# Q 50: Quantum Gases (Bosons) V

Time: Wednesday 14:00–16:00 Location: K 2.020

Q 50.1 Wed 14:00 K 2.020

**Detecting genuine multipartite entanglement in a spatially extended Bose-Einstein condensate** — •Philipp Kunkel, Maximilian Prüfer, Helmut Strobel, Daniel Linnemann, Anika Frölian, Thomas Gasenzer, Martin Gärttner, and Markus K. Oberthaler — Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg

The ability to produce genuine multipartite entangled states between addressable modes is a prerequisite for engineering states relevant for quantum information tasks such as measurement based quantum computation. We use contact interactions in a tightly confined Bose-Einstein condensate of $^{87}$Rb to generate an entangled state of indistinguishable particles in a single mode. Subsequent expansion of the atomic cloud in a shallow waveguide potential distributes this entanglement spatially making it addressable via local operations. We verify Einstein-Podolsky-Rosen steering between distinct regions of the expanded atomic cloud by analyzing the correlations between different parts of the absorption image. We show that bipartite steering serves as a witness for genuine multipartite entanglement. With this we demonstrate genuine up to 5-partite entanglement in the elongated condensate.

Q 50.2 Wed 14:15 K 2.020

**Many-body interference in a bosonic Josephson junction** — •Gabriel Dufour[1,2], Jasper Dohse[1], Tobias Brünner[1], Alberto Rodríguez[1], and Andreas Buchleitner[1] — [1]Physikalisches Institut, Albert-Ludwigs-Universität-Freiburg, Hermann-Herder-Straße 3, D-79104, Freiburg, Germany — [2]Freiburg Institute for Advanced Studies, Albert-Ludwigs-Universität-Freiburg, Albertstraße 19, D- 79104 Freiburg, Germany

The interference of two photons on a balanced beamsplitter reveals their mutual degree of indistinguishability, with the probability of measuring one photon in each output mode going from zero if the photons are identical, to one half if they are fully distinguishable, as demonstrated in the Hong-Ou-Mandel experiment [1]. We extend this line of thought to the case of many interacting bosons trapped in a double-well potential and study how the evolution is affected when the bosons can be distinguished through an internal degree of freedom. Based on the structure of the underlying many-body Hilbert space, we identify dynamical signatures of the initial state's degree of distinguishability both in the weakly and strongly interacting regimes [2,3].

[1] C.K. Hong, Z.Y. Ou, L. Mandel, Phys. Rev. Lett. 59, 2044 (1987)

[2] G. Dufour, T. Brünner, C. Dittel, G. Weihs, R. Keil, A. Buchleitner, arXiv:1706.05833 (2017), to appear in NJP

[3] T. Brünner, G. Dufour, A. Rodríguez, A. Buchleitner, arXiv:1710.08876 (2017)

Q 50.3 Wed 14:30 K 2.020

**Entanglement between two spatially separated atomic modes** — •Alexander Idel[1], Karsten Lange[1], Jan Peise[1], Bernd Lücke[1], Ilka Kruse[1], Guiseppe Vitagliano[2,3], Iagoba Apellaniz[3], Matthias Kleinmann[1], Géza Tóth[3,4,5], and Carsten Klempt[1] — [1]Institut für Quantenoptik, Leibniz Universität Hannover — [2]Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences — [3]Department of Theoretical Physics, University of the Basque Country UPV/EHU — [4]IKERBASQUE, Basque Foundation for Science — [5]Wigner Research Centre for Physics, Hungarian Academy of Sciences

Large ensembles of ultra-cold atoms offer the possibility to generate an unprecedented level of multi-particle entanglement. However, the creation relies on the fundamental indistinguishability of the particles. Entanglement between spatially addressable systems is required for most applications in the field of quantum information. We employ spin changing collisions in a $^{87}$Rb BEC to generate entanglement. By utilizing the natural mode structure of the spin resonances we show entanglement between two spatially separated modes. We prove the entanglement between the modes with a novel criterion, which accounts for imperfections of the state preparation, e.g. varying atom numbers in our condensate and the imperfect symmetry of the state.

Q 50.4 Wed 14:45 K 2.020

**Periodic Quantum Rabi Model with Ultracold Rubidium Atoms in an Optical Lattice** — •Johannes Koch[1], Trim Kasabaci[1], Martin Leder[1], Simone Felicetti[2], Enrique Rico[3,4], Carlos Sabin[5], Enrique Solano[3,4], and Martin Weitz[1] — [1]Institut für Angewandte Physik der Universität Bonn, Wegelerstr. 8, D-53115 Bonn, Germany — [2]Laboratoire Matériaux et Phénomènes Quantiques, Sorbonne Paris Cité, Université Paris Diderot, CNRS UMR 7162, 75013, Paris, France — [3]Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain — [4]IKERBASQUE, Basque Foundation for Science, Maria Diaz de Haro 3, E-48013 Bilbao, Spain — [5]Instituto de Física Fundamental, CSIC, Serrano 113-bis, E-28006 Madrid, Spain

The quantum Rabi model describing the interaction between a two-level quantum system and a single bosonic mode has been thoroughly studied in the moderate and strong coupling regimes. Here we investigate the model in the deep strong coupling regime, where a pattern of collapse and revival of the initial quantum state is expected. Our experimental implementation to simulate the quantum Rabi model uses ultracold rubidium atoms in a tailored optical lattice potential, with the two-level system being represented by the occupation of Bloch bands of the lattice. This effective qubit interacts with a quantum harmonic oscillator provided by an optical dipole potential. Using atom interferometric techniques, the revival of the phase imprinted initial state is observed. The present status of the experiment will be presented.

Q 50.5 Wed 15:00 K 2.020

**Al'tshuler-Aronov-Spivak oscillations of coherent bosonic matter-wave beams in the presence of interaction** — •Renaud Chrétien[1], Josef Rammensee[2], Cyril Petitjean[1], and Peter Schlagheck[1] — [1]CESAM research unit, University of Liege, 4000 Liège, Belgium — [2]Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany

We theoretically study the propagation of a guided atom laser across an Aharonov-Bohm ring exposed to a synthetic gauge field. The presence of disorder within the ring gives rise to Al'tshuler-Aronov-Spivak oscillations [1], seen in the disorder-averaged transmission as a function of the effective gauge flux that is contained within the ring. Those oscillations are induced by coherent backscattering and represent a manifestation of weak localization. Through analytical and numerical calculations based on the mean-field Gross-Pitaevskii approximation for the propagating Bose-Einstein condensate, we show that the presence of a weak atom-atom interaction within the ring leads to an inversion of the AAS oscillations, in a very similar manner as for the coherent backscattering of Bose-Einstein condensates within two-dimensional disorder potentials [2]. Truncated Wigner simulations reveal that this signature of weak antilocalization becomes washed out if the interaction strength is increased, which is in qualitative agreement with the findings of the diagrammatic study undertaken in Ref. [3].

[1] B. L. Al'tshuler, et. al., JETP Lett. 33, 94 (1981).

[2] M. Hartung, et. al., PRL. 101, 020603 (2008).

[3] T. Geiger, et. al., New J. Phys. 15, 115015 (2013).

Q 50.6 Wed 15:15 K 2.020

**A noiseless matter wave readout amplifier for atom interferometry** — •Daniel Linnemann, Philipp Kunkel, Helmut Strobel, Maximilian Prüfer, Stefan Lannig, Rodrigo Rosa-Medina Pimentel, Martin Gärttner, Thomas Gasenzer, and Markus K. Oberthaler — Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, Heidelberg

We present a quantum-enhanced atom interferometer whose output state is magnified by a noiseless readout amplifier for matter waves. In presence of spurious technical detection noise, subsequently amplifying the interferometer's output can improve the overall sensitivity.

The amplification process which usually degrades the signal-to-noise ratio by at least three decibels, is rendered noiseless in our scheme by entangling the amplifier with its input. In this way, non-classical correlations are leveraged in two respects: they enhance the interferometer's phase sensitivity and facilitate the readout.

Experimentally, we employ spin exchange in a Bose-Einstein condensate as the underlying entangling interaction. This scattering process among spins can be understood as parametric amplification. We detail the noise characteristics when using spin exchange as a phase-preserving linear amplifier. Attaching the amplification stage to an interferometer, we explicitly demonstrate that quantum-enhanced phase sensitivity is maintained even for large magnifications of the signal.

Q 50.7 Wed 15:30 K 2.020

**Beating the classical precision limit with spin-1 Dicke state** — Yi-Quan Zou, •Ling-Na Wu, Qi Liu, Xin-Yu Luo, Shuai-Feng Guo, Jia-Hao Cao, Meng Khoon Tey, and Li You — State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084, China

Entanglement plays an important role in quantum information and precision measurement. The generation of entangled states thus constitutes a research frontier and tremendous progresses along this direction have been made during the past decade. Among the variety of entangled states, Dicke states form an important class. Most of the Dicke states produced to date are limited to pseudo-spin-1/2 (two-level) particles. Here, we report the first generation of a balanced spin-1 Dicke state in a Bose Einstein condensate. We also demonstrate its application in precision measurement by performing a precise rotation angle measurement with the generated state as input, which leads to a measurement sensitivity beyond the classical limit.

Q 50.8 Wed 15:45 K 2.020

**Emergence of striped states in quantum ferrofluids** — •Antun Balaž[1] and Axel Pelster[2] — [1]Scientific Computing Laboratory, Center for the Study of Complex Systems, Institute of Physics Belgrade, University of Belgrade, Serbia — [2]Physics Department and Research Center OPTIMAS, Technical University of Kaiserslautern, Germany

In the recent experiment [1], striped states in a many-body system of tilted dipoles were observed in a quantum ferrofluid of a strongly dipolar BEC of dysprosium, leading to a formation of atomic droplets. In Ref. [2] it was demonstrated that the stability of such droplets is due to a quantum fluctuation correction of the ground-state energy [3, 4]. Here we extend this previous theoretical description and develop a full Bogoliubov-Popov theory, which also takes into account the condensate depletion due to quantum fluctuations. We apply our novel approach to study in detail the emergence of striped states and their properties. To this end we perform extensive numerical simulations and determine how the critical tilting angle depends on both the atom number and the trap geometry. Our investigations turn out to be relevant for extracting the yet unknown s-wave background scattering length of dysprosium from the experiments of Ref. [1].

[1] M. Wenzel, et al., arXiv:1706.09388 (2017).
[2] L. Chomaz, et al., Phys. Rev. X **6**, 041039 (2016).
[3] T. D. Lee, et al., Phys. Rev. **106**, 1135 (1957).
[4] A. R. P. Lima and A. Pelster, Phys. Rev. A **84**, 041604(R) (2011); Phys. Rev. A **86**, 063609 (2012).