QI 10: Quantum Information: Concepts and Methods I

Time: Wednesday 9:30–12:45 Location: BEY/0137

QI 10.1 Wed 9:30 BEY/0137

Deciding finiteness of Hamiltonian algebras I — •David Edward Bruschi, Tim Christoph Heib, and Robert Zeier — Forschungszentrum Jülich, Jülich, Germany

The ability to exactly obtain the dynamics of a physical system is a core goal of most areas of modern physics. Full knowledge of the state of a system at all times would be of greatest advantage for a myriad of tasks of current interest, such as quantum simulation, computing, and control. Quantum dynamics are characterized by the non-commutativity of operators in the Hamiltonian, which in turn implies that analytical solution are, in general, impossible to obtain. A standard way to approach this problem is to use of ad-hoc solutions or numerical techniques. While this allows for a better understanding of the physical processes of interest, such understanding remains only partial, and the question of how to obtain full control over the dynamics remains open.

We introduce a novel approach to determine the dimensionality of a Hamiltonian Lie algebra of interacting bosonic systems by appropriately classifying the space of its generating terms, thereby dividing the space of arbitrary linear Hermitian operators into classes with a meaningful physical interpretation. A first main result on the constraints that must be fulfilled by Hamiltonians without drift in order for the Hamiltonian Lie algebra to be finite-dimensional is obtained. Extension of this work to the classification of such algebras for one self-interacting bosonic mode is also provided. Our work has important implications for theoretical (quantum) physics as well as the theory Lie algebras.

QI 10.2 Wed 9:45 BEY/0137

Deciding finiteness of bosonic dynamics II — •Tim Heib — Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, 52425 Jülich, Germany — Theoretical Physics, Universität des Saarlandes, 66123 Saarbrücken, Germany

Determining the exact dynamics of a given system is paramount in most areas of physics, especially in quantum mechanics. A well-known method for systematically solving these dynamics by factorizing the time-evolution operator into a finite product of exponentials is the Wei-Norman method.

Recently, a new approach has been proposed to investigate the classes of Hamiltonians for which this method is applicable. This involves analyzing the dimensionality of Hamiltonian Lie algebras by appropriately characterizing their generating terms. In our work, we generalize previous results by significantly extending their applicability to a broader class of physically relevant bosonic Hamiltonians. We reduce the complexity of verifying finiteness conditions from quadratic to linear, and we also introduce a visual algorithm to implement the corresponding procedure. Furthermore, we identify a universal Lie algebraic structure encompassing all finite-dimensional algebras within this framework. Our contributions represent a substantial step toward a comprehensive classification of Hamiltonian Lie algebras, with potential impact for practical applications in quantum technologies.

QI 10.3 Wed 10:00 BEY/0137

Identification of unital channels without mixed-unitary representation — •Charlotte Bäcker and Walter Strunz — Dresden University of Technology, Dresden, Germany

Unital quantum channels are characterized by their property of leaving the maximally mixed state invariant. Among these channels are mixed-unitary channels, which can be represented as a probabilistic mixture of unitary operations. For qubits ($d = 2$), any unital channel is also mixed-unitary, however this does not hold for $d > 2$. A well-known, open NP-hard problem is to distinguish between these two classes of channels in higher-dimensional quantum dynamics. This question is relevant not only from a theoretical perspective but also for applications in quantum technology (e.g., error correction). In this talk, we will present a new method to identify non-mixed-unitary channels using tools from quantum memory theory. After introducing the relevant concepts, we will demonstrate how this method allows for a more sensitive characterization, illustrated by specific examples.

QI 10.4 Wed 10:15 BEY/0137

Understanding Quantum Reservoir Computing through the lens of Krylov Complexity — •Saud Cindrak, Lina Jaurigue, and Kathy Lüdge — Technische Universität Ilmenau, Ilmenau, Deutschland

Recent years have seen growing interest in using information-theoretic and dynamical measures to characterize quantum systems. Krylov complexity, in particular, quantifies how an operator or state spreads within a Krylov basis and distinguishes integrable from chaotic dynamics.

Here we show that time-evolved states and operators generate the same Krylov space, leading to a natural formulation of time-dependent Krylov spaces. Instead of relying on Krylov complexity, we introduce an effective phase-space dimension on the Krylov space that does not inherently assign larger complexity to states deeper in the Krylov chain. We term this measure Krylov observability (for operators) and Krylov expressivity (for states).

We then compare Krylov observability with the data generalizability of a quantum reservoir computer, quantified by its information processing capacity (IPC), and find that the two exhibit almost identical behavior. Lastly, we introduce a quantum Zeno time for operators and use it to further clarify the behavior of Krylov observability up to the Heisenberg time obtained from level statistics.

[1] S. Čindrak, L. Jaurigue, K.Lüdge, Phys. Rev. Res. 7, L042039
[2] S. Čindrak, L. Jaurigue, K.Lüdge, Phys. Rev. Res. 7, 043190
[3] S. Čindrak, L. Jaurigue, K.Lüdge, J. High Energ. Phys 2024, 83

QI 10.5 Wed 10:30 BEY/0137

Characterizing Criteria of Non-Markovian Dynamics and Quantum Memory — •Nick Maryshchak, Charlotte Bäcker, and Walter Strunz — Dresden University of Technology, Dresden, Germany

The occurrence of non-Markovianity in the dynamics of open quantum systems gives rise to the classification of memory phenomena. While in classical dynamics, non-Markovian processes are well defined, there is no unique quantum analogue. Several concepts of quantum non-Markovianity have been proposed, based for example on divisibility of the quantum map or on distinguishability of quantum states. We examine the fraction of non-Markovian dynamics in regard to different criteria in the state space of time-discrete dynamics. A growing debate is whether these memory effects are of truly quantum origin. In the subclass of non-Markovian dynamics, we examine different proposed witnesses for quantum memory and their relation among themselves.

QI 10.6 Wed 10:45 BEY/0137

Use of Neural Networks to Reconstruct Information on NV-Center Spin Registers — •Alessia Camuti Borani[1], Matthias Müller[2], and Tommaso Calarco[1,2,3] — [1]Università di Bologna — [2]Forschungszentrum Jülich — [3]Universität zu Köln

The presentation will focus on the use of Neural Networks to reconstruct information about spin states in NV-center platforms from computational-basis measurement outcomes. Neural Networks can in fact serve as a more efficient alternative to standard reconstruction protocols, thanks to their ability to detect patterns in data.

The quantum platform we simulate consists of the electronic spin of a Nitrogen-Vacancy (NV) defect in diamond, used for initialization and readout, together with the surrounding nuclear carbon spins, which serve as the actual qubits.

In the first part of the talk, we will discuss results on full-state tomography of spin states in NV-center registers using Neural Networks. We will compare the performance obtained when feeding the network with Pauli-basis measurement outcomes to that of a randomized protocol, in which randomly selected gates are applied prior to measurement. In the second part of the talk, we will instead present results on the reconstruction of observables of NV-center systems, rather than full density matrices.

30min. break

QI 10.7 Wed 11:30 BEY/0137

Entanglement quantification with randomized measurements is maximally difficult — Julian Eisfeld and •Nikolai Wyderka — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, 40225 Düsseldorf, Germany

The certification of quantum systems is essential for emerging quantum technologies, particularly in quantum communication, networks, and distributed computing, where maintaining a common reference frame across distant nodes poses significant challenges. Reference frame independent approaches, such as randomized measurement schemes, offer a promising route by reducing experimental demands while granting access to basis-independent quantities, including entanglement. However, the efficiency of such schemes in measuring local invariants has remained unclear.

In this contribution, we determine the minimal number of measurement settings required to access all two-qubit invariants using randomized measurement schemes. We further demonstrate that entanglement certification necessarily involves the most demanding invariants, establishing it as a maximally difficult task. Our results reveal a fundamental hierarchy among invariants, with direct implications for experimental feasibility and theoretical understanding of quantum certification. Finally, we extend our analysis beyond bipartite systems by applying it to the Kempe invariant in three-qubit systems, providing a first step toward uncovering similar hierarchies in higher dimensions.

QI 10.8 Wed 11:45 BEY/0137

The three kinds of three-qubit entanglement — •Szilárd Szalay — Wigner Research Centre for Physics, Budapest, Hungary

We construct an important missing piece in the entanglement theory of pure three-qubit states, which is a polynomial measure of W entanglement, working in parallel to the three-tangle, which is a polynomial measure of GHZ entanglement, and to the bipartite concurrence, which is a polynomial measure of bipartite entanglement. We also show that these entanglement measures are ordered, the bipartite measure is larger than the W measure, which is larger than the GHZ measure. It is meaningful then to consider these three types of three-qubit entanglement, which are also ordered, bipartite is weaker than W, which is weaker than GHZ, in parallel to the order of the three equivalence classes of entangled three-qubit states.

QI 10.9 Wed 12:00 BEY/0137

Gaussian fermionic embezzlement of entanglement — •Alessia Kera, Lauritz van Luijk, Alexander Stottmeister, and Henrik Wilming — Institute for Theoretical Physics, Leibniz University Hanover, Hanover, Germany

Embezzlement of entanglement allows to extract arbitrary entangled states from a suitable embezzling state using only local operations while perturbing the resource state arbitrarily little. A natural family of embezzling states is given by ground states of non-interacting, critical fermions in one spatial dimension. This raises the question of whether the embezzlement operations can be restricted to Gaussian operations whenever one only wishes to extract Gaussian entangled states.

In our work we showed that this is indeed the case and proved that the embezzling property is in fact a generic property of fermionic Gaussian states. Our results provide a fine-grained understanding of embezzlement of entanglement for fermionic Gaussian states in the finite-size regime and thereby bridge finite-size systems to abstract characterizations based on the classification of von Neumann algebras. To prove our results, we established novel bounds relating the distance of covariances to the trace-distance of Gaussian states, which may be of independent interest.

QI 10.10 Wed 12:15 BEY/0137

The relative entropy of magic and its nonadditivity — •Carolin Deckers, Justus Neumann, Hermann Kampermann, and Dagmar Bruss — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, 40225 Düsseldorf, Germany

The resource theory of magic is a theoretical framework that quantifies the non-stabilizer quantum resource "magic", which is crucial for universal quantum computation. To quantify the amount of magic in states or operations, measures such as the relative entropy of magic have been introduced. The relative entropy of magic is a subadditive measure. Previous results [R. Rubboli, R. Takagi, and M. Tomamichel, Quantum 8, 1492 (2024)] have shown that this measure is additive for a special class of states. We show that for n-qubit product states, the relative entropy of magic is not additive if the states do not belong to that special class and fulfill an additional condition.

QI 10.11 Wed 12:30 BEY/0137

Characterizing covariance matrix and entanglement with finite Fourier transformed Observables — •Dimpi Thakuria[1], Konrad Szymański[2], Shuheng Liu[1], and Giuseppe Vitagliano[1] — [1]Atominstitut, Technische Universität Wien, Stadionallee 2, 1020 Vienna, Austria — [2]Research Center for Quantum Information, Slovenská Akadémia Vied, Dúbravská cesta 9, 84511 Bratislava, Slovakia

In Quantum physics, a covariance matrix provides us a means to certify a physically valid quantum system (through its positive semidefiniteness). It constrains the allowed quantum states and fully characterizes the Gaussian states. In continuous variable systems the covariance matrix is known to capture key properties like entanglement, squeezing, the purity of the states etc.. In this work we explore these concepts in the context of the discrete phase-space observables in finite-dimension, focusing on canonical position/momentum observables linked by finite Fourier transforms. Our approach is complementary to the typical way of using finite-dimensional Heisenberg-Weyl framework (especially discrete-displacement operators) for studying such systems. We characterize the allowed states via characterization of the invariants : the trace and the determinant of the covariance matrix. We also study the structure of the allowed covariance matrix transformations in the discrete phase-space, as well as the underlying Hilbert space. Our insights help us to discuss applications like entanglement detection in finite-dimensional systems, akin to covariance matrix criteria in continuous-variable systems.