circuit, a problem thought to be exponentially hard to solve classically. Unlike universal quantum computation, boson sampling merely requires indistinguishable bosons, linear state evolution, and detectors, imperfections of which may result in systematic errors. Our studies open the way to larger devices that could offer the first definitive quantum enhanced computation.

SYQS 1.3 Fri 12:00 Audimax
Antiresonance in a Strongly-Coupled Atom-Cavity System — •Christoph Hamsen, Christian Sames, Haytham Chibani, Paul A. Altin, Tatjana Wilk, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching

The strongly-coupled atom-cavity system has proven useful for the observation of fundamental quantum effects. Recently, it has found application as a building block for more complex structures in elementary quantum circuits for quantum information processing. Moreover, large networks of strongly-coupled systems have been proposed for simulation of quantum phase transitions. However, due to the strong coupling these compound systems cannot be treated perturbatively, but require a holistic analysis of all constituents making characterization a challenging task.

Here, we provide a route to address this challenge. It is based on an experiment where, by heterodyne detection of the light transmitted through a cavity containing a single atom, we see a hitherto unobserved negative phase shift which is associated with an antiresonance. The linewidth and frequency of this antiresonance are solely determined by the atom. The corresponding phase shift can be optically controlled via the AC stark shift and reaches values of up to 140° - the largest ever reported for a single emitter. We explain how this opens up new routes towards characterization of complex quantum circuits.

SYQS 1.4 Fri 12:15 Audimax
Tuning the Quantum Phase Transition of Bosons in Optical Lattices via Periodic Modulation of s-Wave Scattering Length — Tao Wang[1,2], •Xue-Feng Zhang[1], Francisco Ednilson Alves dos Santos[3], Sebastian Eggert[1], and Axel Pelster[1] — [1]Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany — [2]Department of Physics, Harbin Institute of Technology, China — [3]Instituto de Física de São Carlos, Universidade São Paulo, Brazil

We investigate how the superfluid-Mott insulator quantum phase transition for bosons in a 2D square and a 3D cubic optical lattice changes due to a periodic modulation of the s-wave scattering length. At first we map the underlying periodically driven Bose-Hubbard model approximately to an effective time-independent Hamiltonian with a conditional hopping [1]. Combining different analytical approaches with quantum Monte Carlo simulations then reveals that the location of the quantum phase boundary turns out to depend quite sensitively on the driving amplitude. A more quantitative analysis shows even that the effect of driving can be described within the usual Bose-Hubbard model provided that the hopping is rescaled appropriately with the driving amplitude. This finding indicates that the Bose-Hubbard model with a periodically driven s-wave scattering length and the usual Bose-Hubbard model belong to the same universality class from the point of view of critical phenomena.

[1] A. Rapp, X. Deng, and L. Santos, Phys. Rev. Lett. **109**, 203005 (2012).

SYQS 2: Characterization and control of complex quantum systems II

Time: Friday 14:00–16:00 Location: Audimax

Invited Talk SYQS 2.1 Fri 14:00 Audimax
Charge transfer and quantum coherence in solar cells and artificial light harvesting systems — •Christoph Lienau — Carl von Ossietzky University, Institute of Physics, Oldenburg, Germany

In artificial light harvesting systems the conversion of light into electrical or chemical energy happens on the femtosecond time scale [1], and is thought to involve the incoherent jump of an electron from the optical absorber to an electron acceptor. Here we investigate the primary dynamics of the photoinduced electronic charge transfer process in two prototypical structures: (i) a carotene-porphyrin-fullerene triad, a prototypical elementary component for an artificial light harvesting system and (ii) a polymer:fullerene blend as a model system for an organic solar cell. Our approach [2] combines coherent femtosecond spectroscopy and first-principles quantum dynamics simulations. Our experimental and theoretical results provide strong evidence that the driving mechanism of the primary step within the current generation cycle is a quantum-correlated wavelike motion of electrons and nuclei on a timescale of few tens of femtoseconds. We furthermore highlight the fundamental role played by the flexible interface between the light-absorbing chromophore and the charge acceptor in triggering the coherent wavelike electron-hole splitting.

[1] C. J. Brabec et al., Chem. Phys. Lett. 340, 232 (2001). [2] C. A. Rozzi et al., 'Quantum coherence controls the charge separation in a prototypical artificial light-harvesting system', Nature Communications 4, 1602 (2013).

SYQS 2.2 Fri 14:30 Audimax
Designing Disorder-Assisted Energy Transfer — •Mattia Walschaers[1,2], Roberto Mulet[1,3], and Andreas Buchleitner[1] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3, D-79104 Freiburg, Germany — [2]Instituut voor Theoretische Fysica, KU Leuven, Celestijnenlaan 200D, B-3001 Heverlee, Belgium — [3]Complex Systems Group, Department of Theoretical Physics, University of Havana, Havana, Cuba

Common wisdom suggests that complex structures typically have a negative impact on quantum transport, due to localization phenomena and the strong fluctuations which they cause. We show that localization and strong fluctuations can also be used to the benefit of transport.

By controlling typical spectral properties of an ensemble of complex systems, we design localization properties. In doing so, we can build systems such that the energy transport is mainly governed by only two scattering resonances.

When, however, these resonances start to overlap considerably, the transfer efficiency decreases drastically. We explain that a suitable control of some average properties of the energy spectrum gives rise to a statistical repulsion between the two scattering resonances. Hereby we can avoid drastic losses of the transfer efficiency, rendering the transport mechanism very robust.

SYQS 2.3 Fri 14:45 Audimax

Cooperative effects of external control and dissipation in open quantum systems — •Rebecca Schmidt, Jürgen T. Stockburger, and Joachim Ankerhold — Institut für Theoretische Physik, Universität Ulm, Albert Einstein-Allee 11, 89069 Ulm

Coherent optimal control of non-Markovian open quantum systems is crucial in tailored-matter such as quantum information processing. In general, the presence of dissipative reservoirs is considered as detrimental to quantum coherence and entanglement. However, tailored control pulses [1] may change the role of a heat bath from being destructive on quantum resources to an asset promoting them. Here we show that the cooperative interplay between optimal control signals and a dissipative medium may indeed induce phenomena such as entropy reduction (cooling) [1,2] and creation of bi-partite entanglement [3].

[1] R. Schmidt, A. Negretti, J. Ankerhold, T. Calarco and J.T. Stockburger, PRL **107**, 130404 (2011)

[2] R. Schmidt, S. Rohrer, J.T. Stockburger and J. Ankerhold, Phys. Scr. **T151**, 014034 (2012)

[3] R. Schmidt, J.T. Stockburger, and J. Ankerhold, PRA **88**, 052321 (2013)

SYQS 2.4 Fri 15:00 Audimax

Nonlinear spectroscopy with quantum light — •Frank Schlawin[1], Konstantin Dorfman[2], Benjamin Fingerhut[2], and Shaul Mukamel[2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79108 Freiburg, Germany — [2]Department of Chemistry, University of California, Irvine, California 92697-2025, USA

Nonlinear spectroscopy has evolved into an indispensable tool to probe non-equilibrium dynamics of complex quantum systems. Typically, the interpretation of these signals suffers from the enormous number of free parameters in the underlying Hamiltonians of the system and its coupling to the environment. It is highly desirable to develop new tools to extract further information from those systems. We will discuss the possibility of exploiting strong correlations of entangled light to manipulate nonlinear spectra of complex quantum systems such as photosynthetic complexes. Exciton transport can be suppressed, and two-exciton states can be selectively excited.

SYQS 2.5 Fri 15:15 Audimax

Dynamical Algebras and Many-body Physics — •Zoltán Zimborás[1], Robert Zeier[2], Zoltán Kádár[3], Michael Keyl[2], and Thomas Schulte-Herbrüggen[2] — [1]University of the Basque Country (UPV/EHU), Bilbao, Spain — [2]Technische Universität München (TUM), Germany — [3]University of Leeds (UL), UK

Dynamical algebras, i.e., Lie algebras generated by Hamiltonians, are basic tools both in Quantum Control and Quantum Simulation Theory. In this talk, we will argue that these algebras might also have relevance in Many-Body Physics. By studying Lie closures of translation-invariant Hamiltonians, we show that nearest-neighbor Hamiltonians do not generate all translation-invariant interactions. We discuss the relevance of this result in simulating many-body dynamics. Furthermore, we point out that our results [1] also provides a surprising Lie algebraic explanation of a previous finding of ours concerning the absence of gap in quasifree models with (twisted) reflection-symmetry breaking [2].

[1] Z. Zimborás, R. Zeier, M. Keyl, and T. Schulte-Herbrüggen, “A Dynamic Systems Approach to Fermions and Their Relations to Spins”, arXiv:1211.2226.

[2] Z. Kádár and Z. Zimborás, “Entanglement entropy in quantum spin chains with broken reflection invariance”, Phys. Rev. A 82, 032334 (2010).

Invited Talk SYQS 2.6 Fri 15:30 Audimax

Feedback control: from Maxwell’s demon to quantum phase transitions — •Tobias Brandes — TU Berlin

I will give an overview of our recent attempts to understand the thermodynamics and quantum mechanics of closed loop (feedback) control. I will discuss a minimal implementation of Maxwell’s demon in a solid state system with only four states [1], but also the opposite case of many collective degrees of freedom, i.e. models for phase transitions (Dicke superradiance model [2], quantum Ising chain [3]).

[1] P. Strasberg, G. Schaller, T. Brandes, and M. Esposito, Phys. Rev. Lett. 110, 040601 (2013). [2] T. Brandes, Phys.Rev.E 88 032133 (2013). [3] M. Vogl, G. Schaller, T. Brandes, Phys. Rev. Lett. 109, 240402 (2012).

SYQS 3: Characterization and control of complex quantum systems III

Time: Friday 16:30–18:30 Location: Audimax

SYQS 3.1 Fri 16:30 Audimax

Exciton-polariton lasing in disordered ensembles of correlated Mie resonators — •Regine Frank[1] and Andreas Lubatsch[2] — [1]Institute for Theoretical Physics, Eberhard-Karls University Tübingen, Germany Center for Light-Matter-Interaction, Sensors and Analytics (LISA+) and Center for Complex Quantum Phenomena (CQ) — [2]Electrical Engineering, Precision Engineering, Information Technology, Georg-Simon-Ohm University of Applied Sciences, Kesslerplatz 12, 90489 Nürnberg, Germany

The spectral density of electronic states of ZnO is investigated for experimentally relevant pump power values of random lasers. Non-equilibrium Keldysh theory and numerics for the Hubbard model predicts unusal broadening of the electronic bands. We discuss whether this leads to exciton-polariton coupling within the single ZnO cylinders in the Mie resonance condition. The cylinders are considered random in space but coherently correlated by photonic transport and multiple scattering. Long range interferences are found to be crucial for the development of a polariton condensate and lasing of large-area quantum efficiency.

R. Frank, A. Lubatsch, Phys. Rev. A 84, 013814 (2011) R. Frank, Phys. Rev. B 85, 195463 (2012)

SYQS 3.2 Fri 16:45 Audimax

Tomography of squeezed and oversqueezed states of mesoscopic atomic ensembles — •Baptiste Allard, Roman Schmied, Caspar F. Ockeloen, and Philipp Treutlein — Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

The experimental characterization of the quantum state of a mesoscopic ensemble of particles is a major challenge in quantum physics, especially when multi-particle entanglement is present.

We experimentally demonstrate tomographic state reconstruction of non-classical many-body (pseudo-)spin states. The system consists of a two-component ^{87}Rb Bose-Einstein condensate of a few hundred atoms created on an atom-chip [1]. A state-selective potential gives rise to a S_z^2 interaction term in the Hamiltonian in the collective spin representation. Using this one-axis twisting dynamics [2], we prepare non-classical spin states such as spin-squeezed and spin-oversqueezed states.

Using well-controlled Rabi rotations and projective measurements, we perform a Stern-Gerlach-type analysis to characterize the many-body quantum states. From the results of measurements along many quantization axes, we determine the most likely positive-semidefinite density matrix; this represents an improvement over our previously published backprojection technique [3].

[1] M. F. Riedel, *et al.*, Nature **464**, 1170 (2010). [2] M. Kitagawa

and M. Ueda, Phys. Rev. A **47**, 5138-5143 (1993). [3] R. Schmied and P. Treutlein, New J. Phys. **13**, 065019 (2011).

SYQS 3.3 Fri 17:00 Audimax

On the versatility of quantum master equations: an effective description of disorder dynamics — •Chahan M. Kropf, Clemens Gneiting, and Andreas Buchleitner — Institute of Physics, Albert-Ludwigs University of Freiburg, Hermann-Herder-Str.3, D-79104 Freiburg, Germany

In order to describe the dynamics of quantum systems subject to disorder, one typically computes the ensemble average either with a perturbative approach or by direct numerical simulation. Another possibility consists in an effective description of the ensemble-averaged dynamics.

Here we propose to derive general, local-in-time, quantum master equations for the ensemble-averaged dynamics of finite, isolated, disordered quantum systems. To do so, we first invert the exact dynamics for single realizations, and then perform the ensemble averaging explicitly. Under rather general conditions do we find Non-Markovian dynamics and master equations with time-dependent decay rates and Hermitian Lindblad operators.

Invited Talk SYQS 3.4 Fri 17:15 Audimax

Multi-photon dynamics in complex integrated structures — •Fabio Sciarrino — Dipartimento di Fisica, Sapienza Università di Roma, Italy

Integrated photonic circuits have a strong potential to perform quantum information processing. Indeed, the ability to manipulate quantum states of light by integrated devices may open new perspectives both for fundamental tests of quantum mechanics and for novel technological applications. The evolution of bosons undergoing arbitrary linear unitary transformations quickly becomes hard to predict using classical computers as we increase the number of particles and modes. Photons propagating in a multiport interferometer naturally solve this so-called boson sampling problem, thereby motivating the development of technologies that enable precise control of multiphoton interference in large interferometers. Here, we use novel three-dimensional manufacturing techniques to achieve simultaneous control of all the parameters describing an arbitrary interferometer. We implement a small instance of the boson sampling problem by studying three-photon interference in a nine-mode integrated interferometer, confirming the quantum-mechanical predictions. Scaled-up versions of this set-up are a promising way to demonstrate the computational advantage of quantum systems over classical computers. The possibility of implementing arbitrary linear-optical interferometers may also find applications in high-precision measurements and quantum communication.

Invited Talk SYQS 3.5 Fri 17:45 Audimax

Complexity and many-boson coherence — •Malte Tichy — Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus, Denmark

Many-boson systems feature a subtle interplay of complexity and coherence. Many-boson coherence is a source of complexity, which makes Boson-Sampling – the simulation of many-boson interference – a paradigm that may demonstrate the superiority of quantum devices. However, current protocols that aim at certifying the functionality of Boson-Sampling setups are shown to be bypassed by an efficient model with randomly prepared independent particles. An alternative test based on a solvable instance of the problem is shown to permit more stringent certification for arbitrarily many particles [1]. The protocol paves the road to rule out alternative models for many-particle behavior that extricate themselves from true complexity. Bosonic composites made of two constituents, however, deviate from ideal elementary bosonic behavior when their constituents are not sufficiently entangled. The complexity of the constituent wavefunction thus becomes a requirement for the ideal collective bosonic behavior of composites and the absence of complexity leads to observable deviations [2].

[1] Malte C. Tichy, Klaus Mayer, Andreas Buchleitner, Klaus Mølmer, arXiv:1312.3080 (2013). [2] Malte C. Tichy, P. Alexander Bouvrie, Klaus Mølmer, Phys. Rev. A 86, 042317 (2012); Phys. Rev. A 88, 061602(R) (2013).

Questions & answers (18:15 - 18:30)