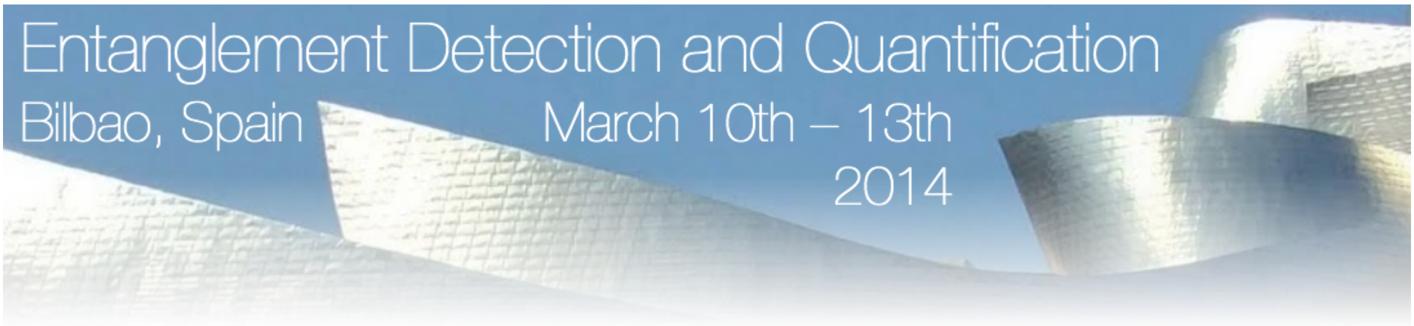

Book of Abstracts

Organizers:
Géza Tóth (Bilbao)
Otfried Gühne (Siegen)
Marcus Cramer (Ulm)

Contents

1 Program

All talks will be in the Sala Garate of the Universidad de Deusto, Avda. de las Universidades 24. Poster session will be in the inner yard.

	Mo., 10th	Tu., 11th	We., 12th
8:30	Welcome		
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9:45	D. Bruß	M.W. Mitchell	C. Wunderlich
10:30	Coffee Break	Coffee Break	Coffee Break
11:00	M. Cheneau	C. Klempt	A. Sanpera
11:45	R. Sewell	S.M. Giampaolo	O. Marty
12:10	C. Budroni	M. Huber	T. Moroder
12:35	J. Dunningham	H. Kampermann	A. Osterloh
13:00	Lunch	Lunch	Lunch
15:00	H. Weinfurter		F. Illuminati
15:45	A. Gábris	Coffee	M. Ziman
16:10	Coffee Break	B. Kraus	Coffee Break
16:40	F. Jelezko	N. Killoran	R. Schmied
17:25	M. Gessner	Y-C. Liang	M. Sanz
	19:30 — 22:00 Guggenheim reception	18:30 — 20:30 Poster session	

Th., 13th	
M. Oberthaler	9:00
J. Siewert	9:45
A. Stefanov	10:10
Coffee Break	10:35
P. Richerme	11:05
L. Tagliacozzo	11:50

Monday, Mar. 10th

9:00 – 9:45:	S. Kuhr: Towards single-site-resolved detection of fermions in an optical lattice
9:45 – 10:30:	D. Bruß: Entanglement distribution without sending entanglement
10:30 – 11:00:	Coffee Break
11:00 – 11:45:	M. Cheneau: Atomic twin Fock state in momentum space
11:45 – 12:10:	R. Sewell: Generation of macroscopic singlet states in a cold atomic ensemble
12:10 – 12:35:	C. Budroni: Bounding Temporal Quantum Correlations
12:35 – 13:00:	J. Dunningham: Quantum-enhanced metrology in lossy systems
13:00 – 15:00:	Lunch
15:00 – 15:45:	H. Weinfurter: Analysing multi-qubit entangled quantum states
15:45 – 16:10:	A. Gábris: Quantum state generation by parametric down-conversion in coupled waveguide arrays
16:10 – 16:40:	Coffee Break
16:40 – 17:25:	F. Jelezko: Qubits in diamond
17:25 – 17:50:	M. Gessner: Local detection of quantum correlations with a trapped ion
19:30 – 22:00:	Reception at the Guggenheim Museum (Private Tour, Food, and Drinks)

Tuesday, Mar. 11th

9:00 – 9:45:	A. Acín: Non-locality detection in many-boy systems
9:45 – 10:30:	M.W. Mitchell: Extreme photonic entanglement using concepts from spin squeezing
10:30 – 11:00:	Coffee Break
11:00 – 11:45:	C. Klempt: Detecting multiparticle entanglement of Dicke states
11:45 – 12:10:	S.M. Giampaolo: Frustration, Entanglement, and Correlations in Quantum Many Body Systems
12:10 – 12:35:	M. Huber: Quantifying high-dimensional and/or multipartite entanglement via few local observables
12:35 – 13:00:	H. Kampermann: Optimization of Bell inequalities with invariant Tsirelson bound
13:00 – 15:45:	Lunch
15:45 – 16:15:	Coffee
16:15 – 17:00:	B. Kraus: The maximally entangled set of multipartite quantum states
17:00 – 17:25:	N. Killoran: Extracting and quantifying entanglement in identical particle systems
17:25 – 17:50:	Y-C. Liang: From device-independent entanglement detection to device-independent entanglement quantification
18:30 – 20:30:	Poster Session

Wednesday, Mar. 12th

9:00 – 9:45:	A. Smerzi: Entanglement and Distinguishability in Quantum Interferometry
9:45 – 10:30:	C. Wunderlich: Entanglement of Trapped Ions using MAGIC
10:30 – 11:00:	Coffee Break
11:00 – 11:45:	A. Sanpera: Bipartite versus multipartite entanglement in many-body systems
11:45 – 12:10:	O. Marty: Quantifying entanglement of many-body systems with simple measurements
12:10 – 12:35:	T. Moroder: Lower bounding convex roofs
12:35 – 13:00:	A. Osterloh: Maximally entangled states for higher local Hilbert space dimension
13:00 – 15:00:	Lunch
15:00 – 15:45:	F. Illuminati: Entanglement, symmetries, frustration: a toolbox for the investigation of complex quantum matter
15:45 – 16:10:	M. Ziman: Dissociation and annihilation of multipartite entanglement structure
16:10 – 16:40:	Coffee Break
16:40 – 17:25:	R. Schmied: Practical tomography of many atoms
17:25 – 17:50:	M. Sanz: Multipartite Entanglement Classification for Permutational Invariant States

Thursday, Mar. 13th

9:00 – 9:45:	M. Oberthaler: Bose Einstein condensates: Squeezing and beyond
9:45 – 10:10:	J. Siewert: Entanglement resources of noisy cluster states
10:10 – 10:35:	A. Stefanov: Characterization and manipulation of frequency entangled qudits
10:35 – 11:05:	Coffee Break
11:05 – 11:50:	P. Richerme: Simulating Excited-State Many-Body Dynamics with Trapped Ions
11:50 – 12:15:	L. Tagliacozzo: Physics of the 1D long range Ising model in a transverse field

2 Abstracts

2.1 Talks

(alphabetically by last name)

Non-locality detection in many-body systems, Antonio Acín (ICFO Barcelona)

Little is known about the role of quantum nonlocality in many-body systems. This is because standard many-body observables involve correlations among few particles, while there is no multipartite Bell inequality for this scenario. We provide the first example of non locality detection in many-body systems using two-body correlations. To this aim, we construct families of multipartite Bell inequalities that involve only second order correlations of local observables. We then provide examples of systems, relevant for nuclear and atomic physics, whose ground states violate our Bell inequalities for any number of constituents. Finally, we show how some of these inequalities can be tested by measuring collective spin components, opening the way to experimental detection of many-body nonlocality, for instance with atomic ensembles.

Entanglement distribution without sending entanglement, Dagmar Bruß, A. Streltsov, H. Kampermann (University of Düsseldorf)

We show that the cost for distributing entanglement is not given by a measure of entanglement, but by a measure of quantum correlations. Our results provide an optimal protocol for entanglement distribution. While the presence of quantum correlations is necessary to enable entanglement distribution, it is not sufficient: separable states with rank two do not allow entanglement distribution. Our study of minimal requirements for entanglement distribution leads to a new classification for separable states.

Bounding Temporal Quantum Correlations, Costantino Budroni[1], Tobias Moroder[1], Matthias Kleinmann[1], Otfried Gühne[1], and Clive Emary[2] (1: Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany; 2: Department of Physics and Mathematics, University of Hull, Kingston-upon-Hull, United Kingdom)

Sequential measurements on a single particle play an important role in experimental tests of the Kochen-Specker theorem and in Leggett-Garg inequalities. We provide a general method to analyze temporal quantum correlations, which allows to compute the maximal correlations in quantum mechanics. For the case of dichotomic measurements, we present the full characterization of temporal correlations in the simplest Leggett-Garg scenario as well as in the most fundamental proof of the Kochen-Specker theorem. Moreover, the above method shows that the quantum bound for temporal correlations in a sequential measurement scenario strongly depends on the number of levels that can be accessed by the measurement apparatus via projective measurements. For the simplest Leggett-Garg scenario, we provide exact bounds for small N, that exceed the known bound for the Leggett-Garg inequality, and show that in the limit of an infinite number of levels the Leggett-Garg inequality can be violated up to its algebraic maximum.

Atomic twin Fock state in momentum space, Marc Cheneau (Institut d'Optique, Paris)

In this talk, I will report on our current work to establish a new source of atomic twin Fock state where the two modes consist of real-space momentum states instead of spin states. Since the entangled atoms fly apart of each other, such a source would enable the direct observation of non-locality with massive particles (instead of photons). Here, the two modes are the output channels of elastic collisions occurring in a Bose-Einstein condensate loaded in a moving optical lattice. Thanks to a unique detection method in the cold atom community, we are able to fully reconstruct the 3-dimensional momentum distribution of the output state with single atom resolution. Combined with the possibility to rotate the state on the Bloch sphere using Bragg pulses, this opens the route to a tomography of this highly non-classical state with excellent precision. Beside our most recent progress, I will discuss the experimental difficulties inherent to our approach, such as multi-modality, which underlines the need for more generic and robust entanglement measures.

Quantum-enhanced metrology in lossy systems, Jacob Dunningham (University of Sussex)

Quantum entanglement offers the possibility of making measurements beyond the classical limit, however some issues still need to be overcome before it can be applied using realistic lossy systems. Recent work has used quantum Fisher information to show that entangled coherent states may be useful for this purpose as they combine sub-classical phase precision capabilities with robustness [1]. However, to date no effective scheme for measuring a phase in lossy systems using an entangled coherent state has been devised. I will present an experimentally accessible scheme that does just this and could measure a phase with a precision close to the Heisenberg limit over a wide range of losses. I will also discuss the link between the entanglement present and the measurement precision that can be achieved.

[1] J. Joo et. al., Phys. Rev. Lett. 107, 83601 (2011).

Quantum state generation by parametric down-conversion in coupled waveguide arrays, Aurél Gábris (Czech Technical University)

Parametric down-conversion (PDC) using bulk non-linear crystals or non-linear waveguides has been a popular way of creating entangled quantum states. We have considered PDC in coupled waveguide arrays which allow precise control over not only the spectral modes but also over the discrete spatial modes. The experimental results confirmed the strong influence spectrally dependent coupling effects, further complicating the test for the presence of entanglement.

Local detection of quantum correlations with a trapped ion, Manuel Gessner (University of Freiburg)

Trapped ions experiments provide precise control at the single quantum level of electronic and motional states. This renders this technology suitable for the investigation of elementary quantum processes and the implementation of quantum computation algorithms. Quantum correlations play an important role for many applications in quantum information technology and can significantly influence the dynamics of a multipartite or open quantum system. In this talk I present theoretical and experimental results on the detection of quantum correlations in an unknown bipartite state only by access to one of the two systems. This method is applicable to detect system-environment correlations in a typical open quantum system since no experimental access to the environment is required.

Frustration, Entanglement, and Correlations in Quantum Many Body Systems, Salvatore Marco Giampaolo (University of Wien)

Many body systems are typically modelled by Hamiltonians that are sums of local terms. Each local term operates only on a part of the entire system and acts to minimize the corresponding energy. If different subsystems overlap, the competition among the different local terms can preclude the existence of configurations satisfying all such minimizations simultaneously, a phenomenon known as frustration. For classical Hamiltonian systems, frustration is associated to some non trivial geometric property of the system itself. On the other hand, due to quantum non-commutativity and entanglement, classically unfrustrated systems may admit frustrated quantum counterparts. I illustrate how it is possible to define a measure of the frustration that is valid both in classical and in quantum case that, in this latter, bounds from above the sum of entanglement and quantum correlations between a part of the system and the rest of it. Starting from it I'll show how it is possible to generalize the Toulouse criterion to the quantum world and I'll illustrate some example of feasible experiment in which such measure of the frustration can be experimentally measured.

Quantifying high-dimensional and/or multipartite entanglement via few local observables, Marcus Huber (Universitat Autonoma de Barcelona)

We introduce different experimentally friendly criteria that allow to lower bound different measures of (multipartite) entanglement. As a precursor we investigate operationally relevant substructures of entanglement in high dimensional systems an describe a generalized version of the Schmidt rank for multipartite systems. This connects different questions concerning the quantification to a general mathematical theory of entropy distribution in multipartite systems. For the 0-entropy we introduce new inequalities that are reminiscent of famous inequalities for the Von Neumann entropy and provide further monogamy like lower bounds for the witness quantification.

Entanglement, symmetries, frustration: a toolbox for the investigation of complex quantum matter, Fabrizio Illuminati (University of Salerno)

I will review recent work on the study of many-body quantum systems in terms of entanglement spectra, Rényi entropies, and hierarchical measures of geometric entanglement. Emphasis will be given to foundational and methodological aspects in view of possible forthcoming applications to the physics and the quantum simulation of frustrated magnetism, exotic phases of matter, and lattice field theories.

Qubits in diamond, Fedor Jelezko (University of Ulm)

Diamond is not only the king gemstone, but also a promising material in modern technology (which holds a promise to replace silicon). Less known is that defects in diamond can be used for quantum technologies. Owing to their remarkable stability, colour centres in diamond have already found an application in quantum cryptography. In this talk I will discuss recent progress regarding spin-based quantum information processing and sensing at nanoscale.

Optimization of Bell inequalities with invariant Tsirelson bound, Hermann Kampermann, Michael Epping, Dagmar Bruss (HHU Düsseldorf)

We investigate operations on CHSH type Bell inequalities which leave their Tsirelson bound invariant, but influence the classical bound. These operations allow changing the violation of a given Bell inequality, i.e. the ratio of the optimal quantum value with respect to the maximal classical value. For several examples in the literature we show that the violation can be increased. Another feature of our procedure is to derive and improve dimension witnessing Bell inequalities.

Extracting and quantifying entanglement in identical particle systems, Nathan Killoran (University of Ulm)

When identical particles all occupy a single spatial mode, such as in Bose-Einstein condensates, the nature of entanglement requires careful consideration. Due to symmetrization, many states (e.g., spin-squeezed states) appear to have a high degree of inter-particle entanglement. However, because the particles are identical and hence not individually addressable, such entanglement is commonly considered to be unphysical and therefore not a resource for standard quantum information tasks. In this talk, we show that any entanglement evident between the identical particles can be transferred faithfully onto independent mode subsystems using elementary operations. This extracted entanglement can then be applied to other tasks without restriction. Interestingly, the amount of mode entanglement in the final state can be exactly quantified from the initial state's inter-particle entanglement. Thus, the multi-particle entanglement inherent to identical particle systems is a full-fledged, quantifiable resource for quantum information tasks.

Detecting multiparticle entanglement of Dicke states, Carsten Klempt (University of Hannover)

Recent experiments demonstrate the production of many thousands of neutral atoms entangled in their spin degrees of freedom. We present a criterion for estimating the amount of entanglement based on a measurement of the global spin. It outperforms previous criteria and applies to a wide class of entangled states, including Dicke states. Experimentally, we produce a Dicke-like state using spin dynamics in a Bose-Einstein condensate. Our criterion proves that it contains at least genuine 28-particle entanglement. We infer a generalized squeezing parameter of ?11.4(5) dB.

The maximally entangled set of multipartite quantum states, Barbara Kraus (University of Innsbruck)

Entanglement is a resource in quantum information theory when state manipulation is restricted to Local Operations assisted by Classical Communication (LOCC). It is therefore of paramount importance to decide which LOCC transformations are possible and, particularly, which states are maximally useful under this restriction. While the bipartite maximally entangled state is well known (it is the only state that cannot be obtained from any other and, at the same time, it can be transformed to any other by LOCC), no such state exists in the multipartite case. In order to cope with this fact, we introduce here the notion of the Maximally Entangled Set (MES) of n-partite states. This is the set of states which are maximally useful under LOCC manipulation, i. e. any state outside of this set can be obtained via LOCC from one of the states within the set and no state in the set can be obtained from any other state via LOCC. We determine the MES for states of three and four qubits and provide a simple characterization for them. In both cases, infinitely many states are required. However, while the MES is of measure zero for 3-qubit states, almost all 4-qubit states are in the MES. This is because, in contrast to the 3-qubit case, deterministic LOCC transformations are almost never possible among fully entangled four-partite states. We determine the measure-zero subset of the MES of LOCC convertible states. This is the only relevant class of states for entanglement manipulation [1].

[1] J. I. de Vicente, C. Spee, B. Kraus, "The maximally entangled set of multipartite quantum states", Phys. Rev. Lett. 111, 110502 (2013).

Towards single-site-resolved detection of fermions in an optical lattice, Stefan Kuhr (University of Strathclyde)

Ultracold atoms in optical lattices have become a tool to simulate and test fundamental concepts of condensed matter physics, in particular to simulate electrons in solid crystals. Recent experiments with single-site resolution of single atoms at individual lattice sites have resulted in the direct observation of quantum phase transitions, such as the superfluid to Mott insulator transition for bosonic particles [1], and, e.g. single-site addressing [2] and the quantum dynamics of spin-impurities [3]. However, an experimental proof of single-site-resolved detection of correlated phases of ultracold fermions in a lattice is still missing. I will report on our current progress to realise single-site resolved, in-situ imaging and manipulation of strongly correlated fermionic 40K in an optical lattice. Such a system would be an ideal environment to simulate the Fermi-Hubbard Hamiltonian, allowing for the direct observation and characterisation of, e.g., temperature, spin-structure, or entropy distribution of quantum phases such as fermionic Mott insulators, Band insulators or Nel antiferromagnets.

[1] J. F. Sherson, C. Weitenberg, M. Endres, M. Cheneau, I. Bloch, S. Kuhr, Single-atom-resolved fluorescence imaging of an atomic Mott insulator, Nature 467, 68 (2010).
[2] C. Weitenberg, M. Endres, J. F. Sherson, M. Cheneau, P. Schau, T. Fukuhara, I.Bloch, S. Kuhr, Single-spin addressing in an atomic Mott insulator, Nature 471, 319 (2011).
[3] T. Fukuhara, A. Kantian, M. Endres, M. Cheneau, P. Schau, S. Hild, D. Bellem, U. Schollwck, T. Giamarchi, C. Gross, I. Bloch, S. Kuhr, Quantum dynamics of a single, mobile spin impurity, Nature Physics 9, 235 (2013).

From device-independent entanglement detection to device-independent entanglement quantification, Yeong-Cherng Liang (ETH Zürich)

The device-independent paradigm is one that aims to draw conclusion about some system of interest without relying on any assumption about the underlying Hilbert space dimension nor the measurements performed. In contrast to one's naive intuition, device-independent entanglement witnesses for genuine multipartite entanglement can be constructed using Bell-like inequalities without resorting to the detection of genuine multipartite nonlocality. As with conventional entanglement witnesses, the violation of such a device-independent entanglement witness — using solely measurement data and independent of any quantum description of the employed devices — can also be used to provide lower bounds on the underlying entanglement in both the bipartite and multipartite scenarios.

Quantifying entanglement of many-body systems with simple measurements, Oliver Marty (Institut für Theoretische Physik, Universität Ulm)

We present different methods to give lower bounds on entanglement measures in current experiments. These methods will be discussed in the context of quantum simulator experiments—well controlled and very accessible systems—and of large crystalline systems for which accessible measurements are strongly restricted. In particular, we report on how the bipartite entanglement can be lower bounded based on a few already available observables. The bounds do not depend on any assumptions on the system but only on the measured data. Motivated by recent experiments, we demonstrate the feasibility by numerical simulations of a chain of trapped ions simulating a transverse field Ising model with algebraically decaying couplings. We report on results for ground states across quantum phase transitions and sudden quenches under this Hamiltonian. The necessary optimization may be formulated as a semidefinite program. We further discuss how the optimization may be completely avoided at the hand of two examples: Lower bounds for the ground state of the Ising model may be directly obtained from a sequence of Bell measurements. Secondly, we show how other entanglement measures like, e.g., the best separable approximation may be bound from below directly using scattering experiments from samples consisting of large numbers of qubits. Again, the required data, here the measurement of the structure factor, is simple to obtain and the bounds do not rely on any assumptions on the system.

Extreme photonic entanglement using concepts from spin squeezing, Morgan Mitchell (ICFO Barcelona)

I will describe the application of ideas from spin squeezing to bright non-classical beams of light. In particular, polarization squeezing is attractive because the photon's two polarizations are analogous to a spin-1/2 system, for which many results are known. On the other hand, photonic systems have a spatio-temporal degree of freedom usually not considered in atomic systems, and moreover can exist in a superposition of different number states, which makes questionable an immediate application of atomic spin-squeezing results. The Glauber theory of photodetection is very helpful in this regard. I will describe a photonic spin-squeezing inequality based on the Glauber theory, i.e. a proof that non-classical polarization correlations imply bipartite photonic entanglement described (and detectable) by the Glauber theory. Continuing in this direction, I consider multi-partite entanglement of the photons in a polarization-squeezed beam, and find results analogous to Sorensen and Molmer's "extreme spin squeezing," but if anything more extreme: Wineland-criterion polarization squeezing implies an entanglement depth proportional to system size. Polarization squeezing is a source of genuine multi-partite entanglement. 1000-partite photonic entanglement should be directly observable with available experimental resources. If time permits, I will briefly describe an experiment underway to observe the more modest of these predictions.

Lower bounding convex roofs, Tobias Moroder (University of Siegen)

The convex roof construction plays an important role in quantum information theory. In this work we develop a general method to find lower bounds on the convex roof for a large class of functions using insights from entanglement theory. It can be tackled numerically with the help of semidefinite programming and can be applied to various different problems. We demonstrate this for entanglement questions of the bipartite and multipartite setting, including: bipartite entanglement quantification via full, partial or device-independent knowledge, Schmidt rank determination, detection of genuine multiparticle entanglement and discrimination between the W and GHZ class of three qubit systems.

Bose Einstein condensates: Squeezing and beyond, Markus Oberthaler (Kirchhoff Institut für Physik, Heidelberg University)

We report on a new path for the generation of spin squeezed atomic states by employing the quantum dynamics close to an unstable fixed point of the underlying classical dynamics. This new method allows the generation of 6dB spin squeezed states on a short time scale. In the later evolution the states loose coherent spin squeezing and thus entanglement cannot be flagged by a mere variance analysis. Therefore we implemented a novel method based on distances of distribution functions for the extraction of the Fisher information of mesoscopic ensembles. With that we confirm that entanglement is still present although no squeezing observed. We will also report on our recent achievements concerning accurate atom counting of mesoscopic atomic ensembles. This is an important step towards quantum atom optics with larger atomic ensembles at the single atom level. Concluding, we will present a route for upscaling of coherent spin squeezing to large atomic ensembles. With that we recently achieved 5dB squeezing of atomic ensembles with more than 10000 atoms.

Maximally entangled states for higher local Hilbert space dimension, Andreas Osterloh (Universität Duisburg-Essen)

The maximally entangled states for qubits are so called balanced states. There it means that as many 1's occur in the state as 0's. This concept is extended to arbitrary dimension of the local Hilbert space, or spin. Based on the simplest SL invariance, the determinant, a simple rule is extracted. This rule is hence transported into a set of equations, a state has to satisfy for being called "balanced". The "irreducibly balanced" states play a crucial role among these "maximally entangled" states, which are those states that are detected by some SL invariant.

Unified approach towards detection of quantum correlations, Michał Oszmaniec (Center For Theoretical Physics PAS)

Given a class of pure states of an arbitrary quantum system we call a mixed state non-correlated if it can be expressed as a convex mixture of states from this class. We give a general sufficient criterion for deciding whether a given mixed state is correlated. Our criterion is given by a simple formula involving expectation value of some hermitian operator acting on many copies of a considered quantum state. Our criterion is valid for arbitrary dimension of the considered Hilbert space. We implement our method to particular classes of pure states: separable states, separable bosonic states, Slater determinants and fermionic Gaussian states. We study typical correlation properties of mixed states belonging the set of isospectral density matrices. Using our criterion and concentration of measure techniques we prove that for purity exceeding some critical value measure of non-correlated states on a given set of isospectral density matrices is bounded above by the factor exponentially decreasing with the dimension of the relevant Hilbert space.

Simulating Excited-State Many-Body Dynamics with Trapped Ions, Phil Richerme (University of Maryland & NIST)

For quantum systems of only 30 interacting spins, it can become difficult or impossible to calculate frustrated many-body ground states or dynamical evolution due to the exponential scaling of the Hilbert space with the system size.

Trapped-ion quantum simulators map the difficult many-body problem of interest onto a well-controlled and tunable system that can be initialized and read out using standard atomic physics techniques. Phonon-mediated spin-dependent optical dipole forces act globally on a linear chain of up to 18 trapped Yb-171+ ions to generate effective spin-spin interactions, with the form and range of such interactions controlled by laser and trap parameters. State-dependent fluorescence imaging of the ions onto a camera allows for readout of the individual spin states. I will describe two experiments that probe the excited-state dynamics in this effective many-body system. In the first, we have developed a coherent spectroscopic technique to resolve the excited state energy levels of our effective many-body system and verify the experimentally applied Hamiltonian. This technique also allows for the creation of entangled W-type states and the measurement of a critical gap near a quantum phase transition. In the second experiment, we perform a global quench in a long-range interacting system and measure the speed at which correlations propagate through the ion chain, observing velocities which violate Lieb-Robinson type predictions and cannot be explained by any current theory. We expect that such studies of many-body dynamics will be a prime use of quantum simulators as system sizes are extended to 30+ spins, where classical computations become intractable.

This work was supported by grants from the U.S. Army Research Office with funding from IARPA, the DARPA OLE program, and the MURI Hybrid Quantum Circuits program; and the NSF Physics Frontier Center at JQI.

Bipartite versus multipartite entanglement in many-body systems, Anna Sanpera (UAB Barcelona)

In this talk I will review key concepts linking entanglement with quantum many-body systems. In particular, I want to discuss how the entanglement content of the many-body systems reflects many key properties of the many-body system, including critical parameters, excitations, etc. Finally, we will address the question of multipartite entanglement. Although frequently present in many-body systems it is really necessary to describe these complex systems?

Multipartite Entanglement Classification for Permutational Invariant States, Mikel Sanz (University of the Basque Country)

A complete entanglement classification is one of the main open questions in quantum information science. We present here an entanglement classification invariant under SLOCC for N-qubit permutationally-invariant states[1,2]. We use the Majorana representation of the aforementioned states to define a classification criterion of the different families which has a natural experimental realization. Additionally, we analyze the connection of these results with the many-body formalism known as Matrix Product States, establishing non-trivial links between techniques in tensor networks and entanglement classification[3].

[1] T. Bastin, S. Krins, P. Mathonet, M. Godefroid, L. Lamata, and E. Solano, Phys. Rev. Lett. 103, 070503 (2009).
[2] T. Bastin, C. Thiel, J. von Zanthier, L. Lamata, E. Solano, and G. S. Agarwal, Phys. Rev. Lett. 102, 053601 (2009).
[3] M. Sanz, H. Saberi, L. Lamata, and E. Solano, in preparation.

Practical tomography of many atoms, Roman Schmied (University of Basel)

In our experiment we entangle hundreds of Rubidium-87 atoms within a Bose-Einstein condensate [1], and have successfully used these entangled states for quantum metrology [2]. While quantum metrology is an entanglement witness [3], our goal is to quantify the non-classicality of our experimental states in more detail. As our quantum system is very large, a full tomographic reconstruction of its density matrix is certainly infeasible. We present a didactic overview of techniques that we are applying to extract as much information on the density matrix as possible from our measurements, including inverse (backprojection) methods [4] as well as maximum likelihood and Bayesian mean estimates [5], and discuss their applicability to our system and their capability to quantify entanglement via the quantum Fisher information.

[1] M. F. Riedel et al., Nature 464,1170 (2010).
[2] C. F. Ockeloen et al., PRL 111,143001 (2013).
[3] A. S. Srensen et al., PRL 86,4431 (2001).
[4] R. Schmied et al., New J. Phys. 13,065019 (2011).
[5] R. Blume-Kohout, New J. Phys. 12,043034 (2010).

Generation of macroscopic singlet states in a cold atomic ensemble, Robert Sewell (ICFO-The Institute of Photonic Sciences)

Macroscopic singlet states are highly entangled states that appear as ground states of condensed matter model systems, for example the anti-ferromagnetic Heisenberg model, and are of interest to current activities in quantum simulation using optical lattices [1,2]. They are also interesting in quantum metrology, where singlet states have been proposed for sub-projection-noise detection of magnetic field gradients [3]. An ideal singlet has total angular momentum with zero mean and zero variance, a truly zero angular momentum. Approximate singlets can be identified with spin squeezing inequalities for unpolarized states [4], which show that total spin variance below a standard quantum limit (SQL) implies entanglement among the spins. We generate approximate singlet states using the tools of measurement-induced spin squeezing: quantum non-demolition measurement [5,6] and coherent magnetic rotations [7,8]. By squeezing all three spin components, we approach the zero of total spin. Perhaps surprisingly, the uncertainty relations permit simultaneous squeezing of all components of the angular momentum when the mean value of angular momentum is zero [9]. Using a cold rubidium atomic ensemble and near-resonant Faraday rotation probing, we have observed up to 2.8 dB of squeezing relative to the SQL, and a violation of the SSI by more than 3 standard deviations.

[1] A. Klein, D. Jaksch, Simulating high-temperature superconductivity model Hamiltonians with atoms in optical lattices, Phys. Rev. A73, 053613(2006).
[2] Kai Eckert, Oriol Romero-Isart, Mirta Rodriguez, Maciej Lewenstein, Eugene S. Polzik, Anna Sanpera, Quantum non-demolition detection of strongly correlated systems, Nature Physics 4, 50-54(2008).
[3] Iñigo Urizar-Lanz, Philipp Hyllus, Iñigo Luis Egusquiza, Morgan W. Mitchell, and Géza Tóth, Macroscopic singlet states for gradient magnetometry, Phys. Rev. A 88, 013626(2013).
[4] Géza Tóth, Christian Knapp, Otfried Gühne, and Hans J. Briegel, Optimal Spin Squeezing Inequalities Detect Bound Entanglement in Spin Models, PHys. Rev. Lett. 99, 250405 (2007).
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Entanglement resources of noisy cluster states, Jens Siewert (UPV/EHU Bilbao and Ikerbasque, Basque Foundation for Science)

We pose the question of a mathematical characterization for the diverse entanglement resources of multipartite quantum states in the case of linear (and also more general) cluster states. We quantitatively investigate the persistence of these resources for linear clusters of a few qubits under the addition of white noise. We hypothesize what the actual resource for measurement-based quantum computation (MBQC) might be, and we prove that it vanishes at significantly lower noise levels than genuine multipartite entanglement (GME). Technically, we introduce new analytical criteria for GME detection and for the assessment of the MBQC resource.

Entanglement and Distinguishability in Quantum Interferometry, Augusto Smerzi (QSTAR, INO-CNR and LENS, Firenze, Italy)

Entanglement is deeply connected to the concept of distinguishability of quantum states. Two systems can be more easily recognized to be different if they are quantum rather than classically correlated. This has important implications in interferometric precision measurements, quantum phase transitions and in foundational problems as the quantum Zeno paradox.

Characterization and manipulation of frequency entangled qudits, André Stefanov (University of Bern, Institute of Applied Physics)

Entangling qudits, the d-dimensional extension of qubits, has been shown to give more insights into the nature of entanglement compared to the simplest entanglement system composed of a bipartite two-level system. We demonstrate here a new way to encode qudits in the frequency spectrum of broadband entangled photons generated by continuous wave parametric down-conversion and detected in coincidence by sum frequency generation. By means of experimental methods used to shape fs-laser pulses, the photons spectra is subdivided into frequency-bins. Controlling each frequency component individually then allows to characterize and manipulate the quantum states. The dimension of the entangled qudit states is in practice only limited by the optical resolution of the setup. Entangled qudits are generated up to d = 4 and characterized by quantum state tomography. We further measure the Bell parameter for both, maximally and non-maximally entangled qubit and qutrit states. The here discussed method to implement and manipulate entangled qudits is intrinsically phase stable and offers the possibility to encode qudits not only as frequency bins but also as time-bins or any other encoding scheme based on frequency entanglement.

Physics of the 1D long range Ising model in a transverse field, Luca Tagliacozzo (ICFO)

Long range interacting systems can show different behaviour from their short range version. Recently experiments with trapped ions have started to investigate them. I will charaterize the ground state and low energy excitations of the long range Ising model in a transverse field, the simplest interacting long range model in 1D. In particular I will focus on the complexity of the ground state wave function in terms of entanglement measure and more traditional spin correlations. I will also present some results about the violation of causality when the long range interactions decay slowly enough with the distance. I will also briefly review the experiments with trapped ions that have confirmed our predictions.

Analysing multi-qubit entangled quantum states, Harald Weinfurter (LMU Munich)

With the number of qubits increasing steadily in experiments we need simple and efficient schemes to evaluate the quality as well as basic properties of the states. We present several optimized schemes for classification, entanglement detection and quantum state tomography. We show the usability of the methods in multi-photon experiments and discuss their benefits but also their weak points.

Entanglement of Trapped Ions using MAGIC , Christof Wunderlich (University of Siegen)

Unsurpassed control of the quantum degrees of freedom of individual particles has been achieved with trapped ions. When contemplating the scalability of trapped ions for quantum information science one notes that the use of laser light for *coherent manipulation* gives rise to fundamental and technical issues. Recently, however, laser-less addressing of ions in a magnetic field gradient and Magnetic Gradient Induced Coupling (MAGIC) between ion spins and their motion using radio-frequency radiation has been demonstrated [1].

Here, we report on the demonstration of essential features of a trapped ion spin "molecule" that exhibits long range spin-spin interactions due to MAGIC [2], analogous to J-coupling between nuclear spins in molecules. Resonances of individual spins are well separated and are addressed with high fidelity. Quantum CNOT gates are carried out using rf radiation. In addition, we characterize experimentally the spin-spin-coupling in strings of two and three ions and prove the dependence of this coupling on the trap frequency which can be used to create tailored coupling patterns relevant, for instance, for quantum simulations.

The addressing of a particular qubit within a quantum register is a key prerequisite for scalable quantum computing. We demonstrate addressing of individual qubits within a quantum byte (eight qubits) and measure a crosstalk associated with the application of single-qubit gates on the order of 10^{-5} breaching the threshold for fault-tolerant quantum computing.

Decoherence due to fluctuating magnetic fields can be strongly suppressed using microwave-dressed states [3]. At the same time, using dressed states retains the magnetic gradient-induced coupling. Fast quantum gates even with a small effective Lamb-Dicke-parameter are possible. This approach is generic and applicable also to laser-based gates as well as other types of physical qubits. Furthermore, dynamical decoupling (DD) sequences are applied to protect CNOT gates. The sequences employed here are robust against imperfections of DD pulses that otherwise may destroy quantum information or interfere with gate dynamics. A CNOT gate is implemented, despite the gate time being more than one order of magnitude longer than the intrinsic coherence time of the system [4].

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2.2 Posters

(alphabetically by last name)

Generation of quadrature squeezed light using phase conjugate mirror in optical fiber, Abhishek Anchal (Indian Institute of Technology, Kanpur)

tba

Accuracy bounds for gradient metrology with a single atomic ensemble, Iagoba Apellaniz (U. of the Basque Country)

We study gradient magnetometry with atomic ensembles. The accuracy bounds for the estimation of the gradient for a single atomic ensemble is determined, assuming that the state of the ensemble is permutationally invariant. Our bounds are obtained from calculations based on the multi-parametric quantum Fisher information, and they are generally valid for all possible measurements. A setup with a single atomic ensemble has several advantages: (i) the spatial resolution can be better and the experimental requirements are smaller since they are globally prepared, and (ii) single ensemble states insensitive to homogeneous also be used and they make it possible to measure the gradient without the need to measure the homogeneous fields, for instance singlet states, can also be used and they make it possible to measure the gradient without the need to measure the homogeneous field.

A novel proposal for entanglement detection and estimation in continuous variable systems, Ali Asadian (Atominstitut)

tba

On the identification of N-qubit maximally entangled symmetric states, Dorian Baguette, T. Bastin, J. Martin (Université de Liège)

Maximally entangled states can serve as a useful resource in many different contexts. It is therefore important to identify those states. Here we are interested in the identification of maximally entangled states in the symmetric subspace of an N-qubit system. By maximally entangled states, we refer to symmetric states characterized by a one qubit reduced density matrix proportional to the identity. These states maximise various entanglement measures [1] such as von Neumann and Meyer-Wallach entropy and are unique up to LU in their SLOCC class [2]. We give a physical interpretation of maximally entangled states in the symmetric subspace in terms of collective spin and we identify and characterize all maximally entangled symmetric states up to 4 qubits. We provide general conditions for a symmetric state with an arbitrary number of qubits to be maximally entangled and identify families of SLOCC classes which do not contain any maximally entangled states.

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Separability for Weak Irreducible Matrices, Daniel Cariello (Universidad Complutense de Madrid)

This work is devoted to the study of the separability problem in the field of Quantum Information Theory. The results described here are in [1].

Let $A \in M_k \otimes M_m$ be a positive semidefinite Hermitian matrix with the following Hermitian Schimidt decomposition, $A = \sum_{i=1}^{n} \gamma_i \otimes \delta_i$. We proved that if A is PPT then A has another Hermitian Schmidt decomposition, $A = \sum_{i=1}^{n} \gamma_i' \otimes \delta_i'$, such that γ_i', δ_i' are positive semidefinite hermitian matrices for every i. Therefore A is separable. This result is the first part of the theorem that we call *split decomposition* for PPT matrices. We defined the notion of weak irreducible matrix, based on the concept of irreducible state defined recently in [2] and [3]. This split decomposition theorem together with the notion of weak irreducible matrix, imply that the PPT matrices are weak irreducible or a sum of weak irreducible PPT matrices. We also provided a complete description of weak irreducible PPT matrices. The separability problem can be reduced to the set of weak irreducible PPT matrices. This reduction and the complete description of this set can be seen as a generalization of the main result of [4]. Using the fact that every positive semidefinite Hermitian matrix with tensor rank 2 is separable, we found a sharp inequality providing separability for PPT matrices. It's worth mentioning that all the theorems described above for PPT matrices are also true for another class of matrices with a nice symmetric property.

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Local unitary equivalence of locally maximally entangleable states, Marti Cuquet, B. Kraus (Institut für Theoretische Physik, Universität Innsbruck)

Multipartite states are present in many quantum information applications: one-way quantum computation, error correcting codes and secret sharing. One of the main goals of quantum information theory is to understand the non-local properties of quantum states. Although bipartite entanglement is now well understood, a complete understanding of multipartite entanglement is still missing. Results in this area include the identification of the minimal set of 3- and

4-qubit states from which any other state can be obtained deterministically via local operations and classical communication (LOCC), the complete classification of equivalent classes of 3- and 4-qubit states under stochastic LOCC and necessary and sufficient conditions for local unitary (LU) equivalence of n-partite states. Recently, it has also been shown that any positive homogeneous function of degree smaller or equal to 4 and invariant under determinant-1 SLOCC operations is an entanglement monotone.

As the number of relevant nonlocal parameters grows exponentially with the size of the system, one can think of two possible approaches to the study of multipartite entanglement: either study the entanglement properties of general but small systems, or that of large systems of a restricted class. In this work we present some results in the latter direction: we study entanglement properties of locally maximally entangleable states. This is a class of multipartite quantum states characterized by 2^n real phases, where n is the number of qubits. These are states that can be maximally entangled to local auxiliary systems using controlled operations. Prominent examples of LMESs are graph states and stabilizer states. They can be prepared by applying general multiqubit phase gates to a product state. One can associate any LMES to a weighted hypergraph, identifying each of these phase gates acting non-trivially on a subset of qubits to a weighted hyperedge connecting a subset of vertices in the hypergraph. In this regard, they can be understood as a generalization of (weighted) graph states. Here we consider a subclass of LMESs, namely π-LMESs or hypergraph states, whose phases are either 0 or π. A k-uniform hypergraph state is a π-LMES with all controlled-Z gates of order k, so the class of graph states corresponds to that of 2-uniform hypergraph states. Hypergraph states have been subject of recent attention. Some results include the inequivalence of uniform hypergraph states under the local Pauli group and the identification of the 6 LU-equivalent classes for 3-qubit hypergraph states.

Here we study local unitary (LU) equivalence of these π-LMESs or hypergraph states and show that, for generic states, the LUs one has to consider are only Pauli gates. This simplifies the characterization of LU-equivalent classes. States that are LU equivalent possess the same amount of entanglement and hence are equally useful for any kind of application. Hence for almost all π-LME states, LU equivalence reduces to the much simpler local Pauli equivalence. Important exceptions are connected graph states, which do not fall into the category of generic states. There are two direct implications of this result. First, using the local Pauli inequivalence of *uniform* π-LMESs, it follows that generic, uniform π-LMESs are also LU inequivalent. Second, application of gates Z or X to a given qubit of a π-LMESs corresponds to simple graph transformations of the associated hypergraph.

Detection of entanglement with optimal witness bases measurement, Jibo Dai (CQT, NUS)

Experiments were carried out to determine whether given two-photon states are entangled or separable, with least tomographic effort, by measuring the bases of the entanglement witnesses. Furthermore, the detections of entanglement were greatly sped up by using adaptive measurement schemes. The experiments were performed on states from classes of different ranks, and good agreements with results from computer simulations were obtained.

Entanglement criterion and nonlocality for two qudits with noise, Arijit Dutta, Junghee Ryu, Wieslaw Lakowski (Institute of Theoretical Physics and Astrophysics, University of Gdansk, 80-952 Gdansk, Poland)

We analyze the entanglement criterion of a two-qudit symmetric system by introducing dierent kinds of noisy channels. We extend the proposal, given in [1] for N-qubits to an arbitrary dimenssion d for a bi-partite system using the concept of correlation tensor method introduced in [2]. We use Gell-Mann matrices and Bloch-vectors to dene a density matrix of a bi-partite system in an arbitrary dimension d. Dierent kinds of Kraus operators in higher dimensions are introduced to describe noisy channels, e.g., local depolarizing channel and amplitude damping channel. We compute precise critical visibilities of entanglement for bi-partite d dimensional symmetric quantum states analytically with numerical results. Also, we investigate the robustness against dierent noises, e.g., white noise, amplitude damping noise and local depolarizing noise for CGLMP-inequality [3] in a two-qudit maximally entangled symmetric state. We give an analytical proof of our result in case of innite dimension.

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Negativity as a counter of entangled dimensions, Christopher Eltschka (Unversität Regensburg)

Among all entanglement measures negativity arguably is the best known and most popular tool to quantify bipartite quantum correlations. It is easily computed for arbitrary states, including mixed states, of a composite system and can therefore be applied to discuss entanglement in an ample variety of situations. We show that the negativity can be viewed as an estimator of the number of degrees of freedom in which two subsystems are entangled. As it is possible to give lower bounds for the negativity even in a device-independent setting, it is the appropriate quantity to certify quantumness of both parties in a bipartite system and to determine the minimum number of dimensions that contribute to the quantum correlations. Unlike other methods to certify the dimension of a system, it does not need an independent upper bound to the number of dimensions in order to certify quantumness.

Time-space correlation between excited three-level systems in two-photon cooperative interaction through the vacuum of electromagnetic field, Nicolae A. Enaki, Tudor Rosca (Institute of Applied Physics of Academy of Sciences of Moldova, Academiei str.5, Chisinau 2028, Republic of Moldova)

The collective decay effects between the dipole active three-level subsystems in the nonlinear interaction with dipole forbidden transitions, like $2S-1S$ of Hydrogen-like radiators, is proposed, taking into consideration the cooperative scattering and two-photon resonances through vacuum field. One of them corresponds to the situation when the total energy of the emitted two photons by the three-level radiator in the cascade configuration enters into the two-photon resonance with the dipole-forbidden transitions Hydrogen-like or Helium-like atom. Another effect corresponds to the scattering situation, when the difference of the excited energies of the two dipole-active transitions of three level radiator are in the resonance with the dipole-forbidden transitions of the Hydrogen-like radiator. These effects are accompanied with the interferences between single- and two-quantum collective transitions of the inverted radiators from the ensemble. The two particle collective decay rate is defined in the description of the atomic correlation functions. the kinetic processes as the function of time and correlation dependence between the radiators are studied.

Information Dissipation in Random Quantum Networks, Umer Farooq (University of Camerino, Italy)

We study the information dynamics in a network of spin-1=2 particles when edges representing XY interactions are randomly added to a disconnected graph accordingly to a probability distribution characterized by a weighting parameter. In this way we model dissipation of information initially localized in a single or two qubit all over the network. We then show the dependence of this phenomenon from weighting parameter and size of the network.

Entanglement dynamics of discrete and continuous variable systems subjected to dissipation, attenuation, and amplification, Sergey Filippov (Russian Quantum Center, Skolkovo, Moscow Region, Russia; Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia)

Any realistic entanglement-enabled experiment poses the question "What is the noise strength that impedes the successful experiment performance?" The answer depends on the particular noise model and the admissible degree (type) of entanglement in the noisy output state. We present the answer for particular local and global quantum channels acting on multipartite systems such as depolarization (for discrete variables) and attenuation/amplification (for continuous variables). We analyze the dynamics of entanglement structure for increasing noise levels and find the analogy with chemical processes [1]. Multipartite (genuine) entanglement behaves as a chemical compound, and the particles of environment play role of the solvent in which the entanglement compound dissociates. The solvent can act on the whole compound (global quantum noise) or particular elements of the compound (local quantum noise). The differences between these two mechanisms are in the presence of clustering stages in the case of global noise, when particles of the compound reassemble to form almost equal bipartitions, tripartions, etc. For a given quantum channel, we formulate operational sufficient conditions ensuring one or another entanglement behavior of the output. Finally, we consider the ultimate form of entanglement degradation and answer the question "What is the fundamental noise level beyond which all initial states become fully separable?" This question is complementary to the entanglement detection problem and identifies the situations when any form of entanglement is surely destroyed. The characterization of such entanglement annihilating channels is provided [2] and the crucial differences from entanglement breaking channels are discussed [3].

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Probing quantum mechanics with macroscopic continuous variable systems, Oleg Gittsovich (Institute for Theoretical Physics, University of Innsbruck)

Recent experimental progress in the control of micro- and nanomechanical resonators in the quantum regime opens up new possibilities for testing the laws of quantum mechanics on a macroscopic level. In Ref. [1] the authors introduced a simply scheme for measuring modular variables of such macroscopic continuous variable system, and showed that correlations thereof violate a Leggett-Garg inequality.

Here we describe a set of measurement protocols which generalize these ideas and pave a way for testing Bell inequalities with macroscopic superposition states. In particular, we introduce a class of quasi-eigenstates of modular variables, which can be prepared, entangled and measured using a set of experimentally feasible protocols.

Quantum dynamics of spin waves in ultracold bosonic systems, Sebastian Hild (Max-Planck-Institut für Quantenoptik)

Ultracold quantum gases in optical lattices are promising candidates to simulate spin Hamiltonians, which describe a variety of different phenomena. Single-site resolved imaging of a single spin species allows for the spatially resolved measurement of spin-spin correlations. The atomic Mott insulator corresponds to a spin polarized state with very low entropy. Together with precise local or global spin manipulation, this allows for the study of the dynamics of precisely defined initial spin states.

We report on experiments studying the dynamics of bound and free magnons following local spin flips as well as globally imprinted spin spirals, which are highly excited states of the system. The ability to control the tunneling rate in the ultracold atomic gas allows us to study the scaling behavior of the spin spiral lifetime in one and two dimensions. The data is compared with theoretical predictions based on direct diagonalization.

Analytic expressions for the genuine multiparticle negativity, Martin Hofmann, Tobias Moroder, Otfried Gühne (University of Siegen, Germany)

Entanglement is considered a very useful resource in quantum information. It is involved in some quantum key distribution protocols, quantum metrology, quantum phase transitions and many other physical applications and phenomena. Therefore it is one of the main tasks to detect and quantify entanglement, especially in the multiparticle setting. In our recent work [1] we investigate a renormalized version of the genuine multiparticle negativity, which was introduced in Ref. [2]. That is a computable mixed state monotone detecting genuine multiparticle entanglement. We show that this measure can be seen as coming from a mixed convex roof construction with naturally arising upper and lower bounds. These can be used to derive exact analytic expressions for the renormalized genuine multiparticle negativity for n-qubit GHZ-diagonal and four-qubit cluster diagonal states. These formulas are necessary and sufficient to fully characterize the set of genuine multiparticle entangled states within both families.

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Bell-type Inequality Violations in Systems of Entangled Neutral Kaons, Marius Paraschiv (University of Siegen)

The quantum mechanical violation of Bell inequalities has been thoroughly verified during the last thirty years through various ion and photon experiments. In this contribution I will present our work on the study of Bell inequality violations for pairs of entangled neutral K mesons. The important difference from the usual ion / photon cases is that K mesons decay, therefore all decay products must be included. By considering both strangeness and the combined CP operation, an analogy can be made with other, well known, two-level systems. Bell inequalities are treated both in terms of quasi spin measurements and different time measurements. A special type of inequality besides the standard CHSH inequality is the Sliwa-Collins-Gisin inequality. Besides being another example of Bell test, the investigation of entanglement in particle physics may have applications for entanglement-enhanced measurements.

Topological Geometric Entanglement: Exact Results and Numerical Calculations with Tensor Networks, Roman Orus (Johannes-Gutenberg-Universität Mainz)

Here we investigate the connection between topological order and the geometric entanglement, as measured by the logarithm of the overlap between a given state and its closest product state of blocks. We do this for a variety of topologically-ordered systems such as the toric code, double semion, color code, and quantum double models, with and without perturbations. As happens for the entanglement entropy, we find that for sufficiently large block sizes the geometric entanglement is, up to possible sub-leading corrections, the sum of two contributions: a bulk contribution obeying a boundary law times the number of blocks, and a contribution quantifying the underlying pattern of long-range entanglement of the topologically-ordered state. This topological contribution constitutes an alternative characterisation of topological order for these quantum states based on a multipartite entanglement measure. Furthermore, we analyse the robustness of the topological contribution by using a numerical Tensor Network approach based on PEPS and

MPS, which allows to extract this quantity for very large systems. Additionally we observe that, as measured by the geometric entanglement per block, there is no entanglement loss along RG flows in the studied topological quantum phase transitions.

Embedded Quantum Algorithms for Entanglement and Correlation Measurements, Julen S. Pedernales (University of the Basque Country UPV/EHU)

We introduce the concept of embedding quantum simulators, a novel paradigm allowing efficient computation of dynamical quantities requiring full quantum tomography, as is the case of entanglement monotones relying on antilinear operations [1] and n-time correlation functions [2]. The concept consists in the suitable encoding of a simulated quantum dynamics in the enlarged Hilbert space of an embedding quantum simulator. In this manner, non-trivial quantities are mapped onto physical observables, overcoming the necessity of full tomography, and reducing drastically the experimental requirements. Furthermore, we discuss a method for implementing the embedding concepts in trapped ions technologies [3]. Finally, we expect that the proposed embedding framework paves the way for a general theory of enhanced one-to-one quantum simulators.

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On the SLOCC-classification of multilevel tripartite entanglement, Christina Ritz, Matthias Kleinmann, Otfried Gühne (Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany)

The classification of entanglement regarding their invariance under SLOCC-transformations for tripartite systems has been studied thoroughly for the case of qubits whereas when dealing with higher dimensions only the case of 2x2xN has been studied in detail [1]. We present a classification for the qubit-qutrit-qutrit (2x3x3) case, based on a finite classification due to Lamata [2]. We discuss possible generalizations to the case of 2xNxN and difficulties that occur in the case of three qutrits.

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Commensurate quasiprobabilities for qudits and quantum entanglement, Junghee Ryu (University of Gdansk)

Quantum physics exhibits striking features against classical physics [1]. These are said to be nonclassical if the classical theory does not predict them. In quantum optics, a quasiprobability distribution function e.g., the Wigner function, is used to represent a joint distribution of position x and momentum p, where one observable cannot be measured without disturbing the other due to the uncertainty principle. The quasiprobability function is not always positive semidefinite for some quantum states. As it is not allowed by any classical probability distribution, the negativity is regarded as a signature of nonclassicality. However, the Wigner function and its classical counterpart can be associated with different kinds of observations, e.g. the average value of the product xp in a joint measurement, by the same functionals. This incommensurability makes it difficult to interpret the nonclassicality of the quasiprobability. This problem remains unsolved in the approaches of generalizing quasiprobability functions to discrete systems [2].

We propose an operational approach to define a commensurate quasiprobability function for discrete systems (qudits), enabling a direct comparison between quantum and classical statistics [3]. We prove that the quasiprobability function is positive semidefinite if the expectations of the measurements are described by a hidden variable model with noninvasive measurability [4]. Based on the result, we classify classical and nonclassical states of a qubit by showing the negativity of the commensurate quasiprobability function. Remarkably, we find that the nonclassicality is operationally determined in the sense that the degree of the nonclassicality depends on the observables to be measured, e.g., a measurement setup, even for a given quantum state. Finally, we derive a sufficient condition for the entanglement of two-qudit Werner states using a marginal quasiprobability function [5].

Our results suggest that a quasiprobability function can be used to detect nonclassicality of quantum systems with respect to appropriate measurement situations and to separate quantum features from classical ones. This enables one to directly compare quantum and classical statistics for a hidden variable model with noninvasive measurability. This work can be applied to demonstrate nonclassicality of physical systems and of quantum information processing, and could perhaps even help in developing a new measure of quantumness of discrete and continuous variable systems.

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Optimal LOCC conversion of 3-qubit states, Katharina Schwaiger (Institute for Theoretical Physics, University of Innsbruck)

Pure, truly tripartite entangled 3-qubit states can be transformed into either the GHZ- or the W-state with a finite success probability. In literature local protocols are provided, which achieve this transformation of a single copy of a quantum state with the maximum success probability, using only local operations and classical communication. We found simplified expressions of the maximum success probability using a specific decomposition of 3-qubit states. The dependence on the corresponding parameters was analyzed and a relation between the three-tangle and the success probability was obtained. Furthermore, we investigated transformations between general pure 3-qubit states and found optimal protocols, which achieve the maximum success probability for certain sets of states.

Efficient Tomographic Analysis of a Six Photon State, Christian Schwemmer,[1,2] Géza Tóth,[3] Alexander Niggebaum,[4] Tobias Moroder,[5] David Gross,[6] Otfried Gühne,[5] and Harald Weinfurter[1,2] (1: Max-Planck-Institut für Quantenoptik, Germany; 2: LMU University, Germany; 3: University of the Basque Country UPV/EHU, Spain; 4: University of Birmingham, UK; 5: Universität Siegen, Germany; 6: Universität Freiburg, Germany)

Quantum state tomography has become a standard tool for the experimental analysis of multi-qubit states. However, the measurement effort to obtain a tomographically complete set of data scales exponentially with the number of qubits. Moreover, also the computational resources necessary to store and to further process that data scale exponentially. Since the number of controllable qubits has been constantly rising over the last years and is very likely to increase further, the limits of full quantum state tomography will soon be reached. Hence, new approaches for scalable quantum state analysis are required. It has been shown recently, that permutationally invariant states like W, Dicke or GHZ states enable tomographic analysis with both the measurement effort and the analysis of the recorded data scaling polynomially with the number of qubits [1,2]. We apply this novel tomography scheme together with a highly efficient state reconstruction algorithm based on convex optimization to a six-photon state obtained from spontaneous parametric down-conversion. In order to test the reliability of the scheme we compare it to full tomography. Therefore, the largest complete state tomography of a photonic multi-qubit state until now has been performed [3]. The measurement effort can be further reduced by combining both schemes with compressed sensing [4]. In our experiments we show that a combination of permutationally invariant tomography and compressed sensing enables to study the influence of the UV pump power on the noise present in a six-qubit Dicke state with a measurement effort reduced by a factor of about 50 without a significant change of the parameters quantifying the state.

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Roots of completely positive maps, Ritabrata Sengupta (Indian Institute of Science Education & Research, Mohali, India)

The structure of positive maps between matrix algebras gained importance with the development of quantum information theory. Positive maps which are not completely positive can detect entangled states. Extending the works of Wolf and Cirac [10], we study various roots of completely positive (CP) maps in dimensions 3 and above. The study of roots of positive operators is an well developed subject. We try to make a similar study for the case of CP maps. In this way, we try to discover new examples of positive maps which are not CP and can potentially detect new entangled states. We also try to comment on the divisibility of CP maps and the structure of different roots (for the cases where the division is possible). This work is the first step towards a systematic study of the above mentioned problem.

On Relations Between Usual and Genuine Multipartite Entanglement for Tripartite Quantum Systems, Florian Sokoli (Arbeitsgruppe Operatoralgebren und Quantenstochastik, Fachbereich Mathematik, Technische Universtät Darmstadt)

Given a tripartite quantum state one can study its entanglement in the "usual" sense, that is in comparison to the set of fully separable states. Moreover, one can also ask whether or not such a state is generalized biseparable leading to the concept of genuine multipartite entanglement. In this context William Arveson has provided a general theory which allows the construction of norm-based entanglement measures for both kinds of entanglement. We compute these measures for GHZ-states and W-states. As a result we obtain that both measures coincide on GHZ-states. From that we can conclude that, according to Arvesons measure, W-states are less GME-entangled than GHZ-states. On the other hand W-states are known to be more entangled than GHZ-states in the usual sense. In particular, the relation between the two measures is not monotonous. Therefore, we gain some interesting insight into the geometry of tripartite quantum states.

Bound entanglement in continuous variables through degaussification, Frank Steinhoff (Universität Siegen)

In this work we propose a class of infinite-dimensional genuinely (two-mode) bipartite bound entangled states that can be unconditionally prepared in optical systems with simple extensions on current experimental techniques. Our approach is to degaussify a thermal state by a modified photon-addition followed by an incoherent mixing with a squeezed vacuum in an orthogonal polarization. These states serve as the inputs for generation of entanglement when mixed with vacuum states. The detection of entanglement is simple and is made using the well-known Range Criterion. Choosing properly the parameters involved, it is possible to design a state that is Positive under Partial Transposition (PPT), hence undistillable. As a side result we derive some theoretical insights on one-mode states nonclassical features through connections between PPT property and Hankel operator theory, which are used together with Hadamard products and Gerschgorin Disk's perturbation theorems for the proof of bound entangled states.

Engineering a Source of Multi-Photon, Multidimensional Spatially Entangled States for Quantum Control of Nanostructures, Andrea Tabacchini (Macquarie University, Sydney, Australia)

In this presentation we will put forward a scheme to generate multi-photon multidimensional entangled states. In particular, we are interested in four photon states spatially correlated, for example in the Orbital Angular Momentum (OAM) degree of freedom. These states will be suitable for enhancing the interaction with nanostructures for quantum metrology applications.

Multi-particle entangled states are becoming more and more interesting for different applications of quantum information, such that quantum multi-particle teleportation [I], entangled-based cryptography [II, III] and quantum communication schemes based on multi-particle states [IV], but also for more fundamental reasons like testing local realism by means of the Greenberger-Horne-Zeilinger states (GHZ) arguments [V, VI]. Indeed the greater the number of particles involved in the entangled state, the more clearly the quantum effects are exhibited. Our particular purpose will be to exploit the multi-photon entangled states for quantum metrology. By the interaction of those states with nanostructures (mostly nanoholes), we expect to reach sub-wavelength sensitivity phase measurements [VII, VIII] (beating the Standard Quantum Limit [IX]). The heart of our source is based on Spontaneous Parametric Down-Conversion (SPDC). In the last two decades it has been extensively studied for the generation of two-photon entangled states, since Kwiat et al. published in 1995 the new scheme based on polarization entangled photons [X]. Multi-photon entangled states are also possible to be created by SPDC. Most of the studies rely on the entanglement in the polarization degree of freedom (for instance, see [XI, XII]) or in the path of the down converted beams [XIII]. Our aim is to generate down-converted photons which are entangled in a spatial degrees of freedom, i.e. in the momentum or in the orbital angular momentum of photons. In order to reach our purposes, we will exploit the high non-linearity offered by periodically-poled KTP crystals, which leads to very high brightness down-converted beams. We designed an optical apparatus based on a two-crystal configuration for type-0 SPDC [XIV]. The pairs generated this way are well known to be inherently entangled in the polarization degree of freedom. They are also inherently entangled in the OAM [XV]. By properly shaping the pump [XVI], its possible to engineer the spatial profile of the down-converted photons, i.e. to project the bi-photon state on a desired superposition of spatial eigenmodes (for instance eigenmodes of the OAM such as the Laguerre-Gaussian modes [XVII]).

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Microtrap Arrays on a Magnetic Film Atom Chip for Quantum Information Science, Lara Torralbo-Campo (University of Amsterdam)

We present our latest results based on two-dimensional Ioffe-Pritchard type microtraps arrays created using a patterned permanent-magnetic film atom chip [1]. We have recently demonstrated the loading of 87Rb ultracold atoms simultaneously in 600 square and hexagonal lattices with 400 atoms/trap and T=30 ?K in average. This is an easily scalable system well suited for quantum information using Rydberg blockade [2] . Furthermore, the downscaling of the microtraps to sub-optical dimensions could lead to a quantum simulator in a parameter regimen no yet accessible for conventional techniques [3].

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Multiparticle singlet states and their metrological applications, Iñigo Urizar-Lanz (University of the Basque Country)

Singlet states are quantum states of vanishing angular momentum. When composing the angular momenta of 2 spin-1/2 particles, there exists a unique singlet. If we are dealing with an ensemble of N spin-j particles, things get more involved. We present a precise definition for multipartite SU(2) and SU(d) singlet states, and then we focus on the Permutationally Invariant (PI) ones. Their basic properties and a characterization of them are given, and some specific PI singlets are studied for metrological applications. We calculate the maximum achievable accuracy when measuring the gradient of a magnetic field using these states and we find which is the measurement that saturates the bound given by the quantum Fisher Information.

Spin squeezing and entanglement for arbitrary spin, Giuseppe Vitagliano (University of the Basque Country)

We discuss the problem of finding inequalities useful to detect entanglement in systems of many particles with a spin higher than 1/2. We look for entanglement criteria that are based on the measurement of collective spin components and their moments, analogous to the approach followed in [1], where the so called spin squeezing inequality has been introduced for spin-1/2 particle systems. These are separability criteria based on the first and second moments of the collective angular momentum operators and detect states that have immediate applications, e.g. in quantum metrology. The result of Ref. [1] has been later generalized in several directions: a complete set of spin squeezing inequalities (SSIs) was derived in [2] and was then extended to arbitrary spin-j particle systems in [3]. Here we follow the same approach and present the following new results [4]:

(i) We present the complete set of conditions for the $j > 1/2$ case, that we call optimal spin squeezing inequalities for spin-j particles.

(ii) We present a generalization of the original spin squeezing parameter of Ref. [1] that can be used for entanglement detection for particles with $j > 1/2$.

(iii) We define a new spin squeezing parameter and show that in the large particle number limit it detects strictly more states than the original spin squeezing parameter of Ref. [1] and its generalization for particles with $j > 1/2$ already mentioned in (ii).

(iv) Finally, we will present other spin squeezing parameters that are tied to detect planar squeezed states and states close to the singlet state.

All the quantities appearing in these parameters are easily accessible in current experiment with many body systems because they involve only measurements of the first two moments of collective spin operators. Moreover our set of parameters detect all states that can be detected with these quantities and is more tolerant to noise than other spin squeezing parameters. Therefore our results can be immediately used in experimental systems such as BEC and atomic ensembles to prove entanglement in the state with few measurements and with higher tolerance to noise with respect to other approaches based on spin squeezing criteria.

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The Cauchy-Schwarz inequality: A powerful tool to detect entanglement, Sabine Wölk (University of Siegen)

Entanglement is an important resource for quantum cryptography, quantum computing and quantum metrology. So far, no entanglement criteria exist, which are necessary and sufficient for all states. Therefore, many different criteria coexist. Some of them are in the form of inequalities of expectation values. These criteria are especially useful for experimental application.

In this talk, we show how to derive such entanglement criteria by using two non-hermitian operators per subsystems and the help of the Cauchy-Schwarz inequality. In this way, new criteria and already existing criteria can be proven. In the bipartited case the collectivity of criteria derived with Cauchy-Schwarz are closely connected to the PPT-criterion. However, our criteria do not require a complete state tomography, a few measurement direction are sufficient. Furthermore, in the multipartite case, our criteria can also detect entangled states, which are biseparable under every bipartition and can therefore not be detected by the PPT-criterion.

Entanglement properties of permutation invariant many-body singlet states, Zoltán Zimborás, I. Urizar-Lanz, G. Tóth (UPV/EHU, Bilbao)

The poster presents our study of the structure of many-body singlet states, focusing especially on the entanglement properties. Such states can be created in experiments with atomic ensembles, and it has been suggested that they may play an important role in quantum metrology, especially in measuring gradients of magnetic fields. As singlet states, by definition, are supported on the 0-spin subspace of the angular momentum algebra, representation theory provides the natural mathematical tools for our investigations. Using these tools, we determine the reduced density matrices for various singlet states, and calculate different entanglement(-like) measures such as the von Neumann and Rnyi entropies, various squeezing parameters, and the quantum Fisher information.

3 Participants

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