Q 23: Quantum Information I

Time: Tuesday 16:30–18:30 Location: P

Q 23.1 Tue 16:30 P

Continuous vs. discrete truncated Wigner approximation for driven, dissipative spin systems — •Christopher D. Mink[1], David Petrosyan[2], and Michael Fleischhauer[1] — [1]Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, 67663 Kaiserslautern, Germany — [2]Institute of Electronic Structure and Laser, FORTH, GR-71110 Heraklion, Crete, Greece

We present an alternative derivation of the recently proposed discrete truncated Wigner approximation (DTWA) for the description of the many-body dynamics of interacting spin-1/2 systems. The DTWA is a semi-classical approach based on Monte-Carlo sampling in a discrete phase space which improves the classical treatment by accounting for lowest-order quantum fluctuations. We provide a rigorous derivation of the DTWA based on an embedding in a continuous phase space. We derive a set of operator-differential mappings that yield an exact equation of motion (EOM) for the continuous spin Wigner function. The truncation approximation is then identified as neglecting specific terms in the exact EOM, allowing for a detailed understanding of the quality of the approximation and possible systematic improvements. Furthermore, we show that the continuous TWA (CTWA) yields a straightforward extension to open spin systems. We derive exact stochastic differential equations for dephasing, decay and incoherent pump processes, which in the standard DTWA are plagued by problems such as non-positive diffusion. We illustrate the CTWA by studying the dynamics of dissipative 1D Rydberg arrays and compare it to exact results for small systems.

Q 23.2 Tue 16:30 P

Euclidean volume ratios for entanglement and detectability by Bell inequalities in bipartite quantum systems — •Alexander Sauer[1], József Zsolt Bernád[1,2], Héctor Moreno[1], and Gernot Alber[1] — [1]Institut für Angewandte Physik, Technische Universität Darmstadt — [2]Peter Grünberg Institute (PGI-8), Forschungszentrum Jülich

Euclidean volume ratios between quantum states with positive partial transpose and all quantum states in bipartite systems are investigated. These ratios allow quantitative exploration of the typicality of entanglement and of its detectability by Bell inequalities. With our numerical approach, which is based on the Peres-Horodecki criterion and the hit-and-run algorithm, we obtain reliable results for qubit-qudit and qutrit-qutrit systems [1]. With the help of the Clauser-Horne-Shimony-Holt inequality and the Collins-Gisin inequality the degree of detectability of entanglement is investigated for two-qubit quantum states.

[1] Sauer, A., et al., Journal of Physics A: Mathematical and Theoretical 54.49 (2021): 495302.

Q 23.3 Tue 16:30 P

Towards EIT ground-state cooling of a lattice of individually trapped atoms — •Apurba Das, Deviprasath Palani, Florian Hasse, Lennart Guth, Amir Mohammadi, Ulrich Warring, and Tobias Schaetz — Physikalisches Institut, Hermann-Herder-Str. 3, 79104 Freiburg i. Br.

Customized trap architectures for single trapped atoms with suitable local and global control fields enable us to set up and tune increasingly complex quantum systems with a high level of control. For individual state control and coupling of internal and external degrees of freedom in the system, we typically implement two-photon stimulated Raman transition. In our future work, in addition to our established control features, we want to bring ground state cooling based on electromagnetically-induced transparency to enable broadband cooling of multiple modes to deterministically prepare the system to its global ground state. This will allow us to prepare our $^{25}Mg^{+}$ arrays for further quantum operations more efficiently. Here in this presentation, we give an overview of required technical developments, recent advancements and discuss important steps towards near-future applications.

Q 23.4 Tue 16:30 P

Quantum computing with Rydberg Atoms — •Christoph Rupprecht, Philipp Ilzhöfer, Christian Hoelzl, Jennifer Krauter, Tilman Pfau, and Florian Meinert — 5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart

In the race of building a quantum computer, several different platforms like superconducting circuits, trapped ions and nitrogen vacancy centers are competing in terms of scalability and fidelity. Our project 'QRydDemo' aims to develop a quantum computer demonstrator based on arrays of up to 500 Strontium Rydberg atoms in optical tweezer arrays. Exploiting a so far unexplored qubit encoded in the 3PJ fine structure levels capable of realizing 'triple-magic-wavelength' tweezer traps, we want to improve the coherence properties of the Rydberg platform by orders of magnitude aiming for up to 10 ms coherence time and ~100ns-long single- and two-qubit gate operations [1]. Our machine will be able to shift atoms within a single row of 2D trap arrays individually and fast, which will allow for rearranging the array during a computation, providing new algorithmic possibilities and advantages for realizing multi-qubit gates. We plan to benchmark our architecture by demonstrating advantages of these multi-qubit gates for the calculation of two-dimensional fermionic systems and the implementation of basic aspects for quantum error correction on the Rydberg platform.

[1] F. Meinert, T. Pfau, C. Hölzl, EU Patent Application No. EP20214187.5

Q 23.5 Tue 16:30 P

Towards benchmarking two-qubit quantum processor — •Hardik Mendpara[1,2], Nicolas Pulido-Mateo[1,2], Markus Duwe[1,2], Giorgio Zarantonello[3], Henning Hahn[4], Amado Bautista-Salvador[1,2,4], Ludwig Krinner[1,2], and Christian Ospelkaus[1,2,4] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]PTB, Bundesallee 100, 38116 Braunschweig — [3]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA — [4]QUDORA Technologies GmbH

A prerequisite for a scalable quantum computing platform is to perform elementary gates with a low rate of error. One can quantify the error per gate using randomized benchmarking schemes which are independent of the state-preparation and measurement error [1,2]. Here, we implement the elementary gates (single- and two-qubit gates) using microwaves. The control fields are generated by microwave conductors embedded directly into the trap structure. Using this fully integrated microwave approach, we obtain a preliminary infidelity of 10^{-4} for single-qubit gates and approaching 10^{-3} for two-qubit operations [3]. Further, to better characterize the performance of two-qubit entangling gates, we will report on our recent progress in benchmarking our two-qubit quantum processor in a computational context using the protocol described in [1,2].

[1] J. Gaebler *et al.*, Phys. Rev. Lett. **109**, 179902 (2012)
[2] A. Erhard *et al.*, Nat. Commun. **10**, 5347 (2019)
[3] G. Zarantonello et al., Phys. Rev. Lett. 123 260503 (2019)

Q 23.6 Tue 16:30 P

Apparatus design for three new cryogenic trapped-ion quantum computing experiments — •Lukas Kilzer, Tobias Pootz, Celeste Torkzaban, Timko Dubielzig, and Christian Ospelkaus — Institut for Quantum optics, Leibniz University Hannover

Further progress in trapped-ion quantum computing requires a dramatic increase in the number of ion qubits that can interact with each other, development of more integrated systems including optical waveguides, and sympathetic cooling provided by a secondary ion species to keep qubits cold without destroying their stored quantum state. We aim in our next generation of cryogenic trapped ion quantum computers to be able to engineer interactions between dozens of qubits, implement sympathetic cooling, and incrementally test and characterize new components necessary for further scaling. This poster will provide an overview of the design for the cryostats and elaborate on particular design challenges faced while integrating components developed by several other teams. Each cryostat will house a cryogenic inner vacuum chamber inside a room-temperature outer vacuum chamber, a socket-mounted surface RF trap, a cryogenic RF resonator, a cryogenic Schwarzschild objective for detecting ion fluorescence, a vibration isolation system protecting the experiment from vibrations of the cold head, feedthroughs for hundreds of DC lines and several high frequency lines, and extra space for the future integration of optical fibers. These experiments are being developed in collaboration with other research groups at LUH, the University of Siegen, TU Braunschweig, and PTB.

Q 23.7 Tue 16:30 P

Trapped Ion Architecture for Multi-dimensional Quantum Simulations — •Deviprasath Palani, Florian Hasse, Apurba Das, Ulrich Warring, and Tobias Schaetz — Physikalisches Institut, Hermann-Herder-Str. 3, 79104 Freiburg i. Br.

A rich and powerful toolbox for individually trapped atomic ions is available for quantum information processing, including quantum metrology and quantum simulation, demonstrating control with the highest fidelities. Building on this success, our architecture for analogue quantum simulations aims at setting up fully controlled and reconfigurable quantum lattices by individually trapped ions in multidimensional arrangements [1]. In this presentation, we give an overview of recent developments and demonstrations of prototype operations. We discuss features and limitations of our architecture and lay out crucial steps toward mid and long-term simulation applications.

[1] U. Warring, F. Hakelberg, P. Kiefer, M. Wittemer, T. Schaetz, Adv. Quantum Technol. 2020, 1900137.

Q 23.8 Tue 16:30 P

Towards high-fidelity Mølmer-Sørensen gate in a cryogenic surface-electrode ion trap — Niklas Orlowski[1], •Niels Kurz[1], Timko Dubielzig[1], Sebastian Halama[1], Chloë Allen-ede[1], Celeste Torkzaban[1], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]Physikalisch-Technische-Bundesanstalt Braunschweig, Bundesallee 100, 38116 Braunschweig

Practical scalable quantum computing requires quantum logic gate errors below 10^{-4} in order for error-correction strategies to work. The microwave near-field approach for trapped-ion quantum logic gates has the potential to be scalable and has been shown to allow entangling gates on $^9Be^+$ ions in a room temperature surface trap with infidelities approaching 10^{-3}. In an equivalent cryogenic setup based on a similar trap structure [2], we expect the infidelity contribution due to anomalous motional heating to be strongly suppressed. We describe technical improvements in our setup that aim at reducing other sources of infidelities related to the motion of the ions to similar levels. We characterize the shift of mode frequencies that occur during gate operations due to heating effects in constant duty-cycle sequences and evaluate the performance of a newly installed, galvanically coupled RF resonator with regard to the radial mode stability.

Q 23.9 Tue 16:30 P

A symmetric RF X-junction for register-based surface-electrode ion traps compatible with the near-field microwave approach — •Florian Ungerechts[1], Rodrigo Munoz[1], Axel Hoffmann[1,2], Brigitte Kaune[1], Teresa Meiners[1], and Christian Ospelkaus[1,3] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — [2]Institut für Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover, Appelstraße 9a, 30167 Hannover, Germany — [3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Register-based ion traps are among the leading approaches for scalable quantum processors. A fundamental component of these are junctions that allow the ions to be moved between the specialized zones of the quantum processor via ion transport. We discuss the design and optimization of such a junction and further present a symmetric RF X-junction with a shallow pseudopotential barrier and a substantial trap depth that is feasible for multilayer microfabrication. Furthermore, we present a transition zone making the symmetric RF X-junction compatible with an asymmetric RF near-field microwave gate-zone. Moreover, we present time-dependent transport voltages for reliable multi-zone and through-junction ion transport of a single $^9Be^+$ ion.

Q 23.10 Tue 16:30 P

A Quantum Enhanced Learning Algorithm for Maze Problems — •Oliver Sefrin and Sabine Wölk — Institut für Quantentechnologien, Deutsches Zentrum für Luft- und Raumfahrt, 89077 Ulm, Deutschland

In reinforcement learning, a so-called agent should learn to optimally solve a given task by performing actions within an environment. As an example, we consider the grid-world, a two-dimensional maze for which the shortest way from an initial position to a given goal has to be found. The agent receives rewards for helpful actions which enables him to learn optimal solutions.

For large action spaces, a mapping of actions to a quantum setting can be beneficial in finding rewarded actions faster and thus in speeding up the learning process. A hybrid agent which alternates between classical and quantum behavior has been developed previously for deterministic and strictly epochal environments. Here, strictly epochal means that an epoch consists of a fixed number of actions, after which the environment is reset to its initial state.

We present and analyze strategies which aim at resolving the hybrid agent's current restriction of searching for action sequences with a fixed length. This is a first step towards applying the hybrid agent on environments with a generally unknown optimal action sequence length such as in the grid-world problem.

Q 23.11 Tue 16:30 P

Software-Struktur für die Internetanbindung eines Ionenfallen-Quantencomputers — •Christian Melzer[1], Janine Hilder[1], Fabian Kreppel[2], Janis Wagner[1], Björn Lektisch[1], Ulrich Poschinger[1], André Brinkmann[2] und Ferdinand Schmidt-Kaler[1] — [1]QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany — [2]Zentrum für Datenverarbeitung, Universität Mainz, Anselm-Franz-von-Bentzel-Weg 12, 55128 Mainz, Germany

Segmentierte Ionenfallen sind ein erfolgversprechender Kandidat für skalierbare Quantencomputer mit hoher Operationsgüte. Um Algorithmen auf eine solche Architektur abbilden zu können, wird eine mehrschichtige Softwarestruktur benötigt. Diese muss beliebige Quanten-Schaltkreise auf native Gatter abbilden können, die erzeugten Gattersequenzen optimieren und anschließend die Ionenkonfigurationen über die Zeit hinweg kontrollieren. Dabei müssen Randbedingungen wie Fehleranfälligkeiten unterschiedlicher Operationen, Kohärenzzeiten, Streulicht und Inhomogenitäten des Magnetfelds berücksichtigt werden. Für eine möglichst effiziente Kontrolle über den Quantencomputer erlaubt es die entwickelte Softwarestruktur, auf drei unterschiedlichen Abstraktionsebenen zu arbeiten: universelle Quantenschaltkreise, architekturabhängige Operationssequenzen und präzise Kontrollsignale.

Q 23.12 Tue 16:30 P

Assessing the Precision of Quantum Simulation of Many-Body Effects in Atomic Systems using the Variational Quantum Eigensolver Algorithm — •Sumeet Sumeet[1,2,3], V. S. Prasannaa[3], B. P. Das[4], and B. K. Sahoo[5] — [1]Lehrstuhl fur Theoretische Physik I, Staudtstraße 7,FAU Erlangen-Nuremberg, D-91058 Erlangen, Germany — [2]Qu & Co B.V., Palestrinastraat 12H, 1071 LE Amsterdam, The Netherlands — [3]Centre for Quantum Engineering, Research and Education,TCG CREST, Salt Lake, Kolkata 700091, India — [4]Department of Physics, Tokyo Institute of Technology,2-12-1-H86 Ookayama, Meguro-ku, Tokyo 152-8550, Japan — [5]Atomic, Molecular and Optical Physics Division,Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India

In this pilot study, we investigate the physical effects beyond the mean-field approximation, known as electron correlation, in the ground state energies of atomic systems using the classical-quantum hybrid variational quantum eigensolver (VQE) algorithm in a quantum simulation. To this end, we consider three isoelectronic species. We employ the unitary coupled-cluster (UCC) ansatz to perform a rigorous analysis of two very important factors that could affect the precision of the simulations of electron correlation effects within a basis, namely mapping and backend simulator. When more qubits become available, our study will serve as among the first steps taken towards computing other properties of interest to various applications such as new physics beyond the Standard Model of elementary particles and atomic clocks using the VQE algorithm.

Q 23.13 Tue 16:30 P

A quantum logic gate on remote matter qubits — Severin Daiss, Stefan Langenfeld, Stephan Welte, Emanuele Distante, Philip Thomas, Lukas Hartung, •Olivier Morin, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

Most quantum computing systems are currently developed in monolithic hardware architecture e.g. ions in the same trap, superconducting qubits on the same chip, Rydberg atoms in the same vacuum chamber etc. However, on the long run, a modular architecture offers a more obvious scalability when large number of qubits is required, leading to the so-called distributed quantum computing. This can typically be achieved by single qubit modules interconnected via photonic qubits travelling through a network of regular optical fibers.

Here, we present the realization of the proof of principle of this vision [1]. Our qubit modules consist of single atoms of ^{87}Rb coupled to high finesse optical cavities. While local quantum gates can easily be realized with local Raman or microwave manipulations, we show that a two-qubit gate can be mediated by a single photon successively reflected on the two cavities [2], the interface of our qubit modules. Hence, we realized a CNOT gate on two atomic qubits separated by a 60m-long optical fiber.

[1] Severin Daiss *et al.*, Science **371**, 614-617 (2021)
[2] L.-M. Duan *et al.*, Phys. Rev. A **72**, 032333 (2005)

Q 23.14 Tue 16:30 P

Ion Trap Development for Quantum Computing Applications — •Alexander Müller, Björn Lekitsch, Daniel Wessel, Robin Strohmaier, Ulrich Poschinger, and Ferdinand Schmidt-Kaler — JGU Mainz, Institute for Physics, Staudingerweg 7, 55128 Mainz, Germany

Trapped ion quantum computers are one of the leading contenders for the implementation of useful quantum algorithms. Ion traps for such systems have to meet many requirements like precise alignment of individual structures and layers, good optical access and sufficient thermal conductivity, just to name a few. But most importantly, these traps have to be fabricated in a reliable and repeatable way.

We present the fabrication of a two-layer segmented linear ion trap based on 4-inch fused silica wafers. The fabrication steps include 3D structuring using selective laser-induced etching, PVD gold-coating, electroplating, wafer dicing and μm-precision die bonding. The mounting of the ion trap will enable quick turnaround of traps and the use in different setups.

We will show a suitable setup in more detail. This experimental apparatus will include a titanium vacuum vessel intended for XHV pressures, a high-performance mu-metal shielding to suppress external magnetic fields, high NA opitcs for individual addressing of qubits in a string of 10 ions, and laser systems and compact optical components for dual species operation.

Q 23.15 Tue 16:30 P

Towards estimating molecular ground state energies on current quantum hardware — •Felix Rupprecht and Sabine Wölk — Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

Quantum simulation may achieve a quantum advantage in the near future. One immediate application is then the design of materials for energy storage systems. In the QuESt project we aim at estimating ground and exited states of relevant molecules using variational quantum eigensolvers. In order to get meaningful results on current noisy intermediate scale quantum (NISQ) computers, efficient algorithm implementation and error mitigation techniques are needed.

We present first results on running variational quantum eigensolvers with a unitary coupled cluster (UCC) ansatz on current IBM superconducting quantum processors using error mitigation methods such as zero noise extrapolation.

The QuESt project is funded by the Baden-Württemberg Ministry of Economic Affairs, Labour and Housing.

Q 23.16 Tue 16:30 P

Toward control of charge state dynamics and spin manipulation in diamond NV color center for quantum information processing — •Min-Sik Kwon[1], Jonas Meinel[1,2], Qi-Chao Sun[1], Durga Dasari[1], Vadim Vorobyov[1], and Jörg Wrachtrup[1,2] — [1]3. Physikalisches Institut, University of Stuttgart, Stuttgart, Germany — [2]Max Planck Institute for Solid State Research, Stuttgart, Germany

Nitrogen-Vacancy (NV) color center is an artificial atom with optically accessible spin qubit. It is consisted of a vacancy of a missing carbon atom and substitutional nitrogen impurity in diamond crystal lattice. Due to longer electron spin relaxation (T1) and dephasing time(T2*) of negatively charged state of NV center, it is well available for coherent spin control, optical nanoscopy, charge-based memories, and electrical spin detection. For stable charged state in NV center, we studied optically induced interconversion between charge states, understanding charge state dynamics in NV color center to enhance the high fidelity measurement of spin readout. Additionally, for emergent quantum information processor and experimental quantum simulator, we designed and operated programmable quantum circuits and selectively harness the various neighbor nuclear spins by central NV electron spin to build quantum simulator to test interaction Hamiltonians at ambient condition.

Q 23.17 Tue 16:30 P

A multi-site quantum register of neutral atoms with single-site controllability — •Tilman Preuschoff, Dominik Schäffner, Lars Pause, Tobias Schreiber, Stephan Amann, Jan Lautenschläger, Malte Schlosser, and Gerhard Birkl — Institut für Angewandte Physik, TU Darmstadt, Schlossgartenstraße 7, 64289 Darmstadt, Germany

Assembled arrays of neutral atoms offer a versatile platform for quantum technologies. As effectively non-interacting particles with identical intrinsic properties they also feature switchable interactions when excited to Rydberg states [1].

We present a micro-optical platform for defect-free assembled 2D clusters of more than 100 single-atom quantum systems [2]. Combined with a digital micromirror device (DMD), site-selective manipulation of the trapping potentials is possible while utilizing the robust architecture of microlens-based systems. We also discuss recent work with microlens arrays fabricated by femtosecond direct laser writing [3].

In addition, we present our open-source digital controllers for laser frequency and intensity stabilization [4]. Using the STEMlab (originally Red Pitaya) platform we achieve a control bandwidth of up to 1.25 MHz resulting in a laser line width of 52(1) kHz (FWHM) and intensity control to the $1 \cdot 10^{-3}$ level.

[1] M. Schlosser et. al., J. Phys. B: At. Mol. Opt. Phys **53** 144001 (2020).
[2] D. Ohl de Mello et. al., Phys. Rev. Lett. **122**, 203601 (2019).
[3] D. Schäffner et. al., Opt. Express **28**, 8640-8645 (2020).
[4] T. Preuschoff et. al., Rev. Sci. Instrum. **91**, 083001 (2020).