Q 3: Quantum Information: Concepts and Methods I

Time: Monday 11:00–13:00 Location: e214

Q 3.1 Mon 11:00 e214

Testing Bell's inequality with atoms entangled over a distance of 400m — •Daniel Burchardt[1], Robert Garthoff[1], Norbert Ortegel[1], Kai Redeker[1], Markus Rau[1], Wenjamin Rosenfeld[1,2], and Harald Weinfurter[1,2] — [1]Ludwig-Maximilians-Universität, Munich, Germany — [2]Max-Planck-Institut für Quantenoptik, Garching, Germany

Bell's inequality allows to exclude local hidden variable theories and forms the basis for certified generation of random numbers and device-independent quantum key distribution. Experimentally it requires highly efficient and spacelike separated measurements on entangled particles.

We present our approach using heralded entanglement of two neutral ^{87}Rb-atoms [1]. Based on state selective ionization and detection of the ionization fragments, we implemented a sub-μs atomic state readout with very high detection efficiency [2]. To close the locality loophole the two setups were separated by a distance of 400m. We will discuss the critical experimental details, namely the control of the coherence properties of the atoms and the synchronisation of both setups and present first results of a test of Bell's inequality.

[1] J. Hofmann et al., Science 337, 72 (2012).
[2] F. Henkel et al., Phys. Rev. Lett. 105, 253001 (2010).

Q 3.2 Mon 11:15 e214

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres — •Andreas Reiserer[1,2], Bas Hensen[1,2], Hannes Bernien[1,2], Anais Dreau[1,2], Norbert Kalb[1,2], Machiel Blok[1,2], Juist Ruitenberg[1,2], David Elkouss[2], Stephanie Wehner[2], Tim Taminiau[1,2], and Ronald Hanson[1,2] — [1]Kavli Institute of Nanoscience, TU Delft, The Netherlands — [2]QuTech, TU Delft, The Netherlands

More than 50 years ago, John Bell proved that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. Meanwhile, many experiments that violate Bell's inequality have been reported. However, all of these experiments relied on additional assumptions, most prominently the absence of signaling between the entangled particles, and fair-sampling of the full dataset when using inefficient detectors. Closing the *loopholes* that arise from these assumptions has been one of the major research goals of experimental quantum physics, with applications ranging from device independent quantum key distribution to the certification of random numbers.

In our experiment, we entangle two Nitrogen-vacancy (NV) centers in diamond that are located in independent setups at a distance of 1.3km. Efficient spin read-out avoids the fair-sampling assumption, while the use of fast random-basis selection and spin read-out ensure the required locality conditions. This has enabled us to perform a loophole-free test of Bell's inequality.

Q 3.3 Mon 11:30 e214

Quantum non-demolition measurement enables macroscopic Leggett-Garg tests — •Costantino Budroni[1], Giuseppe Vitagliano[2], Giorgio Colangelo[3], Robert J. Sewell[3], Otfried Gühne[1], Geza Tóth[2], and Morgan W. Mitchell[3] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, D-57068 Siegen, Germany — [2]Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain — [3]ICFO – Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain

We show how a test of macroscopic realism based on Leggett-Garg inequalities (LGIs) can be performed in a macroscopic system. Using a continuous-variable approach, we consider quantum non-demolition (QND) measurements applied to atomic ensembles undergoing magnetically-driven coherent oscillation. We identify measurement schemes requiring only Gaussian states as inputs and giving a significant LGI violation with realistic experimental parameters and imperfections. The predicted violation is shown to be due to true quantum effects rather than to a classical invasivity of the measurement. Using QND measurements to tighten the "clumsiness loophole" forces the stubborn macrorealist to re-create quantum back action in his or her account of measurement.

References
C. Budroni, G. Vitagliano, G. Colangelo, R.J. Sewell, O. Gühne, G. Tóth, and M.W. Mitchell Phys. Rev. Lett. **115**, 200403 (2015)

Q 3.4 Mon 11:45 e214

Quantifying the clumsiness in a Leggett-Garg test — •Giuseppe Vitagliano[1], Costantino Budroni[2], Giorgio Colangelo[3], and Morgan W. Mitchell[3,4] — [1]Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain — [2]Naturwissenschaftlich-Technische Fakultat, Universitat Siegen, Walter-Flex-Str. 3, D-57068 Siegen, Germany — [3]ICFO – Institut de Ciencies Fotoniques, Av. Carl Friedrich Gauss, 3, 08860 Castelldefels, Barcelona, Spain — [4]ICREA – Institucio' Catalana de Recerca i Estudis Avancats, 08015 Barcelona, Spain

Leggett-Garg tests aim to witness macroscopic quantum coherence effects through the violation of an inequality involving correlations among measurements, at different instants of time, of a macroscopic quantity. However, clumsy measurements are able to violate a Leggett-Garg inequality even in absence of genuine quantum effects. We formalise the notion of clumsiness in a Leggett-Garg test and, starting from the simplest examples, we provide a general recipe for computing the clumsiness parameter in any LG test. Finally, we analyse in detail the clumsiness parameter of a recent proposal for a Leggett-Garg test on atomic ensembles via simulations with realistic experimental parameters.

Q 3.5 Mon 12:00 e214

Information Inequalities for Classical and Quantum Networks — •Nikolai Miklin[1], Rafael Chaves[2], and Costantino Budroni[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, 57068 Siegen, Germany — [2]Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany

Causal dependencies among random variables can be investigated via information-theoretic quantities (e.g. Shannon entropy, mutual information, etc.): for unconstrained variables, their entropies form a convex cone and causal dependencies can be added as linear constraints [1]. However, such a method is computationally demanding in the case of restrictions on the observable variables (e.g., latent variables, marginal scenarios), since it involves the projection of the entropy cone via the Fourier-Motzkin method, which has a double exponential complexity [2]. Actual computation has been performed in case of few variables.

To overcome such problems, we develop alternative techniques (e.g. based on adhesivity of entropies [3]) able to completely characterize scenarios with higher number of variables. Finally, we apply these techniques to investigated several new causal structures associated both with classical and quantum scenarios such as Bell scenarios, classical and quantum networks.

[1] R. Chaves, et al. Proc UAI 2014, pp. 112 - 121, AUAI Press, 2014
[2] A. Schrijver, Theory of Linear and Integer Programming, John Wiley & sons, 1998
[3] F. Matúš, Discrete Mathematics 307.21, 2007

Q 3.6 Mon 12:15 e214

Measurement uncertainty is larger than preparation uncertainty — •Reinhard F. Werner, Kais Abdelkhalek, David Reeb, and René Schwonnek — Inst. für Theoret. Physik, Leibniz Universität Hannover

Measurement uncertainty is the quantitative expression of the non-existence of a joint measurement of two observables A and B. It relates the minimal errors one incurs in any attempt at approximate joint measurement and, in particular, in successive measurements like Heisenberg's microscope. This is conceptually different from the usual preparation uncertainty which expresses that there are no states in which both observables have a sharp distribution. Nevertheless, as the new result reported here shows, under very general circumstances preparation uncertainty bounds also give a lower bound on measurement uncertainty. We establish a chain of inequalities involving in decreasing order (1) the errors in a joint measurement based on an approximate quantum cloner (2) the lower bounds on measurement uncertainty, when devices are tested with arbitrary input state (3) the same when the tests are of calibration type, i.e., involve only states with known sharp results for the reference observable and (4) preparation uncertainty. For the standard case of position and momentum (and more generally for observables linked by the Fourier transform on an abelian group) all these inequalities are equalities, but we also give examples showing that each of them may be a proper inequality.

Q 3.7 Mon 12:30 e214

Uncertainty relations for angular momentum — •Lars Dammeier, René Schwonnek, and Reinhard F. Werner — Institut für Theoretische Physik, Leibniz Universität Hannover

In this talk we present various notions of uncertainty for angular momentum in the spin-s representation of SU(2). This is a natural example of how the concept of uncertainty applies to more than two non-commuting observables. For preparation uncertainty we present a method for computing the trade-off regions, and show results for various values of s. Concerning measurement uncertainty, we optimize a joint measurement of all three components such that the distribution of the projection of the output vector in any direction approximates the distribution of the corresponding angular momentum component.

Q 3.8 Mon 12:45 e214

Measurement uncertainty relations in discrete metric — •René Schwonnek, Louis Fraatz, Kais Abdelkhalek, David Reeb, and Reinhard F. Werner — Institut für Theoretische Physik, Leibniz Universität Hannover

Given two non-commuting sharp observables what is the best joint measurement approximating them? A quantitative answer to such a question is given by a measurement uncertainty relation. In this talk we consider observables with finite outcome spaces and employ the Wasserstein metric to quantify the distance between an approximate observable and a sharp one. We will show how this optimization problem can be solved exactly for arbitrary observables by semi-definite programming. Furthermore, we provide analytic lower bounds on the measurement uncertainty in terms of the norms of certain commutators.