# MON 9: Quantum Entanglement

Time: Monday 14:15–16:15 Location: ZHG101

MON 9.1 Mon 14:15 ZHG101

**Measurable entanglement lower bounds for cold atom quantum simulators using kinetic operators** — •Maike Reckermann[1], Niklas Euler[1,2], and Martin Gärttner[1] — [1]Institute of Condensed Matter Theory and Optics, Friedrich-Schiller-University Jena, Germany — [2]Physikalisches Institut, Universität Heidelberg, Deutschland

The entanglement dimension plays a key role for understanding quantum many-body phenomena such as topological order, recently realized with cold atoms in lattice geometries. Although, it is challenging to measure the entanglement spectrum directly, the entanglement dimension, which is the number of non-zero values in the spectrum, can be lower bounded with measurements in two bases using fidelity witnesses. We develop a method to bound the entanglement dimension, using the information contained in the measurement of kinetic operators in double wells, which was recently pioneered with ultracold bosonic atoms in a 2D optical lattice. We also develop a method to estimate reliable error intervals for the fidelity witnesses, which are obtained using semi-definite programming. We demonstrate our scheme by showing that it can be used to detect entanglement between two attractively interacting distinguishable atoms in 1D and 2D lattice geometries.

MON 9.2 Mon 14:30 ZHG101

**Analytical structures in high-dimensional entanglement** — •Robin Krebs and Mariami Gachechiladze — Technische Universität Darmstadt, Darmstadt, Hesse, Germany

Efficient and generic methods for analyzing high-dimensional entanglement are crucial for scalable and resilient quantum computation and quantum communication protocols. Understanding the necessary mathematical structures requires analyzing high Schmidt number (SN) PPT states. We prove a generalization of the projection property, which relates the Schmidt number of a quantum state with its lower-dimensional projections. Then, we introduce the concept of a local extension, increasing local dimensions and entanglement content. This new method is then used to construct an extreme point of the PPT set in dimensions 4x5 with SN 3, the lowest dimensional known instance of SN 3 PPT entanglement. To accurately detect the SN for such extreme points, a sufficient and necessary generalization of the range criterion is introduced. We also present various examples of the implications of these results for the structure of high-dimensional entanglement.

MON 9.3 Mon 14:45 ZHG101

**Metrological entanglement criteria** — •Szilárd Szalay[1] and Géza Tóth[1,2] — [1]Wigner Research Centre for Physics, Budapest, Hungary — [2]University of the Basque Country UPV/EHU, Bilbao, Spain

We show that the quantum Fisher information in quantum metrology in a multiparticle system provides a lower bound on the average size of entangled subsystems. Before it has been known only that the quantum Fisher information puts a lower bound on the entanglement depth. We illustrate the strength of this new criterion and compare it to the previous approach.

[1] Sz. Szalay and G. Tóth, Quantum 9, 1718 (2025)
[2] Sz. Szalay, Quantum 3, 204 (2019)

MON 9.4 Mon 15:00 ZHG101

**Exact steering bound for two-qubit Werner states** — •Martin J. Renner — ICFO - The Institute of Photonic Sciences, 08860 Castelldefels, Barcelona, Spain

Many quantum technologies rely on nonlocality, correlations between distant particles that defy classical explanation. To harness this, it's essential to know which quantum states can or cannot display nonlocal behavior. A seminal 1989 result by Reinhard Werner showed that some entangled states can be fully explained by local models, but only under the restricted class of projective measurements. We extend this result for two-qubit Werner states to the most general class of measurements, known as positive operator-valued measures (POVMs). Our model identifies exactly which of these states can demonstrate quantum steering, the effect Einstein famously called "spooky action at a distance." Surprisingly, we find that POVMs offer no advantage over projective measurements for revealing steering in these states, resolving a long-standing open question in quantum foundations. Beyond this, our results have implications for measurement incompatibility: we determine the critical visibility under white noise at which all qubit measurements become jointly measurable.

Reference: MJ Renner, Compatibility of Generalized Noisy Qubit Measurements, Phys. Rev. Lett. 132, 250202

MON 9.5 Mon 15:15 ZHG101

**Chiral Symmetries of Multiparticle Entanglement** — •Sophia Denker[1], Satoya Imai[2], and Otfried Gühne[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany — [2]QSTAR, INOCNR, and LENS, Largo Enrico Fermi 2, 50125 Firenze, Italy

Symmetries play a central role in physics. Particularly in entanglement theory many works investigate the separability of states with certain symmetries. However, while in bipartite systems quantum states can show symmetric or antisymmetric behavior, when exploring multipartite systems also quantum states with chiral symmetries can appear.

In this work we investigate chiral subspaces with respect to their entanglement properties. Starting with the case of three qubits we show that these subspaces are highly entangled with respect to their geometric measure of entanglement and are further related to measurements that are useful to estimate entanglement. We then consider these spaces in higher dimensions and define operators related to the structure constants of Lie algebras whose eigenspace coincides with the sum of those chiral subspaces. These operators act as strong entanglement witnesses, which can detect genuine multipartite entangled states with positive partial transpose. Moreover, while we find that these operators are sums of permutations and therefore invariant under unitary transformations, we further translate those operators to sums of permutations and their partial transposed leading to subspaces invariant under orthogonal transformations, which are even more entangled.

MON 9.6 Mon 15:30 ZHG101

**Improved bounds on Quantum Max-Cut via entanglement theory constraints** — •Minh Duc Tran, Lucas Vieira, and Mariami Gachechiladze — Department of Computer Science, Technical University of Darmstadt, Darmstadt, 64289 Germany

The Quantum Max-Cut (QMC) problem is a paradigmatic example in the study of many-body physics and quantum Hamiltonian complexity. While variational methods present lower bounds on the energy of the most exciting state of the given Hamiltonian, semidefinite programming (SDP) hierarchies have been used to obtain upper bounds by solving a relaxed problem. The feasible points for the solutions, which in the relaxed problem may not represent valid quantum states, are then rounded back to a valid state to obtain the approximation ratio. There are two potential venues for improvements: first, speeding up convergence of the SDP by adding extra constraints, and second, improving the rounding schemes. In this work, we present an improved SDP relaxation of QMC for arbitrary graphs by applying polynomial constraints from entanglement theory, achieving tighter bounds on the true values compared to existing approximations. We further extend this framework to the rounding schemes by using the solutions of the SDPs to obtain better initial parameters for variational algorithms.

MON 9.7 Mon 15:45 ZHG101

**Symmetric extensions for the geometric measure of entanglement** — •Lisa T. Weinbrenner[1], Xiao-Dong Yu[2], and Otfried Gühne[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany — [2]Department of Physics, Shandong University, Jinan 250100, China

Entanglement plays an important role in quantum information theory and is often considered to be a resource for quantum metrology, quantum cryptography or other applications. As such, there is an ongoing search for characterization and quantification techniques, measuring the amount and usefulness of entanglement in quantum states. One possible approach is given by the geometric measure of entanglement, which quantifies the entanglement of a state by its distance to the separable states. Although this measure is easily defined, it is known to be in general hard to obtain for multipartite states. The aim of this contribution is to investigate how the geometric measure can be determined by using multiple copies of the state and applying different symmetrization arguments, deriving a hierarchy for the geometric measure.

MON 9.8 Mon 16:00 ZHG101

**Strong quantum nonlocality in multipartite system** —
•Mengying Hu[1,2], Ting Gao[1], and Fengli Yan[3] — [1]School of Mathematical Sciences, Hebei Normal University, Shijiazhuang 050024, China — [2]University of Siegen, Siegen, Germany — [3]College of Physics, Hebei Normal University, Shijiazhuang 050024, China

Strong quantum nonlocality is a stronger form of nonlocality than that manifested by locally indistinguishable quantum states. It has efficient applications in quantum information hiding and quantum secret sharing. We construct strongly nonlocal orthogonal genuinely entangled sets and strongly nonlocal orthogonal genuinely entangled bases in an N -qutrit system, which provide an answer to the open problem in Ref. [Phys. Rev. Lett. 122, 040403 (2019)]. The strongly nonlocal orthogonal genuinely entangled set we constructed in N-qutrit systems contains much fewer quantum states than previous one. When $N > 3$, our result answers the open question in Ref. [Phys. Rev. A 104, 012424 (2021)]. A sufficient and necessary condition for the strongest nonlocality in general $N$-partite systems is presented. We successfully construct the strongest nonlocal genuinely entangled sets in $(C^d)^{\otimes N}$ for $d \geq 4$, which have a smaller size than the existing sets as N increases.