BOOK OF ABSTRACTS

INVITED SPEAKERS & POSTER CONTRIBUTIONS

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TABLE OF CONTENT

INVITED SPEAKERS

1. CHAO-YANG LU

University of Science and Technology of China

QUANTUM LIGHT SOURCE ENGINEERING FOR QUANTUM SUPREMACY

The main challenge for scaling up photonic quantum technologies is the lack of perfect quantum light sources. In this talk, I will report progress in developing high-performance single photons, entangled photons, and squeezed light. We have pushed the parametric down-conversion to its physical limit and produce two-photon source with simultaneously a collection efficiency of 97% and an indistinguishability of 96% between independent photons. Using a single quantum dot in microcavities, we have produced on-demand single photons with high purity (>99%), near-unity indistinguishability, and high extraction efficiency—all combined in a single device compatibly and simultaneously. Based on the high-performance quantum light sources, we have implemented boson sampling—which is an intermediate model of quantum computing, a strong candidate for demonstrating quantum computational advantage and refuting Extended Church Turing Thesis—with up to 76 photon clicks after a 100-mode interferometer. The photonic quantum computer, Jiuzhang, yields an output state space dimension of 10^30 and a sampling rate that is 10^14 faster using the state-of-the-art simulation strategy on supercomputers. This special-purpose photonic platform will be further used to investigate practical applications linked to the Gaussian boson sampling. Reference: http://staff.ustc.edu.cn/~cylu

2. GEMMA DE LAS CUEVAS

University of Innsbruck

UNIVERSALITY EVERYWHERE: FROM SPIN MODELS TO AUTOMATA AND NEURAL NETWORKS

Why is it so easy to generate complexity? I will suggest that this is due to the phenomenon of universality — essentially every non-trivial system is universal, and thus able to explore all complexity in its domain. We understand the phenomenon of universality in spin models, automata and neural networks. I will explain the first step toward rigorously linking the first two, as well as perspectives of extending this study to other fields. I will also talk about one of the consequences of universality, namely undecidability.

3. NORBERT SCHUCH

University of Vienna

QUANTUM MANY-BODY SYSTEMS: AN ENTANGLEMENT-BASED PERSPECTIVE

Quantum many-body systems exhibit a wide range of exciting and unconventional phenomena, such as order outside the conventional framework of symmetry breaking ("topological order") which is accompanied by excitations with exotic properties ("anyons"), and the ability to store and process quantum information. All these phenomena are deeply rooted in the complex global quantum entanglement present in these systems. In my talk, I will explain how Quantum Information Theory, and in particular the theory of entanglement, provides us with a comprehensive perspective on these systems, which reconciles their global entanglement with the locality inherent to the physical laws, using the language of tensor networks. I will discuss how this allows us to obtain a full picture of how symmetries and entanglement interplay, and how it provides us both with a mathematical framework to analytically study exotic topologically ordered quantum systems, and with a wide range of numerical tools which allow to probe their unconventional physics at a microscopic level.

4. BARBARA KRAUS

University of Innsbruck

ON CHARACTERIZATION, VALIDATION, AND VERIFICATION OF QUANTUM DEVICES

Significant advances in building small scale quantum computers and quantum simulators have been reported with various physical platforms, from atomic and photonic systems to solid state devices. A central aspect in further developments is the verification of proper functioning of these quantum devices. In this talk I will discuss several protocols designed for the characterization, validation and verification of quantum devices.

5. PETER LODAHL

University of Copenhagen

SCALING-UP SINGLE-PHOTON QUANTUM HARDWARE TOWARDS QUANTUM-INFORMATION PROCESSING WITH A QUANTUM ADVANTAGE

Semiconductor quantum dots embedded in photonic nanostructures offer a highly efficient and coherent deterministic photon-emitter interface [1]. It constitutes an on-demand single-photon source for quantum-information applications, enables single-photon nonlinear, optics and the constructing of deterministic quantum gates for photons [2]. We review recent experimental progress, and demonstrate that the current technology can be scaled up to reach quantum advantage [3] with the demonstration of near-transform-limited emitters in high-cooperativity planar nanophotonic waveguides [4]. The coherent control of a single spin in the quantum dot [5, 6] offers additional opportunities of generating advanced multi-photon entangled states [7]. We finally discuss how this emergent hardware may be applied in a resource-efficient manner, e.g., for constructing a one-way quantum repeater [8].

[1] Lodahl et al., Rev. Mod. Phys. 87, 347 (2015). [2] Lodahl, Quantum Science and Technology 3, 013001 (2018). [3] Uppu et al., Science Advances 6, eabc8268 (2020). [4] Pedersen et al., ACS Photonics (2020). [5] Javadi et al., Nature Nanotechnology 13, 398 (2018). [6] Appel et al., Phys. Rev. Lett. 126, 013602 (2021). [7] Tiurev et al., Arxiv: 2007.09295. [8] Borregaard et al., Phys. Rev. X 10, 021071 (2020).

6. VALERIA SAGGIO

University of Vienna

EXPERIMENTAL QUANTUM SPEED-UP IN REINFORCEMENT LEARNING AGENTS

Artificial intelligence (AI) has been experiencing rapid progress in the past few years. As famous examples, one may think of robots solving tasks like recognizing human voices, optimizing medical treatments, or playing computer games. At the same time, significant advances in the field of quantum technologies have been driving the scientific community towards deeper investigations of how and for what applications quantum physics can be particularly beneficial. In this talk, I will focus or reinforcement learning (RL), a particular class of AI where decision-making entities called "agents" learn to accomplish a task via feedback exchange with an outer world called "environment". If the agent makes the correct move, the environment issues a reward that the agent uses to learn. Bridging RL and quantum physics has led to several studies investigating how quantum mechanics can aid in RL, or vice versa [1-3]. Yet, a speed-up in the agent's learning process was never demonstrated. In order to achieve this, the agent and the environment are required to interact quantumly [4]. This means that, contrary to classical interactions where agent and environment can exchange only signals from a fixed discrete alphabet (for example, the classical bits 0 and 1), a quantum interaction also allows for exchange of arbitrary quantum superpositions. This concept allows the agent to make use of the Grover search algorithm to find the correct moves faster, and hence learn faster than entirely classical agents. Additionally, I will show that combining this with classical communication enables optimal control of the learning process. This idea was implemented [5] using a photonic processor interfaced with single photons at telecommunication wavelengths. The device is fully programmable and features a fast active feedback mechanism that enables the agent to update its behaviour based on the obtained rewards, and thus to learn.

[1] Paparo G. D. et al. Phys. Rev. X 4(3), 031002 (2014). [2] Sriarunothai T. et al. Quantum Sci. Technol. 4, 015014 (2019). [3] Krenn, M. et al. Phys. Rev. Lett. 116, 090405 (2016). [4] Dunjko, V. et al. Phys. Rev. Lett., 117, 130501 (2016). [5] Saggio, V. et al. Nature (in print).

7. ROBERT SCHOELKOPF

Yale University

CONTROLLING BOSONIC MODES IN CIRCUIT QED AND THE APPLICATION TO VIBRONIC MOLECULAR SIMULATIONS

Circuit quantum electrodynamics, in which microwave cavity modes are coupled to "artificial atoms" realized with Josephson junction qubits, has allowed for a variety of investigations in quantum optics and quantum information. In recent years, our team at Yale has focused on a hardware-efficient approach, where high-Q microwave cavities serve as quantum memories. When dispersively coupled to transmon qubits, quite complex non-classical states can be created in these cavities, and operations between cavities can be enacted through parametric driving or other means. For instance, we have recently shown high-quality cavity-cavity swaps via a beam-splitter or conversion operation, single and two-mode squeezing, and engineered cross and self Kerr interactions. Finally, one can perform strong projective measurements of the photon number, the photon parity, or indeed any other binary-valued operator within the multi-dimensional Hilbert space. This system therefore has all of capabilities of linear optical systems, but with the addition of deterministic state preparation, measurement, and nonlinear interactions. One way to employ these capabilities is to directly simulate problems which are "naturally" bosonic in nature, to calculate vibronic spectra, Franck-Condon factors, or nonlinear molecular dynamics. I will present a demonstration of using this platform as a novel but programmable simulator for small molecules.

8. MAGNETIC FIELD-FREE NON-RECIPROCAL RAMAN AMPLIFICATION OF FIBRE-GUIDED LIGHT ENABLED BY CHIRALLY COUPLED SPIN-POLARISED ATOMS

PHILIPP SCHNEEWEISS, SEBASTIAN PUCHER, CHRISTIAN LIEDL, SHUWEI JIN, ARNO RAUSCHENBEUTEL

Non-reciprocal elements are key components for fibre-optical networks and integrated optical chips. They allow one to e.g. protect lasers from harmful optical feedback, to implement add-drop multiplexers or cascaded quantum systems. A novel class of such non-reciprocal elements uses the internal spin of quantum emitters in order to break Lorentz reciprocity. We demonstrate non-reciprocal Raman amplification of light pulses using spin-polarised atoms that are chirally coupled to an optical nanofibre. We control the direction in which amplification occurs via the Zeeman state in which the atoms are prepared. We observe an exponential increase of the optical output power with the number of atoms and obtain over 40% single-pass gain for about 2000 atoms. In addition, we show that non-reciprocal amplification prevails in the absence of an offset magnetic field. Our scheme can be readily implemented with other types of nanophotonic waveguides and quantum emitter with circular transitions.

1. COMBINED CALIBRATION AND CHARACTERIZATION

FEDERICO ROY, N. WITTLER, M. WERNINGHAUS, D.J. EGGER, S. MACHNES, S. FILIPP, F.K. WILHELM

Efforts to scale-up quantum computation have reached a point where the principal limiting factor is not the number of qubits, but the entangling gate infidelity. Current methodology is inefficient: pulses are designed using simplified models, resulting in initial poor fidelities and limiting pulse complexity. The pulses are then calibrated in-situ, achieving high-fidelities, but in absence of a good model. To rectify the situation, we provide a new integrated open-source tool-set for Control, Calibration and Characterization (C^3), capable of open-loop pulse optimization, model-free calibration, model fitting and refinement. We present a methodology to combine these tools to find a quantitatively accurate system model, high-fidelity gates and an approximate error budget, all based on a high-performance, feature-rich simulator. We illustrate our methods using simulated fixed-frequency superconducting qubits for which we learn model parameters to an accuracy of < 1% and derive a coherence limited cross-resonance (CR) gate that achieves 99.6% fidelity without need for calibration.

2. GENERATION OF PHOTONIC TENSOR NETWORKS WITH CIRCUIT QED AND RYDBERG ATOMIC ARRAYS

ZHIYUAN WEI, DANIEL MALZ, ALEJANDRO GONZALEZ-TUDELA, J. IGNACIO CIRAC

We show how one can deterministically produce large-scale strongly-entangled photonic states by sequentially applying unitaries on a qubit-oscillator system followed by the emission from the qubit. We realize such a qubit-oscillator system with two physical setups, one is a microwave cavity coupled to a transmon qubit for generating microwave photons, the other is a Rydberg-blockaded atomic array for generating free-space optical photons. We show both of these two setups can produce photonic matrix product states (MPS) of high bond dimension with a large number of photons. The circuit QED setup further features producing high-dimensional entanglement structure, including three-dimensional projected entangled pair states (PEPS) of high bond dimension. The atomic array setup further features generating qudit MPS and efficiently distributing photons to multiple free-space ports.

3. FASTER ADIABATIC GROUND STATE PREPARATION WITH FEW MEASUREMENTS

BENJAMIN SCHIFFER, JORDI TURA, J. IGNACIO CIRAC

Preparing the ground state of a Hamiltonian is a problem of great significance in physics with deep implications in the field of combinatorial optimization. While adiabatic state preparation is known to return the ground state for sufficiently long preparation times only, variational quantum algorithms require a very large number of measurements in the training phase. In our work, we aim at combining the strengths of the adiabatic and the variational approaches on noisy-intermediate scale quantum devices for fast and high-fidelity ground state preparation while keeping the number of measurements as low as possible. We present a toolbox for variational quantum adiabatic algorithms (VQAA) including new ancilla-based methods. Our methods allow to directly evaluate the ground state overlap using one or two entangled ancillas, respectively. Our algorithms are benchmarked for a non-integrable spin-1/2 transverse and longitudinal Ising chain (ZZXZ model) with N=100 sites using tensor network techniques. We report a promising significant increase in the overlap with the ground state from 5.7% to 17.4% when compared to naive QAA for fixed total evolution time. Finally, we show that our approach only requires a modest number of measurements and that it offers an inherent robustness towards noise, making VQAA a promising candidate for current quantum devices.

4. IMPROVING KEY RATES OF THE UNBALANCED PHASE-ENCODED BB84 PROTOCOL USING THE FLAG-STATE SQUASHING MODEL

NICKY LI, NORBERT LÜTKENHAUS

All phase-encoded BB84 implementations have signal states with unbalanced amplitudes in practice. Thus, the original security analyses a priori do not apply to them. Previous security proofs use signal tagging of multiphoton pulses to recover the behaviour of regular BB84. This is overly conservative as for unbalanced signals the photon number splitting attack does not leak full information to Eve. In this work we exploit the flag-state squashing model to preserve some parts of the multiphoton-generated private information in our analysis. Using a numerical proof technique, we obtain significantly higher key rates compared with previously published results in the low-loss regime. It turns out that the usual scenario of untrusted dark counts runs into conceptual difficulties in some parameter regimes. Thus, we discuss the trusted dark-count scenario in this paper as well. We also report a gain in key rates when part of the total loss is known to be induced by a trusted device. We highlight that all these key rate improvements can be achieved without modification of the experimental setup.

5. QUANTUM REFERENCE FRAMES FOR GENERAL SYMMETRY GROUPS

ANNE CATHERINE DE LA HAMETTE, THOMAS D. GALLEY

Treating reference frames as physical systems, subject to the laws of quantum mechanics, they become quantum reference frames. Located at the interplay of quantum and gravitational physics, their treatment marks an essential step towards the construction of a relational quantum theory. In this work, we introduce a relational formalism which identifies coordinate systems with elements of a symmetry group G. We define a general operator for reversibly changing between quantum reference frames associated to a group G. This generalises the known operator for translations and boosts to arbitrary finite and locally compact groups, including non-Abelian groups.

6. INTERFERENCE IN MULTI-PHOTON QUANTUM WALK

YUSUF KARLI, OZGUR CAKIR

Quantum walks can be described as quantum analogues of classical random walks. In quantum walks, the direction of the walker is dictated by the quantum state of a coin in a coherent fashion. Unlike classical random walk with a fair coin, quantum walk has non-Markovian property. We studied average photon number correlations for 1-D quantum walk with many body bosonic walkers, like different light sources, to investigate quantum interference effects and we showed the second-order intensity correlations function (g (2) (Ï„)) in terms of the probability amplitudes of the 1-D quantum walk with Hadamard coin. We compared the resulting correlations for various initial many photon states.

7. TOWARDS DUAL-SPECIES ENTANGLEMENT OF TRAPPED IONS - COMPARISON OF APPROACHES

PAVEL HRMO, MARTIN VAN MOURIK, BENJAMIN WILHELM, LUKAS GERSTER, PHILIPP SCHINDLER, THOMAS MONZ, RAINER BLATT

A large family of two-qubit entangling gates has been theoretically proposed and experimentally realized individually within various trapped ion quantum computers. We investigate the applications of four different types of these gates within a cryogenic surface chip ion trap. We demonstrate fidelities above 99% for both Molmer-Sorenson type gates as well as geometric phase gates. Furthermore, we realize for the first time a newly proposed type of laser wavelength-insensitive phase gate that entangles qubit states separated by an optical transition rather than by microwave wavelengths. Our goal in the near future is to apply this scheme for simple and robust entanglement of two different ion species. Such dual-species entangled states could find applications in remote entanglement generation or ancilla-based qubit readout that doesn't decohere neighboring unmeasured qubits due to fluorescence scatter.

8. EMERGENCE OF CLASSICALITY AT HIGH ENERGIES: SPONTANEOUS COLLAPSE PERSPECTIVE

KYRYLO SIMONOV

Spontaneous collapse models aim to resolve the measurement problem in quantum mechanics by considering wave-function collapse as a physical process. We analyze how these models affect a decaying flavor-oscillating system whose evolution is governed by a phenomenological non-Hermitian Hamiltonian. In turn, we apply two popular collapse models, the Quantum Mechanics with Universal Position Localization and the Continuous Spontaneous Localization models, to a neutral meson system. By using the equivalence between the approaches to the time evolution of decaying systems with a non-Hermitian Hamiltonian and a dissipator of the Lindblad form in an enlarged Hilbert space, we show that spontaneous collapse can induce the decay dynamics in both quantum state and master equations. Moreover, we show that the decay property of a flavor-oscillating system is intimately connected to the time (a)symmetry of the noise field underlying the collapse mechanism. This (a)symmetry, in turn, is related to the definition of the stochastic integral and can provide a physical intuition behind the Itō-Stratonovich dilemma in stochastic calculus.

9. QUANTUM INFORMATION PROCESSING WITH TRAPPED ION QUDITS

MARTIN RINGBAUER, L. POSTLER, M. METH, R. STRICKER, A. ERHARD, P. SCHINDLER, T. MONZ, R. BLATT

Building on the success of classical computing, quantum information is widely encoded in a binary fashion. The underlying quantum systems carrying such information, however, occupy high-dimensional Hilbert spaces and thus need to be artificially constrained to serve the binary paradigm. This not only leads to potential leakage errors in binary computing, but also wastes valuable resources in the additional states that can typically be controlled equally well. Here we demonstrate a universal qudit quantum processor built on a state-of-the-art trapped-ion platform. Our quantum processor achieves comparable performance to a qubit system and is seamlessly scalable up to d=7. In addition to a universal gate set, we demonstrate simultaneous multi-ion addressing and methods to mitigate crosstalk errors, which are a leading source or errors in a qudit system.

10. POLYLOG-OVERHEAD HIGHLY FAULT-TOLERANT MEASUREMENT-BASED QUANTUM COMPUTATION: ALL-GAUSSIAN IMPLEMENTATION WITH GOTTESMAN-KITAEV-PRESKILL CODE

HAYATA YAMASAKI, KOSUKE FUKUI, YUKI TAKEUCHI, SEIICHIRO TANI, MASATO KOASHI

Scalability of flying photonic quantum systems in generating quantum entanglement offers a potential for implementing large-scale fault-tolerant quantum computation, especially by means of measurement-based quantum computation (MBQC). However, existing protocols for MBQC inevitably impose a polynomial overhead cost in implementing quantum computation due to geometrical constraints of entanglement structures used in the protocols, and the polynomial overhead potentially cancels out useful polynomial speedups in quantum computation. To implement quantum computation without this cancellation, we construct a protocol for photonic MBQC that achieves as low as poly-logarithmic overhead, by introducing an entanglement structure for low-overhead qubit permutation. Based on this protocol, we design a fault-tolerant photonic MBQC protocol that can be performed by experimentally tractable homodyne detection and Gaussian entangling operations combined with the Gottesman-Kitaev-Preskill (GKP) quantum error-correcting code, which we concatenate with the 7-qubit code. Our fault-tolerant protocol achieves the threshold 7.8 dB in terms of the squeezing level of the GKP code, outperforming 8.3 dB of the best existing protocol for fault-tolerant quantum computation with the GKP surface code. Thus, bridging a gap between theoretical progress on MBQC and photonic experiments towards implementing MBQC, our results open a new way towards realization of a large class of quantum speedups including those polynomial.

11. UNRAVELING THE ADVANTAGE OF A QUANTUM VERSUS A CLASSICAL ANNEALING PROCESS

ELIAS STARCHL, HELMUT RITSCH

Quantum annealing aims at finding optimal solutions to complex classical optimization problems using suitable quantum many-body Hamiltonians. Here we explore whether full quantum dynamics generates an advantage when compared to the corresponding semi-classical mean-field approximation. Already two interacting atoms in a four-site tight-binding lattice with a small impurity and cavity generated long-range interactions prove complex enough to exhibit significant differences. We find a large parameter region of successful quantum annealing where the semi-classical approach largely fails. We see strong evidence for the importance of entanglement in finding an optimal solution and reducing the minimal time for successful annealing. Different numerical cut-offs of the mode Hilbert space reveal a counter-intuitively improved performance for lower cut-offs at short simulation times. However, higher cut-offs are still relevant to obtain near-perfect fidelity for long simulation times.

12. GENERAL DECOMPOSITIONS WITH INVARIANCE, POSITIVITY AND APPROXIMATIONS

ANDREAS KLINGLER, GEMMA DE LAS CUEVAS, TIM NETZER

We develop a framework to decompose elements of a tensor product space in a general way, explicitly expressing the element's invariance under group actions. If the element is positive in some sense (in other words it is contained in some cone), we define and characterise the corresponding, inherently positive decompositions. Subsequently, we study the approximate case for all such decompositions, using various norms. For all of these cases, we show under which assumptions the invariant decomposition does or does not exist and provide explicit constructions for existing ones. This framework is a vast generalisation of already well-studied decompositions, including nonnegative, completely positive, and positive semidefinite matrix-factorisations, to name a few. We also study the ranks of these decompositions, i.e. the minimum number of terms necessary to decompose a given element. We show that the separations of ranks between positive decompositions disappear in the approximate case.

13. BAYESIAN PARAMETER ESTIMATION USING GAUSSIAN STATES AND MEASUREMENTS

SIMON MORELLI, AYAKA USUI, ELIZABETH AGUDELO, NICOLAI FRIIS

Bayesian analysis is a framework for parameter estimation that applies even in uncertainty regimes where the commonly used local (frequentist) analysis based on the Cramér-Rao bound is not well defined, i.e. when no initial information about the parameter value is available and few measurements are performed. We consider three paradigmatic estimation schemes in continuous-variable quantum metrology (estimation of displacements, phases, and squeezing strengths) and analyse them from the Bayesian perspective, investigating the precision achievable with single-mode Gaussian states under homodyne and heterodyne detection. We identify Bayesian estimation strategies that combine good performance with the potential for straightforward experimental realization in terms of Gaussian states and measurements. This allows to reach uncertainties where local estimation techniques apply, thus bridging the gap to regimes where asymptotically optimal strategies can be employed.

14. DETECTING ENTANGLEMENT FROM PARTIAL TRANSPOSE MOMENTS

ANTOINE NEVEN & JOSE CARRASCO, RICHARD KUENG, ANDREAS ELBEN, VITTORIO VITALE, CHRISTIAN KOKAIL, PASQUALE CALABRESE, MARCELLO DALMONTE, PETER ZOLLER, BENOIT VERMERSCH, BARBARA KRAUS

Even though very powerful from a theoretical point of view, using the Positive Partial Transpose (PPT) criterion to detect entangled states in an experimental setting is very challenging. Nevertheless, it was recently shown that entanglement can in some cases already be detected from the first three moments of the partial transpose, which can for instance be measured using classical shadows. In this poster, we generalize this approach by showing that each higher order moment can be used to define a new entanglement condition, and that this list of conditions eventually becomes equivalent to the PPT criterion. Inspired by the concept of symmetry-resolution, which uses the symmetry present in certain states as a lens to gain a more detailed characterization of their quantum features, we also propose a Symmetry-Resolved (SR) version of our entanglement detection tools. Interestingly, we show that the SR tools can also be used to detect the entanglement of states without any symmetry.

15. PHOTON PAIR GENERATION IN ULTRA-THIN CARBON NANOTUBE FILMS WITHOUT PHASE-MATCHING

PHILIPP JENKE, IRATI ALONSO CALAFELL, ALESSANDRO TRENTI, KIMMO MUSTONEN, LEE ROZEMA, PHILIP WALTHER

In sufficiently thin nonlinear materials, the phase-matching condition of four-wave mixing (FWM) relaxes. We characterize the resulting broadband biphoton states by stimulated emission tomography, and present progress towards photon pair generation in ultra-thin carbon nanotube films. Our 200nm thick single-walled carbon nanotube films (much smaller than the pump wavelength of around 810nm) impose energy conservation as the only requirement in the nonlinear interaction, resulting in strong two-photon energy correlations. Additionally, the absence of phase-matching means that the photon pairs are highly entangled in frequency and separable in all other degrees of freedom. Using stimulated emission tomography we characterize the joint spectral intensity of the generated biphoton state. We keep the pump wavelength constant and stimulate the FWM process with different wavelengths. The measured spectral width of the state extends over more than 50THz. To conclude, broadband stimulated emission tomography measurements on single-walled carbon nanotubes have been successfully demonstrated, which shows the potential to generate photon pairs with broadband entanglement.

16. A 51-QUBIT TRAPPED-ION QUANTUM SIMULATOR

FLORIAN KRANZL, CHRISTINE MAIER, TIFFANY BRYDGES, JOHANNES FRANKE, MANOJ K. JOSHI, BEN P. LANYON, RAINER BLATT, CHRISTIAN ROOS

We present our work for scaling up our analog quantum simulator to over 50 single-addressable qubits. The computation of quantum systems gets practically impossible for a large number of qubits due to the exponentially growing size of the Hilbert space. A trapped-ion based quantum simulator with many qubits gives a highly controllable quantum system at hand and therefore offers a platform with the possibility to simulate physics beyond classical computation capabilities. Trapped-ion based systems are an advanced candidate due to their advantage of individual qubit control and high readout fidelities. In our setup we realize an analog quantum simulator with calcium ions trapped in a linear Paul trap. We create many-body interactions of the Ising Hamiltonian by coupling the electronic and vibrational degrees of freedom which enables us to perform analog quantum simulations of various interesting physics models. In my poster I present improvements on our system and techniques that allow us to efficiently cool, control and fully address a 51-ion string. We present a 51-ion Néel-state evolving under an Ising-Hamiltonian and show entanglement in the time-evolved state.

17. MULTI-USER DISTILLATION OF COMMON RANDOMNESS AND ENTANGLEMENT FROM QUANTUM STATES

FARZIN SALEK, ANDREAS WINTER

We construct new protocols for the tasks of converting noisy multipartite quantum correlations into noiseless classical and quantum ones using local operations and classical communications (LOCC). For the former, known as common randomness (CR) distillation, two new lower bounds on the "distillable common randomness" an operational measure of the total genuine (classical) correlations in a quantum state, are obtained. Our proof relies on a generalization of communication for omniscience (CO) [Csisz´ar and Narayan, IEEE Trans. Inf. Theory 50:3047-3061, 2004]. Our contribution here is a novel simultaneous decoder for the compression of correlated classical sources by random binning with quantum side information at the decoder. For the latter, we derive two new lower bounds on the rate at which Greenberger-Horne-Zeilinger (GHZ) states can be asymptotically distilled from any given pure state under LOCC. Our approach consists in "making coherent" the proposed CR distillation protocols and recycling of resources [Devetak et al. IEEE Trans. Inf. Theory 54(10):4587-4618, 2008]. The first lower bound is identical to a recent result by Vrana and Christandl [IEEE Trans. Inf. Theory 65(9):5945-5958, 2019], which is based on a combinatorial method to achieve the same rate. Our second lower bound generalises and improves upon this result, and unifies a number of other known lower bounds on GHZ distillation.

18. TOWARDS QUANTUM SIMULATIONS OF 2D SPIN LATTICES WITH ION CRYSTALS

HELENE HAINZER, DOMINIK KIESENHOFER, TUOMAS OLLIKAINEN, MATTHIAS BOCK, CHRISTIAN ROOS

On this poster we present the first results from our new ion trap apparatus that allows us to trap large, stationary planar ion crystals. The centerpiece of the apparatus is a novel monolithic micro-fabricated linear Paul trap, enabling us to create the anisotropic potentials required for trapping 2D ion crystals while still being able to maintain sufficient optical access for imaging as well as single-ion addressing. The long term vision of our work is to apply the proven methodology for realizing spin models in 1D ion crystals stored in linear Paul traps (i.e. combining coherent single-ion operations and measurements with engineered spin-spin interactions mediated by the motional modes of the crystal to directly implement e.g. Ising-type Hamiltonians) to 2D structures. This will enable studies of 2D non-equilibrium physics with a larger particle number (>50) as some scalability-related problems arising in long ion strings can be circumvented with our approach.

19. INTERFERENCE AS AN INFORMATION-THEORETIC GAME

SEBASTIAN HORVAT, BORIVOJE DAKIĆ

The double slit experiment provides a clear demarcation between classical and quantum theory, while multi-slit experiments demarcate quantum and higher-order interference theories. In this work we show that these experiments pertain to a broader class of processes, which can be formulated as information-processing tasks, providing a clear cut between classical, quantum and higher-order theories. The tasks involve two parties and communication between them with the goal of winning certain parity games. We show that the order of interference is in one-to-one correspondence with the parity order of these games. Furthermore, we prove the order of interference to be additive under composition of systems both in classical and quantum theory. The latter result can be used as a (semi)device-independent witness of the number of particles in the quantum setting. Finally, we extend our game formulation within the generalized probabilistic framework and prove that tomographic locality implies the additivity of the order of interference under composition. These results shed light on the operational meaning of the order of interference and can be important for the identification of the information-theoretic principles behind second-order interference in quantum theory.

20. ENTANGLEMENT AND SYMMETRIES OF STABILIZER STATES

MATTHIAS ENGLBRECHT, BARBARA KRAUS

Stabilizer states constitute a set of pure states which plays a dominant role in quantum error correction, measurement–based quantum computation, and quantum communication. To study their entanglement properties we characterize all local invertible symmetries of arbitrary stabilizer states and derive partial results on the non-invertible ones. Based on this characterization we derive an algorithm, which determines all local invertible symmetries of a stabilizer state. We demonstrate the usefulness of these results by showing applications in entanglement theory and quantum error correction.

21. GIANT ENHANCEMENT OF THIRD-HARMONIC GENERATION IN GRAPHENE–METAL HETEROSTRUCTURES

LEE ROZEMA, IRATI ALONSO CALAFELL, DAVID ALCARAZ IRANZO, ALESSANDRO TRENTI, PHILIPP K. JENKE, JOEL D. COX, AVINASH KUMAR, HLIB BIELIAIEV, SÉBASTIEN NANOT, CHENG PENG, DMITRI K. EFETOV, JIN-YONG HONG, JING KONG, DIRK R. ENGLUND, F. JAVIER GARCÍA DE ABAJO, FRANK H. L. KOPPENS, PHILIP WALTHER

Nonlinear nanophotonics leverages engineered nanostructures to funnel light into small volumes and intensify nonlinear optical processes with spectral and spatial control. Owing to its intrinsically large and electrically tunable nonlinear optical response, graphene is an especially promising nanomaterial for nonlinear optoelectronic applications. Here we report on exceptionally strong optical nonlinearities in graphene–insulator–metal heterostructures, which demonstrate an enhancement by three orders of magnitude in the third-harmonic signal compared with that of bare graphene. Furthermore, by increasing the graphene Fermi energy through an external gate voltage, we find that graphene plasmons mediate the optical nonlinearity and modify the third-harmonic signal. Our findings show that graphene–insulator–metal is a promising heterostructure for optically controlled and electrically tunable nano-optoelectronic components.

22. ENTANGLEMENT-ASSISTED ENTANGLEMENT PURIFICATION

FERRAN RIERA SABAT, PAVEL SEKATSKI, ALEXANDER PIRKER, WOLFGANG DÜR

The efficient generation of high-fidelity entangled states is the key element for long-distance quantum communication, quantum computation and other quantum technologies, and at the same time the most resource-consuming part in many schemes. We present a new class of entanglement-assisted entanglement purification protocols with improved yield and fidelity as compared to previous approaches. The scheme utilizes high-dimensional auxiliary entanglement to perform entangling non-local measurements and determine the number and positions of errors in an ensemble in a controlled and efficient way, without disturbing the entanglement of good pairs. Our protocols can deal with arbitrary errors, but are best suited for few errors, and work particularly well for decay noise.

23. TOWARDS NPT BOUND ENTANGLEMENT: COMPUTATIONAL COMPLEXITY AND FIELD EXTENSIONS

MIRTE VAN DER EYDEN, GEMMA DE LAS CUEVAS, TIM NETZER

One of the classic open problems in quantum information is the existence of bound entangled states with a non-positive partial transpose (NPT). This problem is related to the positivity of linear maps under tensor powers. In our ongoing work we prove undecidability of the following problem: is a given linear map positive under tensor powers when the input are neighbouring Bell pairs? Proving undecidability of the same question without a specified input would prove existence of NPT bound entangled states. However, we show that the most natural reduction to this more general problem is not possible. In a second line of research we prove existence of NPT bound entangled states considered on the hyper-complex field.

24. STABILITY OF MOBILITY EDGES IN DISORDERED INTERACTING SYSTEMS

PIETRO BRIGHI, DMITRY A. ABANIN, MAKSYM SERBYN

Many-body localization provides a mechanism to avoid thermalization in isolated interacting quantum systems. The breakdown of ergodicity can be partial, when a many-body mobility edge separates localized and delocalized parts of the spectrum. Recently, De Roeck et al. suggested a possible instability of the many-body mobility edge in energy density. Local ergodic regions resonantly spread throughout the system, leading to delocalization. In order to study such mechanism, in this work we design a model featuring many-body mobility edge in particle density. Using numerical simulations with matrix product states, we demonstrate the stability of many-body localization with respect to small ergodic regions in large dilute systems for experimentally relevant timescales. In addition, we show that local thermal regions have a larger probability of decaying rather than tunneling through the system, suggesting a possible mechanism behind the observed stability of many-body mobility edge.

25. OPTOMECHANICAL CONTROL OF QUBITS

PRASOON SHANDILYA, DAVID P LAKE, MATTHEW MITCHELL, DENIS SUKACHEV, PAUL E BARCLAY

Quantum networks enable a broad range of practical and fundamental applications. Experimental realization of such networks is hampered by many challenges, one of them being a lack of an efficient interface between stationary and flying qubits working at room temperature. We demonstrate an interface between ensembles of the nitrogen-vacancy centers in diamond and photons with wavelengths near 1550 nm. Photons are coupled to spins via local dynamical stress produced by optomechanical driving of a diamond microdisk. Our approach does not involve intrinsic optical transitions and can be easily adapted to many other colour centers.

26. LOCAL TRANSFORMATIONS OF MULTIPLE MULTIPARTITE STATES

DAVID GUNN, ANTOINE NEVEN, MARTIN HEBENSTREIT, BARBARA KRAUS

Multipartite entanglement underpins many phenomena across physics. One can quantify entanglement by studying state transformations via Local Operations assisted by Classical Communication (LOCC), as it induces a partial order in the Hilbert space. However, for systems with fixed local dimensions, this order is generically trivial. To obtain a non-trivial partial ordering, we study a physically motivated extension of LOCC: multi-state LOCC. Here, one considers simultaneous LOCC transformations of a finite number of entangled pure states. In the multipartite case, we show one can change the stochastic LOCC (SLOCC) class of the individual states; that one can perform state conversions not possible in the single copy case, transferring entanglement from one state to the other; provide examples of multipartite entanglement catalysis; and find improved probabilistic protocols. In the bipartite case, we find non-trivial LU transformations and show that the source entanglement is not additive.

27. RESERVOIR LEARNING WITH QUANTUM MEMRISTORS

JOSHUA MORRIS, MICHELE SPAGNOLO, SIMONE PIACENTINI, MICHAEL ANTESBERGER, FRANCESCO MASSA, FRANCESCO CECCARELLI, ANDREA CRESPI, ROBERTO OSELLAME, PHILIP WALTHER

The applications of quantum computers are diverse, reaching from well-known quantum algorithms to quantum machine learning and neural networks. Quantum neural networks are technologically challenging however, as the underlying computation tends to require non-unitary operations when mimicking the behavior of neurons. A landmark development for classical neural networks was the realization of memory-resistors, or memristors. A recent result for the quantum equivalent promises to do the same for quantum machine learning. Here we introduce a reservoir based machine learning architecture using a quantum memristor where the heavy duty computation is performed by a quantum optics platform acting coherently on encoded quantum information. This enables high performance learning tasks to be completed with greatly reduced resources, both in terms of computational complexity and training data.

28. AUTONOMOUS THERMAL MACHINE POWERED BY ENERGETIC COHERENCE

GONZALO MANZANO, KENZA HAMMAM, YASSINE HASSOUNI, ROSARIO FAZIO

The characterization and control of quantum effects in the performance of thermodynamic tasks may open new avenues for small thermal machines working in the nanoscale. We study the impact of coherence in the energy basis in the operation of a small thermal machine which can act either as a heat engine, or as a refrigerator. We show that input coherence may enhance the machine performance and allow it to operate in otherwise forbidden regimes. Our results also indicate that, in some cases, coherence may also be detrimental, rendering optimization of particular models a crucial task for benefiting from coherence-induced enhancements.

30. COHERENT RANDOMIZED BENCHMARKING

JORGE MIGUEL RAMIRO, ALEXANDER PIRKER, WOLFGANG DUR

Randomized benchmarking is a powerful technique to efficiently estimate the performance and reliability of quantum gates, circuits and devices. Here we propose to perform randomized benchmarking in a coherent way, where superpositions of different random sequences rather than independent samples are used. We show that this leads to a uniform and simple protocol with significant advantages with respect to gates that can be benchmarked, and in terms of efficiency and scalability. We show that e.g. universal gate sets, the set of multi-qudit Pauli operators, multi-qudit controlled gates or more general operations such as the Molmer-Sorensen gate can be efficiently benchmarked. We also show how to benchmark a particular n−qudit Clifford gate using only the Pauli operators. The price to pay is an additional complexity to add control to the involved quantum operations. However, we demonstrate that this can be done by using auxiliary degrees of freedom that are naturally available in basically any physical realization, and are independent of the gates to be tested. We provide explicit schemes for photonic and ion-trap set-ups.

31. FABRICATION AND CHARACTERIZATION OF COMPACT VACUUM GAP TRANSMON QUBITS

MARTIN ZEMLICKA, E. REDCHENKO, M. PERUZZO, F. HASSANI, S. BARZANJEH, J. M. FINK

The large shunt capacitance of the transmon decreases the sensitivity to charge fluctuations, but requires sizeable qubit dimensions. Very large capacitor designs can systematically lower the coupling to parasitic losses localized in material interfaces. This approach improves coherence times consistently, but it lowers the achievable integration density of superconducting processors and it increases parasitic cross coupling and leakage. Our goal is the development of a compact low-loss transmon qubit by minimizing the electric field participation ratio of metal-dielectric and dielectric-air interfaces. Several attempts to realize vacuum gap capacitors were already implemented, usually relying on an out-of-plane geometry that involved a sacrificial layer before releasing the structure. We utilize silicon membranes to fabricate micro-machined resonators and transmon qubits based on suspended in-plane vacuum capacitors with qubits sizes as low as 20 x 20 Î¼m^2.

32. BOUNDING TEMPORAL CORRELATIONS IN MEASUREMENT SEQUENCES

LUCAS VIEIRA, COSTANTINO BUDRONI, GIUSEPPE VITAGLIANO, MISCHA P. WOODS

We investigate the role of nonclassical temporal correlations in enhancing the performance of ticking clocks in a discrete-time scenario. We show that the problem of optimal models for ticking clocks is related to the violation of Leggett-Garg-type temporal inequalities formulated in terms of, possibly invasive, sequential measurements, but on a system with bounded memory. We present analytical and numerical results showing that quantum ticking-clock models violating the classical bound are also those violating Leggett-Garg-type temporal inequalities for a particular class of sequences. Expanding upon this, we further investigate the optimal classical bounds achievable by arbitrary finite sequences of measurements with bounded memory, revealing a rich non-trivial structure. We introduce a complexity measure for sequences which is closely related to their bounds, and with it present a conjecture for their upper bounds connecting to the previous discrete-time ticking clocks problem.

33. STRICT HIERARCHY BETWEEN PARALLEL, SEQUENTIAL, AND INDEFINITE-CAUSAL-ORDER STRATEGIES FOR CHANNEL DISCRIMINATION

MARCO TULIO QUINTINO, JESSICA BAVARESCO, MIO MURAO

We present an instance of a task of minimum-error discrimination of two qubit-qubit quantum channels for which a sequential strategy outperforms any parallel strategy. We then establish two new classes of strategies for channel discrimination that involve indefinite causal order and show that there exists a strict hierarchy among the performance of all four strategies. Our proof technique employs a general method of computer-assisted proofs. We also provide a systematic method for finding pairs of channels that showcase this phenomenon, demonstrating that the hierarchy between the strategies is not exclusive to our main example.

34. MACROSCOPIC NONLOCAL QUANTUM CORRELATIONS

MIGUEL GALLEGO, BORIVOJE DAKIĆ

It is usually believed that coarse-gaining of nonlocal quantum correlations leads to classical (local) correlations in the macroscopic limit. Such a principle is known as \emph{macroscopic locality}. The level of coarse-gaining is captured by a simple parameter $\alpha\in[0,1]$, with N^α being the order of the resolution when a collective measurement is performed on a system of size N (number of particles). It is well known that no coarse-graining ($\alpha=0$) exhibits non-local correlations, while there are strong indications that fully coarse-grained ($\alpha=1$) quantum correlations become local in the macroscopic limit. It is natural to ask what is the critical value α_c of the quantum-to-classical transition, such that for $\alpha<\alpha_c$ nonlocal correlations survive and for $\alpha > \alpha_c$ locality is restored. So far, it has been believed that $\alpha_c \leq 1/2$, as it follows from the result of Navascu\'{e}s and Wunderlich (NW). This result coincides with the heuristic statement of $\sqrt{N}$ being the error scaling associated with a typical quantum experiment. However, the work of NW is restricted to the study of correlations arising from \emph{independent and identically distributed} (IID) quantum states. In this work, we show that relaxing this constraint and employing non-IID states leads to fully quantum correlations. This implies that $\alpha_c \geq 1/2$, and the question of the quantum-to-classical transition still remains open. In fact, we derive a much stronger result by showing that the \emph{quantum superposition principle} remains fully valid in the macroscopic limit for quantum measurements with a resolution of the order of $\sqrt{N}$.\\

35. ENTANGLEMENT-ENABLED COMMUNICATION

JANIS NÖTZEL

We introduce and analyse a multiple-access channel with two senders and one receiver, in the presence of i.i.d. noise coming from the environment. Partial side information about the environmental states allows the senders to modulate their signals accordingly. An adversarial jammer with its own access to information on environmental states and the modulation signals can jam a fraction of the transmissions. Our results show that for many choices of the system parameters, entanglement shared between the two senders allows them to communicate at non-zero rates with the receiver, while for the same parameters the system forbids any communication without entanglement-assistance, even if the senders have access to common randomness (local correlations). A simplified model displaying a similar behaviour but with a compound channel instead of a jammer is outlined to introduce basic aspects of the modeling. We complement these results by demonstrating that there even exist model parameters for which entanglement-assisted communication is no longer possible, but a hypothetical use of nonlocal no-signalling correlations between Alice and Bob could enable them to communicate to Charlie again.

36. EXPERIMENTAL HIGHER-ORDER INTERFERENCE IN QUANTUM MECHANICS INDUCED BY OPTICAL NONLINEARITIES

PETER NAMDAR, IRATI ALONSO CALAFELL, ALESSANDRO TRENTI, MILAN RADONJIC, BORIVOJE DAKIĆ, PHILIP WALTHER, LEE A. ROZEMA

Double- or multi-slit experiments are a direct demonstration of interference between quantum objects. The produced interference patterns can all be explained in terms of interference between pairs of slits, i.e. second-order interference terms without any arising of higher-order terms. However, it was shown that one can obtain higher-order interference without violating the laws of quantum physics when taking nonlinear effects into account. Experimentally we realize this by proposing and carrying out a “nonlinear triple-slit" experiment. We let three laser beams interact in a nonlinear crystal. Then we measure the power in one of the beam paths behind the nonlinear crystal while blocking all permutations of the 3 input beams and obtain third-order interference from there. We measure a third-order interference component of 5.5mW ± 1.5mW with a total input power of approximately 1W. Our results show that quantum theory can in fact allow for higher-order interference.

37. OPTICAL DETECTION OF THE POSITION AND THE VARIANCE OPERATORS

GIOVANNI CERCHIARI, L. DANIA, D. BYKOV, K. HEIDEGGER, T. NORTHUP, R. BLATT

We are developing a method to characterize motional quantum states of a dipolar scatterer confined in a harmonic potential. In the experiment, we will couple the scattered light with a mirror to modify the spontaneous emission of the scatterer in a position-dependent way. By controlling the scattering rate with the mirror, we aim to detect the position and the variance of the scatterer's state of motion. The technique can identify motional quantum states in a fully optical way, without resorting to changing the trapping potential or to interacting with a forbidden transition of the scatterer with a laser. The method offers future perspectives for the full-optical characterization and preparation of quantum states of motion. We are currently preparing the setup to test the technique with trapped ions.

38. DEMONSTRATION OF HIGH Q FACTORS AND OPTICAL ABSORPTION IN HBN INTEGRATED MICRODISKS

ANUSTUP DAS, PRASOON K. SHANDILYA, DONG JUN LEE, SEJEONG KIM, KANG GUMIN, DAVID P. LAKE, MATTHEW MITCHELL, IGOR AHARONOVICH, DENIS SUKACHEV, JAEHYUN PARK, PAUL E. BARCLAY

Quantum networks have the potential to transmit data securely. To make these feasible, we need to develop technologies to send information in between quantum nodes at telecom wavelengths. Hexagonal Boron Nitride (hBN) is a 2D material with a wide bandgap (6 eV) and a high refractive index (1.8) which can sport a high number of single-photon emitters. These can be coupled and driven by photons and phonons absorbed by the material. The current state-of-the-art in hBN devices has been limited to an optical quality factor (Q) of 10000. In this work, hBN integrated microdisks with varying amounts of hBN thickness (0-400 nm) and device dimensions (17-180 um) having Q between 10000-280000 have been optically characterized. The absorption of 980 nm and 1550 nm light, in hBN, was studied and it was determined that the absorption in hBN is mainly dominated by photo-thermal effects. This gives us an insight into the optical properties of hBN and helps us understand its use in quantum networks.

39. COMPUTATIONAL POWER OF MATCHGATES WITH SUPPLEMENTARY RESOURCES

MARTIN HEBENSTREIT, RICHARD JOZSA, BARBARA KRAUS, SERGII STRELCHUK

Although it is believed that quantum computation cannot be classically efficiently simulated in general, there exist certain restricted classes of quantum circuits for which classical simulation is possible. The most prominent example are the Clifford circuits. Here, we consider another such class, the matchgate circuits (MGCs). We study the simulation complexity of MGCs supplemented with additional resources such as e.g. intermediate adaptive measurements, magic state inputs, or multi-line outputs. We find a striking parallel to known results for Clifford circuits, after some rebranding of resources. We also give bounds on the simulation effort required in case of limited access to intermediate measurements and entangled inputs.

40. ENTANGLEMENT-ASSISTED DATA TRANSMISSION AS AN ENABLING TECHNOLOGY: A LINK-LAYER PERSPECTIVE

STEPHEN DIADAMO, JANIS NÖTZEL

Quantum entanglement as a resource has repeatedly proven to add performance improvements for various tasks in communication and computing, yet no current application justifies a wide spread use of entanglement as a commodity in communication systems. In this poster, we present how the addition of an entanglement storage system at the end-points of a communication link integrated seamlessly into the current Internet can benefit that link's capabilities via a protocol implementing the simple rule to ``create entanglement when idle'', and use entanglement-assisted communication whenever possible. The benefits are shown with regards to throughput, packet drop-rate, and average packet processing time. The modelling is done in an information-theoretic style, thereby establishing a connecting from information-theoretic capacities to statistical network analysis.

41. EFFICIENT PREPARATION OF A FAMILY OF GROUND STATES OF LOCAL HAMILTONIANS AND THEIR VERIFICATION PROPERTIES

ESTHER CRUZ RICO, FLAVIO BACCARI, JORDI TURA, NORBERT SCHUCH, IGNACIO CIRAC

In this work we propose an algorithm for the preparation and verification of ground states of local, gapped and frustration-free Hamiltonians in near-term devices, by means of an adiabatic algorithm. Our method works by smoothly deforming an adiabatic path of commuting Hamiltonians, such that a spectral gap is preserved. The family of proposed states includes all injective, isometric MPS and PEPS as well as paradigmatic states in 2D such as graph states. For each Hamiltonian, we provide a uniform bound for its spectral gap along the adiabatic path, thus guaranteeing the efficiency of the algorithm. Moreover, we study a potential useful application for our algorithm, namely a verification protocol which could potentially be used for the generation of certifiable randomness. This protocol works as a two-player game, in which a classical, limited verifier and a quantum prover communicate through a classical channel. The prover returns samples that result from measuring the ground state on a certain basis and must convince the verifier that they come from the correct distribution.

42. QUANTUM RECEIVER DESIGN

ANDREA CACIOPPO, JANIS NÖTZEL, MATTEO ROSATI

Compound channel models offer a simple and straightforward way of analyzing the stability of decoder design under model variations. Here we provide a coding theorem for the class of compound attenuation channels. We then apply the theory of compound channels to motivate a nontrivial choice of the displacement parameter of the Kennedy receiver when used for an attenuation channel.

43. CLASSICAL WAVE-PARTICLE DUALITY

POLINA POGREBINSKAYA, BORIVOJE DAKIĆ

Interference of single particles lies at the core of quantum mechanics. The most prominent demonstration of this effect is the double-slit experiment: the presence of a quantum particle is verified by a single spot on the detection screen. While this clearly indicates an experiment with particle-like objects, the statistics of repeated runs reassembles interference fringes. This observation is the source of the wave-particle duality and it is dedicated to genuine quantum behavior. Nonetheless, it is unclear whether this conclusion is justified and to which extend we can reproduce such an experiment with classical waves? In this work we show that standard (classical) wave mechanics combined with the statistical detection model completely reproduces quantum interference experiments with single particles. We dubbed this phenomenon the “classical particlewave duality”. The recreation of quantum double-slit experiment using classical waves shows that the “unusual behavior” of quantum systems in this experiment is not necessarily proof of a genuine quantum effect.