QTech 2024

QUANTUM TECHNOLOGY INTERNATIONAL CONFERENCE

SEPTEMBER 10-12, 2024 | BERLIN

BOOK OF ABSTRACTS

premc.org/QTech

ISSN 2678-2820

Table of Contents

Fundamental Physics from Quantum Technologies: the quantum gravity quest

Oral - Abstract ID: 298

Markus Aspelmeyer [1]

1. *University of Vienna*

No experiment today provides evidence that gravity requires a quantum description. Recent developments in quantum sensor technology may change that situation. In particular, the growing ability to quantum control solid-state mechanical devices (quantum optomechanics) may enable experiments that directly probe the phenomenology of quantum states of gravitational source masses. This can lead to experimental outcomes that are inconsistent with the predictions of a purely classical field theory of gravity. These developments showcase the important role quantum technologies play in exploring new regimes of fundamental physics.

Quantum key distribution: from security proofs to implementations

Oral - Abstract ID: 299

Antonio Acin [1]

1. *ICFO-The Institute of Photonic Sciences*

We discuss several aspects of quantum key distribution protocols, from security proofs to implementations, using continuous or discrete degrees of freedom. On the one hand, we provide a security proof for discrete-modulated continuous-variable quantum key distribution. On the other hand, we discuss the challenges for the implementation of device-independent quantum key distribution protocols and present a proposal using single-photon sources.

Tight models of rigorous quantum complexity growth

Oral - Abstract ID: 304

Richard Kueng [1]

1. Institute for Integrated Circuits and Quantum Computation, Johannes Kepler Universität, Linz, Austria

The concept of quantum complexity has far-reaching implications spanning theoretical computer science, quantum many-body physics, and high energy physics. The quantum complexity of a unitary transformation or quantum state is defined as the size of the shortest quantum computation that executes the unitary or prepares the state. A couple of years ago, we established a rigorous connection between complexity growth and unitary k-designs – ensembles which capture the randomness of the unitary group. This allowed us to conclude that random brick wall circuits of depth T have quantum complexity (at least) T^{1/11} up to exponential circuit depths (arXiv:1912.04297). Rigorously proving sublinear growth has been a step in the right direction, but still falls short of the (tight) linear quantum complexity growth conjectured by many experts in the community. A recent draft by Chi-Fang Chen, Jeongwan Haah, Jonas Haferkamp, Yunchao Liu, Tony Metger and Xinyu Tan has now closed this gap (arXiv:2406.07478) by establishing a much tighter connection between k-designs and random brickwall circuits. As a consequence, they prove that the quantum complexity of random brickwall circuits must indeed grow linearly in circuit depth.

Quantum Tanner codes

Oral - Abstract ID: 303

Anthony Leverrier [1]

1. *Inria*

Quantum Low-Density Parity-Check (LDPC) codes are a class of quantum error correcting codes that have attracted a lot of attention lately in the context of building fault-tolerant quantum computers. In particular, the existence of good families of quantum LDPC codes was recently established by Panteleev and Kalachev: these codes encode logical qubits within physical qubits, and have a minimum distance linear in the code length, meaning that they can correct arbitrary errors supported on a constant fraction of the qubits.
In this talk, I will discuss quantum Tanner codes (introduced in collaboration with Gilles Zémor) which are another family of good quantum LDPC codes, arguably simpler than the codes of Panteleev and Kalachev.

National Quantum Computing Centre (NQCC), UK: Pioneering Quantum Computing with a Unified Stack

Poster - Abstract ID: 30

Manish Chowdhary [1], *Tim Boyle* [2], *Ali Muhammad* [2], *Connor Pettitt* [2], *Sundaresan Jothiraj* [2], *Danny Hindson* [2]

1. National Quantum Computing Center, 2. NQCC

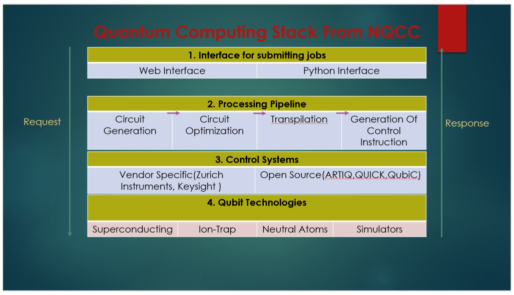
The National Quantum Computing Centre (NQCC) stands at the forefront of quantum computing innovation in the UK. Our mission at NQCC is to spearhead research and development in quantum computing technologies that accommodate multiple modalities. Situated within our Software and Control Systems group is a vision to create an extensive stack—from control systems right up to the application layer—built using open-source platforms.

Our approach is designed to support a variety of qubit technologies at the control level, with a universal application stack that facilitates seamless execution of algorithms across diverse platforms. This stack will have the capability to adapt to various hardware frameworks. Our open source focus sets us apart from existing quantum computing solutions and, upon its completion, is expected to significantly advance the field by offering a versatile tool for expansive quantum research.

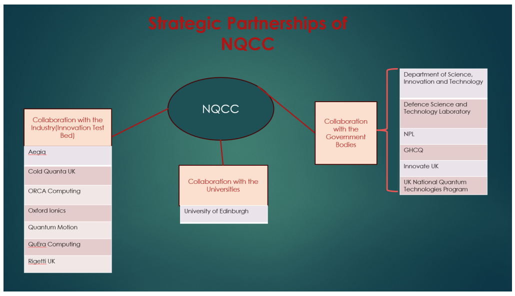
This poster highlights our current milestones and provides an architectural overview of our ongoing projects. Key features of our initiative include:

- **Emphasis on Open Source:** At the quantum control layer, our system employs the open-source software ARTIQ (Advanced Real Time Infrastructure for Quantum Physics) along with SINARA hardware components to ensure precise, stable operations tailored for ion-trap platforms.
- **Modular and Integrative Design:** Our system's architecture champions modularity, which simplifies the integration of different qubit modalities. We have already incorporated a quantum simulator and are taking strides toward integrating the ion-trap hardware platform.
- **Fostering Collaboration:** We are dedicated to propelling the quantum revolution by encouraging collaborations that address existing challenges and propel advancements within the field.

We invite you to join us at NQCC as we pave the way to the future of quantum computing, leveraging the power of open-source components to foster innovation and enhance research capabilities. Our collaborative efforts are essential for overcoming current limitations and achieving breakthroughs in quantum computing technology.



Quantum computing stack from nqcc.png



Strategic partmenrships of nqcc.png

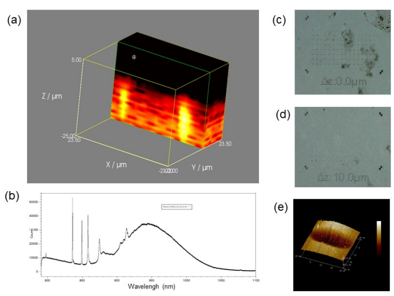
fs-laserwriting of quantum defects in SiC

Poster - Abstract ID: 36

Ivan Shishkin [1]***, Martin de Biasio*** [1]***, Bernardo Realista-Ferreira*** [1]***, Nikolai Andrianov*** [1]***, Muhammad Khan*** [1]***, Thang Duy Dao*** [1]***, Gerald Auböck*** [1]***, Andreas Tortschanoff*** [1]

1. *Silicon Austria Labs*

Defects in SiC are under much investigation since they are interesting candidates for quantum technology applications like single photon sources or for room temperature quantum sensing. Most often, defects are created using ion implantation. An alternative route is to use fs-laser pulses to introduce defects. This method introduces relatively little damage to the crystal structure and can generate localized defects at defined positions, including also well-defined depths.
Here we will present very first results from our defect writing experiments. Using 200 fs laser pulses with a center wavelength of 515 nm, dot arrays were written onto SiC wafers. We used bulk semi-insulating 4H-SiC-wafers. (Note, that it turned out, that there was a significant background fluorescence from defects already present in the pristine wafers, so before laser-writing all wafers were pre-annealed at 1000°C for 2 hours under argon atmosphere. This strongly reduced the background fluorescence.)
The laser power, as well as the number of laser pulses at each spot was varied systematically. A 50x objective with NA=0.8 was used for writing the defects. Pulse energies were varied from 15-800 nJ. While for high pulse energies, significant surface damage is visible, no damage is optically visible for pulses with energies of less than 300nJ, focused to 10µm below the surface. This was also investigated with atomic-force microscopy.
Fluorescence measurements were performed in a confocal microscopy setup with excitation at 780 nm. Mapping of the irradiated area showed significant increase of the integral fluorescence at the irradiated spots. 3D-maps were performed to confirm, that the position of defect generation can be localized in a well defined volume.
We also performed low temperature fluorescence measurements at 80K. Here we clearly observe narrow bands at 860nm and 914nm appearing at the irradiated spots, which correspond to the zero-phonon lines of the single Si-vacancy defect. This is probably the best known spin-defect in SiC, which has been investigated for multiple quantum applications.
We expect that the possibilities of localized selective laser-writing of these quantum-defects, in combination with photonic elements like meta-lenses directly fabricated in SiC will open new opportunities in the field of quantum-sensing.



(a) 3d-Mapping of defect fluorescence at room temperature, (b) typical spectrum, (c),(d) laser-written spot pattern with variation in pulse energy and number of shots for a depth of writing of z=0 and z=10 µm. (e) AFM image at a given spot.

Results on laserwriting of quantumdefects in sic.jpg

Distributing photons from a single atom quantum network node to a telecom fiber

Poster - Abstract ID: 50

Pau Farrera [1]***, Maya Büki*** [1]***, Gianvito Chiarella*** [1]***, Tobias Frank*** [1]***, Emanuele Distante*** [2]***, Gerhard Rempe*** [1]

1. Max Planck Institute of Quantum Optics, 2. ICFO - The Institute of Photonic Sciences

Single Rubidium atoms coupled to high finesse optical cavities provide numerous solutions for the challenges of future quantum communication. Some examples are the implementation of a photonic quantum memory [1], quantum logic gates between photonic and atomic qubits [2], or photonic qubit tracking through nondestructive detection [3]. However, due to the atomic level structure of Rubidium, in these schemes the atoms are interfaced with photonic polarization qubits that have a wavelength of 780nm or 795nm. Photons at such a wavelength range experience high losses in optical fibers (around 3dB/km) and are therefore unsuitable for long-distance quantum communication. To circumvent these losses, we implemented a quantum frequency converter that can translate the wavelength of single photonic polarization qubits from 780nm to 1514nm. The design allows for high-fidelity conversion with fiber-to-fiber efficiency of 50%. Deploying a narrow band filtering system, we achieve a high signal-to-noise ratio and a high converted single photon purity. We envision using this frequency converter to distribute quantum states over a long telecom fiber across the metropolitan area of Munich.

[1] M. Brekenfeld et al., Nature Physics 16, 647-651 (2020)
[2] A Reiserer et al., Nature 508 (7495), 237-240 (2014)
[3] D. Niemietz et. al., Nature 591, 570–574 (2021)

Qubit-environment entanglement in time-dependent pure dephasing for transmon qubits

Poster - Abstract ID: 64

Malgorzata Strzalka [1], ***Radim Filip*** [2], ***Katarzyna Roszak*** [3]

1. *Faculty of Mathematics and Physics, Charles University,* ***2.*** *Department of Optics, Palacký University,* ***3.*** *Institute of Physics (FZU), Czech Academy of Sciences*

We generalized the methods for quantification of system-environment entanglement that were previously developed for interactions that lead to pure decoherence (PD) of the system for time-independent Hamiltonians to time-dependent Hamiltonians. We have shown that the if-and-only-if criteria of separability [1], the entanglement measure [2], and the methods of detecting entanglement through operations and measurements performed only on the system without access to the environment [3] generalize in a straightforward manner to the case of time-dependent Hamiltonians. Thus the theoretical study of this type of entanglement is straightforward, while the time-dependence can enable experimental detection of entanglement for a wider class of PD interactions. The methods were used to study the evolution of system-environment entanglement of a transmon qubit interacting with microwave cavity photons [4] for an interaction switching between an entangling and a non-entangling one. This allows us to study nontrivial dependencies between the buildup of classical and quantum correlations, as the buildup of entanglement does not directly follow the switching of the interaction [5]. Furthermore, we show how to detect entanglement in this system, which is undetectable by the time-independent methods due to symmetries in the Hamiltonian, by taking advantage of the controllable time-dependence of the interaction.

[1] K. Roszak and L. Cywiński, Characterization and measurement of qubit-environment-entanglement generation during pure dephasing, Phys. Rev. A 92, 032310 (2015).

[2] K. Roszak, Measure of qubit-environment entanglement for pure dephasing evolutions, Phys. Rev. Research 2, 043062 (2020).

[3] M. Strzałka and K. Roszak, Detection of entanglement during pure dephasing evolutions for systems and environments of any size, Phys. Rev. A 104, 042411 (2021).

[4] P. Campagne-Ibarcq, A. Eickbusch, S. Touzard, E. Zalys-Geller, N. E. Frattini, V. V. Sivak, P. Reinhold, S. Puri, S. Shankar, R. J. Schoelkopf, et al., Quantum error correction of a qubit encoded in grid states of an oscillator, Nature 584, 368 (2020).

[5] M. Strzałka, R. Filip, and K. Roszak, Qubit-environment entanglement in time-dependent pure dephasing, Phys. Rev. A 109, 032412 (2024).

Developing a Microwave-Optical Resonator at Millikelvin Temperatures for Hybrid Quantum Systems

Poster - Abstract ID: 70

Tatsuki Hamamoto [1], ***Amit Bhunia*** [1], ***Hiroki Takahashi*** [1], ***Yuimaru Kubo*** [1]

1. Okinawa Institute of Science and Technology Graduate University

Spins in solids have relatively long coherence times in their microwave transition, making them one of the promising candidates for compensating the disadvantages of superconducting qubits as a hybrid quantum system. Additionally, some of these spins have optical transitions, expanding their applications to optically pumped maser amplifiers [1], spin-based quantum memory for optical photons [2], and spin ensemble-based quantum transducers [3], which can bi-directionally convert microwave photons and optical photons.

We are developing a spin ensemble-based quantum transducer, essential for establishing a room-temperature quantum network based on superconducting qubits. Here, we present a hybrid resonator for this quantum transducer, which integrates microwave and optical cavities, effectively overlapping both modes at the sample space (Fig. 1).

Using a dielectric resonator as a microwave resonator has resulted in a high internal quality factor (Qint ~ 10^4) with minimal influence from large apertures (8 mm in diameter) on the resonator housing for free-space optical access [Fig. 2(a)]. Furthermore, we measured the resonator with a diamond crystal containing substitutional nitrogen impurities called P1 centers and observed strong coupling between the spin ensemble and the resonator at 10 mK [4].

We have built a Fabry–Pérot (FP) cavity as an optical cavity and made it as rigid as possible. The optical cavity length fluctuation can be suppressed to 18 pm root mean square (rms) at 13 mK under the mechanical vibration of a pulse-tube cooler inside a cryogen-free dilution refrigerator [Fig. 2(b)]. This value is almost comparable to other reported values at around 4 K (Table 1). We inserted a diamond crystal into the optical cavity for hybrid quantum devices and confirmed that the cavity length fluctuation remains in the same order of magnitude (38 pm rms).

[1] Breeze *et al.*, *Nature* 555, 493–496 (2018).
[2] Khabat *et al.*, *Phys. Rev. A* 89, 040301(R) (2014).
[3] Gavin *et al.*, *Phys. Rev. B* 103, 214305 (2021).
[4] Hamamoto *et al.*, *Appl. Phys. Lett.* 124, 234001 (2024).

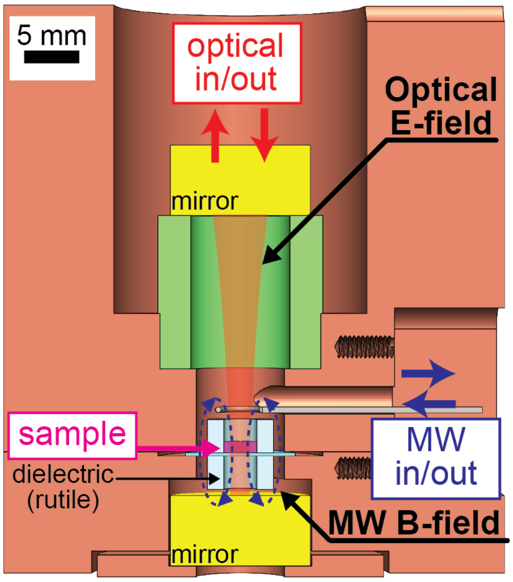


Fig1 cavityschematics.png

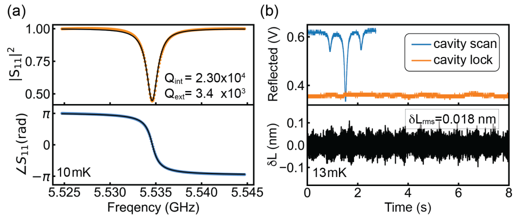


Fig2 results.png

	Pallmann *et al.*, (2023)	Fisicaro *et al.*, (2024)	Ruf *et al.*, (2021)	Kumar *et al.*, (2023)	This work
Configuration	Fiber FP	Bulk FP	Fiber FP with diamond	Bulk FP with trapped atoms	Bulk FP/ (with diamond)
Device temp.	10 K	4 K	4 K	4 K	13 mK
$\boldsymbol{\delta L_{rms}}$	15 pm	10.6 pm	~ 100 pm	<25 pm	18 pm /(38 pm)

Table1 cavitylengthfluctuation.png

Optimising quantum tomography via shadow inversion

Poster - Abstract ID: 97

Andrea Caprotti [1] ***, Joshua Morris*** [1] ***, Borivije Dakić*** [1]
1. *University of Vienna*

Introduction

In quantum information theory, the accurate estimation of observables is pivotal for quantum information processing, playing a crucial role in computation and communication protocols.In the last few years significant advancements have been made made in the realm of quantum information processing from the introduction of classical shadow tomography [Huang et al. Nat. Phys. 16, 1050–1057 (2020)]. This technique represents a milestone in the way quantum measurement are processed using classical means, greatly reducing the amount of resources required for efficient estimation. We introduce a novel technique expanding on classical shadow tomography by improving the often overlooked post-processing aspect of the protocol.

Methods

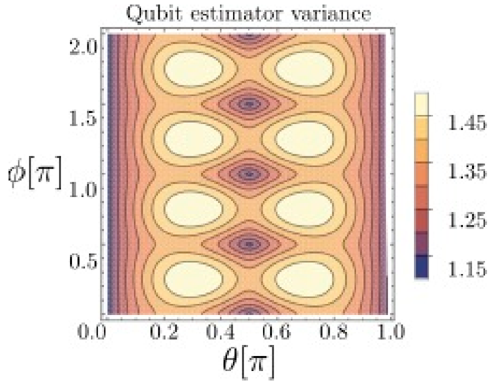
We present a generalised framework for the inversion of classical shadows, usually considered only a fixed step, highlighting a dependence on free parameters. These represent an additional valuable resource for the reduction of estimation costs of target observables. We introduce a figure of merit, the optimal shadow norm, which determines the value of the free parameters identifying the optimal configuration, which guarantees the smallest amount of resources to achieve an accurate estimation from a finite set of data.The optimisation regards solely classical post-processing, making the framework completely device-independent and thus adaptable to a variety of near-term problems.

Results

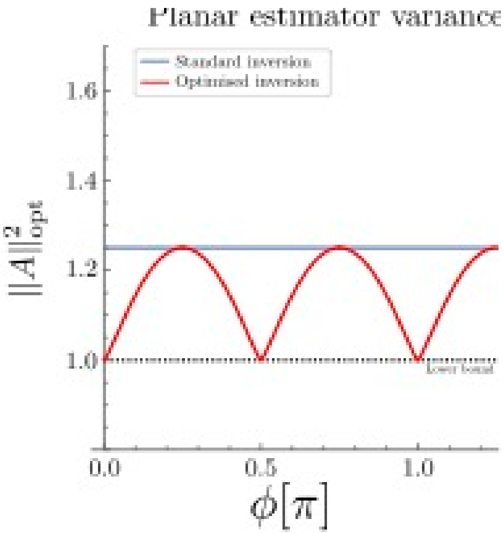
We show exponential separation in sample complexity through feasible optimisation of local measurement strategies, achieving a level of efficiency up to now predicted only for global Clifford measurements.In particular we show a significant improvement in the estimation of projector fidelity (figure a). Moreover, by introducing stricter assumptions on the states to be characterised, we show the possibility of not only further improvement, but also efficient estimation with constant overhead on the required resources independent on the number of qubits considered (figure b).

Discussion

By introducing a generalised framework to obtain families of equivalent parameter-dependent estimators, we have found a clear relation between over-complete POVMs and their ability to reduce the variance in estimation of arbitrary observables.We anticipate that by considering over-complete POVMs containing joint measurements on multiple qubits, further advantage may be found at increased (but still tractable) optimisation difficulty, either in sample complexity or the set of observables.



A projector optimal norm.jpg



B planar projector optimal norm.jpg

Photonic machine learning for image classification

Poster - Abstract ID: 100

Martin Mauser [1], Iris Agresti [1], Solène Four [1], Borivije Dakić [1], Philip Walther [1]

1. University of Vienna

Introduction

Data re-uploading [1] is a well studied quantum machine learning (QML) technique, that enables a single qubit to act as a universal approximator through rotation operations [2]. Herewith the quantum algorithm is structured in distinct layers, each containing an encoding unitary U_{enc} for input data and a trainable unitary U_{ϑ} with adjustable parameters. The model's expressivity hinges on the sequential arrangement of these unitaries. Figure 1 illustrates the data re-uploading approach applied to a 2D dataset.

Methods

In this work, we realized such a data re-uploading scheme in an integrated optical chip using weak coherent laserlight in a two mode system. This integration enables the possibility of transferring the energy-efficiency gains of classical optical chips to enhance QML algorithms. We can execute any unitary operation with a single Mach-Zehnder interferometer (MZI)[3]. Note that multiple layers can be represented by a single MZI, as unitary products can be simplified into a single unitary. Classification in the one-dimensional output space was determined using Linear Discriminant Analysis.

Results

A wide variety of different datasets with increasing complexity and dimensionality were investigated. To manage multiple features, we adopted a sequential approach, processing data pairs one after another, each followed by a trainable gate operation. The complete sequence of unitaries constitutes a single layer in our quantum learning system [4]. The resulting performance is depicted in Figure 2.

Discussion

In order to demonstrate the feasibility of this algorithm to be implemented solely in quantum hardware, we first viability performed some experiments without compressing the unitaries. The main challenge of data reuploading remains training the quantum circuit, we demonstrated the feasibility of on-chip training using the parameter shift method [5]. Hereby, the protocol proved robust, yielding consistent results for both noise-less simulation and a noise heavy experimental realisation.

[1] Quantum4, 226 (2020).
[2] Phys.Rev.A 103, 032430 (2021).
[3] OPTICA3, 1460–1465 (2016).
[4] IEEE QCE 31–37 (2022).
[5] Phys.Rev.A 99, 032331 (2019).

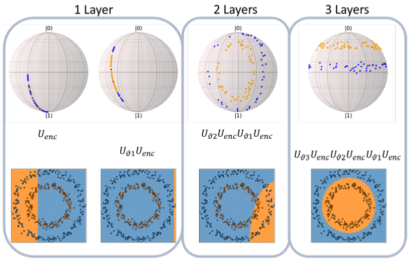
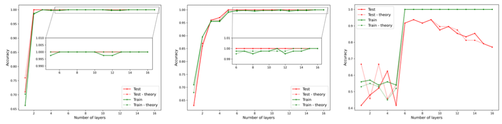


FIG. 1: **Visualisation of a three layered single qubit classifier on the circles dataset.** The top row shows the action after x layer(s) on all of the output states on the Bloch sphere. The middle row denotes the operations applied to our fixed input state. The last row, shows the encoded data set - orange and blue points in the arrangement of two concentric circles with different radii - and the predicted label by the classifier via the background colour.

Fig1 visualisation.png



(a) Circles (b) Moons (c) Tetrominos

FIG. 2: **Achieved accuracy vs. model dimension.** The green curves plot the performance on the training data, while the red curves visualise the performance on unseen test data. The dotted and solid lines represent the theoretical/simulated and the performance on the optical integrated circuit respectively.

Fig2 results.png

Relativistic quantum Deutsch-Jozsa game

Poster - Abstract ID: 103

Marek Lampart [1], ***Paulina Lewandowska*** [2], ***Adam Bílek*** [2]

1. *Moravian-Silesian Innovation Centre Ostrava, Czechia,* ***2.*** *IT4Innovations, VSB-Technical University of Ostrava*

The impact of noise on near-term quantum devices has been studied extensively due to the inherent imperfections in their operation, leading to uncertain protocol correctness, especially for protocols based on shared entanglement.
The excellent example of such protocols are pseudo-telepathy games. In this research, the Deutsch–Jozsa game is considered as a
pioneering example of this field of quantum information. Here, we assume a disturbed initial entangled state caused by the Unruh effect to analyze its impact to reliability of the algoritm.

Time-bin Cluster State Generation

Poster - Abstract ID: 121

Thomas Häffner [1] ***, Siavash Qodratipour*** [1] ***, Oliver Benson*** [1]

1. *Humboldt University of Berlin*

Fusion-based linear optical quantum computing is a promising platform, where the complexity is shifted from two-qubit gates to the generation of a resource state, a highly entangled cluster state [1]. The goal of our research project is an integrated photonic implementation of such a quantum computer and our experiment is therefore realized completely in optical fiber and waveguide components. Therefore, a good choice of the degree of freedom to encode qubits in, is the time-bin degree of freedom of single photons, as polarization encoding, for example, is not suitable due to dispersion.

We pump a type-II periodically-poled LiNbO3 waveguide with two consecutive pulses from a pulsed TiSapph laser at 780 nm. Each pulse has an equal probability of generating a pair of entangled photons in the process of spontaneous parametric down-conversion at telecom wavelength. This creates time-bin entangled pairs of single photons [2]. These pairs of entangled photons can then be combined into larger entangled cluster states in so-called fusion gates. We show Hong-Ou-Mandel (HOM) interference between two single photons from pairs generated by two pump pulses at different times. The visibility of the HOM interference is a measure of the pureness and indistinguishability of single photons, which are necessary to efficiently entangle photons into cluster states. For the unbalanced interferometer used we present a novel phase-stabilization scheme based on short laser pulses. A time-multiplexed pseudo-photon-number-resolving detector was built and is used to optimize the probability of generating exactly one photon pair per pump pulse as well as heralding successful fusion. Results of the experimental implementation of a time-bin fusion gate will be presented.

By performing single qubit measurements and feed-forward operations on such cluster states, a quantum algorithm can be implemented and universal quantum computation can be achieved.

[1] S. Bartolucci, et al., “Fusion-based quantum computation,” Nature Communications, vol. 14, p. 912, Feb. 2023.

[2] S. Tanzilli, et al., “Ppln waveguide for quantum communication,” The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics, vol. 18, p. 155–160, Feb. 2002.

Enhanced axial resolution mid-infrared optical coherence tomography with tuneable-bandwidth undetected photons

Poster - Abstract ID: 134

Emma Pearce [1], *Atta ur Rehman Sherwani* [1], *Rajshree Swarnkar* [2], *Marthe Zeja* [1], *Philipp Hildenstein* [3], *Fabian Wendt* [4], *Álvaro Barroso* [5], *Björn Kemper* [5], *Katrin Paschke* [3], *Sven Ramelow* [1]

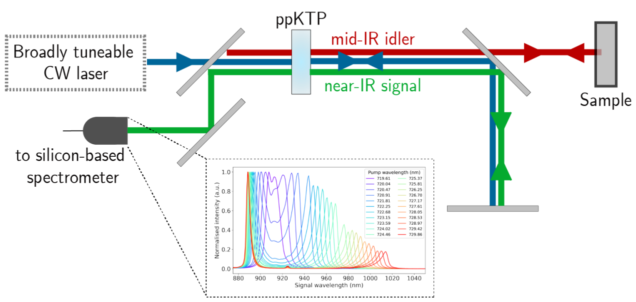
1. Humboldt University of Berlin, 2. Technical University of Darmstadt, 3. Ferdinand Braun Institut, 4. Fraunhofer-Institut für Lasertechnik ILT, 5. Universität Münster

Optical coherence tomography (OCT) is a powerful technique to access cross-sectional images of a sample and reveal sub-surface features [1]. OCT therefore has clear potential in non-destructive testing; however, many interesting materials, such as ceramics and paints, are strongly scattering and prevent penetration of visible and near-infrared (near-IR) light into the sample. Mid-IR OCT allows greater penetration but is typically limited by available detection technology and light sources. Crucially, the axial resolution of OCT is defined by the bandwidth of the light source and so must be spectrally broadband to access high resolution depth information. We present a compact modular device which enables mid-IR OCT to be performed without mid-IR detection or light sources [2], as well as a novel approach to enhancing its axial resolution. The module comprises a nonlinear interferometer, where entanglement between photon pairs means that mid-IR light is used to probe the sample but only near-IR wavelengths are detected using a silicon-based spectrometer (Figure 1). By using a broadly tuneable visible pump laser, the spectrum of the photon pairs generated in the module can be altered (Figure 1, inset). The resulting near-IR spectra can be coherently combined to increase the effective spectral bandwidth. Importantly, the corresponding idler spectrum seen by the sample is also effectively broadened and thereby the axial resolution of OCT measurements is improved. The reduced footprint, use of silicon-based detection, and improved axial resolution further extends the technology readiness levels of mid-IR OCT, with potential applications in areas such as industrial quality control and heritage conservation.

Figure 1: Schematic of a nonlinear interferometer for mid-IR OCT with undetected photons. (inset) Example spectra of signal acquired with widely tuned pump laser which can be combined to increase bandwidth and enhance axial resolution.

[1] R. C. Youngquist, S. Carr, and D. E. N. Davies, “Optical coherence-domain reflectometry: a new optical evaluation technique,” Opt. Lett. **12**, 158–160 (1986).

[2] A. Vanselow, P. Kaufmann, I. Zorin, B. Heise, H. M. Chrzanowski, and S. Ramelow, “Frequency-domain optical coherence tomography with undetected mid-infrared photons,” Optica 7, 1729-1736 (2020).



Highres midir oct schematic.png

Quantum knowledge distillation

Poster - Abstract ID: 136

Francesco Aldo Venturelli [1]

1. *University of Florence*

Introduction

Classical convolutional neural networks (CNNs) have revolutionized image processing in both public and private sectors. Simultaneously, Quantum Machine Learning is emerging as a field that merges Physics and Machine Learning, aiming to leverage quantum mechanics for vastly increased computational power. Despite its promising potential, enhancing quantum models' capabilities remains a challenge. In this abstract, knowledge distillation, a classical Machine Learning technique which transfers knowledge from larger models to lighter, boosting their performance, is used as a method to improve quantum models' results, represented by parameterized quantum circuits (PQCs) that are trained to learn from a high-performing classical CNN.

Methods

We compared distilled and un-distilled models to see if knowledge distillation can improve the performance of QNNs with fewer trainable parameters. Using PyTorch and Pennylane, we trained and validated both CNN and QNNs on an 8-class subset of the MNIST dataset (28x28 features). The PQCs were composed by 10 qubits, 6 layers containing 3 parameterized rotations per gate and were tested on unseen images. Subsequently, the distilled model was trained using Kullback-Leibler divergence loss between teacher (CNN) and student (QNN) logits. Test accuracy was computed with each QNN trained for 50 epochs using different weight distributions for teacher and student. Each simulation was repeated five times with different parameter initializations to ensure robust results.

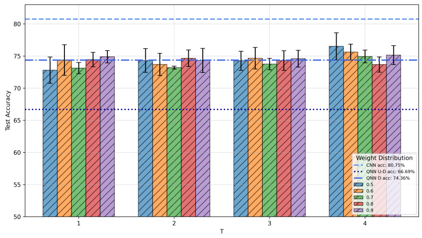
Results

The distilled QNNs showed an improvement of 10%-15% compared to the results of the un-distilled model, as depicted in the histogram. The performance trend was proportional to the temperature (T), which controls the smoothness of output distributions: higher T resulted in smoother distributions with smaller probabilities receiving a larger boost.

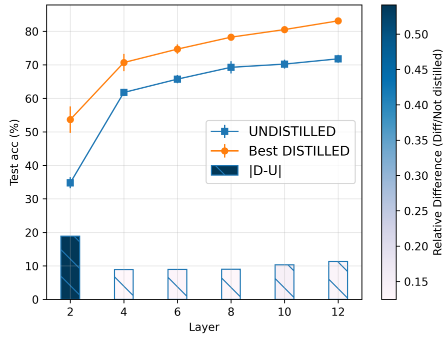
Discussion

Despite the improvements, the overall accuracy remained below the one coming from classical model. However, QNNs used significantly fewer trainable parameters, with a 1:1000 ratio compared to the CNN. Increasing the number of layers could improve generalization but at the cost of simulation efficiency.

To conclude, transferring knowledge from classical to quantum models seems promising: it avoids extensive pre-processing and feature reduction, which often result in loss of information, suggesting a viable path for enhancing quantum models' performance efficiently.



Model performance comparison.png



Performance vs layer.png

Optical Protocol for Generating non-Gaussian state in C-band.

Poster - Abstract ID: 144

Elnaz Bazzazi [1], ***Roger Alfredo Kögler*** [1], ***Leon Reichgardt*** [1], ***Marco Schmidt*** [1], ***Oliver Benson*** [1]

1. *Humboldt University of Berlin*

Non-Gaussian states play a crucial role in fault-tolerant quantum computing, where the encoded information is protected from decoherence processes [1]. Certain classes of non-Gaussian states, such as coherent state superpositions known as cat states, pose challenges in generation. These are due to the complexity of breeding protocols and the limitations of their achievable output states [2,3]. Here, we explore state engineering of squeezed coherent state superpositions (SCSS) through a catalysis protocol [4].
As illustrated in Figure 1, the output state results from a beam splitter operation applied to two input states: a vacuum squeezed state and a Fock state, followed by photon number resolved detection in one of the output arms. Our numerical simulations using the Python library Strawberry Fields [5] demonstrate the potential of this protocol to generate high-amplitude squeezed cat states with realistic quantum resources. Optimizing the protocol parameters achieved fidelities above 98% between the catalysis output and SCSS states. Figure 2 shows an example of the Wigner function of the output state, which has 98.8% fidelity to a state with an 8dB squeezing level and an amplitude of 2.3.
Alongside our simulations, we propose an experimental setup for the practical realization of this protocol. We are currently developing the generation of the necessary resources, including vacuum squeezed states created by a degenerated optical parametric oscillator and heralded Fock states. Next, the optical tomography of the resource states will be carried out through homodyne detection. Preliminary extensions of our simulations account for anticipated system losses, resulting in mixed state outputs. While evaluating the impact of losses, the Wigner function of the output state retains its negativity, indicating the preservation of the non-Gaussianity of the states. This research contributes to quantum state engineering methods, crucial for the generation of resource states for fault-tolerant quantum computing.

[1] DS Schlegel et al., Phys. Rev. A 106, 022431 (2022).
[2] K Takase et al., Phys. Rev. A 103, 013710 (2021).
[3] M Endo et al., Opt. Express 31, 12865-12879 (2023).
[4] RJ Birrittella et al., J. Opt. Soc. Am. B 35, 1514-1524 (2018).
[5] N Killoran et al., Quantum 3, 129 (2019).

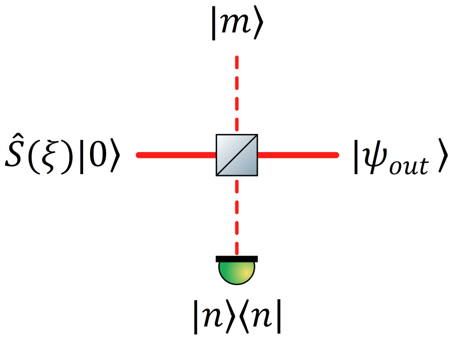


Figure 1. catalysis protocol.png

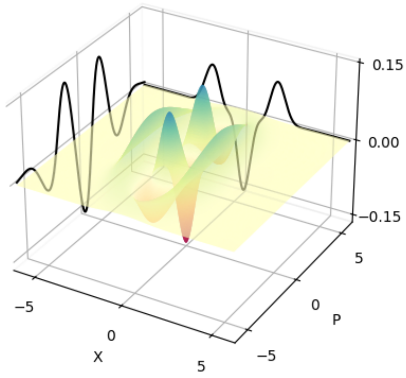


Figure 2. catalysis output.png

Quantum Spectroscopy with Entangled Photon Pairs

Poster - Abstract ID: 145

Giovanni Citeroni [1], ***Giacomo Mazza*** [1], ***Marco Polini*** [1]

1. *Dipartimento di Fisica dell'Università di Pisa*

Entangled light has recently gained interest thanks to its ability to probe ultrafast processes in material sciences, chemistry and biology. Moreover, it exhibits strongly non-classical behaviour such as two-photon double absorption that shows the ability to weakly interact with the target material compared to semiclassical light or separable photon Fock's state. Although these phenomena are theoretically well understood from a spectroscopic point of view, it is not entirely clear how the material interacts with an entangled photon pair, and in particular, what is the role of entanglement non-locality in the interaction process.

Here, by using exact diagonalization methods, we studied the one-entangled photon interaction with a lattice of quantum harmonic oscillators, where only one photon of the entangled pair crosses the material. We compared the results for semiclassical states, separable Fock's state and entangled states. For the entangled light, we considered a pair of frequency entangled photons generated by type-I spontaneous down-conversion.

The results confirm that the interaction of the material with the entangled photon is weaker, and by evaluating the interaction Hamiltonian we were also able to understand how the entanglement non-locality affects the material, putting at the end the non-locality as the main character in the interaction process. Moreover, the data clearly shows how the material inherits the frequency photon correlations in its excitation spectrum, which results in a slowdown of the time of the interaction process.

In conclusion, using a non-perturbative numerical method, we studied the non-stationary dynamics of the interaction process, showing the actual role of entanglement in the interaction, and giving a new understanding of how photon entanglement can be used to modify the material's properties.

Variational quantum multi-objective optimization

Poster - Abstract ID: 283

Sebastian Schmitt [1], Linus Ekstrom [1], Hao Wang [2]

1. Honda Research Institute Europe GmbH, 2. LIACS/aQa Leiden University

Introduction

Solving combinatorial optimization problems on near-term quantum devices has gained a lot of attraction in recent years. Currently, most works have focused on single-objective problems, whereas many real-world applications need to consider multiple conflicting objectives, such as, cost and quality.

Methods

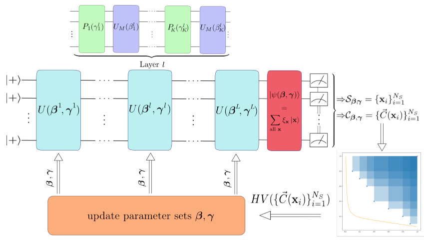
We present a variational quantum optimization algorithm (QMOO) to solve discrete multi-objective integer optimization problems. The quantum circuit incorporates all cost Hamiltonians representing the classical objectives, and generates a quantum state which is a superposition of Pareto-optimal classical solutions. From these we calculate the hypervolume indicator to determine the quality of the approximation to the Pareto-front. By optimizing the variational parameters of the circuit we maximize the hypervolume thereby solving the original multi-objective problem. We formulate five types of integer benchmark problems with two, three and five objectives. The QMMO algorithm is formulated with multi-level qudit variables and operators which naturally represent integer variables.

Results

We show the effectiveness of QMOO on many benchmark instances and evaluate the dependence on number of measurement shots and other hyper parameters. In all settings the hypervolume increases over the iterations of the algorithm indicating that the QMOO quantum state encodes increasingly better approximations to the Pareto front. We compare to several classical multi-objective optimization algorithms where we find that QMOO performance to be only slightly below the classical performance.

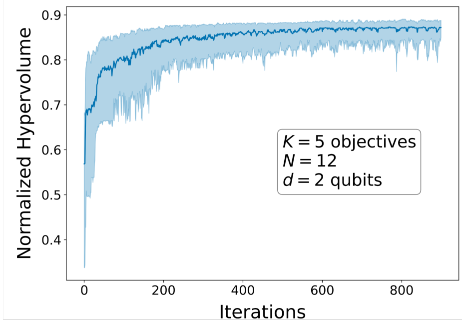
Discussion

Our work represents a first very promising step toward solving realistic multi-objective optimization problems natively on quantum hardware. It emphasizes a novel and promising research area opening a new application domain for quantum optimization algorithms. In this first proof of principle study we did not investigate many aspects such as alternative mixing operators, warm starting, or hyperparameter tuning which are expected to further increase the performance. We also did not elucidate more fundamental questions of circuit complexity, scaling to much larger system sizes or barren plateaus which are left for future research. However, we are convinced that future works will improve the algorithm and identify problems where quantum multi-objective approaches might offer a practical quantum advantage.



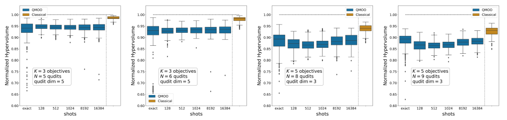
Schematic illustration of the QMOO algorithm

Fig1.png



QMOO results for the hypervolume normalized to its ideal value for a p=1 layer circuit as function of the algorithm iterations aggregated over 40 runs of one specific *K=5* objective problem for *N=12* qubits (d=2). The Hilbert space dimensions are $2^{12} = 4096$. The hypervolume increases over the iterations indicating an improved approximation to the Pareto front.

Fig2.png



Statistics of the QMOO results for the hypervolume normalized to its ideal value (dashed line at 1.0) for a *p=1* layer circuit as function of numbers of shots ('exact' refers to $N_{shot} = \infty$) aggregated over ten different problem instances and 40 runs for each instance. The two left plots are for three objective (*K=3*) problems with *N=5* and *N=6* ququints (*d=5*), while the two right panels are for *K=5* objective problems with *N=8* and *N=9* qutrits (*d=3*). The Hilbert space dimensions are $5^5 = 3125$, $5^6 = 15625$, $3^8 = 6561$, and $3^9 = 19683$ (from left to right). The QMOO algorithm performs equally good for all numbers of shots and is comparable with the classical results (shown on the right in orange).

Fig3.png

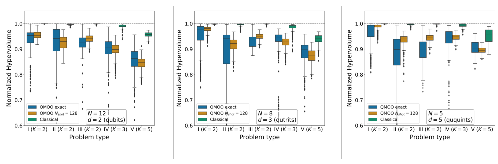


Fig4.png

Measurement incompatibility in the multi-object operational task scenario

Poster - Abstract ID: 209

***Andrés Ducuara* [1], *Ryo Takakura* [1], *Fernando Hernandez* [2], *Cristian Susa* [3], *Paul Skrzypczyk* [4]**

***1.** Yukawa Institute for Theoretical Physics, Kyoto University, Kitashirakawa Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan, **2.** Department of Physics and Electronics, University of Córdoba, 230002 Montería, Colombia, **3.** Department of Physics and Electronics, University of Córdoba, 230002, Montería., **4.** H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom*

Multi-object operational tasks for quantum resource theories of state-measurement pairs have been recently introduced and it has been demonstrated that any resourceful pair exhibits an advantage over any free state-measurement pair in discrimination and exclusion games (Ducuara et. al, Phys. Rev. Research, 2 033374, 2020). However, properties of a set of measurements such as incompatibility cannot be exploited in that multi-object scenario. As measurement incompatibility is a fundamental aspect of quantum mechanics that has been also considered to be a resource in the context of quantum resource theories, in this work, we explore such kinds of properties of set of measurements in the multi-object quantum subchannel discrimination and exclusion games. We show that all sets of incompatible measurements provide an advantage for the games and quantify the amount of resourcefulness by means of the generalized robustness of resource for discrimination games and weight of resource for exclusion games. These results can be extended to general probabilistic theories.

Quantum Sensing and Control with Organic Molecules

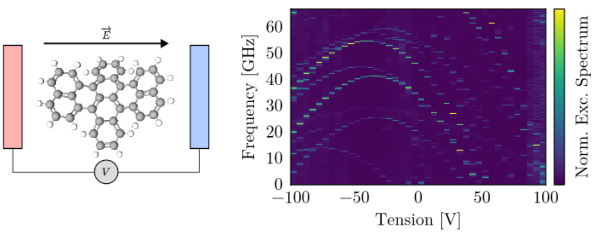
Poster - Abstract ID: 154

Hugo Levy-Falk [1], Rocco Duquennoy [1], Ramin Emadi [1], Daniele De Bernardis [1], Maja Colautti [1], Costanza Toninelli [1]

1. National Institute of Optics [(Consiglio Nazionale delle Ricerche CNR)–INO)], care of European Laboratory for Non-Linear Spectroscopy (LENS), Via Nello Carrara 1, Sesto Fiorentino, 50019, Italy

Developing controlled quantum systems as local probes for their environment and research platforms for fundamental physics is a topic of prime interest. Inthat regard, organic molecules, such as dibenzoterrylene embedded in a molecular matrix, are an easy-to-produce and highly sensitive quantum system thatcan be isolated, providing lifetime-limited linewidth at liquid helium temperature in the wavelength range from the visible to the near-infrared [1].
First, this system couples to the phonons of the environment. We show that the broadening of the zero-phonon line through the interaction with phonons offers a non-invasive probe for temperatures in the range of three to a few tens of Kelvins [2]. Furthermore, this sensitivity to the hardly-explored local phononic environment could enable the use of organic molecules as a transducer for optomechanical experiments.
Second, these molecules are sensitive to electric fields, displaying a shift of their main emission line due to the Stark effect. This well-known property can be used to tune the molecule through laser-induced long-lived charge states in the matrix [3]. Applying an external electrical field, we could shed light on the microscopic charge distribution within the crystal and demonstrate control over thespectral diffusion of the zero-phonon line [4]. This suppression by a factor of 12 of the spectral diffusion of tuned molecular systems is a promising advancement toward molecule-based single-photon sources.
References

1. C. Toninelli et. al., Nat. Mater. 20, 1615–1628 (2021)
2. V. Esteso et. al., PRX Quantum, 4, 040314 (2023)
3. R. Duquennoy et. al., Optica 9, 731-737 (2022)
4. R. Duquennoy et. al., In Preparation (2024)



Starmap.png

Classical shadows for multi-qudit systems

Poster - Abstract ID: 159

Jadwiga Wilkens [1], ***Kristina Kirova*** [1], ***Richard Kueng*** [2]

1. *Institute of Integrated Circuits, Johannes Kepler University Linz, Linz, Austria,* ***2.*** *Institute of Integrated Circuits, Johannes Kepler Universität, Linz, Austria*

Introduction

The classical shadow formalism enables the efficient prediction of numerous physical quantities of complex, large-scale quantum systems without requiring a full physical description. It comes with rigorous performance guarantees, ensuring its reliability and effectiveness. With multilevel quantum systems increasing in popularity now comes the need for generalizing this scalable readout formalism to such systems. This work extends the classical shadow formalism to n-qudit systems utilizing Mutually Unbiased Bases (MUBs) and Symmetric Informationally Complete Positive Operator-Valued Measures (SIC-POVMs).

Methods

We use high dimensional probability theory tools to develop rigorous performance guarantees for multi-qudit classical shadows and complement them with numerical experiments that showcase even better performance in practice. This is further confirmed by the preliminary test studies done on data from real multi-qudit hardware operated by the group of Dr Martin Ringbauer at the University of Innsbruck.

Results

Our results cover estimating expectation values, quantum state fidelities, purities, and trace inner products between two quantum states. Table 1 subsumes our theoretical performance guarantees and their actual performance in numerical Experiment. The latter highlights a substantial improvement in terms of actual resource scaling. Furthermore, we generalize a seminal result by Brydges et al. on estimating entanglement entropies via randomized measurements, showing quadratic improvement in sample complexity. This is demonstrated in Figure 1 for calculating all subsystems purities of an Absolutely Maximally Entangled (AME) state of 4 qutrits.

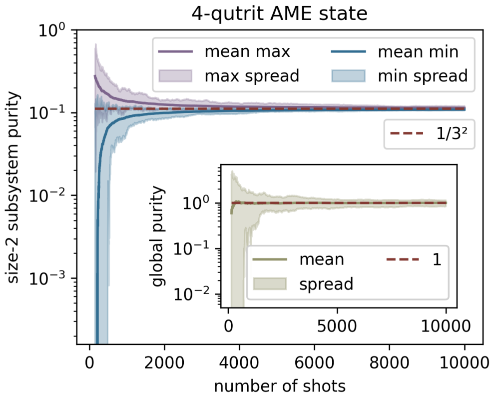
Discussion

These contributions further extend our theoretical understanding of d-level quantum systems and pave the way for using such systems in practice. Developed with scalability and efficiency in mind, our toolbox empowers quantum scientists to extract relevant information from complex, large-scale quantum systems and implement innovative protocols tailored to these systems. While an exponential dependence of the sample complexity in the number of systems cannot be avoided in general - rigorous learning bounds dictate that this has to be the case - our work highlights several important use cases for which the curse of dimensionality can be avoided.

Quantity of interest	Estimated using	Asymptotic scaling	Analytical scaling	Numerical prefactor
$\mathrm{tr}[O^{(K)}\rho]$	$\square, \triangle$; $\mathrm{tr}[O^{(K)}\hat{\rho}]$	$\mathcal{O}(d^K/\epsilon^2)$	$8/3\log(2/\delta)\|O^{(K)}\|_2^2(d+1)^K/\epsilon^2$	$7 \cdot 10^0$
$\mathrm{tr}[\rho\sigma]$	$\triangle$; $\mathrm{tr}[\hat{\sigma}\hat{\rho}]$	$\mathcal{O}(d^{2N}/\epsilon^2)$	$8/3\log(2/\delta)(2d^2+2d)^N/\epsilon^2$	$6 \cdot 10^{-5}$
$\mathrm{tr}[\rho\sigma]$	$\square$; $\mathrm{tr}[\hat{\sigma}\hat{\rho}]$	$\mathcal{O}(d^{2N}/\epsilon^2)$	$8/3\log(2/\delta)(2d^2+d)^N/\epsilon^2$	$1 \cdot 10^{-4}$
$\mathrm{tr}[\rho\sigma]$	$\square$; $(d+1)\delta_{\hat{k}\hat{k}'} - 1$	$\mathcal{O}(d^N/\epsilon^2)$	$8/3\log(2/\delta)(2d-1)^N/\epsilon^2$	$2 \cdot 10^{-3}$

Table 1: **Sample complexities** for various quantities of interest calculated using the Bernstein inequality.
$\square$ indicates usage of MUB measurements and $\triangle$ - of SIC POVMs. For a fixed confidence $\delta = 0.05$ the analytical prefactor evaluates to ≈ 9.8 and can be directly compared to the value obtained numerically for $d = 3$. The notation $O^{(K)}$ stands for a K-local observable.

Shadow-sample-complexity-bounds.png



Shadow-purity-estimation-ame-state.png

Exploring the impact of noise on quantum DDPG in portfolio allocation

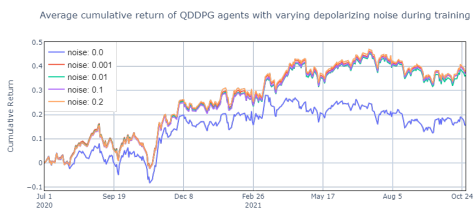
Poster - Abstract ID: 168

Annette Zapf[1], *Sabine Wölk*[1]

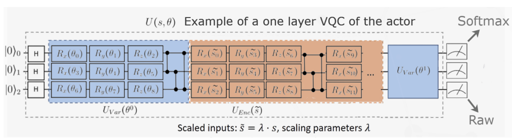
1. Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm

In the era of Noisy Intermediate-Scale Quantum devices, Variational Quantum Circuits in Quantum Machine Learning are gaining attention, advancing towards practical quantum computing applications on NISQ devices. Reinforcement Learning (RL), known for its humanlike, trial-and-error learning, excels in adapting to changing financial environments. In particular, classical algorithms such as Deep Deterministic Policy Gradient (DDPG) and Proximal Policy Optimization (PPO) show promise, while emerging quantum neural networks offer potential for improved function approximation, better generalization capabilities and reduced parameters. In light of these advancements, we introduce a quantum-enhanced version of the DDPG agent (QDDPG), aiming to leverage these quantum capabilities for more efficient financial decisionmaking processes. The quantum part of the model utilizes a parameterized quantum policy, which consists of a sequential reuploading variational circuit with trainable input scaling parameters. Our objective is to explore the practicality and potential benefits of QRL in finance, aiming to realize viable quantum computing applications on NISQ devices. The QDDPG model surpasses traditional analytic strategies in portfolio allocation, achieving higher returns with fewer parameters and a favourable Sharpe ratio. In a simple configuration using a RAW-parameterized quantum policy, the model achieves an average Sharpe ratio of 1.20 across 15 trained agents, compared to 0.96 for the minimum-variance strategy and 0.81 for the buy-and-hold baseline.

Furthermore we investigate the impact of quantum noise, a significant challenge for NISQ devices. We analyze various types of noise, such as general depolarization, amplitude damping, phase damping, measurement noise, and shot noise, which uniquely affect quantum computations. Our study quantifies how these noise types influence the performance, reliability, and robustness of the QRL model. We study new techniques to harness quantum noise as hyperparameter to control the exploration-exploitation balance of the agent, using noise as regularization method and to stabilize the training of the agents. This comprehensive analysis aims to not only highlight the challenges posed by quantum noise but also to explore innovative methods to mitigate these effects and enhance the applicability of quantum algorithms in real-world applications.



Avgreturnwithtrainingdepolarizingnoise-levels.png



Actorcircuitexample.png

New phase estimation method based on functional QADS

Poster - Abstract ID: 172

Guillermo Lugilde [1]***, Elías F. Combarro*** [1]***, Ignacio F. Rúa*** [1]

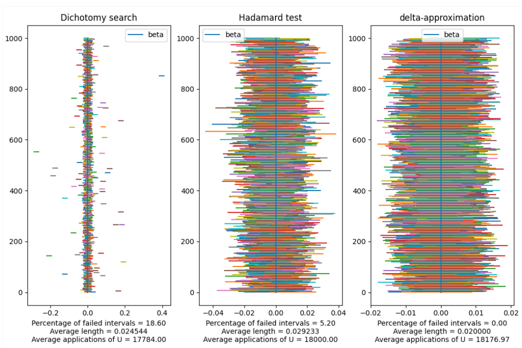
1. *University of Oviedo*

Quantum abstract detecting systems (QADS) provide a common framework to address detection problems in quantum computers. A particular QADS family, that of combinatorial QADS, has been proved to be useful for decision problems on eigenvalues or phase estimation methods. In this paper, we consider functional QADS, which not only have interesting theoretical properties, but also yield an improved phase estimation method, as compared to combinatorial QADS.

Functional QADS are built from another QADS, whose circuit is applied consecutively, controlled by some auxiliary qubits, and inherit its detection ability. In addition, it is proved that the QFT gate can be reinterpreted as a product of functional QADS. This can be helpful when comparing some phase estimation methods that rely on this gate, such as the Quantum Phase Estimation one.

In particular, the new proposed method is called delta-approximation algorithm, and is constructed through a sequence of simpler methods, all of them based on functional QADS. For example, by repeating their circuit multiple times, it is possible to decide whether the desired phase belongs to a given interval or not. Then, checking multiple intervals sequentially until finding one that contains the phase, directly provides a confidence interval for it. The result of comparing the delta-approximation algorithm with the other two considered methods based on combinatorial QADS is showed in the attached figure.

The delta-approximation algorithm was also compared with other methods, showing an advantage in terms of number of qubits needed, and its asymptotic behavior was studied numerically, since no statistic distribution is known yet for its probability of error. Despite the number of operations made seems to be greater than other methods, the fact that it is based on repeating short circuits multiple times, rather than a single long circuit that estimates the phase directly, avoids the accumulation of errors due to excessive circuit length and, therefore, suggests a practical interest. Moreover, some of its parameters can be optimized further, so more study is needed.



Final method comparison.png

A first description of the geometry of Kirkwood-Dirac-positive states.

Poster - Abstract ID: 173

Christopher LANGRENEZ [1]
1. *Université de Lille*

Given two observables A and B on a Hilbert space of finite dimension d, one can define for each quantum state a Kirkwood-Dirac (KD) distribution. This distribution is a quasi-probability, meaning that it has all the properties of a proper joint probability, except that, in this case, it can take negative or even complex values. A quantum state is said to be KD-positive if its KD distribution only takes positive values, meaning that it is a genuine probability distribution. Recently, the KD distribution has come to the foreground as an adaptable tool in different areas of quantum mechanics. The presence of complex values in a KD distribution was linked to quantum advantage in quantum metrology and many other areas. We are thus interested in determining the set of KD-positive states.
In this poster, we will give a brief introduction to KD distribution. Then, we will highlight that, almost always, meaning with probability one over the unitary matrices in any dimension d, the convex geometry of the set of KD-positive states is the simplest possible [1]. In these cases, this set is reduced to the convex combinations of the basis states associated to the two given observables, the set of KD-positive states is thus a polytope in a (2d-1)-dimensional space. There are thus few KD-positive states. This simplest situation is also true if the transition matrix between the two observables is the Discrete Fourier Transform in prime dimension. However, we will also give an example in dimension 3 where the geometry is more complex: there exist extreme KD-positive states that are mixed and pure KD-positive states that are not basis states. In this situation, we show that there exists KD-positive states that cannot be written as convex combinations of KD-positive pure states [2].

[1] C.Langrenez et al., “The set of Kirkwood-Dirac positive states is almost always minimal”, arXiv:2405.17557
[2] C.Langrenez, D.R.M Arvidsson-Shukur and S. De Bièvre, “Characterizing the geometry of the Kirkwood-Dirac positive states”, Journal of Mathematical Physics, 65, 072201 (2024).

.

A group-theoretic approach to quantum gate teleportation

Poster - Abstract ID: 190

Samuel González-Castillo [1], ***Elías F. Combarro*** [1], ***Ignacio F. Rúa*** [1]

1. *University of Oviedo*

The *quantum gate teleportation* scheme introduced by Gottessman and Chuang can be used to extend the sets of gates that can be implemented fault-tolerantly. Given any collection S of quantum gates that can be implemented fault-tolerantly (perhaps using techniques from quantum error correction), the scheme enables the fault-tolerant implementation of any gate V such that the conjugation of the Pauli group by V is included in the set S, subject to the production of a magic state. This motives the definition of the *Clifford Hierarchy* as the sequence of sets of gates in which the first level is the Pauli group and the subsequent levels are the sets of quantum gates that can be implemented fault-tolerantly applying the scheme on the gates of the previous level. The study of the properties of the Clifford hierarchy has been an active area of research.

In this work, we study the Clifford hierarchy from a group-theoretic point of view, deducing general properties about the cardinality of its levels. These properties are applicable not just to the usual Clifford hierarchy, but to any analogous construction. In this regard, we generalise the quantum gate teleportation scheme beyond the Pauli group by considering schemes defined by any orthogonal unitary basis of operators. We then apply our general results to the hierarchies that these schemes induce. With our approach, it is possible to easily deduce results like the finitude of all the levels of these hierarchies, showing that a bounded number of applications of these schemes can only be used to implement a finite number of quantum gates. All of our results are valid for systems with qudits of arbitrary dimensions.

Additionally, we present results on how to compute and compactly represent the levels of the hierarchies of the "general" quantum teleportation schemes defined by nice error bases (particular cases of orthogonal unitary bases), thereby generalising the known algorithms for the Clifford hierarchy.

Autonomous Tomography of Bipartite Open Quantum Systems from Transport Observables

Poster - Abstract ID: 194

Jeanne Bourgeois [1], ***Gianmichele Blasi*** [2], ***Géraldine Haack*** [2]

1. *École Polytechnique Fédérale de Lausanne (EPFL),* ***2.*** *University of Geneva*

Quantum state tomography is a crucial tool in quantum information, enabling the complete characterisation of multipartite states and verifying the presence of entanglement. Considering an open quantum system, we propose a tomography protocol based on quantum transport observables — average currents and current fluctuations induced by temperature and voltage biases. We demonstrate that these transport observables allow for a complete reconstruction of the density operator of a bipartite open quantum system. Remarkably, this protocol is performed autonomously, i.e. without any time control of the dynamics of the system. Our findings open new avenues for witnessing the presence of quantum correlations, contributing to the advancement of quantum information science.

Non-destructive characterization of ceramics using mid-infrared optical coherence tomography with undetected photons

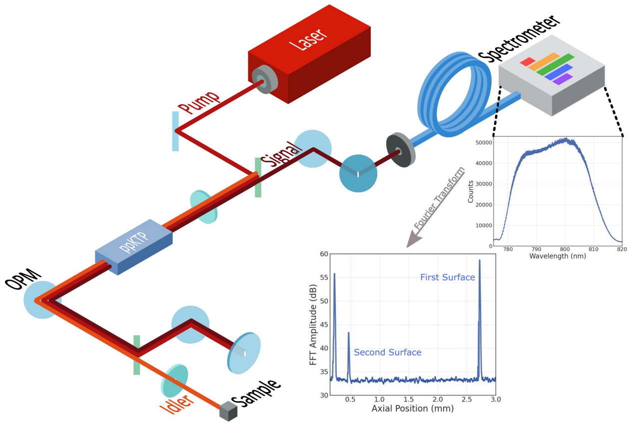
Poster - Abstract ID: 198

Felipe Gewers [1], Emma Pearce [1], Fabian Wendt [2], Aron Vanselow [3], Paul Kaufmann [1], Ivan Zorin [4], Bettina Heise [4], Helen Chrzanowski [1], Sven Ramelow [1]

1. Humboldt University of Berlin, 2. Fraunhofer-Institut für Lasertechnik ILT, 3. Ecole Normale Supérieure de Paris, 4. Research Center for Non-Destructive Testing GmbH

Optical coherence tomography (OCT) is a non-destructive spatial-imaging technique, with consolidated applications in industry, and biomedical area. Ceramic micro-components benefit from complex geometries with desirable properties such as high melting point, low thermal expansion, and hardness, among others. Despite ceramics being a strongly scattering medium, OCT has promising properties to measure and characterize these micro-features, especially for mid-infrared (mid-IR) wavelengths (2-4μm) where the scattering is significantly reduced [1]. Mid-IR detection and broadband laser sources, however, still suffer technological challenges, resulting in expensive and noisy equipment.
In this work, we use an OCT system with undetected photons [2]. The nonlinear interferometer configuration generates entangled photon pairs using a standard visible continuous-wave (CW) laser at 660nm, providing the capability to probe the sample with a mid-IR field (3.3-4.3μm) and detect the interference information with a silicon spectrometer in the 780-820nm range. This solution, in comparison with the mid-IR approach using conventional mid-IR sources and detection, has several advantages including a significant reduction in cost and complexity, as well as intrinsically low noise characteristics, which allows the sample to be exposed to very low IR power levels.
Using this system, we have characterized zirconium dioxide (ZrO_2, zirconia) samples with precise thickness measurements. The preliminary results indicate that the technique can be used to accurately measure the thickness and the group index of refraction of the samples, as well as to acquire scattering information. The measurement of these parameters can be used to visualize ceramics micro-structures and for quality control of highly precise ceramics parts.

1. R. Su, M. Kirillin, E. W. Chang, E. Sergeeva, S. H. Yun, and L. Mattsson, “Perspectives of mid-infrared optical coherence tomography for inspection and micrometrology of industrial ceramics,” Opt. express 22, 15804–15819 (2014).
2. A. Vanselow, P. Kaufmann, I. Zorin, B. Heise, H. M. Chrzanowski, and S. Ramelow, “Frequency-domain optical coherence tomography with undetected mid-infrared photons,” Optica 7, 1729–1736 (2020).



Oct setup.jpg

Mid-infrared spectroscopy of microplastics with undetected photons

Poster - Abstract ID: 201

Atta ur Rehman Sherwani [1], *Emma Pearce* [1], *Philipp Hildenstein* [2], *Fabian Wendt* [3], *Álvaro Barroso* [4], *Björn Kemper* [4], *Katrin Paschke* [2], *Sven Ramelow* [1]

***1.** Humboldt University of Berlin, **2.** Ferdinand Braun Institut, **3.** Fraunhofer-Institut für Lasertechnik ILT, **4.** Universität Münster*

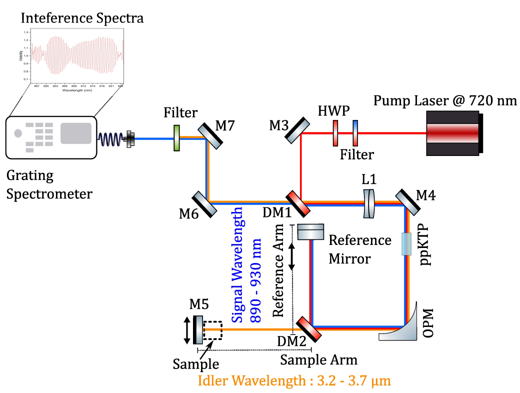
Microplastics, typically ranging from 1 to 10 µm, are inescapable pollutants posing significant environmental and health risks due to their small size and resistance to degradation. Conventional techniques like Fourier-Transform Infrared (FTIR) and Raman spectroscopy identify and characterize these plastics from their infrared (IR) absorption spectra. However, these methods face limitations because of high costs, time-consuming data acquisition, and complex sample preparation [1].

We present a mid-infrared spectroscopy technique that uses entangled photon pairs generated from a periodically-poled KTP crystal in a nonlinear interferometer to detect and identify micro-plastics [2] (Figure 1). The poling of these crystals is specifically engineered such that the idler photons span the mid-IR spectral range showing characteristic absorption profiles of different microplastics, while signal photons remain at shorter and easy-to-detect wavelengths. Unlike traditional FTIR and Raman spectroscopy, this approach overcomes the constraints of mid-IR detectors and sources by utilizing quantum entanglement between the generated photons. The sample is probed with the mid-IR and detection takes place in the near-IR region, allowing the use of highly-efficient silicon detectors instead of expensive and less efficient mid-IR detectors.

Our results show the effectiveness of this method for detecting and characterizing various types of micro-plastic particles. This technique shows promise in detecting plastics of variable sizes and significantly reduces data acquisition time, addressing one of the key limitations of current technologies. This advancement paves the way for more efficient and cost-effective monitoring and analysis of micro-plastic pollution in environmental and biological systems.

[1] W. Zhang, Q. Wang, and H Chen, “Challenges in characterization of nanoplastics in the environment”, Front. Environ. Sci. Eng. 16 (2022)

[2] P. Kaufmann, H. M. Chrzanowski, A. Vanselow, and S. Ramelow, “Mid-IR spectroscopy with NIR grating spectrometers,” Opt. Express 30, 5926-5936 (2022)



Qutec2024-schematic.jpg

Precise Quantum Angle Generator Designed for Noisy Quantum Devices

Poster - Abstract ID: 236

Saverio Monaco [1], ***Florian Rehm*** [2], ***Sofia Vallecorsa*** [3], ***Michele Grossi*** [3], ***Kerstin Borras*** [1], ***Dirk Kruecker*** [4]

1. *DESY Hamburg, RWTH Aachen,* ***2.*** *CERN,* ***3.*** *QTI CERN,* ***4.*** *DESY Hamburg*

Introduction:

The Quantum Angle Generator (QAG) is a novel quantum machine learning model designed to produce precise images on current Noise Intermediate Scale Quantum (NISQ) devices. The QAG model leverages the probabilistic nature of quantum computers in the generation process and functions as an implicit model trained with the Maximum Mean Discrepancy (MMD) loss. To the best of our knowledge, this is the first quantum model to achieve such accurate results.

Methods:

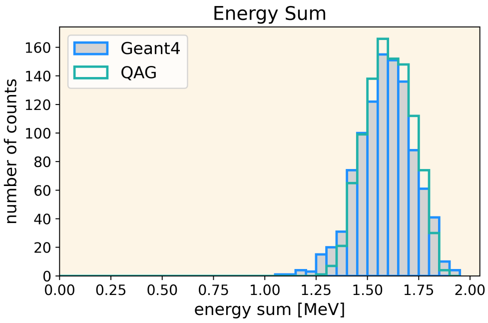
This study consists in a in-depth exploration on the choice of different hyper-parameters to best optimize the training and the learning of correlations between features. Additionally, it includes a comprehensive investigation into the model's robustness to quantum noise at multiple levels. This involves training the model on a quantum device to evaluate its ability to learn and adapt to hardware noise behavior. The model's stability and performance are assessed under simulated quantum hardware noise, with noise levels reaching up to approximately 1.5% during inference and nearly 3% during training. Furthermore, the model's performance is evaluated on actual quantum hardware, comparing the outcomes of noise-less training versus hardware-trained models. The study also examines the model's capacity to maintain precision despite significant hardware calibration changes, with noise levels increasing up to 8% for one qubit.

Methods:

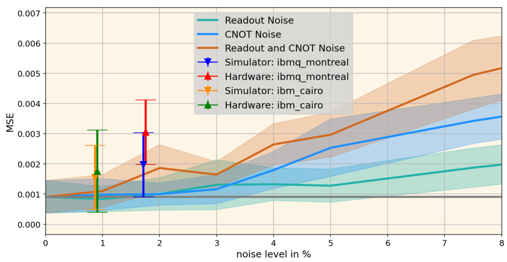
The findings indicate that the QAG model can effectively adapt to hardware noise behavior and produce accurate results, making it suitable for current NISQ devices. Notably, a clear decrease in accuracy is observed when the noise-less trained model is run on real quantum hardware. Conversely, when the model is trained directly on the hardware, it learns the underlying noise behavior, achieving precision comparable to that of the noisy simulator.

Discussion:

This work demonstrates the QAG model's ability to learn and adapt to hardware noise behavior, delivering accurate results under realistic noise levels expected in real-world quantum hardware. The QAG model is used to generate simulated calorimeter shower images, which are crucial in high-energy physics simulations for determining particle energies and identifying unknown particles at CERN's Large Hadron Collider. The performance of the QAG model is compared against Monte Carlo-generated events in Geant4.



Esum.png



Noisestudy.png

Resource state generation in a hybrid matter-photon quantum information processor

Poster - Abstract ID: 291

Yu Liu [1], ***Martin B. Plenio*** [1]

1. Institute of Theoretical Physics, Ulm University

Hybrid quantum architectures that integrate matter and photonic degrees of freedom present a promising pathway towards scalable, fault-tolerant quantum computing. This approach needs to combine well-established entangling operations between distant registers using photonic degrees of freedom with direct interactions between matter qubits within a solid-state register. The high-fidelity control of such a register, however, poses significant challenges. In this work, we address these challenges with pulsed control sequences which modulate all inter-spin interactions to preserve the nearest-neighbor couplings while eliminating unwanted long-range interactions. We derive pulse sequences, including broadband and selective gates, using composite pulse techniques and optimal control methods. This ensures robustness against uncertainties in spin positions, static offset detunings, and Rabi frequency fluctuations of the control fields. These control techniques can be applied to a broad range of physical platforms.

We demonstrate the efficacy of our methods for the resource state generation for fusion-based quantum computing in four- and six-spin systems encoded in the electronic ground states of nitrogen-vacancy centers. We also outline other elements of the proposed architecture, highlighting its potential for advancing quantum computing technology.

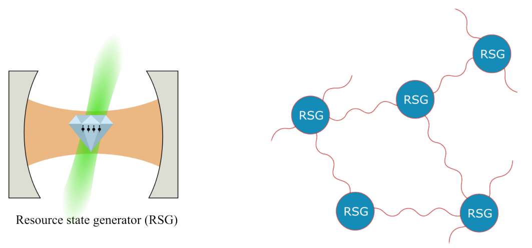


Fig1 hybrid matter-photon quantum information processor.png

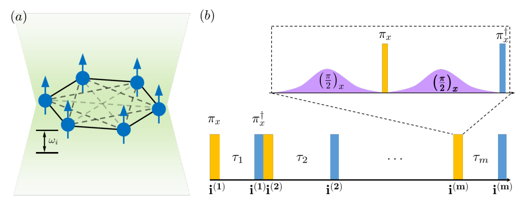


Fig2 scheme of the matter spin-based resource state generation.png

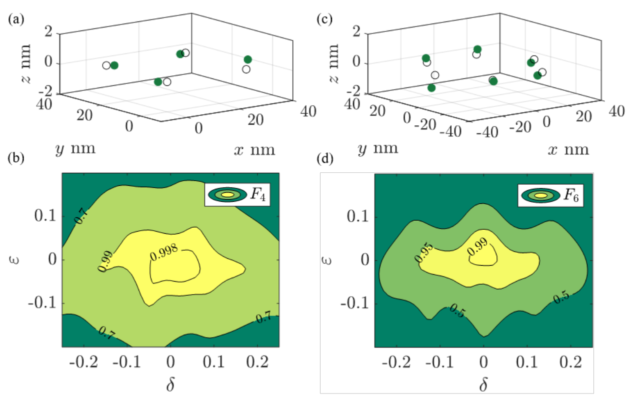


Fig3 numerical simulation of the state generation.png

Quantum key distribution employing atom-photon entanglement over the Saarbrücken fiber link

Poster - Abstract ID: 189

Jonas Meiers [1], *Christian Haen* [1], *Max Bergerhoff* [1], *Stephan Kucera* [2], *Jürgen Eschner* [1]

1. Universität des Saarlandes, 2. Luxembourg Institute of Science and Technology

Quantum cryptographic protocols provide physical security through the use of no-cloning or entanglement. We present our implementation of quantum key distribution based on atom-photon entanglement over a 14-km long, actively polarization-corrected telecom fiber link in a metropolitan network (Fig. 1).

The implemented protocol [1] requires four atomic bases and two photonic bases and enables us to generate a quantum key with security verification via the Bell parameter. Atom-photon entanglement is generated between a single trapped 40Ca+ ion and an emitted photon as described in [2]. The photon is frequency-converted into the telecom band [3] and transmitted via a 14-km long urban dark fiber across Saarbrücken. The photonic measurement basis is set by waveplates before the detection; the atomic basis is set by applying RF π-pulses with different phases, which rotate the atomic qubit before projection (Fig. 2).

The fiber link connects our laboratory at Saarland University (UdS) with a server room at the Saarland University of Applied Sciences (HTW). The trapped single 40Ca+ ion and part of the polarization correction are located at the UdS, while the projection setup for detecting the transmitted photon and the rest of the polarization correction are located at the HTW. A second fiber between the two sites acts as a classical channel for synchronizing the setups at the two locations [4].

For application of the QKD protocol over the fiber link, the main experimental challenge is to achieve a positive secret key rate in the presence of noise and low efficiency. Extrapolated from a laboratory measurement under similar conditions, we expect a rate of one key bit every 30 to 69 minutes. We present preliminary results showing successful secure key generation (Fig. 3) and discuss possible improvement to multiple bits per second through the use of new hardware and new experimental techniques.

1. R. Schwonnek et al., Nat. Commun. 12, 2880 (2021)
2. M. Bock et al., Nat. Commun. 9, 1998 (2018)
3. E. Arenskötter et al., npj Quantum Information 9, 34 (2023)
4. S. Kucera et al., arXiv:2404.04958 (2024).

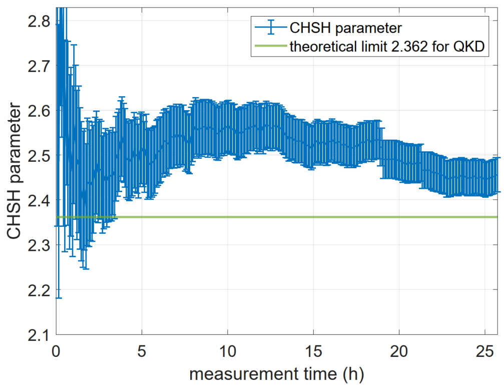


Fig. 3: CHSH parameters including standard deviation plotted against the duration of the measurement in blue, theoretical limit for QKD of 2.362 in green, the window size is 6 fundamental bins of size 0.012π.

Chsh parameter time.png

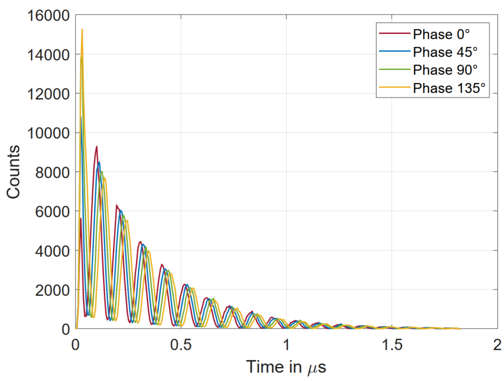


Fig. 2: Oscillation of the temporally detected photon events with the Larmor phase for the four atomic bases [0°, 45°, 90°, 135°] and the resulting phase shift, conditioned on the first photon detector and the atomic state |−⟩.

Photon oscillation.png

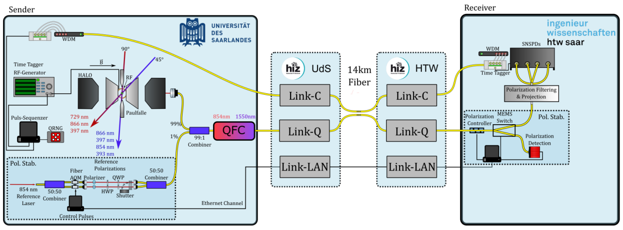


Fig. 1: Schematic layout of a QKD experiment over a 14 km long urban fiber. On the left is the setup in the laboratory of AG Eschner at Saarland University, on the right the setup in a server room at the HTW Saar. The $^{40}Ca^+$ ion and the transmitter station for polarization correction of the fiber are located at the UdS, while the projection setup for detecting the photon entangled with the atom and the receiver station for polarization correction are located at the HTW. There is an internet connection between the two locations, which is used to control the polarization correction. In addition, a fiber-optic-based classical communication channel is implemented, via which the time taggers are synchronised for signal recording using the white-rabbit protocol with sub-nanosecond precession.

Setup qkd.png

Ultra-bright telecom-band SPDC from AlGaAs-on-insulator waveguides

Poster - Abstract ID: 245

Marlon Placke [1]***, Jan Schlegel*** [2]***, Felix Mann*** [1]***, Pietro Della Casa*** [2]***, Andreas Thies*** [2]***, Markus Weyers*** [2]***, Guenther Traenkle*** [2]***, Sven Ramelow*** [3]

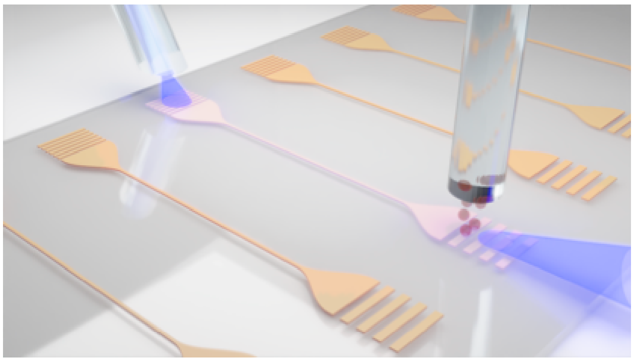
1. *Humboldt-Universität zu Berlin,* ***2.*** *FBH Berlin,* ***3.*** *Humboldt University of Berlin*

III-V semiconductors stand out as a particularly versatile platform for integrated photonics with remarkable features: For these materials, the very high nonlinearities for both second- and third-order parametric processes are equally noteworthy as is the exceptional quality of heteroepitaxial fabrication techniques and most importantly the possibility for monolithic on-chip integration of pump lasers on the same chip.

Implementing highly efficient spontaneous parametric down-conversion (SPDC) on a platform that offers co-integration of the pump laser has been an outstanding challenge. Here, using such a platform based on AlGaAs-on-insulator waveguides, we

report telecom-band SPDC (and second harmonic generation) with efficiencies of

26 GHz generated pairs/mW over a 7 THz bandwidth, which would saturate wavelength-multiplexed QKD-systems at merely 1.7 mW of pump laser power.



Render.png

Stimulated Sum-frequency Generation as an Ideal Detector of Time-energy Entangled Biphotons

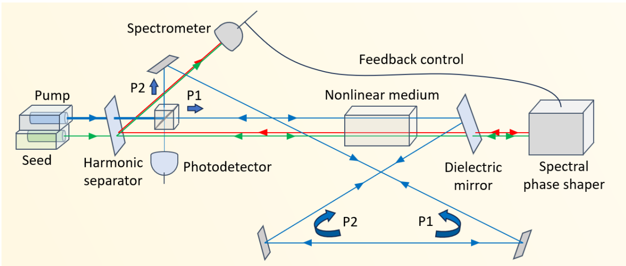
Poster - Abstract ID: 140

Hanzhong Zhang [1], *Nir Nechushtan* [1], *Avi Pe'er* [1]

1. Dept. of physics & QUEST center for quantum science and technology, Bar Ilan University, Ramat Gan, 52900 ISRAEL

We present an experimental scheme to form an ideal detector of time-energy entanglement, which measures the pump depletion in an SU(1,1) interferometer. Specifically, we introduce a seed to enhance our detection, and observe the dependency of the SFG intensity on the spectral dispersion with a constant phase in the seeded mode.

To conduct a theoretical analysis on the experiment, we derive a quantum solution for the pump evolution that is closed in time. Motivated by the derivation, we also develop a novel method to treat general three-wave mixing processes in quantum picture.



Dithering measurement of sfg.png

Noisy gates for simulating quantum computers

Oral - Abstract ID: 180

Michele Vischi [1], ***Giovanni Di Bartolomeo*** [1], ***Francesco Cesa*** [1], ***Roman Wixinger*** [2], ***Michele Grossi*** [3], ***Sandro Donadi*** [4], ***Angelo Bassi*** [1]

1. *University of Trieste,* ***2.*** *ETH Zurich,* ***3.*** *QTI CERN,* ***4.*** *Queen's University Belfast*

We present a novel method for simulating the noisy behavior of quantum computers, which allows to efficiently incorporate environmental effects in the driven evolution implementing the gates acting on the qubits. We show how to modify the noiseless gate executed by the computer to include any Markovian noise, hence resulting in what we will call a noisy gate. We compare our method with the IBM qiskitsimulator, and show that it follows more closely both the analytical solution of the Lindblad equation as well as the behavior of a real quantum computer, where we ran algorithms involving up to 18 qubits; as such, our protocol offers a more accurate simulator for NISQ devices. The method is flexible enough to potentially describe any noise, including non-Markovian ones. The noise simulator based on this work is available as a python package at the link, https://pypi.org/project/quantum-gates.
Reference: Phys. Rev. Research **5**, 043210

A reinforcement learning approach for more efficient exchange-only quantum gates

Oral - Abstract ID: 204

Violeta N. Ivanova-Rohling [1], *Niklas Rohling* [2], *Guido Burkard* [1]

1. University of Konstanz, 2. Hamburg University of Technology

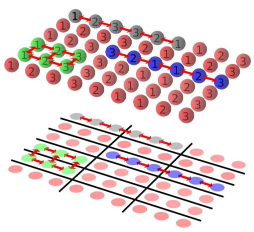
There has recently been rapid progress in the research of spin qubits [1], including the realization of exchange-only qubits [2,3]. Exchange-only quantum computation is a variant of spin-based quantum computation that bypasses the need to control individual spins by a magnetic field and instead functions by sequences of exchange pulses. The challenge for exchange-only quantum computation is to find short sequences that generate the required logical quantum gates and, as a result, minimize the effects of decoherence and control errors.
Here, we use reinforcement learning to optimize the efficiency of exchange-based pulse sequences that encode the universal two-qubit gates CNOT and CZ with nearest-neighbor interaction for quantum dot arrangements in a chain and in a 2 by 3 grid. We improve on gate sequences currently known in the literature. Specifically, with our reinforcement learning framework, we obtain a significant improvement regarding the total gate time compared to previously known results [3,4]. Moreover, the flexibility of our approach makes it applicable for gate-sequence optimization for a variety of desired quantum gates and a variety of different connection topologies.

[1] Burkard, Ladd, Pan, Nichol, Petta, Rev. Mod. Phys. 95, 025003 (2023)

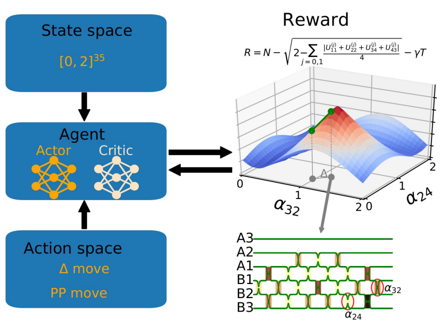
[2] DiVincenzo, Bacon, Kempe, Burkard, Whaley, Nature 408, 339 (2000)

[3] Weinstein et al., Nature 615, 817 (2023)

[4] Fong, Wandzura, Quantum Info. Comput. 11, 1003 (2011)



Qubitgrid3d.jpg



Reward 2 .jpg

Exponentially tighter bounds on limitations of quantum error mitigation

Oral - Abstract ID: 268

***Yihui Quek* [1], *Daniel Stilck França* [2], *Sumeet Khatri* [3], *Johannes Meyer* [4], *Jens Eisert* [4]**

***1.** Massachusetts Institute of Technology, **2.** ENS Lyon, **3.** Virginia Tech, **4.** Freie Universität Berlin*

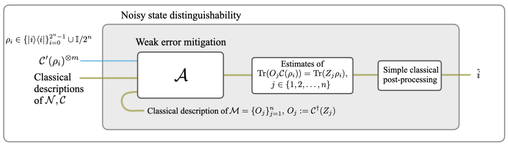
Introduction:
Quantum error mitigation has been proposed as a means to combat unwanted and unavoidable errors in near-term quantum computing without the heavy resource overheads required by fault-tolerant schemes. Recently, error mitigation has been successfully applied to reduce noise in near-term applications. In this work, however, we identify strong limitations to the degree to which quantum noise can be effectively 'undone' for larger system sizes.

Methods:
We establish a model of error mitigation that allows for a theoretical analysis of a wide range of contemporary error mitigation protocols by relating them to statistical inference problems. In a significant method development, we extend the toolbox for the analysis of noisy quantum circuits based on relative entropy decay using novel random circuit constructions that allow us to establish much stronger limitations than previously thought possible.

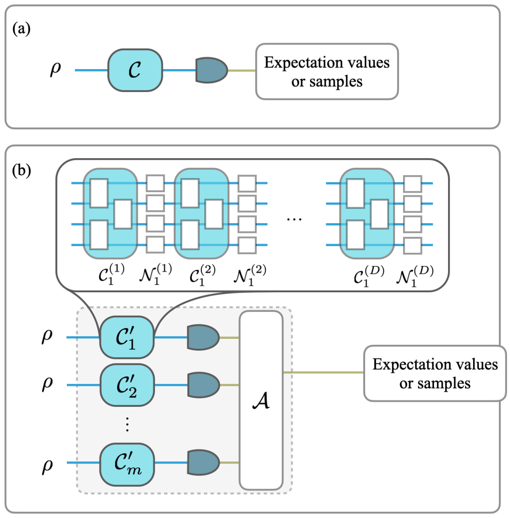
Results:

We show that even at shallow circuit depths comparable to the current experiments, a superpolynomial number of samples is needed in the worst case to estimate the expectation values of noiseless observables, the principal task of error mitigation. This puts a striking limitation on one of the principal avenues near-term devices are hoped to be made more useful, indicating that exponential sample complexities are in general unavoidable even at low circuit depths.

Discussion:
Our construction implies that scrambling due to noise can kick in at exponentially smaller depths than previously thought. They also impact other near-term applications, constraining kernel estimation in quantum machine learning, causing an earlier emergence of noise-induced barren plateaus in variational quantum algorithms and ruling out exponential quantum speed-ups in estimating expectation values in the presence of noise or preparing the ground state of a Hamiltonian.



Mitigation reduction to hypothesis testing.png



Mitigation theoretical model.jpg

Variational quantum computing with diagonal unitaries

Oral - Abstract ID: 13

Philipp Pfeffer [1]

1. *TU Ilmenau*

Variational quantum computing has the potential to speed up tasks like solving iterative numerical and even nonlinear problems by encoding the search of the next time step into a cost function. This can produce complicated quantum circuits with multiple parallel qubit registers or multiple parallel circuits. In this work, the use of diagonal unitaries is explored, where the processing happens in the phases of a uniform superposition state. This enables additive concatenations in the cost function by additions in phases through multiplication of exponential functions. The application for a two-dimensional advection-diffusion equation is discussed, illustrating reduced complexity for the overall algorithm.

Molecular groundstate determination via short pulses on superconducting qubits

Oral - Abstract ID: 261

Noga Entin [1], Mor Roses [1], Reuven Cohen [1], Nadav Katz [2], Adi Makmal [1]

1. Bar Ilan University, 2. The Hebrew University of Jerusalem

Variational quantum algorithms (VQAs) have become popular in the era of noisy intermediate-scale quantum (NISQ) devices, yet despite much scientific effort, they often perform inadequately. Pulse optimization schemes deviate from the standard gate optimization protocol by operating directly on the pulse level, thereby offering greater flexibility and potential reduction in execution time.

Here, we propose a freestyle pulse optimization scheme, which is unique in that it incorporates two-qubit control channels, and does not impose any constraints on the pulse shape; instead, it discretizes the pulse into a series of constant amplitude pulses, each of which is optimized individually.

We assess the efficiency of this method through noisy simulations and real-hardware calculations of the H2 molecule's groundstate using a single qubit, via the variational quantum selected configuration interaction (VQ-SCI) scheme. we attain chemical accuracy for the H2 groundstate with a pulse duration of 0.22 ns on real hardware, reducing the shortest pulse record by more than two orders of magnitude, and nearly saturating the theoretical quantum speed limit (QSL). A 3-qubit pulse preparing the LiH molecule's groundstate is also discovered, being 6 times shorter than its circuit counterpart. To our knowledge, this pulse reaches the most accurate pulse-based determination of LiH groundstate energy reported to date on real-hardware.

The proposed scheme is general and applicable to any VQA.

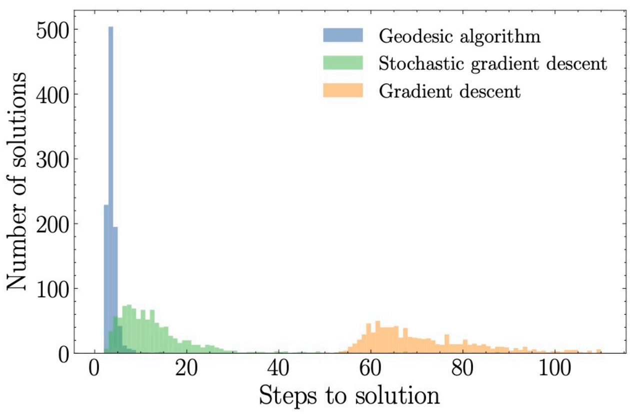
Geodesic Algorithm for Unitary Gate Design with Time-Independent Hamiltonians

Oral - Abstract ID: 256

Dylan Lewis [1], Roeland Wiersema [2], Juan Carrasquilla [3], Sougato Bose [1]
1. University College London, 2. University of Waterloo, 3. ETH Zurich

The primitive quantum gates of quantum computing platforms usually involve only one or two qubits and simple Hamiltonians. Our aim is to take advantage of the more complex Hamiltonians available in experimental platforms to design larger multi-qubit gates. Finding these restricted Hamiltonians that generate desired quantum gates is numerically challenging. Existing methods of stochastic gradient descent, differential evolution, or variational quantum algorithms have been attempted, but have limited success for larger gates.
We offer a solution to the problem of generating multi-qubit gates from time-independent Hamiltonians through the lens of differential geometry of the Lie group structure of quantum gates.
Our algorithm utilises geodesic information and gradients on the group manifold. At each optimisation step, we update the Hamiltonian coupling strengths such that the resulting unitary is closer to the target unitary gate. This can be achieved by updating the couplings such that they follow (as closely as possible) the geodesic towards the target. In our paper, we formalise this comparison and demonstrate how the geodesic can be generated by updating Hamiltonian coupling strengths in time-independent Hamiltonians.
We demonstrate the algorithm's efficiency by comparison to gradient descent techniques for the generation of Toffoli and Fredkin gates. Furthermore, we use the algorithm to generate previously unavailable weight-k parity checks with up to 6 qubits, which are necessary for a wide array of quantum error correcting codes. We find that our geodesic algorithm is significantly more efficient than gradient descent algorithms for finding a restricted generating Hamiltonian of a desired unitary gate, see for example the attached Figure for results for finding a Toffoli gate.
The algorithm allows larger, more complex quantum gates to be implemented directly. Not only could this lead to less noisy gates, but it could also reduce the total time to run a circuit on the hardware. This is crucial for NISQ applications where we have a limited coherence time and increases the clock speed for fault-tolerant quantum computation.

Reference: D. Lewis, R. Wiersema, J. Carrasquilla, and S. Bose, Geodesic Algorithm for Unitary Gate Design with Time-Independent Hamiltonians (2024), arXiv:2401.05973



Toffoli gate comparison max steps 1000 commutes true.jpg

Experimentally verifiable criteria of non-Gaussian coherences

Oral - Abstract ID: 63

Lukas Lachman [1]***, Beate Asenbeck*** [2]***, Ambroise Boyer*** [2]***, Priyanka Giri*** [2]***, Radim Filip*** [1]***, Alban Urvoy*** [2]***, Julien Laurat*** [2]

1. *Department of Optics, Palacký University,* ***2.*** *Laboratoire Kastler Brossel, Sorbonne Universite*

Achieving precise control over photonic states is a fundamental requirement for their integration into future quantum applications. However, to fully harness the potential of these states and enable further technological advancements, they must also exhibit a crucial characteristic known as quantum non-Gaussianity. This attribute is essential for photonic states to perform application-oriented tasks effectively. The quantum non-Gaussianity classifies resources employed in a state generation and rejects all the situations when only the Gaussian evolution suffices for reaching an experimentally achieved outcome.

Development in quantum error correction shed light on the important aspect of coherences of non-Gaussian states in the Fock basis. To certify that a state gains such an advanced quantum property, we employ the resource theory of quantum coherence and connect it with certification of quantum non-Gaussian processes that produce coherence from initial states having no coherence in Fock state basis.

We have developed criteria allowing such certification and demonstrated their power by applying them to experimentally generated photonic states. In our analysis, we target superposition between vacuum and a higher Fock state. We propose a hierarchy that classifies the degree of the quantum non-Gaussianity of coherence according to a targeted state. We test the feasibility of the respective criteria by applying them to state-of-the-art photonic states. We certify that the experimentally generated states overcome limitation that the Gaussian evolution of an arbitrary incoherent mixture of Fock states enforces.

A significant benefit of the proposed methodology is the possibility of establishing a sequence of criteria with ordered requirements on the quality of inspected states. Fulfilling consecutively such an ordered sequence of criteria allows navigation towards challenging demands needed for implementing the states in practical applications such as the error correction. The generic approach increases the possible applicability of this methodology to various experimental platforms engineering photonic states.

State generation via linear optical circuits with photon addition

Oral - Abstract ID: 99

Denis Kopylov [1], *Christian Offen* [1], *Laura Ares* [1], *Boris Wembe Moafo* [1], *Sina Ober-Blöbaum* [1], *Polina Sharapova* [1], *Torsten Meier* [1], *Jan Sperling* [1]

1. Paderborn University, Warburger Straße 100, D-33098 Paderborn

Currently, multimode linear optical circuits (LOC) are of great interest in quantum optics and quantum technologies. Although LOC are the basis for a wide range of applications, the field transformation in such systems is linear, which is insufficient for arbitrary states conversion, in particular, for quantum computation [1]. To resolve these restrictions, nonlinearities should be added to LOC. The commonly studied measurement-induced nonlinearities have two main disadvantages. First, they lead to the reduction of the number of photons in the system. Second, the high-quality multi-photon input states should be carefully generated. For these reasons, the photon addition nonlinearity, which increases the number of photons, is a promising tool for the improvement of quantum optical schemes and protocols based on LOC.

In this work, we theoretically study the LOC with photon-addition nonlinearities. For the multiport linear interferometers with a fixed number of photons, we introduce a classification based on multivariate polynomials [2] and their factorization. Our classification provides a simple description for the state's transformations operated by LOC with photon-addition nonlinearities. We propose a design of LOC that covers all possible states that can be generated via photon addition when the initial state is a vacuum. For a desired state generation, we introduce an effective optimization scheme and present the limitations and restrictions of possible LOC designs.

This work is supported by the "Photonic Quantum Computing" (PhoQC) project which is funded by the Ministry for Culture and Science of the State of North-Rhine Westphalia.

References:

[1] E. Knill, R. Laflamme, G. J. Milburn, Nature 409, 46-52 (2001)

[2] J. Sperling, A. Perez-Leija, K. Busch, C. Silberhorn, Phys. Rev. A 100, 062129 (2019)

Fiber-pigtailed quantum dots in hybrid circular Bragg gratings: Plug-and-play quantum light sources for indistinguishable photons at GHz rates

Oral - Abstract ID: 186

Lucas Rickert [1]***, Daniel Vajner*** [1]***, Martin von Helversen*** [1]***, Kinga Zolnacz*** [2]***, Grzegorz Sek*** [3]***, Anna Musial*** [3]***, Shulun Li*** [4]***, Haiqiao Liu*** [4]***, Johannes Schall*** [1]***, Sven Rodt*** [1]***, Stephan Reitzenstein*** [1]***, Zhichuan Niu*** [4]***, Tobias Heindel*** [1]

1. *Institute of Solid State Physics, Technische Universität Berlin, 10623 Berlin, Germany,* ***2.*** *Department of Optics and Photonics, Wroclaw University of Science and Technology, 50-370 Wroclaw,* ***3.*** *Department of Experimental Physics, Wroclaw University of Science and Technology, 50-370 Wroclaw,* ***4.*** *Institute of Semiconductors, Chinese Acadamey of Sciences, Beijing 100083, China*

Semiconductor quantum dots (QDs) in hybrid circular Bragg gratings (hCBGs) are close to ideal sources of bright, pure and indistinguishable quantum light, a key requirement for photonic quantum technologies. Additionally, attempts to generate quantum light from directly fiber-interfaced QDs in compact source arrangements, so-called ‘plug-and-play’ single photon sources show prospects of readily providing quantum light without the need of bulky laboratory infrastructure. To date, however, no plug-and-play source harnessing the high performance of QD-hCBG systems has been realized.

In this contribution, we report on the fabrication of hCBGs with deterministically integrated QDs spatially and spectrally matched to the cavity mode. The QDs exhibit lifetimes <30 ps under (quasi-)resonant excitation, resulting in Purcell Factors >20, showing near-ideal spectral and spatial QD integration with high reproducibility in combination with single photon purities >98% under quasi-resonant pumping and (uncorrected) two photon-indistinguishabilities >88% under resonant excitation. The signifcantly shortened liftime due to the strong Purcell enhancement leads to robust indistinguishability of the emitted photons up to technologically relevant temperatures of 30 K. Additionally, the shortened lifetime allows for an increase in excitation frequency, enabling high quality quantum light at GHz rates. We further demonstrate the deterministic fiber-pigtailing of these high performance quantum light sources, resulting in plug-and-play devices with emitter lifetimes <100 ps, single-photon purites >99% and capable of emitting indistinguishable photons under GHz excitation rates.

In combination with compact cryocooler technology and advanced fiber-compatible excitation schemes, these fiber-pigtailed QD-hCBG systems hold the promise to provide state-of-the art quantum light in out-of-laboratory scenarios.

Quantum tomography of bright non-classical light generated in an integrated optical parametric oscillator

Oral - Abstract ID: 195

Roger Kögler [1]***, Gabriel Rickli*** [2]***, Renato Domeneguetti*** [3]***, Xingchen Ji*** [4]***, Michal Lipson*** [5]***, Alexander Gaeta*** [5]***, Marcelo Martinelli*** [2]***, Paulo Nussenzveig*** [2]

1. *Humboldt University of Berlin,* ***2.*** *São Paulo University, Brazil,* ***3.*** *Technical University of Denmark,* ***4.*** *Shanghai Jiao Tong University,* ***5.*** *Columbia University*

Optical parametric oscillators (OPOs) favor the enhancement of light-matter interactions with a feedback system and are widely used as non-classical light sources. Scalable quantum devices might take advantage of the miniaturization of OPOs for integrated photonics implementations. Here, silicon nitride-based photonics stands out due to its mature manufacturing techniques, CMOS fabrication compatibility, visible to mid-infrared transparency window and high third-order non-linear coefficient.

We investigated high quality factor ($Q>10^6$) 80 GHz micro-ring resonators designed for the generation of highly correlated optical modes [1]. We pumped the system (1561 nm) with intensities surpassing its oscillation threshold (13 mW). Through four-wave mixing interactions, we observed bright generation of signal (1548 nm) and idler (1570 nm). We characterized the output fields through resonator-assisted homodyne detection [2]. The setup schematics is shown in Figure 1.

Our detection technique allowed the reconstruction of a four-mode covariance matrix, counting with contributions of upper and lower sidebands of the output states [3]. We directly observed 2.30 ± 0.03 dB amplitude difference squeezing while excess of noise in phase sum correlations precluded any observation of entanglement. Increasing the optical pump, the fluctuations present in the phase sum quadrature become even stronger, while we also observed the degradation of the quantum correlations, as summarized in Figure 2. This is in contrast with the observed behaviour of third-order OPOs based on different platforms [4].

To the best of our knowledge, this was the first full optical tomography of twin beams generated in integrated OPOs. The behaviour of the output states with the pump intensity, specially the degradation of its correlations, is attributed to a combination of thermal effects and the mixture of optical quadratures through self- and cross-phase modulations. Current extensions of this work are being carried on the investigation and mitigation of the detrimental effects hindering the observation of entanglement.

[1] - González-Arciniegas, C., et. al. *Optics letters* 42.23 (2017): 4865-4868.

[2] – Barbosa, Felippe AS, et al. *Physical Review A* 88.5 (2013): 052113.

[3] – Kögler, Roger Alfredo, et al. *Optics Letters* 49.11 (2024): 3150-3153.

[4] – Guerrero, A. Montaña, et al. *Physical Review Letters* 125.8 (2020): 083601.

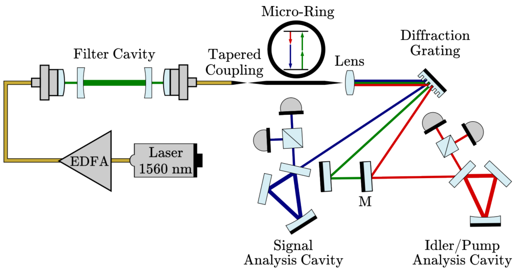


Figure 1 - optical setup.png

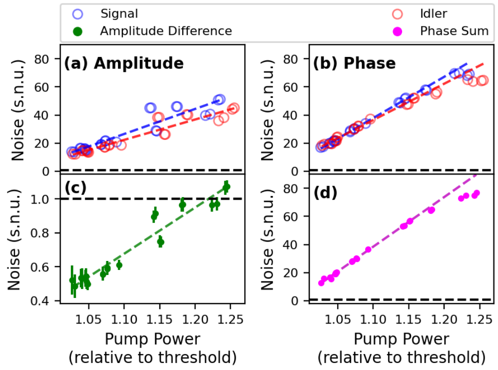


Figure 2 - quadrature noise.png

Quantifying and optimizing the quantum interference between dissimilar photon sources

Oral - Abstract ID: 85

Hubert Lam ***[1], Juan Alvarez [1], Dario Fioretto [2], Petr Steindl [3], Ilse Maillette de Buy Wenniger [4], Stephen Wein [5], Anton Pishchagin [5], Thi-Huong Au [5], Sebastien Boissier [5], Aristide Lemaitre [1], Nadia Belabas [1], Wolfgang Löffler [3], Pascale Senellart [1]***

__1.__ C2N, Université Paris Saclay, 10 Bd Thomas Gobert, 91120 Palaiseau, __2.__ C2N, Université Paris Saclay, 10 Bd Thomas Gobert, 91120 Palaiseau & Quandela, 7 Rue Léonard de Vinci, 91300 Massy, __3.__ Leiden Institute of Physics, Leiden University, 2333 CA Leiden, __4.__ Imperial College London, Quantum Optics and Laser Science, Exhibition Rd, London SW7 2BX, __5.__ Quandela, 7 Rue Léonard de Vinci, 91300 Massy

Semiconductor quantum dot (QD) devices are forefront and versatile quantum light sources that exhibit high in-fiber single-photon brightness [1], very strong single-photon level nonlinearities [2], and can produce controllable photon-number superpositions [3]. These assets position QD as promising light sources for continuous-variable (CV) quantum information processing. In the CV framework, homodyne detection is a crucial technique whose accuracy relies on an optimal mean-wavepacket overlap M between classical and quantum light [4].
We demonstrate two experimental methods to assess and optimize M, in the polarization, timing, spatial, and spectral degrees of freedom. Both methods are based on second-order-correlation measurements of Single-Photons - SP - from a QD in a micropillar-cavity combined with a Local-Oscillator - pulsed laser $\ket{\alpha_\mathrm{LO}}$ with mean-photon-number μ_LO. Both are combined in a Fiber-Beam-Splitter (FBS) with transmissivity (reflectivity) $T\approx0.42$ ($R=0.5$) and analyzed in cross- and auto-correlation configurations (Fig.1).
In the cross-correlation configuration, both FBS outputs are used and correlated in the Single-Photon-Detectors (SPDs), D_1 and D_2. The interference between SP and LO, which depends on the mean-wavepacket overlap M_cross, can result in photon bunching. We use the modified Hong-Ou-Mandel visibility relation from [5] to quantify M_cross: M_cross is deduced from the interference/mixing between SP and LO states of parallel/orthogonal polarization, and is independent of the mean-photon-number μ_LO (see Fig.2a where we measure several values of M_cross by varying the LO-polarization).
The retrieved M_cross are independently confirmed in the auto-correlation configuration, where one FBS output is sent into a Hanbury-Brown-Twiss setup including two SPDs, D_2 and D_3. The normalized second-order correlation function, see Fig.2b, exhibits an anti-bunching to bunching transition dependent on the LO mean-photon-number $R\mu_\mathrm{LO}$. We achieve a maximal M_auto value of 0.76 ± 0.02, which is consistent with independently measured parameters.

The cross-correlation method is well-fitted to monitor the mean-wavepacket overlap M_cross as M_cross is independent of the mean-photon-number. This contrasts with the auto-correlation method which enables optimization of M through maximization of the single value $g^{(2)}_\mathrm{auto}(0)$. These complementary methods are key to observing and optimizing the measurement of non-Gaussianity from optical quantum states.

[1]arXiv:2311.08347 (2023)
[2]Nat.Nanotechnol.12, 663–667 (2017)
[3]Nat.Photonics 13, 803–808 (2019)
[4]Phys.Rev.Lett.105, 253603 (2010)
[5]Phys.Rev.Lett.131, 260401 (2023)

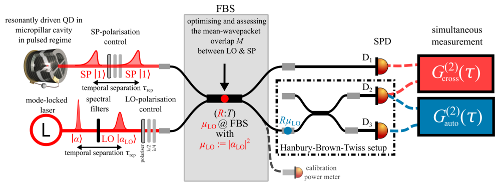


Fig.1 Setup sketch for assessing and optimizing M between SP and LO.

Fig1 setup sketch.png

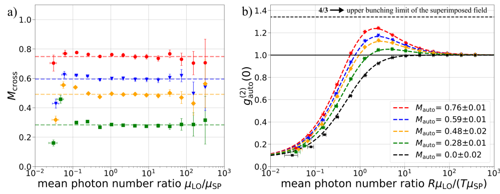


Fig.2 Measurement results from cross- and auto-correlation method. a) M_{cross} deduced from $G^{(2)}_{\text{cross}}(\tau)$ showing the independance from μ_{LO}. b) $g^{(2)}_{\text{auto}}(\tau{=}0)$ deduced from normalizing $G^{(2)}_{\text{auto}}(\tau)$.

Fig2a b results cross-auto correlation meanwavepacket overlap.png

Quantum Phase imaging with a Nonlocal Metasurface

Oral - Abstract ID: 112

***Jinliang Ren* [1], *Dupish Dupish* [2], *Katsuya Tanaka* [3], *Jinyong Ma* [1], *Lukas Wesemann* [4], *Ann Roberts* [4], *Isabelle Staude* [5], *Frank Setzpfandt* [5], *Andrey Sukhorukov* [1]**

***1.** Australian National University, **2.** Friedrich-Schiller-Universit¨at Jena, **3.** Max Plank School of Photonics, **4.** University of Melbourne, **5.** University of Jena*

Quantum imaging using entangled photon pairs from spontaneous parametric down-conversion (SPDC) provides fundamental advantages over classical imaging, such as the operation at ultra-low photon flux and high signal-to-noise ratio [1]. Metasurfaces supporting angle-dependent resonances have recently been employed to achieve phase imaging by extracting phase gradients of incident light [2]. These nanoscale metasurfaces indicate significant potential to replace bulky differential interference contrast microscopes, offering an opportunity for integration into ultra-compact biomedical devices.

However, quantum phase imaging using metasurfaces has not yet been investigated. Here we present an approach to achieve metasurface-based quantum phase imaging using photon pairs produced from a bulk nonlinear crystal or a nonlinear metasurface. With the ghost imaging setup shown in Fig. 1a, the signal photon illuminates a phase object and is then collected with a bucket single-photon detector while the idler photon is received by a detector array. A metasurface incorporating a silicon grating is placed immediately after the phase object. This metasurface supports an optical non-local resonance at the signal wavelength (□1570 nm), where the transmittance depends on the incident angle of light (Fig. 1b). This metasurface is tilted with a small angle, producing a linear optical transfer function in k−space that can be used to perform the first derivative operation of the phase object profile.

As a result, the correlation measurement between signal and idler photons can be used to reconstruct the phase gradient of the object (Fig. 1c). Additionally, we develop the phase imaging using biphotons emitted from a nonlinear metasurface where the emission direction is optically tunable via the pump wavelength [3], facilitating a novel quantum phase imaging protocol combing ghost imaging and all-optical scanning. We expect this work to establish metasurfaces as miniaturized devices for ultra-compact quantum phase imaging.

References

[1] M. J. Padgett and R. W. Boyd, Philos. Trans. R. Soc. A 375, 20160233 (2017).

[2] L. Wesemann, T. J. Davis, and A. Roberts, Applied Physics Reviews 8, 031309 (2021).

[3] M. A. Weissflog, J. Ma, J. Zhang, T. Fan, T. Pertsch, D. N. Neshev, S. Saravi, F. Setzpfandt, and A. A. Sukhorukov, (2024),
arxiv:2403.07651

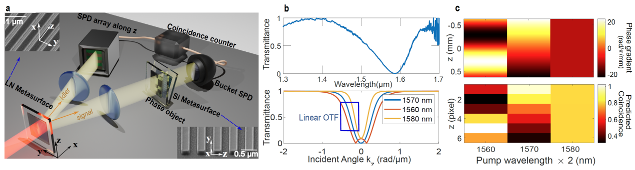


Figure 1 qtech .png

Criticality-based quantum sensors

Oral - Abstract ID: 167

Abolfazl Bayat [1]

1. *University of Electronic Science and Technology of China*

Introduction: At the point of criticality one phase of matter transforms to another. Various types of criticalities (e.g. first order, second order, topological, Floquet etc) have been identified in many-body systems. Each type of these criticalities come with distict features. While quantum criticality is known to be resource for achieving quantum enhanced sensitivity, it is not clear what feature of criticality is instrumental for such achievements. We address this question.

Methods: To identify the sensing capacity of many-body systems we consider the scaling of quantum Fisher information with respect to the probe size. For computing quantum Fisher information, we use different methodologies. For free fermionic systems we rely on analytical solutions while in other system we use numerical simulations based on exact diagonalization and matrix product states.

Results: Conventionally, second order phase transitions support several features such as scale invariance, long-range correlations, spontaneous symmetry breaking and gap closing. In order to identify the key feature for quantum enhanced sensitivity, we have explored various types of critical systems. This includes: (i) zero-energy edge states in symmetry protected topological systems [1]; (ii) sensing both static [2] and periodic [3] fields in Floquet many-body systems; (iii) time crystals in open [4] and closed [5] systems which show long-lasting oscillations in the thermodynamic limit; (iv) Stark localization transitions which affects the entire spectrum of the system [6]; and (v) non-Hermitian quantum systems [7]. Despite being very distinct, in this presentation, we show that “*gap closing*”, as the only common feature between these criticalities, is responsible for achieving quantum enhanced sensitivity.

References:

[1] S. Sarkar, C. Mukhopadhyay, A. Alase, A. Bayat, Phys. Rev. Lett. 129, 090503 (2022)

[2] U. Mishra, A. Bayat, Phys. Rev. Lett. 127, 080504 (2021)

[3] U. Mishra, A. Bayat, Scientific Reports 12, 14760 (2022)

[4] V. Montenegro, M. G. Genoni, A. Bayat, M. G. A. Paris, Commun. phys. 6, 304 (2023)

[5] R. Yousefjani, K. Sacha, A. Bayat, arXiv:2405.00328

[6] X. He, R. Yousefjani, A. Bayat, Phys. Rev. Lett. 131, 010801 (2023)

[7] S. Sarkar, F. Ciccarello, A. Carollo, A. Bayat, New J. Phys. 26, 073010 (2024)

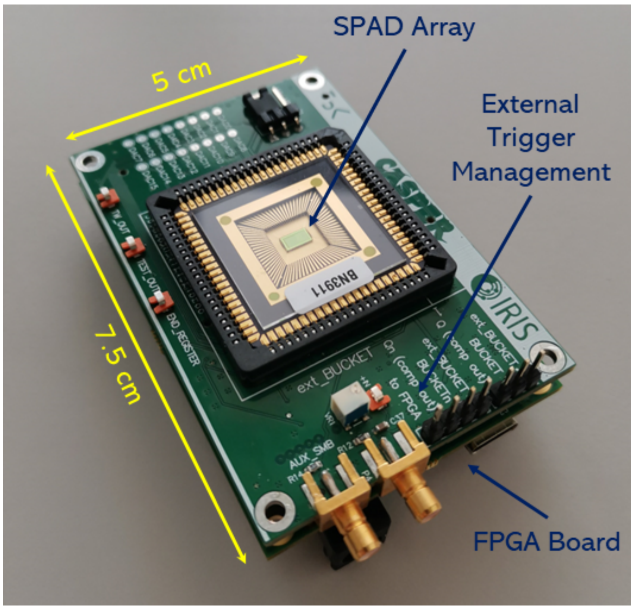
A low-power and low-noise 100x100 SPAD array with in-pixel correlation technique for quantum ghost imaging applications

Oral - Abstract ID: 10

Massimo Gandola [1], _Enrico Manuzzato_ [1], _Alessandro Tontini_ [1], _Valerio Flavio Gili_ [2], _Dupish Dupish_ [3], _Frank Setzpfandt_ [4], _Leonardo Gasparini_ [1]

__1.__ Fondazione Bruno Kessler, __2.__ Fraunhofer Institute for Applied Optics and Precision Engineering, Friedrich-Schiller-Universität Jena, __3.__ Friedrich-Schiller-Universit ̈at Jena, __4.__ Friedrich-Schiller-Universit ̈at Jena, Fraunhofer Institute for Applied Optics and Precision Engineering

The Quantum Ghost Imaging (QGI) technique exploits entanglement between photon pairs, potentially of different wavelengths, to acquire an image of an object performing a temporal correlation between detections. This technique enables decoupling between the wavelengths adopted for imaging and detection involving a dedicated single-channel detector as function of the targeting application.
We present a FPGA-based module integrating a 100x100 CMOS Single Photon Avalanche Diode (SPAD) array designed for quantum imaging applications compatible with an external asynchronous trigger provided by a single-channel detector namely bucket detector. The SPAD Array, with in-pixel backward-looking temporal correlation capabilities, has been implemented to spatially resolve entangled photons in a ghost imaging setup. The correlation is achieved through pixel-wise asynchronous delayed time windows, with tunable width to maximize correlation efficiency. The imager is fabricated in a 110 nm CIS FSI technology featuring a 17 µm pixel pitch with up to 31% fill-factor and an average power consumption of 24 µW/event. The SPAD array allows tuning of the pixel's correlation window width and delay ranging from 2 ns to 27 ns, and from 5 ns to 40 ns, respectively. An average Dark Count Rate noise equal to 720 Hz has been measured, minimizing the probability of false correlation, alongside with the capability of disabling noisy pixels. Additionally, a smart readout architecture exploits the sparseness of detected events reducing the overall readout time by skipping empty rows, therefore increasing the sensor's duty cycle. The module is equipped with an FPGA for programming and controlling the SPAD array through a user-friendly interface, and a discrete comparator potentially enabling the adjustment of different trigger signals from the bucket detector to the SPAD array. Furthermore, a new large-scale 472x456 SPAD Array has been developed with pixel and various enhancements to improve the frame rate and detection efficiency. An integrated address-based event readout circuit enables reading out only the pixels that record a correlation, improving the frame rate and reducing the power consumption. The characterization campaign of the large-scale array is currently underway.



Spad array module.png

Harnessing Machine Learning for efficient calibration of multiplexed quantum devices

Oral - Abstract ID: 183

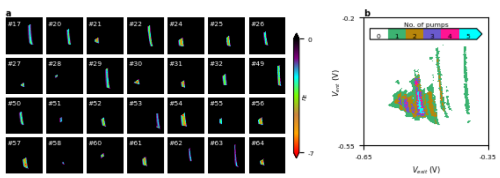
<u>Nikolaos Schoinas</u> [1], *Yannic Rath* [1], *Shota Norimoto* [1], *Wenqing Xie* [1], *Patrick See* [1], *Jonathan Griffiths* [2], *Chong Chen* [2], *David Ritchie* [2], *Masaya Kataoka* [1], *Alessandro Rossi* [1], *Ivan Rungger* [1]

1. National Physical Laboratory, 2. Cavendish Laboratory, University of Cambridge

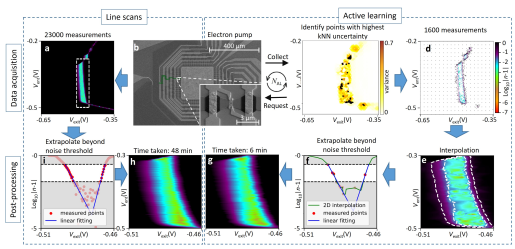
Calibrating quantum devices remains a critical challenge in the pursuit of scalable quantum technologies used in practical applications. Traditional manual tuning methods are time-consuming, underscoring the need for advanced automated solutions. Machine learning offers a promising avenue for addressing these challenges by providing efficient, accurate, and scalable calibration processes.

In this work, we introduce a machine learning framework developed for the rapid and automated characterisation of quantum devices. Our approach leverages active learning algorithms to optimise the calibration process by selectively targeting sparse but informative measurements in the parameter space. This significantly reduces the number of required measurements compared to exhaustive parameter scans, enhancing both speed and efficiency.

As a practical application, we focus on the calibration of single-electron pumps, nanoscale devices capable of generating quantised macroscopic electric currents. Our Active Learning Sparse Measurement (ALSM) framework successfully characterises 28 individual single-electron pump devices arranged in a GaAs/AlGaAs multiplexer array (N. Schoinas, Y. Rath *et al.*, arXiv:2405.20946). By determining quantisation errors via an exponential extrapolation of the first current plateau, our method achieves an eight-fold reduction in the time required for tuning. This efficiency gain is pivotal for the parallel operation of multiple pumps, allowing for the generation of larger quantised currents and the potential scaling of quantum devices. This advancement demonstrates the power of machine learning in optimising quantum device characterization and calibration and paves the way for the broader application of automated frameworks in quantum technologies.



Overlap with heatmaps.png



Alsm schematic.jpg

Efficient Microwave Photon to Electron Conversion in a High Impedance Quantum Circuit

Oral - Abstract ID: 250

Ognjen Stanisavljevic [1]***, Jean-Côme Philippe*** [1]***, Julien Gabelli*** [1]***, Marco Aprili*** [1]***, Jérôme Estève*** [1]***, Julien Basset*** [1]

1. *Universit´e Paris-Saclay, CNRS, Laboratoire de Physique des Solides, 91405 Orsay*

We demonstrate an efficient and continuous microwave photon to electron converter with large quantum efficiency (83%) and low dark current. These unique properties are enabled by the use of a high kinetic inductance disordered superconductor, granular aluminium, to enhance light-matter interaction and the coupling of microwave photons to electron tunneling processes. As a consequence of strong coupling, we observe both linear and non-linear photon-assisted processes where 2, 3 and 4 photons are converted into a single electron at unprecedentedly low light intensities. Theoretical predictions, which require quantization of the photonic field within a quantum master equation framework, reproduce well the experimental data. This experimental advancement brings the foundation for high-efficiency detection of individual microwave photons using charge-based detection techniques.

Quantum defects for neurosignalling research

Oral - Abstract ID: 215

***Filipe Camarneiro* [1], *Beatriz N.L. Costa* [1], *Orlando Cunha* [1], *João P. Silva* [1], *Jana B. Nieder* [1]**

***1.** INL - International Iberian Nanotechnology Laboratory*

The Nitrogen-Vacancy (NV) center in diamond is a versatile quantum defect with various applications in quantum sensing, quantum information, and cryptography. Despite their potential, their application in biological samples remains challenging.

We present advances to create and use these quantum sensing probes for neuroscience applications. We functionalize nanodiamonds via selected antibody linkers placing them close to the cellular surface, where action potentials may create magnetic field changes (1). Further, we implement dedicated Quantum metrology setups that are suited to read out signals from nanodiamonds as well as from distributed NV centers in bulk diamond probes. These NV center probes shall monitor magnetic field changes across neuronal networks.

We present our advances in NV center fabrication, leveraging femtosecond (fs) lasers to create single NV centers, as originally introduced by Chen *et al.* (2), but using a 515nm system, with the aim to provide dedicated NV center substrates for neurosignalling research.

We will present the measurement of intracellular temperature information using the NV in diamond via the detection of fluorescence lifetimes, to monitor the effects of hyperthermia treatment.

To optimize the quantum sensing read-out, we use a biomimicking samples placed on top of bulk diamonds with shallow implanted NV centers (3), allowing us to optimize the used continuous wave and pulsed protocols available. Current limitations and perspectives for NV center based quantum sensing in neurosignalling and research of neurodegenerative diseases will be discussed.

Acknowledgements

This research was supported by Fundação para a Ciência e Tecnologia (FCT) via the project PTDC/NAN-OPT/7989/2020 (DIAMOND-CONNECT) and by La Caixa foundation via the project Diamond4Brain (LCF/PR/HP20/52300001). JPS acknowledges FCT's PhD grant (2022.11803.BD). We thank R. Almeida's (U Aveiro) and A. Salgado's (UMinho/ICVS) teams and P.V.S. Marques and J.M. Maia (INESC-TEC,Porto) for the support on cells and fs laser applications, respectively, and the INL Nanophotonics and Bioimaging research facilities.

References

1. B.N.L Costa, F. Camarneiro, et al., "Functionalized Nanodiamonds for Targeting Single Neurons and Measure Electrical Signalling via Optically Detected Magnetic Resonance", (submitted).
2. Y. C. Chen et al., *Optica* **6**, 662-667 (2019).
3. F. Camarneiro et al. *Particle & Particle Systems Characterization* **38** (8): 2100011(2021).

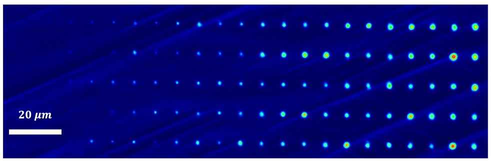


Figure 1: NV center fluorescence emission spots in a fs laser treated bulk diamond measured in a confocal microscope (λ_{exc} of 561 nm). At a focus depth of 15 µm, NV centers were created using a 515 nm fs laser, with a rep rate of 500 kHz and a pulse duration of about 150 fs. Laser writing parameters were varied from left to right by steps of 0.96 nJ from 5.96 to 25.2 nJ energy per pulse with a 2 s exposure time.

Fslaserwrittennvs jananieder.png

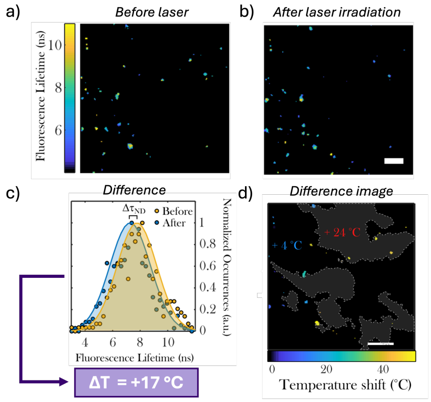


Figure 2: Fluorescence lifetime images taken before (a) and after (b) NIR laser excitation. Gold nanorod containing heat probes were illuminated by an 808 nm laser @ 1 W for 20 minutes. After calibration, the fluorescence lifetime parameter can be used to extract temperature changes in the medium and at the locations of cells. A fluorescence lifetime histogram (c) and resulting temperature map (d) are shown.

Intracellulartemp jananieder.png

Symmetries in quantum metrology: a new path to measurement optimality

Oral - Abstract ID: 207

Jesus Rubio [1]

1. University of Surrey

Introduction

Combining quantum and Bayesian principles leads to optimality in metrology, but exact solutions can be hard to find in practice. In this talk I show that, in many practical cases, finding optimal measurement strategies amounts to identifying which symmetry leaves a state of maximum ignorance invariant.

Methods

For quantities that are isomorphic to location parameters, and using variational calculus, I derive symmetry-informed measurement strategies in closed form that are optimal for any parameter range, prior information, state, and sample size.

Results

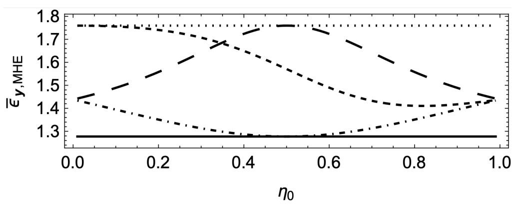
I demonstrate the practical potential of this framework for the estimation of a range of parameter types, including decay rates, atom number, temperature, and quantum coherence. The estimation of blend parameters in mixed states, e.g., can be achieved with a precision gain as high as 75% relative to the initial uncertainty. In general, Bayesian strategies are shown to be substantially more informative than using the widespread Fisher information.

Discussion

Symmetry-informed estimation will reduce the number of metrological calculations needed in sensing experiments, bypassing the hierarchies of error bounds often employed in metrology. Furthermore, this framework will enable the rigorous application of quantum metrology to fundamental physics, where symmetries play a key role.

Selected references:

- J. Rubio, arXiv:2402.16410 (accepted as a Letter in Phy. Rev. A), 2024
- J. Rubio, Quantum Sci. Technol. 8 015009, 2023
- J. Rubio et al., Phys. Rev. Lett. 127 190402, 2022



Blend parameter estimation.png

Minimal assumptions		
Parameter	phase	location-isomorphic
Support	$0 \leq \theta < 2\pi$	$-\infty < f(\theta) < \infty$
Metrological formulation		
Invariance	$\theta' = \theta + 2m\pi$	$f(\theta') = f(\theta) + c$
Ignorance prior	$p(\theta) = 1/2\pi$	$p(\theta) \propto df(\theta)/d\theta$
Error	$4\sin^2[(\tilde{\theta} - \theta)/2]$	$[f(\tilde{\theta}) - f(\theta)]^2$

Symmetry-informed metrologies.png

Demonstrating efficient and robust bosonic state reconstruction via optimized excitation counting

Oral - Abstract ID: 96

Tanjung Krisnanda [1], ***Clara Fontaine*** [1], ***Adrian Copetudo*** [1], ***Pengtao Song*** [1], ***Kai Xiang Lee*** [2], ***Ni-ni Huang*** [1], ***Fernando Valadares*** [1], ***Timothy Liew*** [2], ***Yvonne Gao*** [1]

1. National University of Singapore, 2. Nanyang Technological University

Quantum state reconstruction is an essential element in quantum information processing. However, efficient and reliable reconstruction of non-trivial quantum states in the presence of hardware imperfections can be challenging. This task is particularly demanding for high-dimensional states encoded in continuous-variable (CV) systems, as many error-prone measurements are needed to cover the relevant degrees of freedom of the system in phase space.

In this work, we introduce an efficient and robust technique for Optimized Reconstruction with Excitation Number Sampling (ORENS). It uses the theoretically fewest measured observables, which can be readily implemented across CV platforms. Our protocol is illustrated in Fig. 1, which consists of state preparation of the to-be-reconstructed cavity state, information scrambling by applying a (strategically optimized) displacement and mapping the probability of having *n* cavity excitation to an ancillary qubit for measurement. This sequence is repeated for D^2*-1* different displacements for reconstructing any cavity state within the dimension *D*. The post processing includes inverting the Born's rule and Bayesian inference to arrive at the final reconstructed state.

We experimentally demonstrate our method ORENS in a circuit quantum electrodynamics (cQED) platform to showcase its performance for reconstructing high-dimensional CV states. Our main results are summarized in Fig. 2, where we show that average fidelities of different states (i.e., Fock states, their superpositions, and cat states) contained within a dimension *D* from ORENS outperform those of the state-of-the-art Wigner reconstruction technique using the same *D2-1* number of observables, owing to ORENS' inherent robustness against both coherent and incoherent errors. In the case of severe decoherence (qubit dephasing), we show in Fig. 2(b) that ORENS significantly outperforms even the corrected Wigner technique that requires twice the number of observables.

ORENS relies only on the ability to accurately measure the excitation number of the state, making it a versatile and accessible tool for a wide range of CV platforms (e.g., cavity/circuit-QED, trapped ions/atoms, and mechanical resonators) and readily scalable to multimode systems. Our contribution to bosonic state reconstruction, a key research pillar in CV applications, will reinforce the development and analysis of more complex bosonic states and dynamics across different physical devices.

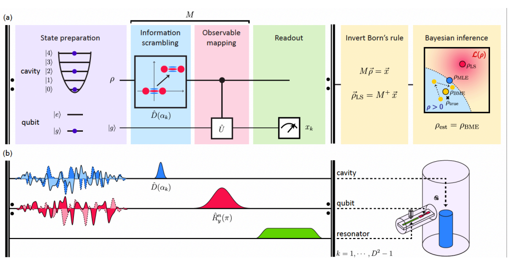


Fig. 1. orens protocol.png

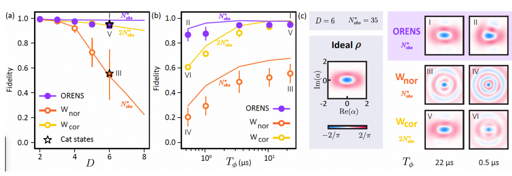


Fig. 2. state reconstruction.png

Variational Quantum Algorithms for Multi-objective Optimization

Oral - Abstract ID: 87

Ivica Turkalj [1]

1. *Fraunhofer Institute for Industrial Mathematics (ITWM)*

Multi-objective optimization is a rapidly evolving research field that addresses complex real-world problems that have multiple, often conflicting, objectives that have to be optimized simultaneously. Unlike traditional optimization, multi-objective optimization problems usually have not one but several optimal solutions, so-called Pareto-optimal solutions representing trade-offs between different objectives. However, finding these solutions is computationally intensive, exacerbated by the potential vast number of Pareto-optimal solutions. This characteristic makes multi-objective optimization problems ideal candidates for quantum computing. In this talk we present an approach that makes solving multi-objective problems accessible for NISQ devices.

Our focus is to adapt known techniques for variational quantum algorithms to the special structure of multi-objective optimization problems. On the one hand, we consider an extension of the well-known QAOA approach, so that conflicting objective functions can be integrated simultaneously. On the other hand, we adapt the cost function to be minimized in such a way that the commonly used expected value of an observable is replaced by quantities that provide a high-quality solution to the multi-criteria problem, such as the hypervolume and the the Pareto-spread (the latter ensuring a uniform distribution of the solutions found). To demonstrate both functioning and effectiveness of our approach, we test our methods on established benchmark problems from the classical literature.

Our research marks a significant step forward in utilizing quantum computing for multi-objective optimization problems, trying to overcome the limitations faced by classical computing approaches. Thus, our research opens up new avenues for solving complex real-world challenges.

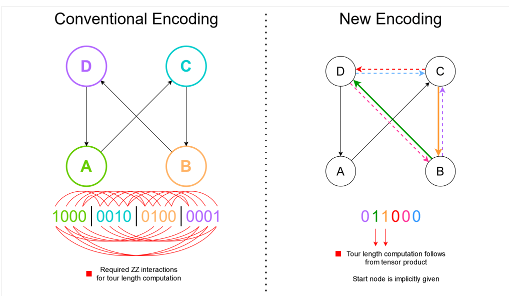
Direct phase encoding in QAOA: Describing combinatorial optimization problems through binary decision variables

Oral - Abstract ID: 52

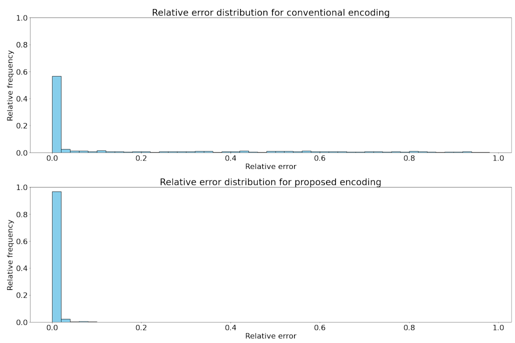
Simon Garhofer [1], ***Oliver Bringmann*** [1]

1. Embedded Systems, University of Tübingen

The Quantum Approximate Optimization Algorithm (QAOA) and its derived variants are widely in use for approximating combinatorial optimization problem instances on gate-based Noisy Intermediate Scale Quantum (NISQ) computers. Commonly, circuits required for QAOA are constructed by first reformulating a given problem as a Quadratic Unconstrained Binary Optimization (QUBO) problem. It is then straight forward to synthesize a QAOA circuit from QUBO equations.
In this work we illustrate a more qubit-efficient circuit construction for combinatorial optimization problems by the example of the Traveling Salesperson Problem (TSP). Conventionally, the qubit encoding in QAOA for the TSP describes a tour using a sequence of nodes, where each node is written as a 1-hot binary vector. We propose to encode TSP tours by selecting edges included in the tour. Each edge is represented by a single qubit. If an edge is part of a tour, the qubit is in state $|1\rangle$, otherwise $|0\rangle$. Removing certain redundancies, the number of required qubits can be reduced by a linear factor compared to the aforementioned conventional encoding. Tour lengths are computed by associating each edge with a phase gate, the angle of which corresponds to the respective edge length. In the tensor product of the phase gate array those angles are subsequently summed up.
We examined implementations of both QAOA encoding variants in terms of their approximation quality and runtime. We opted to use Grover mixers in our QAOA implementations to ensure adherence to boundary conditions. Our experiments show that for small instances results are significantly more accurate using our proposed encoding, whereas the number of required classical optimizer iterations increases only slightly. For 1000 randomly generated TSP instances with 4 nodes, the circuit with p=1 QAOA repetitions using conventional encoding returned optimal solutions in 56.7% of all instances with an average relative error of 68.3% for all non-optimal solutions and required 27 optimization iterations on average. Circuits using our proposed encoding yielded optimal solutions in 96.8% of all cases with an average relative error of 4.3% for all non-optimal solutions, requiring on average 35 optimizer iterations.



Encodingcomparison.png



Errorcomparison.png

Simulating Matrix Models: A Possible Route to Understanding Quantum Gravity

Oral - Abstract ID: 196

Enrico Brehm [1]

1. *DESY Zeuthen*

Matrix models are a promising framework for exploring the principles of quantum gravity. In this talk, we present our work on simulating matrix models using two advanced techniques: Tensor Networks and quantum devices. Tensor Networks enable efficient representation and manipulation of the complex structures in matrix models, revealing underlying quantum gravitational dynamics. Additionally, we implement these simulations on quantum devices, demonstrating their potential to solve problems that are intractable for classical computers. Our results show that combining Tensor Networks and quantum devices is an effective approach for investigating quantum gravity, offering new insights and paving the way for future research in this field.

Multidimensional quantum generative modeling by quantum Hartley transform

Oral - Abstract ID: 197

Hsin-Yu Wu [1], ***Vincent E. Elfving*** [2], ***Oleksandr Kyriienko*** [1]

1. *University of Exeter*, **2.** *PASQAL*

We propose an orthonormal Hartley feature map that enables explicit quantum model building in the Hartley basis. Unlike discrete Fourier transform, the discrete Hartley transform (DHT) maps a real input to a real output and has the convenient property of being its own inverse. The DHT has been shown to offer computational advantages over DFT in applications of power spectrum and convolution computations.

The orthonormal Hartley feature map $U_h(x)$ as a quantum circuit parameterized by a continuous variable x prepares quantum states with amplitudes proportional to the so-called Hartley kernel function, which facilitates building quantum models in the real-valued Hartley space with an exponentially large basis set and allows for model differentiation. We apply the developed quantum protocols for learning financially relevant probability distributions, as shown in **Fig. 1(a-c)**. We then demonstrate the efficient sampling of the Hartley-based quantum models by mapping the Hartley basis to the computational basis via a quantum Hartley transform U_{QHT} circuit , as shown in **Fig. 1(d-f)**. As a demonstration of the double-frequency sampling, the histogram of the sampled probability distribution from the trained model with the extended register of S=1 is presented in **Fig. 1(g,h)**.

We proceed to extend the proposed strategies from univariate to multivariate encoding and sampling for implementation of multidimensional quantum generative modeling. **Fig. 2(a)** reveals density plots of analytical binormal distribution with five different correlation coefficients ρ, set as target distributions (ground trues). The corresponding density plots of the trained quantum models are displayed in each column of **Fig. 2(b)**, respectively. As expected, they all quantitatively follow target distributions. Successful bivariate learning over a wide range of correlation coefficients can be attributed to the well-designed architecture of the latent-space training of the quantum models with a problem-specific correlation circuit included. The corresponding normalized density plots of sampled distributions are shown in **Fig. 2(c)**, which are in excellent agreement with the target distributions.

The proposed framework enables us to systemically build multidimensional quantum models and scale to larger state space. We believe that the developed step-by-step approach is essential when addressing challenging problems in the generative modeling domain with quantum protocols.

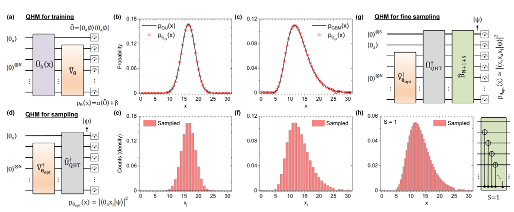


Fig1.png

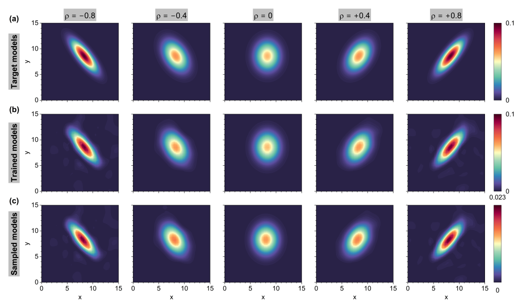


Fig2.png

Efficient, high-fidelity single-photon switch based on waveguide-coupled cavities

Oral - Abstract ID: 83

Mateusz Duda [1], *Luke Brunswick* [1], *Luke Wilson* [1], *Pieter Kok* [1]

1. The University of Sheffield

Creating large-scale, distributed quantum networks for technologies such as computing, communication, sensing, and metrology requires precise control over single photons. A fundamental building block of photonic quantum technologies is therefore a device that can deterministically and faithfully route a single photon within a network, i.e., a single-photon switch with high efficiency and fidelity.

Here, we propose a single-photon switch based on an array of N single-mode cavities coupled to a common single-mode waveguide, with each cavity containing a two-level quantum emitter [see figure (a)]. The switch reflects photons in the weak emitter-cavity coupling regime and transmits photons in the strong coupling regime. We derive the N-cavity transmission and reflection coefficients for the system using the transfer matrix approach and the input-output formalism of quantum optics. We then use these to compute the efficiency and fidelity of the switch for realistic input photon wavepackets propagating in the waveguide.

We find that a single waveguide-coupled cavity can route photon wavepackets with high efficiencies and fidelities if the spectral width of the wavepacket is smaller than the cavity mode linewidth. However, if the wavepacket width is comparable to or greater than the cavity mode linewidth, the switching performance can degrade significantly. We find that increasing the number of cavities increases the reflection bandwidth [see figure (b)], allowing wider photon wavepackets to be routed with high efficiencies and fidelities. For example, for an input Gaussian wavepacket with a full width at half-maximum of 1 nm (corresponding to a few-picosecond pulse), we find that an array of three waveguide-coupled cavities can reflect the wavepacket with efficiency 96.4% and fidelity 97.7%, or transmit the wavepacket with efficiency 99.7% and fidelity 99.8%.

In summary, our work shows that waveguide-coupled cavities with embedded emitters are a promising platform for the realisation of high-performance quantum switches that preserve the input photon state with high fidelity, and forms an important step towards realising fault-tolerant quantum technologies, where near-unity efficiencies and fidelities are critical.

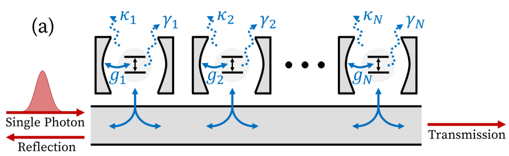


Figure a switch.png

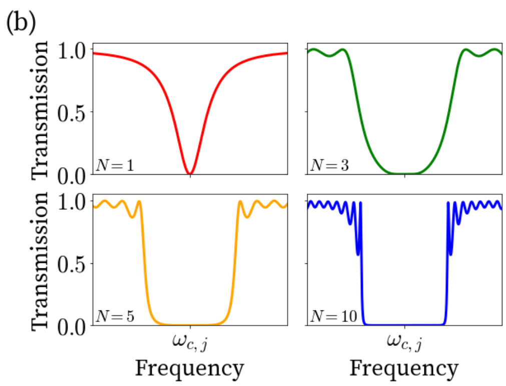


Figure b transmission results.png

Single-qubit rotation algorithm with logarithmic Toffoli count and gate depth

Oral - Abstract ID: 73

Christoffer Hindlycke [1], *Jan-Åke Larsson* [1]

1. Linköping University

Introduction

The Toffoli gate is a fundamental tool in quantum computing, crucial for Shor's algorithm, quantum error correction, and shallow quantum circuits.

Another essential tool is approximation of generic single qubit gates using a finite gate set.

The Solovay-Kitaev theorem tells us that with access to a limited but well-chosen set of single-qubit quantum gates, an approximation to any desired qubit gate to within distance ε can be constructed, with gate depth close to qubic in the logarithm of 1/ε.

We give an explicit construction for approximating any single-qubit quantum gate using the Clifford+Toffoli gate set with exponent 1.

The construction is very simple and efficient: It requires only a trigonometric expression of the desired rotation angle, rounded to the desired accuracy.

The resulting algorithm has expected Toffoli count and gate depth logarithmic in 1/ε.

Methods

We modify a pre-existing circuit by Nielsen & Chuang, see arbitrary_rotation_circuits.jpg, by replacing the two Toffolis with two ≥k-tests with ancillary controls, allowing for control over the ratio of marked/unmarked states. We provide explicit circuit constructions for the ≥k-tests and all constituent parts. The resulting circuit is incorporated into a repeat-until-success rotation algorithm, see arbitrary_rotation_rus_algorithm.jpg. We give a theorem specifying how to select the number of ancillary controls and the integer k based on the desired rotation angle and desired precision ε.

Results

Our modified circuit either applies the desired rotation (to within distance ε) with probability strictly greater than 1/2, or a Z gate; if a Z gate was applied, the measurement of the controls indicate this, allowing for correcting the target state and trying again. Our rotation algorithm utilizing this circuit has expected number of repetitions strictly less than 2, and expected Toffoli count and gate depth logarithmic in 1/ε.

Discussion

Our construction only relies on being able to calculate tan(Θ/2), where Θ is the desired rotation angle, so requires only polynomial classical runtime and space to generate.

In addition, the simplicity of our algorithm makes it attractive as a standard tool in quantum engineering.

This, in combination with its efficient implementation, should make it useful for both theoretical and practical pursuits.

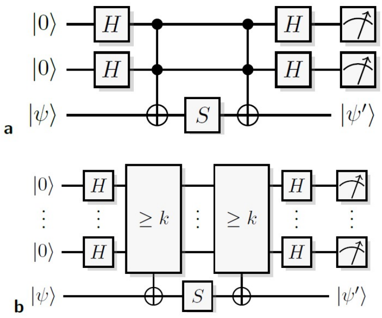


Fig. 1 Circuits for approximate qubit rotation. **a** Circuit that applies R_φ to $|\psi\rangle$ ($\cos\varphi = 3/5$, $\sin\varphi = 4/5$) with probability 5/8; otherwise a Z gate. **b** Circuit that applies $R_{\theta*}$ to $|\psi\rangle$, close to a desired rotation R_θ with high probability, where ancilla count n and comparison k should be chosen according to Theorem 1.

Arbitrary rotation circuits.jpg

Algorithm 1 Rotation algorithm

```
Input θ, ϵ, |ψ⟩
Output R_θ* |ψ⟩ where ||R_θ − R_θ*|| ≤ ϵ
choose n, k, θ* as in Theorem 1
if θ* ≠ 0 repeat
    prepare n ancillary qubits |ϕ⟩ = |0⟩^⊗n
    apply H^⊗n to |ϕ⟩
    apply a ≥ k test on |ϕ⟩ with target |ψ⟩
    apply S to |ψ⟩
    apply a ≥ k test on |ϕ⟩ with target |ψ⟩
    apply H^⊗n to |ϕ⟩
    measure and discard ancillas |ϕ⟩
    if outcomes are not all zero then
        apply Z to |ψ⟩
until outcomes are all zero
```

Arbitrary rotation rus algorithm.jpg

Ground state nature and nonlinear squeezing of Gottesman-Kitaev-Preskill states

Oral - Abstract ID: 143

Petr Marek [1]

1. *Palacky University*

The main bottleneck for universal quantum computation with traveling light is the preparation of Gottesman-Kitaev-Preskill states of sufficient quality. This is an extremely challenging task, experimental as well as theoretical, also because there is currently no single easily computable measure of quality for these states. We introduce such measure in the form of mean value of Hermitian operator and show that it can be interpreted as nonlinear squeezing inherent to GKP states. We then show how it is related to the current ways of characterizing the states. The measure is easy to compute and can be easily employed in state preparation as well as verification of experimental results.

[1] P. Marek, Phys. Rev. Lett. **132**, 210601 (2024).

Fault-tolerant quantum computing with the parity code and noise-biased qubits

Oral - Abstract ID: 122

Anette Messinger [1], Valentin Torggler [2], Berend Klaver [1], Michael Fellner [1], Wolfgang Lechner [1]

1. Parity Quantum Computing GmbH, 2. Parity Quantum Computing Germany GmbH

Introduction

Since quantum computers are affected by noise, the concepts of fault-tolerance are indispensable for implementing useful quantum algorithms. A quantum state is redundantly encoded in an error-correction code and fault-tolerant quantum operations are performed on the encoded quantum state. When qubits with a noise bias (e.g. cat qubits) are used, resource-saving “classical” error-correction codes capable of correcting only a single type of error (e.g. bit flips) can be employed.

We propose to combine the Parity Code with noise-biased qubits for fault-tolerant quantum computation [1]. The Parity Code is a classical error-correction code which can be implemented on a platform with nearest-neighbor interaction on a 2D grid with weight-3 and weigth-4 stabilizers. We explore properties of the Parity Code and present circuits and code layouts for implementing fault-tolerant logical gates of a universal gate set.

Methods

We analyse the Parity Code’s encoding rate, and logical error rate per stabilizer measurement round for different gate and decoherence error rates using Belief Propagation.

We design circuits for fault-tolerant logical gates by transversal application and/or magic state injection employing only bias-preserving gates. Different logical gates may be implemented within different code layouts, wherein code layouts may be converted by code deformation.

Results

Our results reveal that the Parity Code has a higher encoding rate than the repetition code, while still being implementable with nearest-neighbor interactions and low-weight stabilizers. For low CNOT error rates, the logical error rate per stabilizer measurement of the Parity Code is smaller than for the repetition code.

We propose circuits and code layouts for implementing a universal gate set, as well as a parallelizable circuit for the CZ-gate without routing.

Discussion

Our proposed scheme allows for implementing arbitrary quantum algorithms in a fault-tolerant way. CZ gates may be efficiently parallelized without routing limitations, allowing for parallelization beyond the capabilities of known error-correction codes.

The Parity Code is an LDPC code with low stabilizer weight and nearest-neighbor connectivity, allowing for efficient code deformation. Due to the high encoding rate and logical error rate, our proposal is a promising candidate for implementing fault-tolerant quantum computation.

[1] Messinger et al., arXiv:2404.11332 [quant-ph]

Fault-tolerant implementation of an s gate in the parity code.jpg

A globally driven superconducting quantum computing architecture

Oral - Abstract ID: 274

Riccardo Aiudi [1], ***Roberto Menta*** [2], ***Francesco Cioni*** [3], ***Marco Polini*** [4], ***Vittorio Giovannetti*** [2]

1. Planckian, 2. Planckian and SNS, 3. SNS, 4. Planckian and University of Pisa

Introduction:
Our work (https://arxiv.org/pdf/2407.01182) introduces a new approach to build a universal quantum computer using a 2D ladder structure composed of superconducting qubits.
Current architectures require addressing each qubit independently, leading to a large number of control lines entering the quantum processor—a problem known as the “wiring problem”. Additionally, superconducting qubits often interact with unwanted longitudinal ZZ couplings, causing phase accumulations that must be managed during computation.
Our proposed architecture (see Figure 1) addresses these issues by implementing a scalable processor where qubits are globally driven, maintaining a constant number of control lines regardless of qubit count. We developed a quantum computation protocol that exploits the parasitic ZZ coupling between qubits, making it a fundamental building block.
Methods:
We use an always-on ZZ coupling and specific global pulses to emulate a blockade effect between neighboring qubits, similar to Rydberg atom interactions. This enables us to select specific working subspaces for the qubits despite global drives. In our scheme, logical qubits are dynamically stored and move through the ladder of physical qubits. This allows us to perform single and two-qubit gates without local qubit addressing. Specific driving pulses achieve the desired quantum operations. Figure 2 shows the energy scheme allowing the blockade effect and the global pulses that move the logical qubits.
Results:
We developed a complete computational scheme establishing our platform as a universal quantum computer. The design supports essential quantum operations, including single-qubit rotations and two-qubit gates. We tested different designs and checked their behavior using numerical simulations.
Discussion:
Our globally driven superconducting quantum computing architecture offers significant advantages. Our scheme exploits unwanted qubit couplings, which are challenging to eliminate. Our quantum computer requires only three control lines to achieve full quantum computing power, regardless of the number of logical qubits. These features enhance the feasibility of developing large-scale quantum computers. Future work will focus on optimizing the architecture, exploring scalability, and experimentally validating the design. This approach represents a promising advancement towards practical, scalable quantum computing technologies.

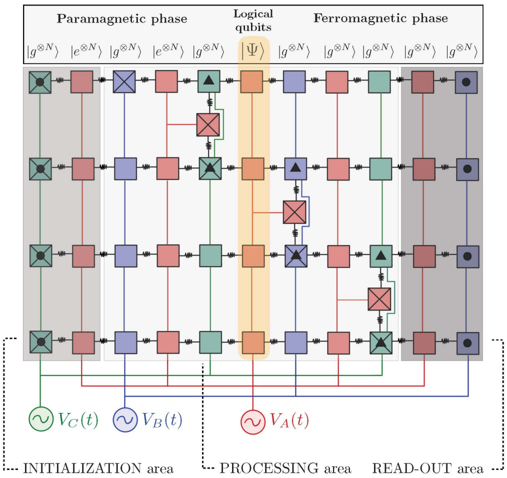


Fig1-main.jpg

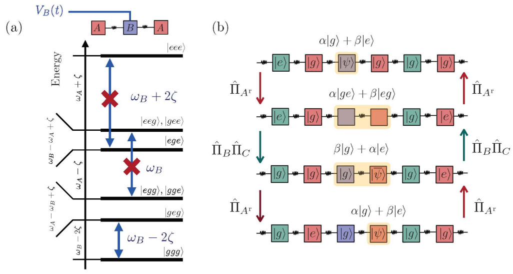


Fig2-main.jpg

Random pure Gaussian states, typical correlations and Hawking radiation

Oral - Abstract ID: 138

Erik Aurell [1]***, Lucas Hackl*** [2]***, Paweł Horodecki*** [3]***, Robert H. Jonsson*** [4]***, Mario Kieburg*** [2]

1. KTH, Royal Institute of Technology, 2. University of Melbourne, 3. University of Gdańsk, 4. Nordic Institute for Theoretical Physics

Introduction

We introduce a new method to the study of random Gaussian states: We consider ensembles of N-mode pure Gaussian states with fixed marginals and construct a probability distribution over their mode-mode correlations. Due to the ubiquity of Gaussian states, this method should be interesting to many areas.

Here, as a first use case, we address black hole physics: Central to the black hole information paradox is the question whether the total quantum state of all radiation emitted from an evaporating black hole can be pure, or not. With our methods, we can characterize the distribution of two-mode correlations resulting from radiation states that are globally pure and Gaussian.

Methods

For given single-mode thermal marginal states, we consider the set of all symplectic transformations which transform the vacuum state of N modes into a state with these prescribed marginals. We restrict the Haar measure on all symplectic transformations to this compact subset. The resulting distribution allows us to study the ensemble's typical two-mode correlations.

Results

We obtain exact expressions for this distribution, as well as powerful approximations, and give an extensive analysis of its asymptotic limits. This results in a detailed understanding of how the set of marginals determines the distribution of two-mode correlations in the state.

Applying this to the Hawking radiation from an evaporating black hole, we show that restoring unitarity and a pure total state after evaporation does not require strong quantum entanglement between any pair of Hawking modes. Whereas specific modes can be strongly correlated, in the ensemble we consider, they are nevertheless very unlikely to be entangled.

Discussion

While being complementary to microscopic studies of Hawking radiation, our work indicates that pure Gaussian states can exhibit the marginals predicted by Hawking theory while exhibiting typically extremely small two-mode correlations.

Beyond black hole physics, our methods should be relevant, for example, in the context of thermalization, typicality or random optical circuits.

(This contribution is based on: E. Aurell, L. Hackl, P. Horodecki, R. H. Jonsson, and M. Kieburg, "Random Pure Gaussian States and Hawking Radiation," *Phys. Rev. Lett.*, vol. 133, no. 6, p. 060202, Aug. 2024.)

Control of multi-modal scattering in a microwave frequency comb

Oral - Abstract ID: 79

Juan Carlos Rivera Hernández [1], *Fabio Lingua* [1]

1. KTH, Royal Institute of Technology

Measurement-based quantum computation (MBQC) utilizing continuous-variable (CV) systems offers promising advantages in speed, error correction, and hardware simplicity. Key to MBQC is the control of quantum correlations, often represented as graph or cluster states. While optical frequency combs have demonstrated such correlations, the flexibility and precision of digital signal processing at microwave frequencies present new opportunities. This study aims to engineer and verify square-ladder correlation graphs in a microwave frequency comb using a Josephson parametric amplifier (JPA).

We generate a microwave frequency comb with 95 modes using a single JPA, driven by three phase-coherent pumps. We manipulate the mode correlations by precisely controlling the relative phases of these pumps. The mode scattering matrix, essential for understanding these correlations, is theoretically derived from the linearized equations of motion of the parametric oscillator. Experimentally, we measure the scattering of a coherent state (□4.2 GHz) through digital synthesis and analysis.
The scattering matrix reveals the creation of square-ladder correlation graphs, with experimental measurements showing strong agreement with theoretical predictions. Specifically, we observe that third-order intermodulation products exhibit significant phase dependence, enabling selective cancellation of specific mode correlations. The experimental scattering matrices, normalized to the pump-off case, show clear patterns of constructive and destructive interference, consistent with the theoretical model.
The ability to control the phase of individual pumps provides a powerful tool for engineering specific correlation topologies in a microwave frequency comb. Our results demonstrate that the digital methods employed can be scaled to more modes and pumps, highlighting the potential for tailored CV quantum states. This work advances the understanding of multi-modal scattering in microwave frequency combs and contributes to the broader goal of realizing practical MBQC with CV systems.
In conclusion, our study showcases the feasibility of creating and controlling complex correlation structures in microwave frequency combs, paving the way for future developments in CV quantum computation. Further research will focus on enhancing mode resolution and exploring additional topological configurations to optimize quantum state control and measurement precision.

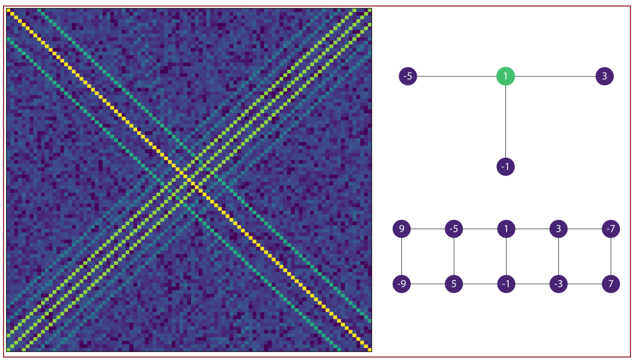


Fig-highlight-v2.png

Novel experimental techniques to close the Post-Selection Loophole for Time-Bin Entanglement

Oral - Abstract ID: 12

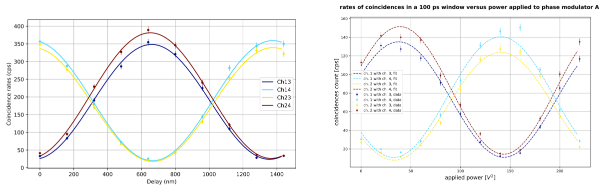
Costantino Agnesi [1]***, Francesco Bruno Leonardo Santagiustina*** [1]***, Kannan Vijayadharan*** [1]***, Paolo Villoresi*** [1]***, Giuseppe Vallone*** [1]

1. *Università degli Studi di Padova*

Entanglement is a crucial resource in quantum communication protocols, and distributing entanglement between distant nodes is an important aspect of a quantum network, enabling various applications like distributed quantum computing, quantum teleportation, quantum secret sharing and quantum key distribution (QKD).

Due to its robustness to propagation in fiber links, Time-bin (TB) entanglement represents a promising resource for entanglement distribution.
This popular entanglement generation scheme consists of an excitation pump laser that is prepared in a superposition of an early and a late time-bin creating photon pairs, via an spontaneous parametric down conversion (SPDC) process, in well-defined times. However, a major issue with both these schemes is related to the discovery of the Post-selection loophole (PSL), a local hidden-variable models (LHVM) which explain the violation due to the post-selection of detection events, thus requiring extra assumptions to trust the Bell test result and rendering it vulnerable to quantum hacking attacks.

In this presentation, novel experimental techniques to close the PSL for TB entanglement are discussed.
Firstly, PSL can be removed through the use of fast and stable optical switches to route the photons in the measurement interferometers to avoid the need for post-selection.
PSL can also be closed by exploiting a topologically different interferometric arrangement called the “hug” interferometer. This scheme, first developed for energy-time entanglement, can be extended to the TB case and allows a reduction in the frequency stability requirements of the pump laser and benefits from having specific photon generation times instead of a uniform distribution.
Both of these methods certify genuine TB entanglement generation, i.e., allowing the violation of a Bell’s inequality free of the Post-Selection Loophole. In this presentation we also present the experimental results that validate these methods. In particular, we implement the optical switches using standard off-the-shelf fiber components and the extinction ratio was observed to be over 99% (27 dB). Instead, we implement the “hug” interferometer in a Silicon Nitride chip. In the attached image we show the modulation of the coincidence rates between Alice and Bob by tuning the local phase shifts of the receivers, hinting at Bell violations for both methods.



(a) (b)

Experimentalresults.png

A fiber testbed and a quantum repeater cell for quantum communication

Oral - Abstract ID: 141

Christian Haen [1], ***Max Bergerhoff*** [1], ***Omar Elshehy*** [1], ***Elena Arenskötter*** [1], ***Stephan Kucera*** [2], ***Jonas Meiers*** [1], ***Tobias Bauer*** [1], ***Christoph Becher*** [1], ***Jürgen Eschner*** [1]

1. Universität des Saarlandes, 2. Luxembourg Institute of Science and Technology

The goal of establishing a quantum internet [1] requires the demonstration of existing quantum communication protocols with regard to challenges posed by deployed urban fibers, such as environmentally induced polarization changes and lossy splices. It also requires quantum repeaters, in order to overcome the exponential attenuation of direct transmission over large distance by asynchronously entangling nodes over smaller segments of the link. For future applications, it is also important to miniaturize and modularize the employed quantum communication hardware, in order to scale it from lab to rack format.

We report on the characterization and operation of a 14-km long urban fiber link running across Saarbrücken for quantum communication (Fig. 1). We implement its polarization stabilization with >99% process fidelity up to 60s and demonstrate quantum communication protocols with a 40Ca+ single-ion quantum memory, an ion-resonant entangled photon-pair source, and quantum frequency conversion. We show that entanglement is distributed without significant degradation of the state fidelity (Fig. 2). Using heralded absorption of one photon of the entangled pair, we demonstrate atom-to-photon quantum state teleportation with ~84% average fidelity over the fiber link [2] (Fig. 3).

In a laboratory experiment we also demonstrate a quantum repeater cell [3] based on asynchronous entanglement of two 40Ca+ ions located in the same Paul trap with one emitted photon each. By entanglement swapping via a Mølmer–Sørensen quantum gate on the ions we generate photon-photon entanglement with ~76% average fidelity (Fig. 4). We also investigate the scaling behavior for different transmission efficiencies.

Lastly, we discuss the construction of a new segmented ion trap with an integrated sub-mm cavity, for increasing the rate of collected photons and enabling rack-based quantum communication.

[1] H. Kimble, Nature 453, 1023–1030 (2008)

[2] S. Kucera et al., 10.48550/arXiv.2404.04958 (2024)

[3] D. Luong et al., Appl. Phys. B 122, 96 (2016)

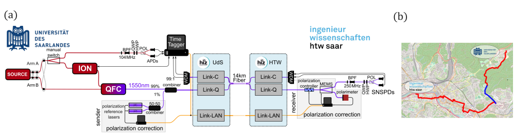


Fig 1: (a) Setup for the quantum communication protocol demonstrations
(b) Map of the Saarbrücken fiber link (map data from www.openstreetmap.org)

Setup v2.png

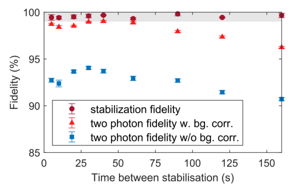
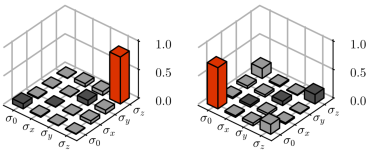


Fig. 2: Fidelity of photon-photon entanglement distribution in dependence of time between two polarization stabilization runs

Entanglement.png



(a) $|\Phi^-\rangle$ (b) $|\Phi^+\rangle$

Fig. 3: Reconstructed process matrices of the ion-to-photon quantum state teleportation conditioned on two Bell-state measurement results

Teleportation.png

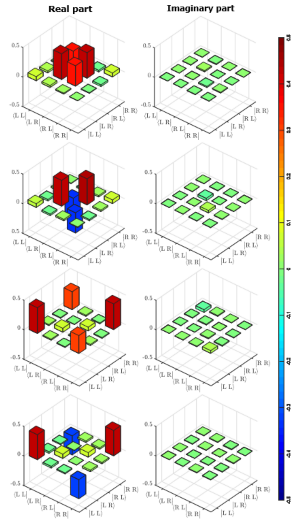


Fig. 4: Tomographically reconstructed density matrices of the entangled photon-photon states for the joint atom-atom state projection results corresponding to the four Bell states

Repeater.png

Creating High-Dimensionally Entangled Photonic States by Sequentially Exciting a Semiconductor Quantum Dot

Oral - Abstract ID: 155

***Daniel Vajner* [1], *Nils Kewitz* [1], *Martin von Helversen* [1], *Stephen Wein* [2], *Yusuf Karli* [3], *Florian Kappe* [3], *Vikas Remesh* [3], *Saimon Covre da Silva* [4], *Armando Rastelli* [5], *Gregor Weihs* [3], *Carlos Anton-Solanas* [6], *Tobias Heindel* [1]**

***1.** Institute of Solid State Physics, Technische Universität Berlin, 10623 Berlin, Germany, **2.** Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France, **3.** Institute für Experimentalphysik, Universität Innsbruck, Innsbruck, Austria, **4.** Universidade Estadual de Campinas, Instituto de Fısica Gleb Wataghin, 13083-859 Campinas, Brazil, **5.** Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Linz, Austria, **6.** Departamento de Fısica de Materiales, Universidad Autonoma de Madrid, 28049 Madrid, Spain*

As recently demonstrated, the sequential resonant excitation of 2-level quantum systems leads to the generation of time bin modes that are entangled in the photon-number-basis [S.C. Wein et al., Nature Photonics 16.5 374-379 (2022)]. Here, we extend this notion to 3-level quantum systems, realized by a biexciton in a semiconductor quantum dot that is subject to sequential pulses that are resonant with the two-photon transition [*arXiv:2407.05902*]. The different decay rates of the exciton and biexciton, in combination with the cascaded emission, lead to the creation of a complex multi-dimensional entangled state which could be used in quantum information applications [Santos, Alan C., et al. *Optics Letters* 48.23 (2023): 6332-6335]. By performing energy- and time-resolved correlation experiments, in combination with extensive theoretical modelling and simulations, we analyze the generated state and confirm its high-dimensional structure. Finally, we outline the requirements for, and predict the expected behavior of, future phase- stabilized experiments that interfere the full state with itself, which will ultimately confirm the presence of photon-number-entanglement. This represents a scalable way towards complex and on-demand entangled photonic states.

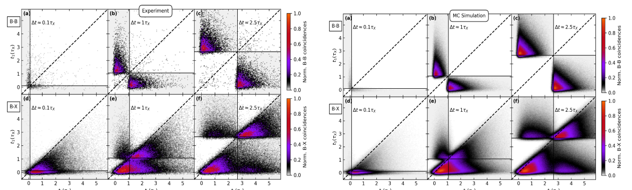


Fig. 1 Measured energy- and time-resolved correlations (left) for different delays between 2 sequential TPE excitation confirm the mode structure predicted from realistic Monte Carlo simulations (right).

Energy and time resolved correlations.png

Experimental Quantum Strong Coin Flipping with Single Photons

Oral - Abstract ID: 206

Koray Kaymazlar [1]**, *Daniel Vajner*** [1]**, *Fenja Drauschke*** [2]**, *Lucas Rickert*** [1]**, *Martin von Helversen*** [1]**, *Shulun Li*** [3]**, *Johannes Schall*** [1]**, *Sven Rodt*** [1]**, *Stephan Reitzenstein*** [1]**, *Zhichuan Niu*** [3]**, *Anna Pappa*** [2]**, *Tobias Heindel*** [1]

1. *Institute of Solid State Physics, Technische Universität Berlin, 10623 Berlin, Germany,* **2.** *Institute of Software Engineering and Theoretical Computer Sciences,* **3.** *Institute of Semiconductors, Chinese Acadamey of Sciences, Beijing 100083, China*

Introduction

Strong coin flipping (SCF) is a protocol to allow two distrustful parties namely Alice and Bob to agree on randomly generated bits. In this work, we implement a quantum strong coin flipping protocol that yields lower cheating probabilities than its classical counterpart [1]. For this, we dynamically modulate polarization states of single photons generated by a semiconductor quantum dot deterministically integrated into a circular Bragg grating (CBG). We report the performance of our quantum strong coin flipping implementation, which is the first with single photons, resulting in a single photon advantage compared to previous demonstrations with attenuated laser pulses.

Methods

To generate single photons a quantum dot in a CBG cavity is excited quasi-resonantly by picosecond laser pulses with a repetition rate of 80 MHz and the trion emission line @921 nm is spectrally selected. We ensured that no coherence was present in the photon number basis via phase-resolved interference experiments. To encode the quantum state on Alice's side, the collected single photons are directed to a fiber-based electro-optic modulator (EOM) driven by a four-level random voltage waveform via custom-built electronics based on a field programmable gate array (FPGA) and a digital to analog converter (DAC). Single photons leave the EOM in four different polarization states chosen to optimize the SCF protocol after numerical simulations. After passing a 30 cm free-space quantum channel, the polarization states are analyzed on Bob's side. A classical link allows to compare sent and detected states to complete the protocol.

Results

Our results show that the system produces successful coin flipping with a rate of 1.8 KHz. The average quantum bit error ratio (QBER) is calculated to be lower than 3%, sufficient to realize a quantum advantage.

Discussion & Conclusion

We successfully implemented quantum strong coin flipping (QSCF) using single photons. Results clearly show the quantum advantage compared to classical counterparts. The QSCF was shown to be fair and balanced, as needed for various applications and can be also integrated into other cryptographic protocols.

[1] Pappa, Anna, et al. "Practical quantum coin flipping." *Physical Review A* 84.5 (2011): 052305.

Elimination of Channel Characterization in Advance in Continuous Variable Quantum Key Distribution via Post-selection

Oral - Abstract ID: 226

Ozlem Erkilic [1], Biveen Shajilal [2], Lorcan Conlon [2], Angus Walsh [1], Oliver Thearle [3], Aritra Das [1], Ping Koy Lam [2], Syed Assad [1], Jie Zhao [1]

*1. Centre for Quantum Computation and Communication Technology, Department of Quantum Science and Technology, Australian National University, Canberra, Australia, 2. A*STAR Quantum Innovation Centre (Q.InC), 138634, Singapore, 3. Defence Science and Technology Group, Canberra, Australia*

Introduction: Quantum key distribution provides an unconditionally secure communication method to establish a secret key between two trusted parties, conventionally known as Alice and Bob. In this work, we focus on continuous-variable quantum key distribution (CV-QKD) protocols which are more compatible with the current telecommunication infrastructure and can operate in daylight applications in comparison to discrete-variable based protocols. However, due to the detrimental effects such as losses in fibers for terrestrial networks and atmospheric scintillation in free-space channels, one of the greatest challenges in CV-QKD is distributing the secret keys over large distances. The performance of CV-QKD can be improved by using processes such as noiseless linear amplification, photon catalysis and photon subtraction. However, the implementation of such processes is experimentally difficult and can be imitated by a method called post-selection in one of the parties' stations. Nevertheless, in these types of post-selections, the post-selection filters are bounded by the properties of the physical processes limiting the probability of success.

Method: Here we study the effect of post-selection on the common GG02 protocol using filters that have unknown physical representation. Our protocol combines post-selection in both stations where a Gaussian filter and a non-Gaussian box-like filter are applied to Alice and Bob's sides, respectively. Alice's post-selection is used to modify the Gaussian ensembles of states whereas Bob's post-selection alters the effective channel parameters.

Results & Discussion: The experimental results show an improvement in the key-rates by surpassing the key-rates of the original GG02 protocol for a given channel and achieving the key-rates of the optimized GG02 protocol (Figure 1). This demonstrates that emulation of a physical process is not necessary to enhance the performance of a CV-QKD system as it can be achieved by any arbitrary post-selection filter. This presents a potential way to increase the key rates through classical post-processing. Moreover, our protocol presents a way to dynamically optimize the secret-key rate for channels with unpredictable conditions such as those found in free-space channels.

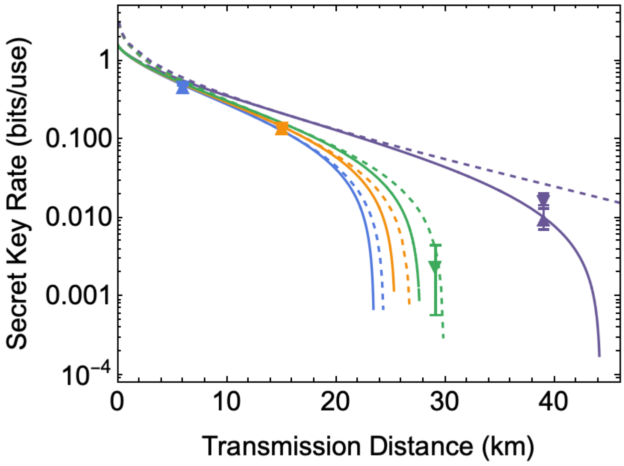

Secret Key Rate (bits/use)
1
0.100
0.010
0.001
10^-4
0
10
20
30
40
Transmission Distance (km)

Figure2.png

Post selection based quantum repeater protocol

Oral - Abstract ID: 81

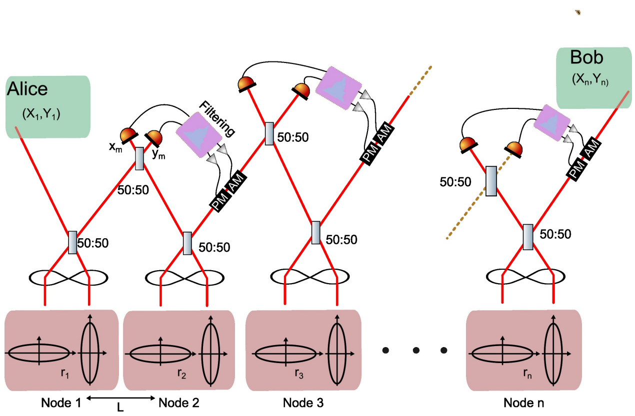
Angela Anna Baiju [1], *Ozlem Erkilic* [2], *Biveen Shajilal* [3], *Lorcan Conlon* [3], *Jie Zhao* [2], *Ping Koy Lam* [3]

1. *A*STAR Quantum Innovation Centre (Q.InC), Institute of Materials Research and Engineering (IMRE), 138634, Singapore,* ***2.*** *Australian National University,* ***3.*** *A*STAR Quantum Innovation Centre (Q.InC), 138634, Singapore*

Introduction: Continuous variable quantum communication offers a scalable and robust approach for long-distance quantum communication. It allows for relatively easier manipulation of quantum states, detection, and integration with current infrastructure. However, both classical and quantum long-distance communications suffer from external noise, degrading the quality of information transfer. This affects the non-classical features of the shared information. Quantum repeaters can mitigate this issue in sharing quantum resources, such as entanglement, over large distances, enabling the construction of a quantum network. In this work we make use of a heralded quantum teleporter to achieve efficient entanglement sharing.

Method: Existing protocols for sharing entanglement rely on entanglement distribution, swapping, and purification. In Zhao et al., 2023 the authors proposed using a heralded teleporter for entanglement sharing and demonstrated its superior performance in sharing entanglement, even in a lossy channel. In this study, we extend the heralded teleportation technique to multiple nodes for entanglement sharing, benchmarking it against other existing protocols as an ideal platform for developing quantum repeaters. As illustrated in the figure, we employ a heralded teleporter to teleport an EPR state between subsequent parties separated by some arbitrary distance, ultimately sharing entanglement between parties A and B.

Results & Discussion: We aim to evaluate the performance of our teleporter for multiple node entanglement sharing using entanglement of formation and the purity of the output state. The performance analysis would be conducted at different nodes in both pure and lossy channels to determine optimal number of nodes for a given distance.



Mbnla teleporter.jpg

The subtle art of benchmarking quantum machine learning models

Oral - Abstract ID: 305

Maria Schuld [1]

1. *Xanadu*

Benchmarking models via classical simulations is one of the main ways to judge ideas in quantum machine learning before noise-free hardware is available. However, the huge impact of the experimental design on the results, the small scales within reach today, as well as narratives influenced by the commercialisation of quantum technologies make it difficult to gain robust insights. In this talk I present some thought-provoking results from a large-scale study that systematically tests 12 popular near-term quantum machine learning models on 160 classification datasets. Most importantly, we found that out-of-the-box classical machine learning models outperformed the quantum classifiers, and that removing entanglement from a quantum model often resulted in as good or better performance. This suggests that "quantumness" may not be the crucial ingredient in many current model designs and questions how we currently search for useful quantum advantage in machine learning. In the last part of the talk I will sketch an alternative approach, using the question of how the quantum Fourier transform could help learning as an example.

Composing quantum programs

Oral - Abstract ID: 300

Stacey Jeffery [1]

1. *QuSoft, CWI & University of Amsterdam*

The usual quantum circuit model does not lend itself well to combining quantum programs using subroutines. For example, it suggests that if you call a subroutine on a superposition of different inputs leading to different running times, you should pay a cost that scales like the maximum running time, whereas in a classical randomized computation, it is clear that the cost should be an average. I will discuss several recent results about combining quantum programs, and the paradigms in which this is more natural. Not only is it possible to get an average cost when calling a superposition of subroutines, certain things actually work better than classical composition: When a quantum algorithm makes many calls to a subroutine with error, it can avoid incurring a logarithmic overhead by amplifying the success probability of the subroutine.

Scalable quantum photonic systems

Oral - Abstract ID: 306

Jelena Vuckovic [1]

1. *Stanford University*

Recent breakthroughs in photonics design, along with new nanofabrication approaches and heterogeneous integration play crucial roles in building photonics for applications including quantum technologies. Towards this goal, the platforms based on color centers in diamond and silicon carbide have been considered promising candidates, because of their high quality optically interfaced spin qubits, and high quality photonics.

Our recent efforts have focused on tin-vacancy (SnV-) color center in diamond where we have shown high fidelity microwave control of an electron-spin at 1.7K temperature [1], high fidelity single shot (optical) readout of an electron spin [2], high quality quantum photonic interface [3], and heterogeneous integration with lithium niobate for frequency conversion [4], making this color center very interesting candidate for implementation of quantum networks. Moreover, our recent demonstration of coherent and controlled interactions of up to 10 silicon vacancy (VSi) color centers strongly coupled to a silicon carbide resonator has established these systems as promising candidates for other quantum technologies, including quantum simulation and possibly even quantum computing [5-7].

However, truly scalable systems require integration of all passive and active photonic devices on the same chip, including sources. Following the same advances in design, fabrication, and heterogenous integration, even Titanium:sapphire laser, the workhorse of optics laboratories, can be miniaturized into sub-cubic centimeter volume together with its pump. We demonstrate such a laser, and show how it can replace commercial tabletop Ti:sapphire lasers in our quantum optics experiments without any loss in performance [8].

1. Eric I. Rosenthal et al, Physical Review X, vol. 13, article 031022 (2023)
2. Eric I. Rosenthal, Souvik Biswas, Giovanni Scuri, et al, Physical Review X, in press, arxiv:2403.13110 (2024)
3. Alison E. Rugar et al, Physical Review X, vol. 11, 031021 (2021)
4. Daniel Riedel, Hope Lee, et al, ACS Photonics, https://doi.org/10.1021/acsphotonics.3c00992 (2023)
5. Daniil M. Lukin, Melissa A. Guidry, et al, Physical Review X, vol. 13, 011005 (2023)
6. Melissa A. Guidry et al, Nature Photonics, DOI 10.1038/s41566-021-00901-z (2021)
7. Eran Lustig, et al, arXiv:2407.13049 (2024)
8. Joshua Yang et al, Nature, vol. 630, pp. 853–859 (2024)

TBC

Oral - Abstract ID: 307

Mikhail Lukin [1]
1. *Harvard University*

A broad effort is currently underway to develop quantum computers that can outperform classical counterparts for certain computational or simulation tasks. Suppressing errors is one of the central challenges for useful quantum computing, requiring quantum error correction for large-scale processing. However, the overhead in the realization of error-corrected "logical" qubits, where information is encoded across many physical qubits for redundancy, poses significant challenges to large-scale logical quantum computing. In this talk, we will discuss the recent advances involving programmable, coherent manipulation of quantum systems based on neutral atom arrays excited into Rydberg states, allowing the control over several hundred qubits in two dimensions. In particular, we use this platform to explore quantum algorithms with encoded logical qubits and quantum error correction techniques. Using this logical processor with various types of error-correcting codes, we demonstrate that we can improve logical two-qubit gates by increasing code size, outperform physical qubit fidelities, create logical GHZ states, and perform computationally complex scrambling circuits using 48 logical qubits and hundreds of logical gates. These results herald the advent of early error-corrected quantum computation, enabling new applications and inspiring a shift in addressing both the challenges and opportunities that lay ahead.

Quantum-Noise-Driven Generative Diffusion Models

Poster - Abstract ID: 146

Marco Parigi [1], *Stefano Martina* [1]

1. University of Florence

Introduction

Generative Diffusion Models (GDMs) are an emerging Machine Learning paradigm where data is corrupted with classical noise and then a Neural Network (NN) learns how to remove it in order to recover the unknown initial data distribution. We propose three approaches for a quantum generalization of GDMs with different combinations of classical/quantum forward and backward dynamics as in Fig. 1. Here, quantum noise is exploited as a beneficial ingredient to generate complex distributions.

Methods

We train the Classical-Quantum GDM model using a dataset composed of random points distributed along a line segment. The diffusion process is implemented via a classical Markov chain of Gaussian transition kernels. The denoising process is realized via a parameterized quantum circuit trained to estimate mean and covariance of the kernel of a denoising Markov chain. For the Quantum-Classical (QCGDM) and Quantum-Quantum (QQGDM) models, the quantum forward dynamics is initialized with a pure quantum state that is iteratively degraded by depolarizing channels until it is maximally mixed. In QCGDMs the denoising is implemented with NNs trained to simulate a dynamic to obtain an approximation of the initial state. In QQGDMs the backward is realized with a non-unitary quantum dynamic in the context of open quantum systems.

Results

The results of a simulation of a CQGDM are shown in Fig. 2a. The model reconstructs the initial data distribution with a good approximation quantified by the Kullback-Leibler divergence between the original and reconstructed distributions. In Fig. 2b we show the evolution of the loss during the training of the model. In Fig. 2c and 2d we show the simulation on a single-qubit system for ten QCGDMs and QQGDMs, respectively. In Fig. 2e is reported the evolution of the loss during the training of both models.

Discussion

Quantum systems can represent intractable distributions that are classically inefficient to reproduce. At the best of our knowledge, CQGDM and QCGDM are the first implementations of a hybrid classical-quantum diffusion models. This work pave the way for new quantum generative diffusion algorithms for real-world applications, and the design and realization of quantum GDMs could alleviate and reduce the computational resources.

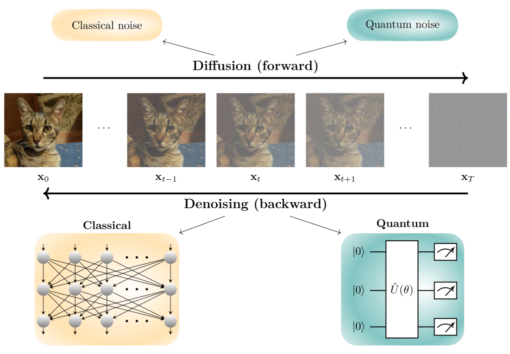


Fig1.png

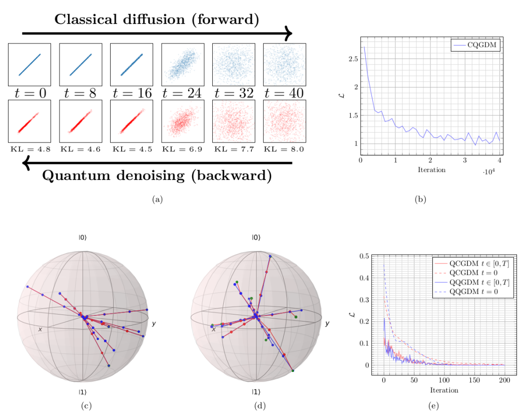


Fig2.png

Exploring quantum obesity in the entanglement swapping scenario

Poster - Abstract ID: 210

Cristian Susa [1] ***, Pedro Rosario*** [2] ***, Andrés Ducuara*** [3]

1. *Department of Physics and Electronics, University of Córdoba, 230002, Montería.,* ***2.*** *Departamento de Física, Universidade Federal de São Carlos, Rodovia Washington Luís, km 235 - SP-310, 13565-905 São Carlos, SP, Brazil,* ***3.*** *Yukawa Institute for Theoretical Physics, Kyoto University, Kitashirakawa Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan*

Entanglement swapping is a fundamental concept in the study of quantum repeaters, the blocks for the quantum Internet, that has been arguably investigated. On the other hand, quantum obesity, defined as the volume of the local steering ellipsoid of a composite quantum state, has been shown to be related with quantum correlations, entanglement and discord. In this work, we explore quantum obesity in the entanglement swapping scenario for qubits. We show that the amount of obesity after swapping is exactly known, opposite to the case of entanglement for which just an upper bound has been reported. We extend the results of obesity swapping to the case of qudits as well as chains of multiple qubit sources, and the effects of locally filtering such a quantum correlation be it before or after swapping.

Higher-order counter-propagating SPDC and a complete analysis of the noise spectrum of a bulk ppKTP quantum frequency converter

Poster - Abstract ID: 228

Felix Mann [1], ***Helen Chrzanowski*** [2], ***Felipe Gewers*** [1], ***Marlon Placke*** [1], ***Sven Ramelow*** [3]

1. *Humboldt-Universität zu Berlin,* **2.** *Humboldt-University Berlin,* **3.** *Humboldt University of Berlin*

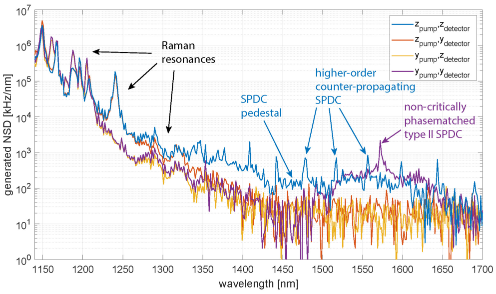
Quantum frequency conversion (QFC) [1] will be an indispensable ingredient in future quantum technologies. For example, large-scale fibre-based quantum networks will require QFC to interconnect heterogeneous building blocks like emitters, channels, memories and detectors [2,3]. The performance of existing QFC devices - typically realised in periodically-poled nonlinear crystals - is often severely limited by parasitic noise that arises when the pump wavelength lies between the wavelengths which are inter-converted [4,5,6]. Here we investigate the noise spectrum of a frequency converter pumped by a CW 1064 nm laser. The converter was realised as a monolithic bulk ppKTP pump enhancement cavity - quasi-phase-matched for the conversion of 637 nm to 1587 nm [7,8]. In the range from 1140 nm to 1330 nm Stokes-Raman resonances can be identified as the dominant noise source while the noise in the range from 1330 nm to 1650 nm can mainly be attributed to parasitic spontaneous parametric down-conversion (SPDC). Further, a succession of narrow-band peaks is observed in the spectrum originating from higher-order counter-propagating SPDC. Both types of counter-propagation, where either the lower-energy idler photon or the higher-energy signal photon counter-propagate relative to the pump beam, are observed, with narrow-band peaks corresponding to quasi-phase-matching orders m from 10 up to 44 identifiable.

[1] Kumar, Prem. Optics Letters 15.24: 1476-1478, (1990)
[2] Kimble, H. Jeff. *Nature* 453.7198 (2008): 1023-1030.

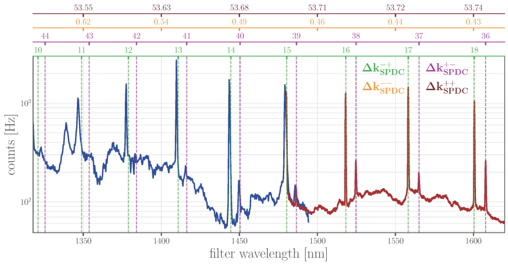
[3] Awschalom, David, et al. *PRX Quantum* 2.1 (2021): 017002.

[4] Pelc, Jason S., et al. Optics Letters 35.16 (2010): 2804-2806.
[5] Strassmann, Peter, et al. Optics Express 27.10 (2019): 14298-14307.
[6] Dreau, Anais, et al. PR Applied 9.6: 064031, (2018)

[7] Mann, Felix, et al. Optics Letters 46:3049-3052 (2021)
[8] Mann, Felix, et al. PR Applied 20.5: 054010. (2023)



3fig all polarisations.jpg



6fig fourdeltakaxis.jpg

Direct quantum states characterization via weak measurements

Poster - Abstract ID: 231

Shane Gervais [1], ***Lambert Giner*** [1]

1. *Université de Moncton*

One of the most critical steps in any application of quantum technologies, whether it is quantum communications or quantum computing, is the ability to fully characterize a quantum state. The primary way to perform this task involves quantum state tomography (QST), which requires performing a set of specific measurements and then "guessing" the most probable state thanks to an algorithm. However, this method presents several drawbacks. First, this method is indirect since it requires a reconstruction algorithm. Second, it is a global reconstruction method since it doesn't allow determining a part of the state (e.g., a term of the density matrix) without first determining the entire state. Third, the number of measurements required increases quadratically with the dimension of the state to reconstruct.

Based on the notion of weak value [1], a direct reconstruction method was proposed [2]. In this method, the quantum state to be characterized (e.g., the polarisation state) is coupled to another quantum state (e.g., the spatial mode) called the pointer. During its characterization, the state undergoes a weak measurement, which will leave unchanged the quantum state to be characterized while the pointer's state will be slightly altered. In the case of the spatial mode of the photon, the central position of the Gaussian mode will be thought shited. It was demonstrated that the measurement of this shift is directly proportional to the state to be characterized. This method was used to reconstruct the polarization state of a photon [3] using the spatial mode of a photon.

However, if one considers the possible application of such a method, altering the spatial mode of the light makes it less appealing for quantum applications in integrated optical systems. In this poster, another possible application of this weak measurement reconstruction will be presented, using time delays as a pointer to reconstruct the polarisation state of a photon. This constitutes the first step towards integrating weak measurements.

[1] Aharonov et al. Phys. Rev. Lett. **60**, 1351 (1988)

[2] Lundeen et al. Phys. Rev. Lett. **108** 070402 (2012)

[3] Thekkadath et al. Phys. Rev. Lett. **117** 120401 (2016)

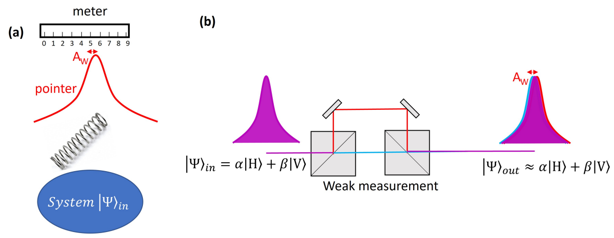


Figure 1 (a) A quantum system is coupled to a pointer with a large width (weak measurement), the pointer is shifted by a value called the weak average, A_W, proportional to the wavefunction (b) Concept of weak measurement performed using time delays

Concept of weak measurement using time delays.jpg

Source of multiplexed heralded down-converted entangled photon pairs

Poster - Abstract ID: 241

Mladen Pavicic [1]

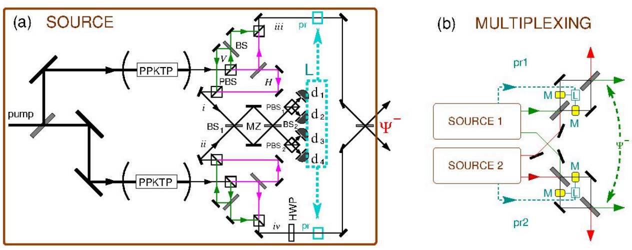
1. Center of excellence CEMS, Photonics and quantum optics unit, Rudjer Boskovic Institute, Zagreb, Croatia

Pairs of entangled photons are indispensable for quantum information processing and protocols such as quantum superdense coding, quantum teleportation, Bell states analysis, quantum repeaters, quantum contextuality, quantum cryptography, and linear optical quantum computation. Recently obtained generation of entangled photon pairs in quantum dots have been considered to be "on-demand" but so far they are on demand only with respect to its high purity. However, with quantum dots there are problems with photon collection efficiency which is under 1% and very low operating temperature. Therefore, in this paper, we consider a down-conversion competitor. We propose a heralded generation of an entangled photon pair conditioned on detecting other combinations of photons, all coming from two down-conversion sources. By means of four detectors and the routers shown in the figure we are able to filter out most of unacceptable photon combinations like - both pairs coming from the same downconversion crystal, or three pairs, or missing photons, etc. So, with taking into account all the losses and inefficiencies of detectors we obtain that the pair of entangled photons will be generated with the probability of 92%. This can be arbitrarily risen by multiplexing the sources as also shown in the figure.

Pavičić, M. and J. Summhammer, Interferometry with Two Pairs of Spin Correlated Photons, *Physical Review Letters*, ***73,*** 3191-3194 (1994). DOI: 10.1103/PhysRevLett.73.3191

Pavičić, M., Spin Correlated Interferometry for Polarized and Unpolarized Photons on a Beam Splitter, *Physical Review*, **A 50,** 3486-3491 (1994). DOI: 10.1103/PhysRevA.50.3486

Pavičić, M., *Companion to quantum communication and communication*, Wiley-VCH, Weinheim (2013)



Herald-berlin-24.jpg

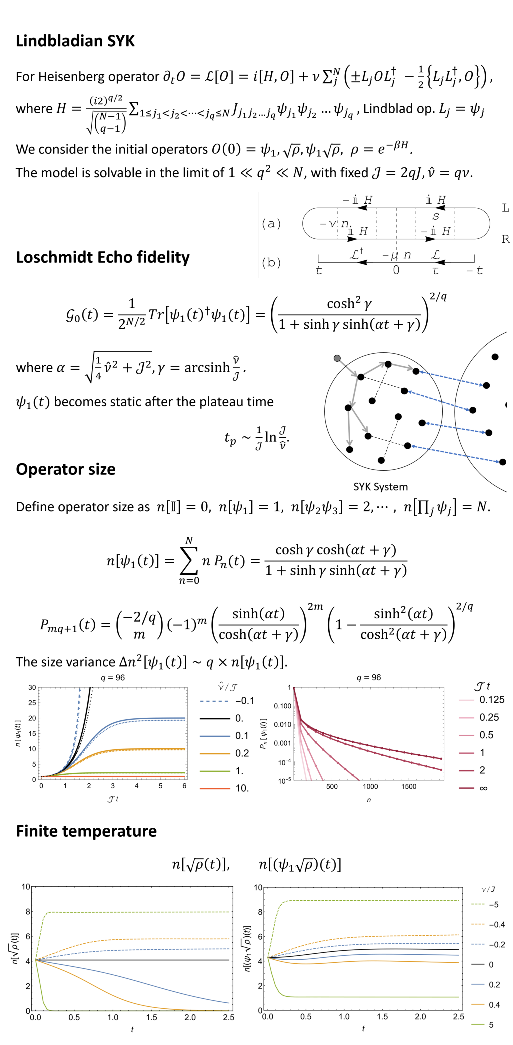
Information scrambling in Lindbladian SYK model

Poster - Abstract ID: 246

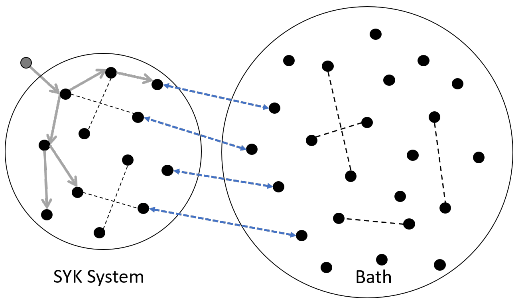
***Jiasheng Liu* [1] *, René Meyer* [2] *, <u>Zhuo-Yu Xian</u>* [2]**

***1.** Ludwig-Maximilians-Universität München, **2.** Julius-Maximilians-Universität Würzburg*

We investigate the information scrambling described by the operator growth in the Lindbladian Sachdev-Ye-Kitaev model with q-body interaction terms and linear jump terms at finite dissipation strength. At weak dissipation, the evolution of operator size displays a quadratic-exponential-plateau behavior. The plateau value is determined by the ratios between the coupling of the interaction and the linear jump term in the large q limit. The operator size distribution remains localized in the finite size region even at late times, contrasting with the unitary case. Finally, we observe that the uncertainty relation for operator size growth is saturated at large q, leading to classical dynamics of the information scrambling with dissipation.



Picture1.png



Sykbathsize.png

How Quantum Computers are Vulnerable to Attacks

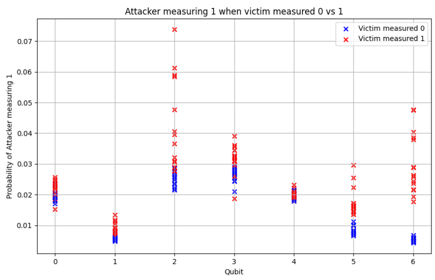
Poster - Abstract ID: 247

Sorin Bolos [1], **Adrian Colesa** [2]

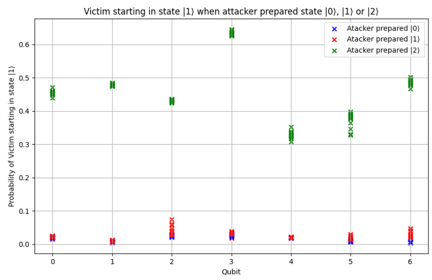
1. Transilvania Quantum, 2. Bitdefender

The impact of quantum computing on classical cybersecurity has been discussed extensively over the past 30 years, leading to the development of post-quantum cryptography. But, in the race to harness this revolutionary technology, a crucial question remains unanswered: how secure are the quantum machines themselves? We've been so fixated on what these machines can break, we've neglected to ask how secure they are.

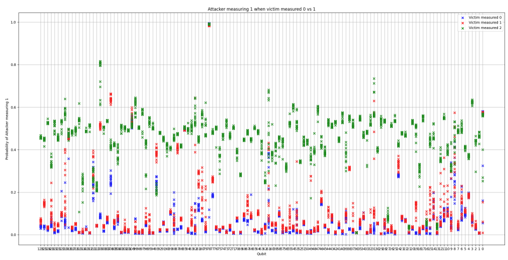
The little research that studied vulnerabilities of quantum computers until now has focused on a scenario where circuits belonging to different users are executed on the same quantum chip at the same time. This mode of operation is not yet in possible.
In my presentation I'll focus on vulnerabilities of superconducting QPUs that are available today. I'll present experiments done on two IBM Eagle quantum chips where I leveraged the imperfections of the reset operation, and we show that: (1) an attacker can infer the final state of the circuit that ran before him, stealing the results of the computation. (2) an attacker can leave qubits in a higher excited state so that the circuit that runs after him will start in a state that is not the ground state, compromising the results.



Infervictimmeasuredonevszero 7qubits.png



Victimstartsinone 7qubits.png



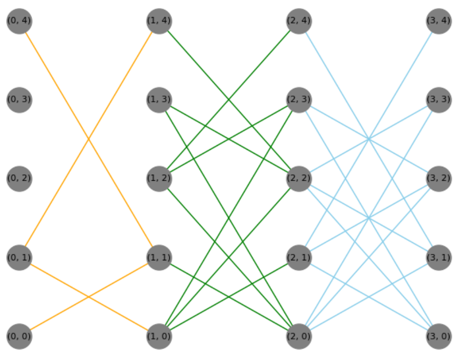
Victimstartsinone allqubits ibmosaka.png

Space-Based Quantum Internet: Entanglement Distribution in Time-Varying LEO Constellations

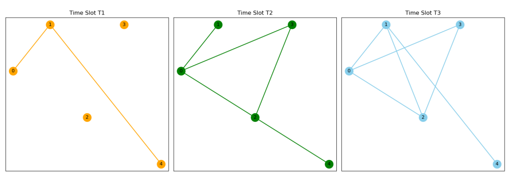
Poster - Abstract ID: 251

Seid Koudia [1], *Junaid ur rehman* [1], *Symeon Chatzinotas* [1]
1. University of Luxembourg

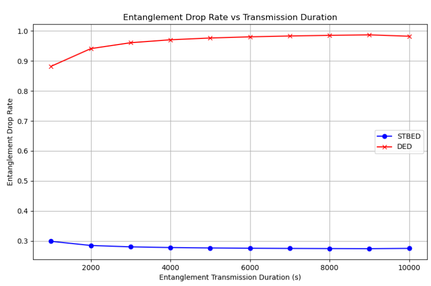
This presentation addresses the complexities of entanglement distribution in LEO satellite networks, particularly those arising from their dynamic topology. Traditional static and dynamic entanglement distribution methods often result in high entanglement drop rates and reduced end-to-end throughput. We introduce a novel framework that leverages the dynamic nature of LEO satellite networks to enhance entanglement distribution efficiency. Employing a space-time graph model to represent the network's temporal evolution, we propose an entanglement distribution strategy based on path utility, incorporating pointing errors, non-ideal link transmittance for intersatellite links, and atmospheric effects for downlinks. Our approach demonstrates superior performance in reducing entanglement drop rates and improving throughput compared to conventional methods. This study advances the field of quantum communication in satellite networks, offering resilient and efficient entanglement distribution strategies that support practical applications such as distributed computing, quantum multipartite cryptography, and distributed quantum sensing. The findings underscore the potential of integrating dynamic satellite networks with quantum technologies to create a reliable and secure quantum internet.



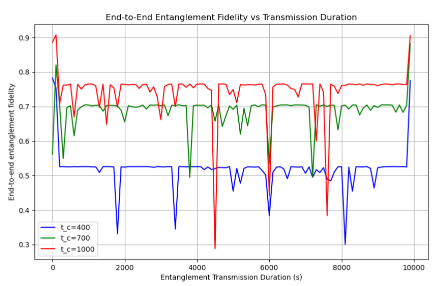
Space-time graph.png



Graphs time slots.png



Entanglement drop rate satellite.png



Fidelity memory.png

Telecom single photon source based on nonlinear photon transport in hot atomic vapor

Poster - Abstract ID: 258

Inna Kviatkovsky [1], Martin Cordier [1], Lucas Pache [1], Leonid Yatsenko [2], Philipp Schneeweiss [1], Jürgen Volz [1], Arno Rauschenbeutel [1]

1. Humboldt University of Berlin, 2. National Academy of Sciences of Ukraine

The generation of single photons is essential for quantum communication and cryptography. However, the efficient generation of Fourier-limited single photons often requires complex and demanding experimental conditions. In this work, we present a novel method for generating single photons using so-called nonlinear photon transport in Rubidium vapor. Our approach leverages the 1529-nm transition between excited states in ^{87}Rb to produce single photons in the telecom C-band, making it compatible with existing communication infrastructure. The single-photon source is based on a two-photon interference technique. The atoms scatter the photons in two ways, typically referred to as coherent and incoherent scattering. In the case of resonant scattering, the two-photon probability amplitudes of the coherent and incoherent components have opposite signs. For a specific atom number, the probability amplitudes then interfere fully destructively, resulting in photon antibunching of the transmitted light [1, 2]. In order to implement this scheme in hot atomic vapor in ^{87}Rb, we use a three-level ladder system, where a strong pump that drives the D2 transition is used to prepare atoms at the intermediate state. This facilitates the generation of single photons at the telecom C-Band upon the transport of laser light at 1529 nm. In this way, we realize a technologically relevant nonlinear filter, generating narrow-band single photons, compatible with atomic transitions.

References

[1] Adarsh S Prasad, Jakob Hinney, Sahand Mahmoodian, Klemens Hammerer, Samuel Rind, Philipp Schneeweiss, Anders S Sorensen, Juergen Volz, and Arno Rauschenbeutel. Correlating photons using the collective nonlinear response of atoms weakly coupled to an optical mode. Nat. Phot. 14, 719 (2020)

[2] Martin Cordier, Max Schemmer, Philipp Schneeweiss, Juergen Volz, and Arno Rauschenbeutel. Tailoring photon statistics with an atom-based two-photon interferometer. Phys. Rev. Lett, 131, 183601 (2023)

From the origin of antibunching to novel quantum light sources based on two-photon interference

Poster - Abstract ID: 267

Martin Cordier [1], Luke Masters [1], Gabriele Maron [1], Xinxin Hu [1], Lucas Pache [2], Philipp Schneeweiss [2], Max Schemmer [1], Jürgen Volz [2], Arno Rauschenbeutel [2]

***1.** Humboldt-Universität zu Berlin, **2.** Humboldt University of Berlin*

Generating useful quantum states of light is key to many applications in quantum science and technology. Here, I will report on a new approach to controlling and tailoring the photon statistics of light fields. It is based on an effect, which we put into evidence in a recent experiment and which challenges the conventional notion that a single two-level emitter can only scatter one photon at a time [1]. There, we show that photon antibunching in resonance fluorescence arises from the destructive interference between two types of two-photon scattering processes, referred to as coherent and incoherent scattering. Building on this insight, we also study the collective enhancement of this incoherently scattered two-photon component when laser light propagates through an atomic ensemble. By adjusting the number of atoms and the laser detuning, we have full control over the two-photon interference, which allows us to tune the photon statistics of the transmitted light from strong photon bunching to antibunching [2,3].

[1] Masters et al., Nature Photonics 17, 972 (2023).
[2] Prasad et al., Nature Photonics 1 (2020). [3] Cordier et al., Phys. Rev. Lett. 131, 183601 (2023).

Development of Quantum Annealing Simulator with Input Signal Uncertainties

Poster - Abstract ID: 275

Akimasa Saito [1], ***Masashi Imai*** [1]

***1.** Hirosaki University, Graduate school of Science and Technology*

Quantum annealing is a quantum metaheuristic that exploits the properties of quantum mechanics to solve combinatorial optimization problems. A quantum annealing machine encodes the Ising model Hamiltonian as a network of qubits, and by adiabatically changing the parameters of this Hamiltonian, it searches the ground state of the Hamiltonian that represents the optimal solution to the combinatorial optimization problem. Today's quantum annealing machines are built with quantum processors based on superconducting quantum circuits.

In today's superconducting quantum systems, a classical computer is installed in a room-temperature environment and connected by cables to each quantum bit in a superconducting quantum circuit in a dilution refrigerator. However, due to the increasing number of cables and the influx of heat they introduce, there is a need for classical electronics to also operate in a cryogenic environment. Since latency is also limited by the cables, it is desirable to perform control operations in a cryogenic environment to achieve higher computing speeds.

In order to optimize the operation of quantum annealing and achieve high accuracy in quantum computation, it is essential to design and evaluate quantum processors and control electronics simultaneously. While there are already several methodologies and implementations of co-simulation environments, to the best of our knowlegde, they are all intended for gate-model quantum computers and have not been developed for quantum annealing machines.

In this study, we aim to construct a quantum-classical co-simulation environment for quantum annealing machines. To achieve this, we develop a simulation environment for the behavior of network of coupled Josephson parametric oscillators (JPO), which is a key component of a quantum processor. Furthermore, for future integration with a classical electronics simulator, we will construct an environment in which the parameters of quantum annealing can be set from microwave information.

In addition, we propose a method for evaluating the robustness of quantum processors against inaccuracies in the control electronics by creating an environment that can assess the fidelity of the quantum annealing operation with control signal inaccuracies. This approach provides a basis for optimizing the overall system performance in quantum annealing machines by considering the trade-offs in the control electronics.

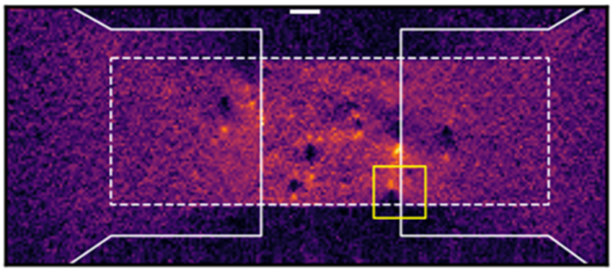
2D-material metrology using nitrogen-vacancy based quantum sensors

Poster - Abstract ID: 150

Saravana Kumar [1], ***Tijmen van Ree*** [1], ***Leon van Dooren*** [1], ***Gabriele Bulgarini*** [1], ***Marco Braibanti*** [1], ***Kaj Dockx*** [2], ***Michele Buscema*** [2], ***Toeno van der Sar*** [3], ***Clara Osorio Tamayo*** [1], ***Abbas Mohtashami*** [1]

1. *TNO (Netherlands Organisation for Applied Scientific Research),* ***2.*** *Applied Nanolayers,* ***3.*** *Delft University of Technology (TU Delft)*

We have developed quantum sensing instruments based on nitrogen-vacancy (NV) defect in diamond in our test facility. Our effort is focused on expediting the market adoption of these instruments in metrology, navigation and medicine. Our scanning NV microscope, which was developed in-house, has a single NV at the tip of an atomic force microscopy (AFM) probe, allowing it to image magnetic fields with high sensitivity and high spatial resolution. This non-invasive way of measuring magnetic field, and by extension electrical current, is paramount to the development and metrology of future semiconductor devices and 2D materials. As a use case, we have characterized graphene devices by measuring the magnetic fields produced by current flowing through them. This data gives interesting information about the way the current flows in the devices (Figure 1). The measured current density map shows regions of hotspots and coldspots, likely stemming from current flow around defects. Such measurements also shed light into the fabrication process flow and ways of improving it for large-scale production of future 2D-semiconductor devices.



Measured current density map on graphene device.png

Hierarchical Quantum Secret Sharing for Multi-Node Satellite Communication Network using the Qline Architecture

Poster - Abstract ID: 284

Chitra Shukla [1], ***Abhishek Shukla*** [2], ***Milos Nesladek*** [2], ***Symeon Chatzinotas*** [3]

1. SnT University of Luxembourg, 1855 Luxembourg, Luxembourg., 2. Institute for Materials Research (IMO), Hasselt University, Wetenschapspark 1, B-3590 Diepenbeek, Belgium, 3. University of Luxembourg

We propose to design a hierarchical quantum secret sharing (HQSS) for multi-node satellite communication network, leveraging the Qline architecture that features a linear quantum network topology, where qubit generation and measurement occur at the endpoint satellites, with intermediate satellite nodes are limited to single-qubit unitary transforms. In designing a HQSS for multi-node satellite communication network, we consider a group of at least four satellites (A, B, C, D), in linear quantum network configuration, where qubit generation and measurement occur at the endpoint Satellites A and D respectively, with two intermediate satellites B and C limited to single-qubit measurement and unitary transforms. This setting will restrict the two intermediate satellites B and C to allow using lower powers needing the cooperation from the endpoint Satellites A and D, however, endpoint Satellite D utilizes the higher powers to reconstruct the secret without the measurement outcome of one of the lower power intermediate Satellite B or C. The hierarchical structure depends on the trusted (end node Satellite D) or untrusted (intermediate Satellite B, C) locations within a satellite quantum network. Our motivation is to use this hierarchical power for long-distance QSS, allowing leading Satellite A to securely share a quantum secret to Satellite D while bypassing one of the intermediate satellites B or C. Satellite A utlizes a 4-qubit cluster quantum entangled state with Satellites B, C, and D to perform HQSS in Qline architecture. The simplicity of hardware at intermediate nodes in the Qline architecture facilitates easier implementation of proposed HQSS for multi-node satellites. Our HQSS based on Q-line configuration shows that hierarchy with minimal hardware would be the standard requirements in future terrestrial and non-terrestrial quantum networks. Moreover, unlike traditional QKD networks, our design based on Qline architecture doesn't require key routing through intermediate nodes, enhancing security by avoiding exposure to these nodes, without consuming established keys for routing security. As the security of key establishment on Qline networks is composable, ensuring that established keys can be utilized for secure entanglement distribution executed by Satellite A among inter-satellite quantum communication network, thereby advancing larger constellations securely.

Interferometer with a driven trapped ion

Poster - Abstract ID: 286

Alvaro Rodriguez-Prieto [1], Sofia Martinez-Garaot [1], Ion Lizuain [1], J. G. Muga [1]
1. University of the Basque Country

First, we propose an interferometric measurement of weak forces using a single ion subjected to designed time-dependent and spin-dependent forces [PRA 98, 043622 (2018)]. Within our scheme a rotation of the trap from the perpendicular direction is required. Explicit expressions of the relation between the unknown force and the final populations are found considering different scenarios. The flexibility to design the trap trajectories is used to minimize errors due to anharmonicities in the trap. The advantages of the approach are the use of geometrical phases, which provide stabilities, the possibility to design faster-than adiabatic processes with sensitivity control, and the independence of the results on the motional states for the small-oscillation regime in which the effective potentials are purely harmonic.

In addition we present a new protocol which differs from the first one on considering that the spin-dependent driving force is generated via a “shaken” optical lattice, while still keeping its advantages. This opens the possibility to an intererometric measurement of the mass of the trapped ion.

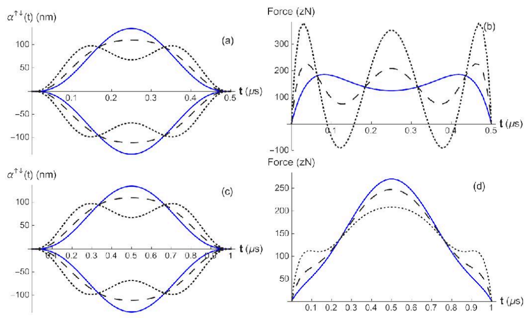


FIG. Trajectories and their corresponding forces. (a,b) $t_f = 0.5$ μs. (c,d) $t_f = 1$ μs.

Fig-page-001.jpg

Simulation of polarisation dynamics in spin-1/2 systems using correlated clusters and Pauli strings

Poster - Abstract ID: 288

Matthias Kost [1], ***Martin B. Plenio*** [1]

1. *Institute of Theoretical Physics, Ulm University*

The study of polarisation dynamics in spin-1/2 systems has gained interest due to its potential applications in quantum information processing. In our work, we present an accessible simulation framework that utilizes correlated cluster techniques to capture spin interactions and exploit the efficiency of Pauli strings to represent quantum states and operators.

Given that the total polarisation in the system is sufficiently low, our framework provides a scalable approach that can be applied to systems of tens or hundreds of spins while keeping them individually addressable. It can be tailored to arbitrary spin geometries and can be extended to multi-layered models inspired by Hartree methods [1].

Finally, we present the application of this simulation method to experimental data gathered from a thin layer of nuclear spins via AXY8 spectroscopy with NV centers close to the layer, marking the first steps towards a quantum simulator as proposed by Cai et al. [2].

[1] H. Wang and M. Thoss. Multilayer Formulation of the Multiconfiguration Time-Dependent Hartree Theory. J. Chem. Phys. 119, 1289 (2003)

[2] J.M. Cai, A. Retzker, F. Jelezko and M.B. Plenio. A large-scale quantum simulator on a diamond surface at room temperature. Nature Physics 9, 168-173 (2013)

Automated polarization basis adjustment for quantum communication protocols on optical fiber networks

Poster - Abstract ID: 293

Tomáš Novák [1], ***Carlos Guerra-Yánez*** [2], ***Josef Vojtech*** [3]

1. *Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Department of Physical Electronics, Prague, 11519, Czech Republic,* ***2.*** *Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Electromagnetic Field, Prague, 16627, Czech Republic,* ***3.*** *CESNET a.l.e., Department of Optical Networks, Prague, 16000, Czech Republic*

One of the main challenges for the successful operation of polarization-based QKD protocols on fiber networks is the unpredictable and time-varying unitary transformations imposed on quantum states by birefringence in single-mode fibers. Unfortunately, setting the correct polarization basis in the detection nodes is an ambiguous and time-consuming procedure. We present a novel approach for automating the polarization basis adjustment using motorized polarization controllers. This method defines scalar variables called coincidence entropies, which characterize the quality of the polarization basis adjustment. These variables are summed into a single scalar variable, which can be exploited for optimization using stochastic gradient descent. The two-sided approach allows the characterization of coincidences as random events, whose distribution can be altered using motorized polarization controllers. A precisely defined set of weights derived from single-photon counts considers the different total efficiencies of the utilized single-photon detectors. This enables successful polarization basis adjustment via stochastic gradient descent, even in situations with unbalanced optical powers. This state-of-the-art approach could facilitate the operation of polarization-based quantum communication protocols in real-time, and the defined metrics could serve as a monitoring signature for secure quantum communication. We present our recent implementation and results in different inter-link configurations.

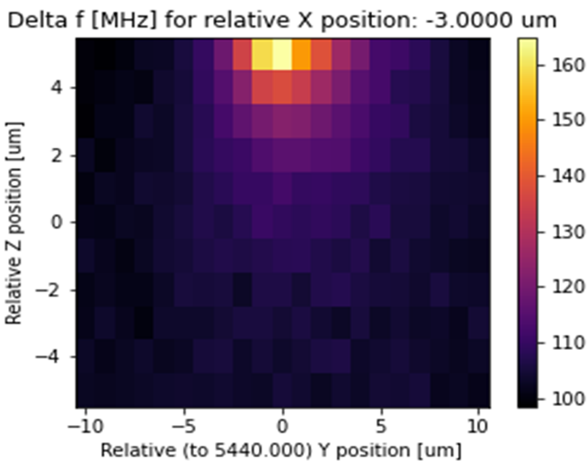
Towards coherent interaction between a solid-state spin and a macroscopic mechanical resonator

Poster - Abstract ID: 297

Anna Olofsson [1]***, Dhiren Manji Kara*** [1]***, Alexander Huck*** [1]***, Ulrik Lund Andersen*** [1]

1. *Technical University of Denmark*

Mechanical resonators are interesting for a range of applications including force sensing, inertial navigation, quantum memories and searches for quantum gravity and dark matter. With improved fabrication techniques and understanding of mechanical losses over the past decade, mechanical resonators can now oscillate more than a billion periods before their energy is lost (i.e. Q-factors that surpass billions). This has opened up the potential of using resonators within the field of quantum technology, for example for the storage or transfer of information for quantum computing, or quantum sensing. Typically, modern systems with coupled resonators use optical coupling to interact with the resonator, such as radiation pressure. This method has proved extremely successful, for example leading to demonstrations of cooling the resonator to the ground-state, mechanical squeezing, entanglement of distant phonon-modes, and conversion between optical and microwave photons. We are exploring a different route using magnetic coupling between micro-scale resonators with the electronic spin state of nitrogen-vacancy centes in diamond. With optically detected magnetic resonance spectroscopy, we first map the magnetic field structure of our resonator through the Zeeman shift of the excited state of the NV center (see figure). Then, using pulsed measurements we dynamically decouple from correlated noise and sense the thermal fluctuations of the mechanical resonator. With these results we show that the oscillations of the resonator affect the quantum state of the NV center, which is the first step towards strong coupling between the systems.



Magnetic field map.png

Narrow-band photon pairs from SPDC for interfacing to atomic transitions

Poster - Abstract ID: 3

Leon Meßner [1], *Henning Mollenhauer* [1], *Helen Chrzanowski* [1], *Benjamin Maaß* [1], *Janik Wolters* [1]

1. *Institute of Optical Sensor Systems, German Aerospace Center (DLR), Berlin*

We present first results and prospects for a photon-pair source based on spontaneous parametric down-conversion (SPDC) in a periodically poled monolithic KTP crystal cavity (Fig. 1). By proper engineering of the cavity parameters and phase-matching, it is possible to design the sources for emission wavelengths from the visible to the infra-red region. This allows interfacing with atomic systems and particularly with quantum memories.

By fabricating the cavity end mirrors directly onto the non-linear crystal we have built a degenerate type-II SPDC source that is set to dedicated signal and idler wavelengths of 895 nm with a spectral bandwidth of 250 MHz (Fig. 2) while retaining a tunability of 20 GHz. Using a CW pump at 447 nm we achieve a brightness of 40 kcts/(mW s) and a heralding efficiency of 38% which is currently limited by the choice of collimation optics. Optimization of the setup for compactness and higher efficiencies are straightforward. A measured second-order auto-correlation of 0.007 at 1 mW pump power confirms a very low multi-photon detection probability in the heralded signal mode.

We plan on interfacing our source with a ladder-type EIT warm vapor quantum memory to explore synchronizing the probabilistically generated photons to a fixed clock rate. In addition to investigating typical parameters of quantum memories such as efficiency and maximum storage time, we will probe the properties of the memory using single- and multiphoton quantum states.

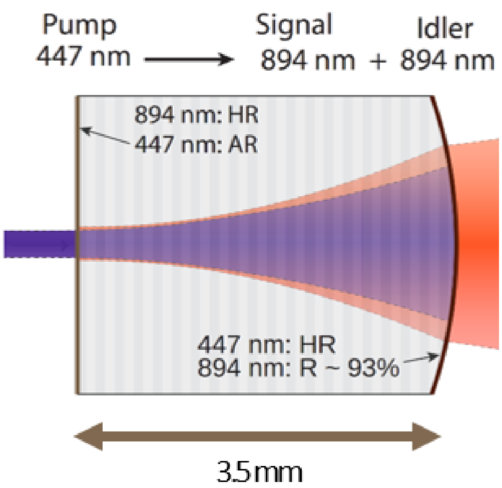


Fig1-cavity.png

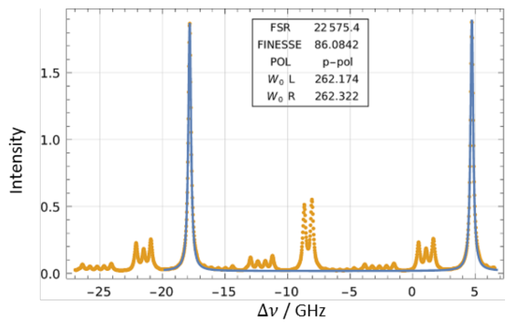


Fig2-spec.png

Square-Ladder Cluster States in a Microwave Frequency comb

Poster - Abstract ID: 80

Fabio Lingua [1], *Juan Carlos Rivera Hernández* [1], *Christoph Leon Bock* [1]
1. *KTH, Royal Institute of Technology*

Introduction

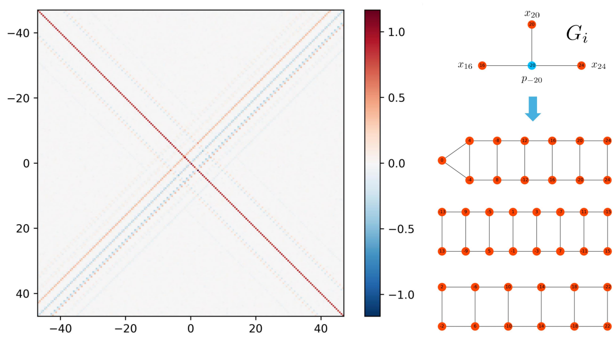
Measurement-based quantum computation (MBQC) using continuous-variable (CV) systems presents significant advantages in terms of speed, error correction, and hardware simplicity. A crucial aspect of MBQC is the ability to engineer and control quantum correlations, typically represented by graph or cluster states. Optical frequency combs have shown the ability to establish these correlations, but the adaptability and precision of digital signal processing at microwave frequencies open up new possibilities. In this study we demonstrates that we can engineer a 2D square-ladder cluster state in a microwave frequency comb using a Josephson parametric amplifier (JPA) cooled at 10mK.

Method

By controlling the phase of a triply-pumped JPA, we engineer correlations between 95 frequency modes equally spaced around the resonant frequency of the JPA (4.2 GHz). The experiment is performed by injecting vacuum fluctuations at 10mK into the JPA. We verify the presence of quantum correlations by measuring the covariance matrix in the output of the JPA. This is obtained by collecting statistics of I/Q quadratures of each mode by a suitable multi-frequency lock-in amplifier.

Results

The output covariance matrix contains all the statistical properties of a gaussian state (i.e. the vacuum). We define a suitable nullifier test capable of testing the presence of quantum fluctuations in the form of multi-mode squeezing between several quadratures of difference frequency modes. The definition of the nullifier specifically addresses the topology of correlations of a square-ladder 2D graph. We achieve 0.7dB of squeezing below shot noise proving the presence of three independent subsets of cluster states featuring square-ladder topology.



Imageastract.jpg

Krylov Spaces in Quantum Machine Learning

Poster - Abstract ID: 117

Saud Cindrak [1], *Lina Jaurigue* [1], *Kathy Luedge* [1]

1. *TU Ilmenau*

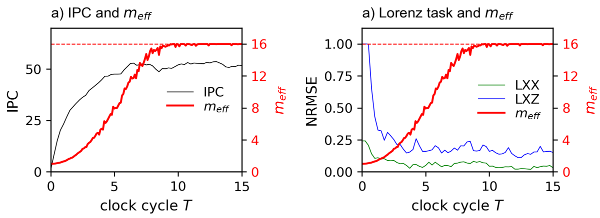
Introduction: The field of operator and spread complexity has been used to understand quantum systems ranging from field theories to chaos, providing insights into the evolution of the Schrödinger equation. Both operator and spread complexity need to be computed classically, making the calculation for ever-increasing qubit sizes and quantum computation infeasible. We bridge that gap by using a measurable basis for constructing the vector space.

Methods: In our work (arXiv:2404.13089), we propose a quantum mechanically measurable space, which captures the time evolution under the Schrödinger picture and proves its equivalence to Krylov spaces. Building upon this, an effective dimension is introduced, which is upper bounded by the number of pairwise distinct eigenvalues of a quantum circuit or a Hamiltonian, making comparison between different systems possible.

We are currently analyzing the influence of the effective dimension in the field of quantum reservoir computing and how the effective dimension and task performance are related. In quantum reservoir computing, one encodes the data into the state. Afterwards, a quantum system is evolved, and a set of observables is measured to construct the readout vector. We use two time series tasks as benchmarks. The first is the information processing capacity, which captures how well the network maps prior data non-linearly, and the second is the Lorenz63 time series prediction task, which is a chaotic attractor.

Results: For both tasks, we observe that task performance follows the same trend as the effective dimension, as shown in the figure. For small clock cycles, the effective dimension starts low and then increases up to a saturation point. This can be observed for the increasing information processing capacity, followed by saturation. The error of the Lorenz prediction task decreases until it saturates at a minimum.

Discussion: Our work shows that task performance strongly relates to the effective dimension. Currently, we are analyzing the effective dimension in the cases of quantum extreme learning machines and wish to extend it to circuit-based models as well. Lastly, we wish to explore the effective dimension in the context of variational quantum machine learning models.



Influence of krylov space dimension on task performance.png

Rapid time dependent noise spectroscopy of superconducting qubits

Poster - Abstract ID: 118

Bhavesh Gupta [1], Vismay Joshi [1], Udit Kandpal [1], Prabha Mandayam [1], Nicolas Gheeraert [1], Siddharth Dhomkar [1]

1. *Indian Institute of Technology Madras*

Introduction: Time-varying noise creates problems for lengthy noise spectroscopy protocols, making them unsuitable for accurately characterizing the noise. This work proposes a rapid, efficient, time-dependent noise spectroscopy protocol based on the deep-learning algorithm. We demonstrate our methodology for superconducting qubits. The network can be catered to a single qubit or many qubits and is pseudo-hardware agnostic. We enhance coherence by applying custom DD protocols to find the optimal filter function for the current noise.
Methodology: We first perform the Rabi experiment to calibrate our Pi pulse and perform the T1 and T2 experiments as in Fig experiment(a,b,c). We then obtain the coherence curves C(t). We do not consider qubits with dominant crosstalk. We first assume the noise to follow some well-defined characteristics:

1. We calculate the analytical C(t).
2. We partition this generated data set into training and test data. We then train the network on the training data, using C(t) as input and the noise spectrum S(ω) as output, and verify its behavior on the test set.
3. The network predicts S(ω) using the previously calculated hardware C(t).

Once S(ω) is known, we run an optimization protocol that minimizes decoherence χ(t) by varying parameters in the sequence, such as separation between pulses. We have used a CPMG-32 pulse sequence, which enabled us to predict the high-frequency region. We have used convolutional neural network architectures with parameters such as the Pi pulse length, the number of pulses, and the total evolution time, which we need to specify beforehand.
Results: We demonstrate the protocol on IBM-Osaka hardware. Fig. experiment(d) shows that T1 and T2 for a qubit are time-varying, implying that the S(ω) varies in time. Fig result(a) shows the predicted S(ω) for the experimental C(t). The model can effectively capture the various noise behaviors. First, we see the initial flat white noise region, the characteristic 1/f region, and the 1/f^2 behavior. Fig result(b) shows the experimental and predicted C(t) on top of each other. Fig result(c) shows the S(ω) network prediction on the test data, with an error rate of around 5%. Fig result(d) shows the improvement in coherence of the optimized filter.

$$\rho = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix} \xrightarrow{noise} \begin{pmatrix} 1+(|\alpha|^2-1)e^{-\Gamma_1 t} & \alpha\beta^* e^{-\Gamma_2 t} \\ \alpha^*\beta e^{-\Gamma_2 t} & |\beta|^2 e^{-\Gamma_1 t}\end{pmatrix} \xrightarrow[noise]{1/f} \begin{pmatrix} 1+(|\alpha|^2-1)e^{-\Gamma_1 t} & \alpha\beta^* e^{-\frac{\Gamma_1}{2}t} e^{-\chi(t)} \\ \alpha^*\beta e^{-\frac{\Gamma_1}{2}t} e^{-\chi(t)} & |\beta|^2 e^{-\Gamma_1 t}\end{pmatrix}$$

Noisy state.png

$$\chi(t) = -lnC(t) = \int_0^\infty \frac{d\omega}{\pi} S(\omega) \frac{F(\omega t)}{\omega^2}$$

Decoherence.png

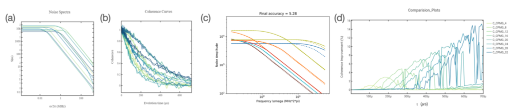


Fig. 2. (a) Predicted noise spectrum. (b) Predicted coherence curves. (c) Prediction on test data (dash - prediction). (d) Optimal DD protocol comparison with corresponding CPMG protocol.

Results.png

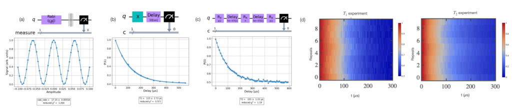


Fig. 1. (a) Rabi experiment. (b) T_1 experiment. (c) T_2 Hahn experiment. (d) The time-dependent heat map of the T1 and T2 coherence. It is repeated one after the other, for 10 times.

Experiement.png

Quantum Computing for Energy Network Optimization

Poster - Abstract ID: 120

***Loong Kuan Lee* [1], *Johannes Knaute* [2], *Florian Gerhardt* [2], *Patrick Völker* [2], *Tomislav Maras* [2], *Alexander Dotterweich* [2], *Nico Piatkowski* [1]**

***1.** Fraunhofer IAIS, **2.** PricewaterhouseCoopers GmbH WPG (DE)*

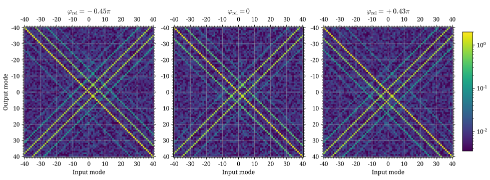
The efficient management of energy generation and distribution is paramount for sustainable and cost-effective energy systems, and it plays a crucial role in the transition towards renewable energy sources. This poster is based on an upcoming research paper and presents a comprehensive study on modeling optimal dispatch for the German energy market, employing binary optimization algorithms to minimize the cost of energy generation while adhering to load constraints. The proposed approach extends the model to optimize dispatch across multiple time steps, incorporating constraints on the maximum change of generation for individual energy sources, which is essential for the stable operation of the energy grid.
In our approach, we implement a Quadratic Unconstrained Binary Optimization (QUBO) framework, leveraging its powerful mathematical foundation for tackling combinatorial problems. We go beyond traditional computational methods by solving the QUBO optimization problem using both real quantum hardware and dedicated QUBO solving hardware, specifically Field-Programmable Gate Arrays (FPGAs). This application allows for efficient and scalable solutions to the energy dispatch problem.
Our findings demonstrate the effectiveness of the QUBO-based approach in achieving cost-efficient energy generation while ensuring system reliability and environmental sustainability. The results highlight the potential of quantum and FPGA technologies in optimizing complex energy market dispatch problems and provide valuable insights for energy market stakeholders and researchers aiming to improve grid management and reduce carbon emissions.

Non-reciprocity in a Microwave Frequency Comb

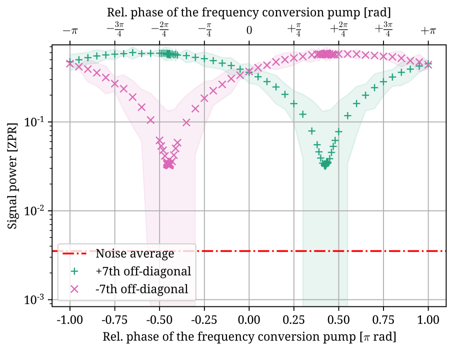
Poster - Abstract ID: 132

Christoph Leon Bock [1], *Fabio Lingua* [1], *Juan Carlos Rivera Hernández* [1]
1. *KTH, Royal Institute of Technology*

This study investigates the experimental demonstration of non-reciprocity in microwave frequency combs using Josephson Parametric Amplifiers (JPA). Non-reciprocity can be a useful tool for measurement based quantum computation (MBQC) applications and superconducting devices.
We measure the scattering matrix of 81 orthonormal modes (~4.2 GHz) to determine the directional dependencies in signal transmission.
The experiments demonstrated significant non-reciprocal behavior in the JPA. By combining parametric and frequency conversion pumps with specific frequencies, amplitudes and phases, we observe pronounced non-reciprocal effects, including the ability to tune the non-reciprocity through external control parameters.
The experimental results confirm the ability to control and tune non-reciprocity through pumping schemes and their parameters. This provides a versatile tool for quantum technology. Future work will focus on refining these effects and integrating them into practical quantum computing systems.



Nonrec-band-scattering-phases.png



Nonrec-band-slices-phase.png

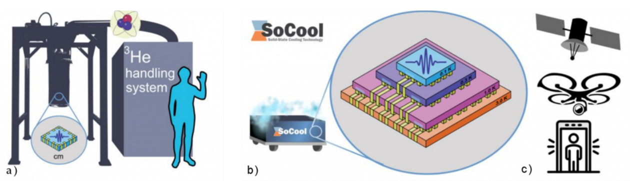
Enabling technologies for scalable superconducting quantum devices

Poster - Abstract ID: 310

Renan Loreto [1], ***Joel Hätinen*** [1], ***Emma Mykkänen*** [1], ***Antti Kemppinen*** [1], ***Klaara Viisanen*** [1], ***Tuure Rantanen*** [1], ***Lassi Lehtisyriä*** [1], ***Janne Lehtinen*** [1], ***Mika Prunnila*** [1]

1. *VTT Technical Research Centre of Finland*

Achieving and measuring low temperatures can enable many developments of technological relevance, from superconducting qubits to x-ray calorimeters. VTT is developing an electronic cooling, thermometry and 3D integration methods that enables a significant reduction in the size of cooling technology based on microelectronics and electric current, in which electronics, photonics and superconducting components operating at low temperatures can take advantage of. Today, such temperatures are typically achieved with complex and large dilution coolers. VTT's electrical method can replace and/or supplement these current solutions based on pumping mixtures of helium isotopes and thus reduce the size of the cooler device. Our technology would make the system significantly simpler, smaller, more efficient and more affordable. Compact and easy-to-use cooling methods contribute to the large-scale implementation of these technologies. Quantum technology is expected to be only the tip of the iceberg for future applications where we also could revolutionize the low temperature sensor technology used in space missions and satellites, where performance, compact size, low mass, and high reliability are crucial.



Picture about abc-1024x278.png

Towards interacting single rare-earth ions

Poster - Abstract ID: 149

Lothaire Ulrich [1]***, Eduardo Beattie*** [1]***, Samuele Grandi*** [1]***, Diana Serrano*** [2]***, Alban Ferrier*** [2]***, Philippe Goldner*** [2]***, David Hunger*** [3]***, Hugues de Riedmatten*** [1]

1. *ICFO - The Institute of Photonic Sciences,* ***2.*** *Chimie ParisTech,* ***3.*** *KIT - Karlsruhe Institute of Technology*

Rare earth ion-doped crystals constitute a promising platform for quantum information processing and networking [1]. They feature exceptional spin coherence times to store information, narrow optical transitions to act as an interface to optical photons, and possibilities to realize quantum gates between single ion qubits through electric dipole interactions. Recent results have shown single rare earth ions in the Purcell-enhanced regime to be excellent spin-photon interfaces [2-4], but the detection of a controlled interaction between two such single ions remains elusive.

We present our work towards detecting the first controlled interaction between single rare earth ions. Our system consists of a praseodymium-doped yttrium oxide nanoparticle placed inside of an open fiber cavity in a closed-cycle cryostat. The large electric dipole moment of the praseodymium transition, combined with the small ion-ion separations enabled by the nanoparticle's small size (70nm diameter), results in interactions which we predict will be strong enough to detect directly as shifts in each ion's optical spectrum.

In a previous experiment we detected single erbium ions in our nanoparticle-cavity system [5]. Since then we have realized major upgrades to the experiment, mainly consisting of a new nanopositioner design which improves the stability of the cavity (2.5 pm RMS down from 30 pm) and allows for operation at lower temperature (1.65K down from 6.5K). This new design also allows for MHz-rate tuning of the cavity length, enabling temporal shaping of the emitted photons.

In this poster we will give an overview of the rare earth ion quantum computing architecture, which motivates the need for controlled ion-ion interactions. A description of our fiber cavity and nanoparticle system will be given, along with quantitative analysis estimating the interaction strength between ions and an outline of the methods we will use to find pairs of interacting ions. Finally, we will include an outlook on the novel experimental capabilities unlocked by our new positioner.

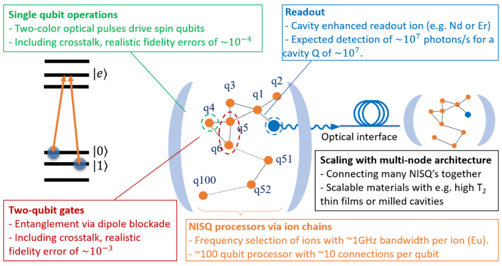
[1] Kinos et al, Preprint arXiv:2103.15743 (2021).

[2] Ourari et al, Nature **620** (2023).

[3] Kindem et al, Nature **580** (2020).

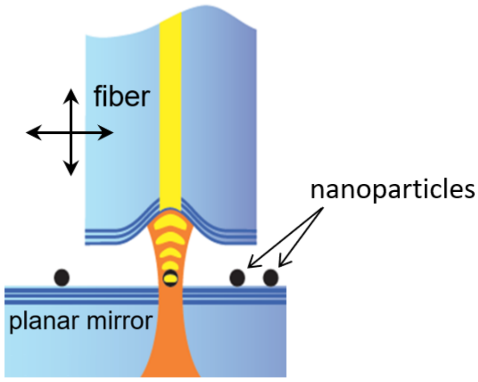
[4] Ulanowski et al, Advanced Optical Mater **12** (2024).

[6] Deshmukh et al, Optica **10** (2023).



Overview of the components of a rare-earth quantum computer, from [1].

Fig1 overview of the components of a rare earth quantum computer.png



Sketch of the optical microcavity

Fig2 sketch of the optical microcavity.png

Minimal criteria for continuous-variable genuine multipartite entanglement

Poster - Abstract ID: 161

Olga Leskovjanová [1], *Ladislav Mišta* [1]

1. *Department of Optics, Palacký University*

Genuine multipartite entanglement is synonymous with the correlations that lie at the heart of multipartite tests of quantum nonlocality and underlie some computational and metrological applications of quantum mechanics. For continuous-variable systems, such as light modes, the presence of genuine multipartite entanglement is verified in practice by criteria resembling the uncertainty relations for variances of combinations of quadrature operators. However, the number of the second moments appearing in these criteria increases quadratically with the number of modes, and thus their use can be challenging for higher number of modes. We address the question what are the simplest criteria in terms of the number of moments needed. We answer this question in several steps. First, we take advantage of the equivalence between entanglement criteria based on second moments and entanglement witnesses in the space of covariance matrices. Next, we use the fact that the simplest genuine multipartite entanglement witness works only with the so-called minimal set of two-mode marginal covariance matrices of the state in question. Since each minimal set is fully characterized by a specific tree graph, the structure of the graph is imprinted onto the corresponding witness. Making use of the relationship between the witnesses and the uncertainty-based criteria, we arrive at a set of genuine multipartite entanglement criteria employing only the second moments of the investigated state, which belong to the minimal set of marginals. Different trees give rise to different criteria which are all minimal in the sense that they contain the minimum number of variances of two-mode quadrature combinations. The biggest advantage of the obtained criteria is that the number of the needed second moments scales only linearly with the number of modes. This can be useful for larger systems where measuring the whole covariance matrix is challenging. The practicality of the derived criteria is demonstrated by detection of genuine multipartite entanglement of the three-mode GHZ-like state, split squeezed state, and a number of numerically found states of up to six modes The presented approach can be extended to get similar minimal criteria of other types of quantum correlations such as steering or other quantum systems.

Modeling Protein Dynamics in Age-Related Macular Degeneration Using Quantum Computing Algorithms

Poster - Abstract ID: 165

Vanessa Zorrilla-Muñoz [1], ***Angel Parra-Sanchez*** [2], ***Gema Martinez-Navarrete*** [3], ***Juan A. Rico-Gallego*** [4], ***Eduardo Fernandez*** [5]

__1.__ Bioengineering Institute, University Miguel Hernández of Elche. University Institute on Gender Studies, University Carlos III of Madrid, __2.__ Bioengineering Institute, University Miguel Hernández of Elche, __3.__ Neuroprosthesis and Visual Rehabilitation Laboratory, Bioengineering Institute, University Miguel Hernández of Elche, __4.__ Foundation for Computing and Advanced Technologies of Extremadura. Extremadura Center for Research, Technological Innovation, and Supercomputing, __5.__ Bioengineering Institute, University Miguel Hernández of Elche. Biomedical Research Network Center (CIBER-BBN)

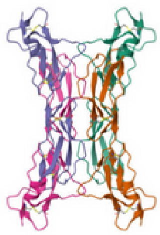
Quantum computing (QC) has the **potential to transform the way Age-related Macular Degeneration (AMD)** is understood, diagnosed, and treated, which could **improve the quality of life for people** affected by this degenerative eye disease. QC help better understand the **complex molecular interactions involved in AMD**, leading to the development of more effective treatments, delaying the diseae progression. **Knowing the three-dimensional structure of proteins** provide us to understand how they interact with other molecules in the eye and how they relate to **disease progression**.
Based on previous studies regarding QC in biology applications [1, 2], QC is applied to more accurately simulate the geometries of molecular interactions determine the three-dimensional structure of these proteins.
The first modeling consists of two proteins: **amyloid-beta (Aβ) protein** [3] and the **complement factor H (CFH) protein** [4]. The second model is a **quantum algorithms** (QA) used to **simulate the molecular dynamics of proteins related to AMD**. It simulates **how proteins change shape and move over time**, which can provide **information about their structure and function**.

The first simulation represents a **model protein using four qubits, where each qubit represents an atom in the protein**. Quantum gates, such as the **CNOT gate**, are applied between neighboring qubits to simulate molecular interactions and the formation of chemical bonds. Subsequently, **qubit measurement is performed to obtain information about the structure of the simulated protein**.

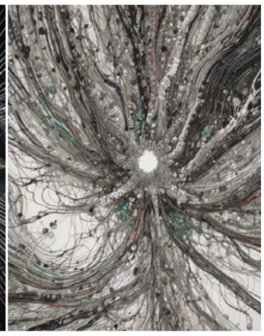
Both models illustrate how QC is used to simulate molecular interactions and temporal evolution of eye proteins related to AMD. These models are simplified examples and do not fully reflect the complexity in real proteins. They provide a basic introduction to how QC can simulate protein structures. In future applications, much more sophisticated algorithms and circuits will be used to accurately model AMD-related proteins and their molecular interactions, i.e. QC could simulate the interaction **between nano-structured Bevacizumab and proteins like vascular endothelial growth factor (VEGF)**, involved in AMD. QA can simulate molecular dynamics and atomic-level interactions, exploring the **efficacy and stability of the drug's nano-structure**. This approach offer valuable insights to optimize the design and **Bevacizumab therapeutic application**.

Aβ protein: unseeded Abeta(1-40) amyloid fibril (morphology ii. https://doi.org/10.2210/pdb8OT3/pdb

Structure of Human **CHF** Carboxyl Terminal Domains 19-20: a Basis for Atypical Hemolytic Uremic Syndrome. https://doi.org/10.2210/pdb2G7I/pdb



Screenshot 2024-08-15 192021.png



First Simulation.
Protein Model using Qubits.
Initial State Preparation Block:

```
q0: —|0>—┤
q1: —|0>—┤
q2: —|0>—┤
q3: —|0>—┤
```

Molecular Interaction Block:

```
q0: —●————————┤
     |
q1: —⊕—●——————┤
       |
q2: ————⊕—●———┤
          |
q3: ———————⊕——┤
```

Measurement Block:

```
q0: ————————M
q1: ————————M
q2: ————————M
q3: ————————M
```

First Simulation.
Protein Model using Qubits.

- ● and ⊕ represent the CNOT gates between adjacent qubits.
- M represents the measurement of each qubit.

This quantum circuit simulates basic molecular interactions between the atoms of a protein using CNOT gates. The resulting structure is obtained by measuring the qubits after the gates are applied.

Second Simulation.
Protein Molecular Dynamics
Initial State Preparation Block:

```
q0: —|0>—┤
q1: —|0>—┤
q2: —|0>—┤
q3: —|0>—┤
```

Molecular Dynamics Block:

```
q0: —Rz—Ry—┤

q1: —Rz—Ry—┤

q2: —Rz—Ry—┤

q3: —Rz—Ry—┤
```

Measurement Block:

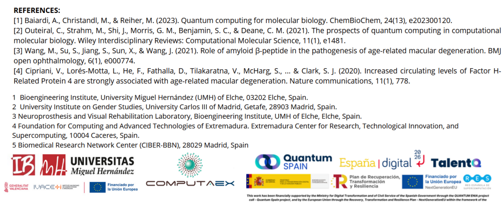
```
q0: ———————M
q1: ———————M
q2: ———————M
q3: ———————M
```

Second Simulation.
Protein Molecular Dynamics

- Rz and Ry represent the rotation gate applied to the qubits to simulate dynamics.
- M represents the measurement of the qubits.

This circuit simulates the molecular dynamics, meaning how the protein's structure changes over time. The Rz gates simulate the rotation of atoms, affecting the protein's shape and function.

Screenshot 2024-08-15 191949.png



REFERENCES:
[1] Baiardi, A., Christandl, M., & Reiher, M. (2023). Quantum computing for molecular biology. ChemBioChem, 24(13), e202300120.
[2] Outeiral, C., Strahm, M., Shi, J., Morris, G. M., Benjamin, S. C., & Deane, C. M. (2021). The prospects of quantum computing in computational molecular biology. Wiley Interdisciplinary Reviews: Computational Molecular Science, 11(1), e1481.
[3] Wang, M., Su, S., Jiang, S., Sun, X., & Wang, J. (2021). Role of amyloid β-peptide in the pathogenesis of age-related macular degeneration. BMJ open ophthalmology, 6(1), e000774.
[4] Cipriani, V., Lorés-Motta, L., He, F., Fathalla, D., Tilakaratna, V., McHarg, S., ... & Clark, S. J. (2020). Increased circulating levels of Factor H-Related Protein 4 are strongly associated with age-related macular degeneration. Nature communications, 11(1), 778.

1 Bioengineering Institute, University Miguel Hernández (UMH) of Elche, 03202 Elche, Spain.
2 University Institute on Gender Studies, University Carlos III of Madrid, Getafe, 28903 Madrid, Spain.
3 Neuroprosthesis and Visual Rehabilitation Laboratory, Bioengineering Institute, UMH of Elche, Elche, Spain.
4 Foundation for Computing and Advanced Technologies of Extremadura. Extremadura Center for Research, Technological Innovation, and Supercomputing, 10004 Caceres, Spain.
5 Biomedical Research Network Center (CIBER-BBN), 28029 Madrid, Spain

This work has been financially supported by the Ministry for Digital Transformation and of Civil Service of the Spanish Government through the QUANTUM ENIA project call - Quantum Spain project, and by the European Union through the Recovery, Transformation and Resilience Plan - NextGenerationEU within the framework of the

Screenshot 2024-08-15 192247.png

Screenshot 2024-08-20 165221.png

Opportunities for quantum technology at European synchrotron radiation facilities

Poster - Abstract ID: 276

Anna Makarova [1], ***Oliver Rader*** [1], ***Kristiaan Temst*** [2], ***Jean Daillant*** [3]

1. Helmholtz-Zentrum Berlin, 2. KU Leuven, 3. Synchrotron Soleil, France

Synchrotron radiation can support quantum technology in many ways. Examples are 2D and 3D imaging using contrast based on chemical sensitivity, oxidation states, and magnetic dichroism, the characterization of impurities in semiconductors by spectroscopy, of strain conditions for Si quantum dot qubits and for nanowires, materials issues in superconducting qubits that lead to decoherence and broken Cooper pairs, the investigation, orbitals involved in single photon emission from hBN defects and transition metal dichalgogenides.

However, use of synchrotron and free-electron laser (FEL) radiation for quantum technology occurs only punctually with the exception of research on quantum materials. We will provide an overview of European synchrotron radiation and FEL sources and instrumentation that is particularly suited for quantum technology.
Moreover, we will give information on access schemes and engage in discussions on the special needs of researchers in quantum technology in terms of instrumentation, proposal submission, experiment, and data analysis.
This project is part of the LEAPS-INNOV WP9. Funded from the European Union´s Horizon 2020 programme under grant.

Creation of multiqubit non-maximally entangled states by linear-optical fusion operations

Poster - Abstract ID: 131

Aleksandr Melkozerov [1]***, Mikhail Saygin*** [2]***, Sergei Kulik*** [3]***, Stanislav Straupe*** [4]

1. *Russian Quantum Center, Moscow, Russia; Quantum Technology Centre of Moscow State University, Moscow, Russia,* ***2.*** *Sber Quantum Technology Center, Moscow, Russia; Quantum Technology Centre of Moscow State University, Moscow, Russia; South Ural State University , Chelyabinsk, Russia,* ***3.*** *Quantum Technology Centre of Moscow State University, Moscow, Russia; South Ural State University , Chelyabinsk, Russia,* ***4.*** *Sber Quantum Technology Center, Moscow, Russia; Quantum Technology Centre of Moscow State University, Moscow, Russia; Russian Quantum Center, Moscow, Russia*

Introduction

Entangled states of photonic qubits play a central role in quantum information processing, particularly in linear-optical quantum computing and quantum networks. Recent approaches, such as fusion-based quantum computing (FBQC), propose a framework for fault-tolerant quantum computation, contingent on the repeated generation of small, constant-sized maximally entangled states (resource states) and the performance of projective entangling measurements (fusions) on them. However, creating even the simplest maximally entangled states is extremely challenging in linear optics.

Non-maximally entangled states appear to be promising candidates for resource states, and small non-maximally entangled states can be generated with higher probabilities than maximally entangled ones. We propose and thoroughly investigate an approach to the linear-optical generation of non-maximally entangled states from smaller ones through an operation similar to the linear-optical fusion known for maximally entangled states.

Methods and Results

First, we study the fusion of states of the GHZ-like form $|\varphi\rangle = \cos(\alpha)|A_0\rangle|0\rangle + \sin(\alpha)|A_1\rangle|1\rangle$. We consider modified Type-II fusion gates (See Fig. 1), which allow us to obtain differently-entangled states as a result of the gate action. We show that under certain conditions, the probability of successful fusion in this case may be higher than in the fusion of maximally entangled states.

Next, we present a method to create large weighted graph states—a generalization of well-known graph states—from smaller ones using linear-optical fusion. We derive the necessary projection that should be applied to the qubits of the initial states, studying weighted graph states within the matrix product state formalism. We then demonstrate how this can be realized using a generalized linear-optical fusion operation, enabling the creation of larger weighted graph states.

Discussion

Recent studies suggest non-maximally entangled states as promising candidates for quantum computing. Here, we propose a method to create multi-qubit non-maximally entangled states using linear optics through operations similar to the linear-optical fusion known for maximally entangled states.

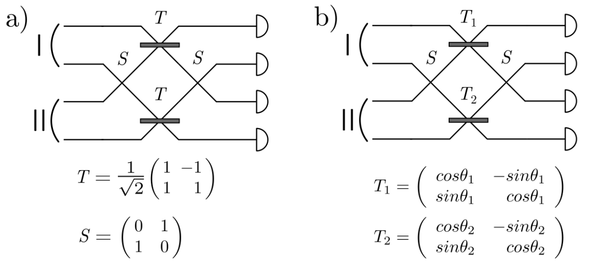


Fig. 1. a) Linear-optical path mode dual-rail encoding version of the standard Type-II fusion gate. Two initial qubits are inserted in the modes I and II respectively. All photons are measured by the PNRDs at the end of the circuit. b) Modified version of the standard Type-II fusion gate used for the fusion of non-maximally entangled states.

Figure1.png

High fidelity Rabi quantum state tomography of single-qubits in NV hybrid system

Poster - Abstract ID: 285

Abhishek Shukla [1], ***Boo Carmans*** [2], ***Michael Petrov*** [2], ***Daan Vrancken*** [2], ***Milos Nesladek*** [1]

1. *Institute for Materials Research (IMO), Hasselt University, Wetenschapspark 1, B-3590 Diepenbeek, Belgium,* ***2.*** *Hasselt University, Wetenschapspark 1, 3590 Diepenbeek, Belgium*

The Implementation of quantum computation is usually a noisy task leading to the deviation of experimentally obtained quantum state from the expected theoretical quantum state, raising the requirement of the characterization of the quantum state i.e., Quantum state tomography (QST). We have devised a novel method for QST based on simple and routine Rabi experiments with its two variants RAQST and RPQST.
The RQST methodology involves the application of two definite phase Rabi experiments differing by phase 90^o. We fit these rabi data to Rabi oscillation and estimate amplitude and phase information. The amplitude and phase information is then used for calculating polar and azimuthal angles with Rabi amplitude and Rabi phase. We detail the experimental results on the electron and nuclear spin test states of an (electron-^{14}N) NV spin register in diamond. Average fidelities we obtain are 0.995 with RPQST and 0.990 with RAQST, which is among the best fidelities on NV systems, especially at room temperature and without using decoherence suppression and optimal control theory (OCT). The average fidelity is obtained by averaging over more than 40 measurements on different states. In further analysis, we found that RPQST outperforms RAQST as it suppresses systematic experimental errors. We believe that such good control of our hybrid system will allow us to have high-quality single-qubit and two-qubit quantum gates. The experimental quantum state can be prepared more accurately further enhancement is possible by characterizing the systematic errors and suppressing the decoherence effect by using dynamical decoupling pulses and using OCT. Though, we have demonstrated our new method for QST using optically detected magnetic resonance ODMR, but we are also working on photoelectric detection of magnetic resonance (PDMR). [18] based QST as the PDMR-QST will be an unavoidable tool for achieving high-fidelity state engineering in a scalable dipole-dipole coupled NV spin register desirable for fault-tolerant programmable quantum computers.

Variational quantum circuit decoupling

Oral - Abstract ID: 192

XIMING WANG [1], *Chengran Yang* [1], *Mile Gu* [1]

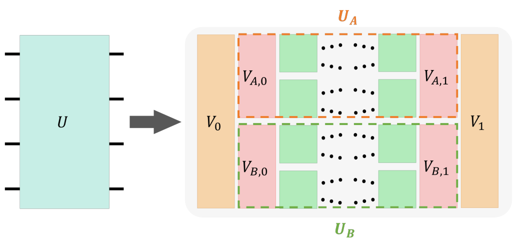
1. *Nanyang Technological University*

Introduction: Decoupling systems into independently evolving components has a long history of simplifying complex systems. They enable a better understanding of the underlying dynamics and causal structures while providing more efficient means to simulate such processes on a computer. Here we outline a variational decoupling algorithm for decoupling unitary quantum dynamics – allowing us to decompose a given n-qubit unitary gate into multiple independently evolving sub-components (see decoupling_structure.png).

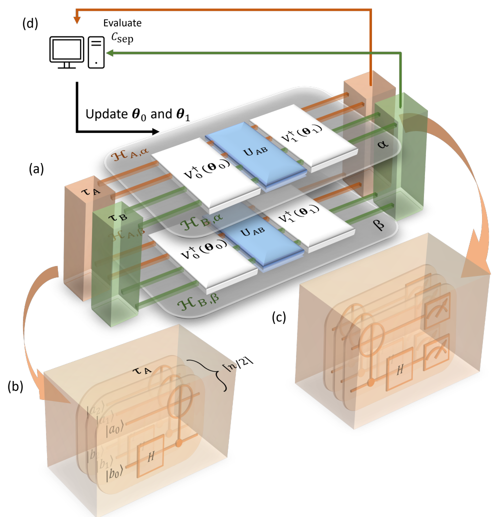
Methods: Here, we adopt the premise of variational quantum circuit discovery, where we are given black-box access to some unknown n-qubit unitary quantum process. This could represent some unknown quantum device we wish to reverse-engineer, or some natural quantum process we wish to simulate. Our goal is to approximate this process with a sequence of parameterized elementary quantum gates. Here we proposed an efficient measurable cost function (a scheme of the measurement is shown in schematicDiag.png) such that the independently evolving sub-components can be found at the optimum.

Results: We apply this approach to quantum circuit synthesis - the task of discovering quantum circuit implementations of target unitary dynamics. Our numerical studies illustrate significant benefits, showing that variational decoupling enables us to synthesize general gates to fidelity that conventional methods cannot reach. This is done by pre-training the variational circuit with our method, such that task is divided to the circuit discovering on each sub-component. In case an exact simulation is feasible, our method helps to find the optimum faster and converges better. Even when the target cannot be simulated by a shallow variational circuit, the numerical simulation shows that our method is more likely to find a shallow circuit that approximates the target better, compared to train the circuit without the pre-train.

Discussion: The decoupling of complex interactions itself has motivations beyond computational advantage. In classical analogs such as coupled oscillators, identification of normal modes helped better express underlying dynamics. One could, for example, envision a seemingly complex many-body quantum system evolving under some joint Hamiltonian. Our methodologies could also help identify potential sub-spaces where there is minimal coupling - and thus aid the discovery of underlying causal restructure.



Decoupling structure.png



Schematicdiag.png

Towards large scale quantum simulation of the Heisenberg model

Oral - Abstract ID: 18

Samuele Piccinelli [1]

1. IBM Research Zurich

Spin systems provide a fundamental test bed for exploring emergent phenomena in condensed matter physics. Their modelling is pivotal in understanding magnetic properties of materials, quantum phase transitions and in the development of spintronic devices. In the study of such systems, the calculation of dynamical correlations and their corresponding spectral functions plays a critical role, as they offer valuable information that can be directly compared to experiments and may contribute to the understanding of phenomena such as high-temperature superconductivity and topological insulation.

Quantum computers offer several scalable solutions to efficiently compute dynamical correlation functions, for instance by leveraging the ability to efficiently implement quantum time evolution operators.

In this work we present novel quantum algorithms designed to simulate dynamical correlations and dynamical structure factors on IBM Quantum processors.

Using randomized and quasi-probabilistic methods, our protocols allow us to circumvent the limited connectivity of the device and to compute arbitrary two-body correlators without gate or sampling overheads. By exploiting a combination of error mitigation techniques, including probabilistic error amplification and suitable algebraic constraints, our approach may practically reach system sizes comparable to classical state-of-the-art. Our results showcase a concrete problem for which quantum computers can be used as effective research tools, thereby opening new avenues in the realm of quantum computational sciences.

Quantum-noise-driven Generative Diffusion Models

Oral - Abstract ID: 54

Stefano Martina [1], ***Marco Parigi*** [1]

1. *University of Florence*

Introduction

Generative Diffusion Models (GDMs) are an emerging Machine Learning paradigm where data is corrupted with classical noise and then a Neural Network (NN) learns how to remove it in order to recover the unknown initial data distribution. We propose three approaches for a quantum generalization of GDMs with different combinations of classical/quantum forward and backward dynamics as in Fig. 1. Here, quantum noise is exploited as a beneficial ingredient to generate complex distributions.

Methods

We train the Classical-Quantum GDM model using a dataset composed of random points distributed along a line segment. The diffusion process is implemented via a classical Markov chain of Gaussian transition kernels. The denoising process is realized via a parameterized quantum circuit trained to estimate mean and covariance of the kernel of a denoising Markov chain. For the Quantum-Classical (QCGDM) and Quantum-Quantum (QQGDM) models, the quantum forward dynamics is initialized with a pure quantum state that is iteratively degraded by depolarizing channels until it is maximally mixed. In QCGDMs the denoising is implemented with NNs trained to simulate a dynamic to obtain an approximation of the initial state. In QQGDMs the backward is realized with a non-unitary quantum dynamic in the context of open quantum systems.

Results

The results of a simulation of a CQGDM are shown in Fig. 2a. The model reconstructs the initial data distribution with a good approximation quantified by the Kullback-Leibler divergence between the original and reconstructed distributions. In Fig. 2b we show the evolution of the loss during the training of the model. In Fig. 2c and 2d we show the simulation on a single-qubit system for ten QCGDMs and QQGDMs, respectively. In Fig. 2e is reported the evolution of the loss during the training of both models.

Discussion

Quantum systems can represent intractable distributions that are classically inefficient to reproduce. At the best of our knowledge, CQGDM and QCGDM are the first implementations of hybrid classical-quantum diffusion models. This work pave the way for new quantum generative diffusion algorithms for real-world applications, and the design and realization of quantum GDMs could alleviate and reduce the computational resources.

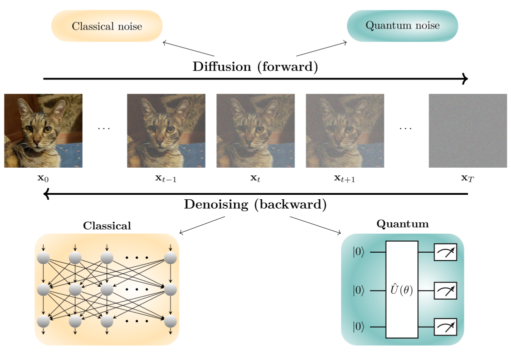


Fig1.png

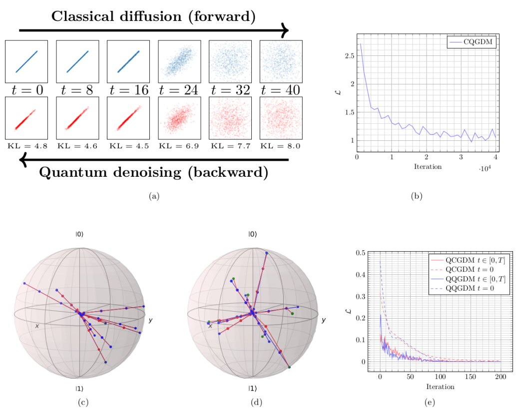


Fig2.png

Variational quantum simulation: a case study for understanding warm starts

Oral - Abstract ID: 238

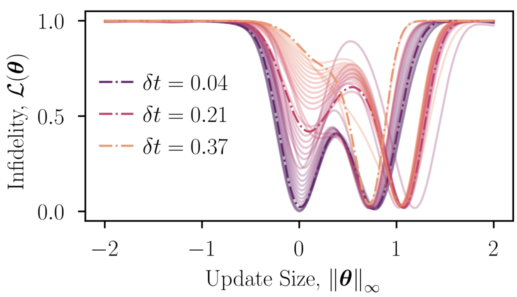
Ricard Puig [1], ***Marc Drudis*** [2], ***Supanut Thanasilp*** [3], ***Zoe Holmes*** [1]

1. École Polytechnique Fédérale de Lausanne (EPFL), 2. IBM Quantum Zurich, 3. Chula Inteligent and Complex Systems, Chulalongkorn University

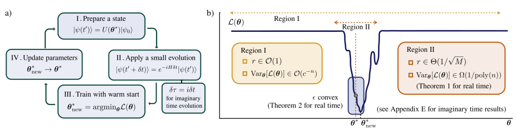
Variational quantum algorithms are a flexible family of quantum algorithms, whereby a problem-specific cost function is efficiently evaluated on a quantum computer, and a classical optimizer aims to minimize this cost by training a parametrized quantum circuit. While popular, the potential of scaling these algorithms to interesting system sizes attracts much debate. Of a particular concern is the barren plateau phenomenon, characterized by loss gradients that vanish exponentially with system size. Recently 'warm-starts', where one initializes closer to a solution in the hope of enjoying a region with substantial gradients, has gained attention as a potential solution. Nevertheless, the existing works remain mostly heuristic.

In this work, we took a rigorous initial step to explore the warm-start from an analytical perspective. Focusing on an iterative variational method for learning shorter-depth circuits for quantum real and imaginary time evolution, see Fig. Schematic a), we conduct a case study to elucidate the potential and limitations of warm starts. We start by proving that the iterative variational algorithm will exhibit substantial (at worst vanishing polynomially in system size) gradients in a small region around the initializations at each time-step, see Fig. Schematic b). This illustrates an existence of trainable small regions within the entire exponential flat loss landscape. Convexity guarantees for these small regions are then established, suggesting trainability for polynomial size time-steps. However, our study highlights scenarios where a good minimum shifts outside the region with trainability guarantees, see Fig. Minima_jump. Our analysis leaves open the question whether such minima jumps necessitate optimization across barren plateau landscapes or whether there exist gradient flows, i.e., fertile valleys away from the plateau with substantial gradients, that allow for training.

The whole paper is available here: https://arxiv.org/abs/2404.10044



Minima jump.jpg



Schematics.jpg

Exploring and Analyzing Quantum Dynamics with GenAI

Oral - Abstract ID: 33

Miri Kenig [1], **Yoav Lahini** [1]

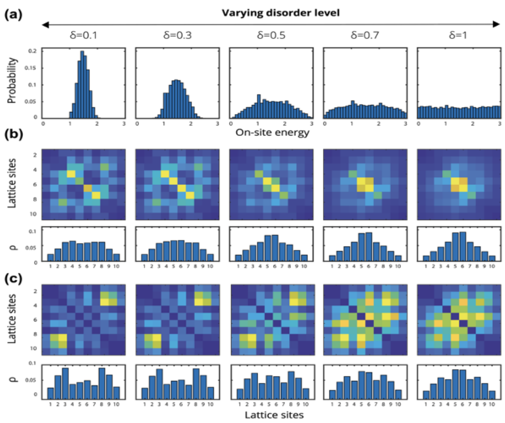
1. Tel-Aviv University

GenAI is already revolutionizing our perspective on a variety of things by creating new content based on patterns and structures learned from existing data

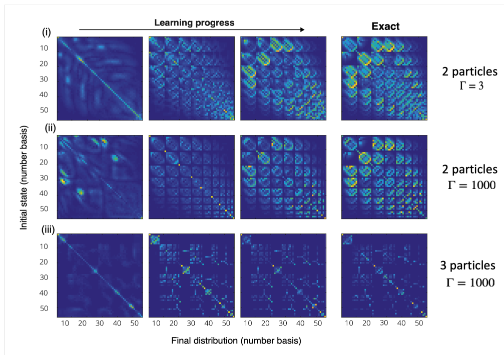
This research shows that GenAI can learn the dynamics of interacting quantum particles on disordered chains, a general scenario underlying a wide range of physical problems, from many-body quantum physics to quantum computation.

Our model learns complex quantum correlations from observation alone and can then generate new physically valid instances with tunable physical parameters.

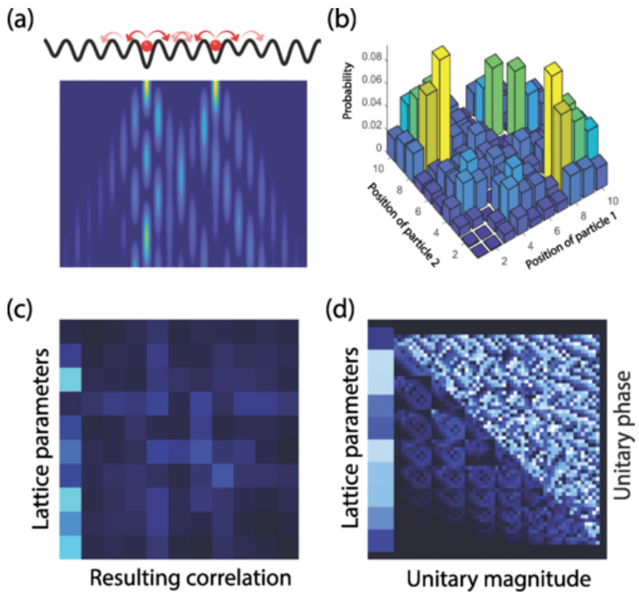
This enables post-training exploration of the problem space, revealing underlying physical phenomena and accelerating the learning of more complex problems. These results suggest a general framework for GenAI in physical analysis and discovery.



Uncovering anderson localization.png



Learning progress.png



Correlated quantum walks and training samples.png

Noise-adapted recovery circuits for quantum error correction

Oral - Abstract ID: 21

Debjyoti Biswas [1], Prabha Mandayam [1]

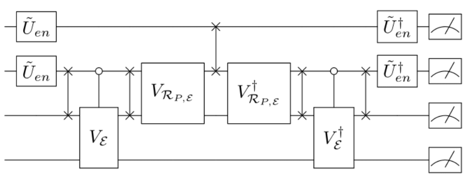
1. Indian Institute of Technology Madras

In contrast to general-purpose quantum error correction (QEC), noise-adapted QEC provides comparable protection against specific noise processes while utilizing fewer physical qubits. In our work (arXiv:2305.11093), we present three quantum circuits that implement a near-optimal channel-adapted recovery map – the Petz map. Our proposed circuits differ from the recent circuit implementation (PhysRevLett.128.220502) of a state-specific variant of the Petz map by offering code-specific recovery that is of greater relevance in the context of QEC.

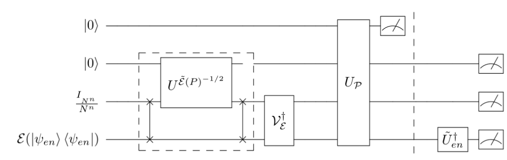
The first approach we introduce involves implementing an isometric extension of any channel, typically requiring $\mathcal{O}(n^24^{3n})$ single and two-qubit gates. In contrast, our implementation requires only $\mathcal{O}(n^2 4^{2n})$ single and two-qubit gates. By utilizing the isometric extension technique along with the *block encoding* approach for density matrices (arXiv:1806.01838), we propose a circuit capable of estimating the fidelity between the recovered state and the encoded input state.

The second approach combines the isometric extension of the noise channel and the projection channel with the block-encoding of the normalizer map (PhysRevA.81.062342), followed by a post-selection procedure to obtain the outcome of the Petz recovery (Theorem 2 in (arXiv:2305.11093)). We demonstrate that our algorithm achieves a success probability *sixteen* times higher than the algorithm presented in (PhysRevLett.128.220502). Furthermore, we show how a simple modification to our circuit allows for the estimation of fidelity between the encoded input state and the recovered state (Corollary 2.1 in (arXiv:2305.11093)). The third approach capitalizes on the fact that the Kraus operators of any channel can be *approximately* realized using a sequence of binary outcome POVMs and unitary operations (arXiv:2305.11093). Leveraging this idea, we construct a circuit for the Petz recovery, employing only **two** ancillary qubits.

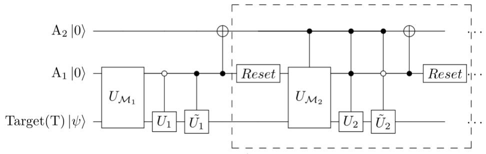
We demonstrate our circuit constructions for the Petz map and its performance for the case of a 4-qubit code~(PhysRevA.56.2567) tailored for the amplitude-damping noise by implementing them both on an ideal simulator and the noisy quantum processors.



Fidelity estimation circuit through isometric extension.png



Fidelity estimation through sequential block encoding.png



Petz circuit through povm.png

Methods	**cnots +** **single-qubit gates**	**Ancilla**
Isometric Extension	$\mathcal{O}(n^2 4^{2n})$	$2n$
POVM	$\mathcal{O}(4^{2n}(5n^2 + 8n + 4))$	2
Block Encoding	$\mathcal{O}(12n + n^2 4^n (1 + 4^n))$	$(2n + 2)$
QSVT	$\mathcal{O}(n^2 4^n + 4^{4n})$	$4n + 4$

Table 1: Resources requirements for different circuit implementations of the Petz recovery map.

Circuit complexity.png

Quantum reservoir computing with linear photonic networks

Oral - Abstract ID: 27

Sam Nerenberg [1], Oliver Neill [1], Giulia Marcucci [1], Daniele Faccio [1]

1. University of Glasgow

Introduction:

Neuromorphic processors improve the efficiency of machine learning algorithms by implementing physical artificial neurons to perform computations. Whilst efficient classical neuromorphic processors have been demonstrated; practical quantum neuromorphic platforms are in early development. Here we propose a linear photonic network (LPN) for quantum reservoir computing (QRC) enabled by photon number-resolving (PNR) detection of the output state. The approach is implementable with accessible technology and lowers the barrier to entry to quantum machine learning.

Methods:

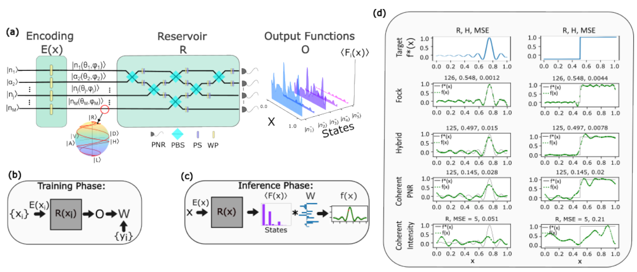
Fig. 1(a) shows the schematic layout of our approach. Light is fed into two sequential LPNs: the encoding layer which operates solely on polarisation and the fixed reservoir which couples spatial and polarisation modes. Data x is encoded in trajectories on the Poincarè sphere of each mode and PNR detectors at the output ports determine the resulting probability distribution over measurement outcomes $\langle \mathbf{F}(x) \rangle$. In the training phase, outlined in Fig. 1(b) the weights **W** are learned from the matrix of outputs $\mathbf{O}_{i,j}=\langle \mathbf{F}_i(x_j) \rangle$ and used in the inference phase, Fig. 1(c) for machine learning tasks. Various classes of input states and encoding trajectories produce different output features, offering versatility.

Results:

In Fig. 1(d) we consider the task of interpolating functions, f(x) using different input states with up to four photons. Coherent inputs with intensity detection are used as a classical reference. To mimic realistic conditions, we employ a binomial detector model with efficiency η=0.9 and draw $N_{samp}=10^7$ samples. QRC performance is determined by the set of independent features it generates and their relative probabilities. We quantify these aspects from **O** by the rank R and entropy H of its normalized singular value spectrum. Increases in each metric are correlated with better performance of the QRC.

Discussion:

The results in Fig. 1(d) show that performance improves with the degree of quantum interference. Even with coherent states as inputs, PNR detection confers an advantage over fully classical operation due to the scaling of the output Hilbert space dimension. This scaling, coupled with an RC architecture, facilitates complex quantum information processing tasks in a compact system using such simple resources as a scattering medium and a standard laser.



Layout and results qtech2024 figure.png

Realisation of versatile and effective quantum metrology using a single bosonic mode

Oral - Abstract ID: 76

Tanjung Krisnanda [1], *Xiaozhou Pan* [1], *Andrea Duina* [1], *Kimin Park* [2], *Pengtao Song* [1], *Clara Fontaine* [1], *Adrian Copetudo* [1], *Radim Filip* [3], *Yvonne Gao* [1]

1. *National University of Singapore,* ***2.*** *Palacky University,* ***3.*** *Department of Optics, Palacký University*

Quantum metrology heralds a paradigm shift in precision measurement, offering superior levels of accuracy beyond classical counterparts. It has enabled transformative advancements across scientific fields, from precise measurements of electromagnetic fields to enhanced detection of gravitational waves in LIGO or the search for dark matter. Traditionally, quantum-enhanced precision is achieved using multi-particle entangled states, which pose practical challenges for both the preparation of non-local states and measurement schemes.

In this work, we realise a versatile and on-demand protocol for deterministic parameter estimation using a single bosonic mode. The protocol is illustrated in Fig. 1, which involves state preparation, to-be-estimated process, and projection measurement with an ancillary qubit that facilitates the operations and measurements on the bosonic cavity state. The information regarding the parameter of interest is carried in the measurement results, from which we compute the parameter estimation error.

We demonstrate the protocol in the context of phase and amplitude estimation using the superposition of coherent states (SCS) in the bosonic circuit quantum electrodynamics (cQED) platform. With low-photon-number (of up to 1.76) states, we achieve quantum-enhanced precision approaching the Heisenberg scaling, reaching a state-of-the-art metrological gain of 7.5(6) dB and 9.3(5) dB respectively for phase and amplitude estimation compared to the use of classically behaving coherent states (CS), see Fig. 2. Our protocol can be adapted to further optimize the desired figures of merit using tailored quantum states or operations.

The simplicity and effectiveness of our protocol stem from the use of a single bosonic mode with two general state-transfer operations that can be realised by any standard gates. As such, our implementation is accessible to systems with different device parameters. Furthermore, the strategy is universal and can be readily performed with many other bosonic systems beyond cQED using their preferred native operations. Our work offers a promising first step towards practical and optimal quantum metrology using a single bosonic system.

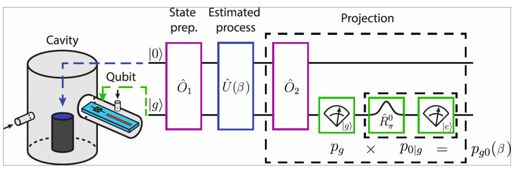


Fig. 1. parameter estimation protocol.png

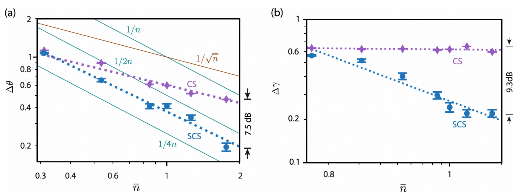


Fig. 2. phase and amplitude estimation error.png

Multiplexed Processing of Quantum Information Across an Ultra-wide Optical Bandwidth

Oral - Abstract ID: 109

Alon Eldan [1], ***Ofek Gillon*** [1], ***Asher Lagemi*** [1], ***Elai Fishman-Furman*** [1], ***Avi Pe'er*** [1]

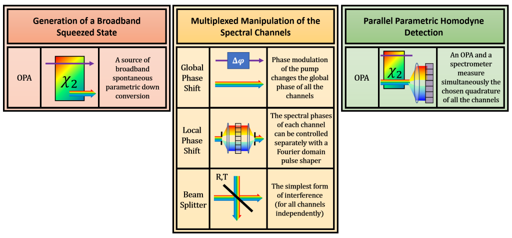
1. *Dept. of physics & QUEST center for quantum science and technology, Bar Ilan University, Ramat Gan, 52900 ISRAEL*

We present a new approach for frequency multiplexing of quantum information which have the potential to significantly increase the processing speed of quantum information.

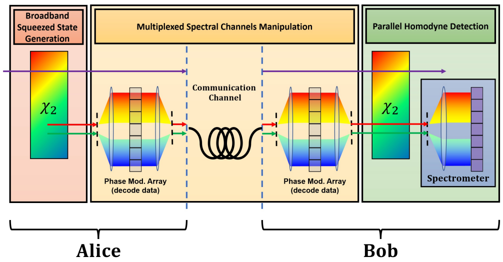
Protocols of quantum information processing are the foundation of quantum technology, allowing to share secrets at a distance for secure communication (quantum key distribution), to teleport quantum states, and to implement quantum computation. While various protocols have already been realized, and even commercialized, the throughput and processing speed of standard protocols is generally low, limited by the narrow electronic bandwidth of the measurement apparatus in the MHz-to-GHz range, which is orders-of-magnitude lower than the optical bandwidth of available quantum optical sources (10-100 THz).

Most generally, quantum information processing could be broken into three primary stages: generation of the quantum state, manipulation of the state, and quantum state measurement. Whereas there are various efficient implementations of the generation and manipulation stages, the primary bottleneck in quantum optical protocols is the measurement, where the relatively slow response of photo-detectors limits the processing rates at several orders of magnitudes below the optical bandwidth of available sources, even with the fastest available detectors. Luckily, this electronic bandwidth limit was recently overcome with the conception of optical parametric homodyne which enables to measure an optical quadrature of interest across a wide, practically unlimited optical spectrum.

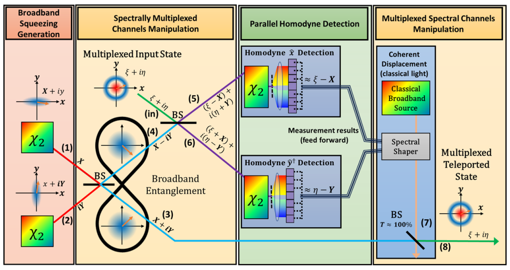
We present a new general approach for parallel processing of quantum information. We highlight a set of tools for parallel generation, manipulation and measurement to process quantum information encoded on the entire optical spectrum of the quadratures of broadband two mode squeezed light. We exemplify out method through conceptualization of multiplexed variations for two basic protocols: Multiplexed Quantum Key Distribution (QKD) and Multiplexed Quantum Teleportation. We demonstrate the multiplexed CV-QKD protocol in a proof-of-principle experiment, where we successfully carry out QKD over 23 uncorrelated spectral channels, with capability to detect eavesdropping in any channel. These multiplexed method (and similar) will enable to carry out quantum processing in parallel over hundreds of channels, potentially increasing the throughput of quantum protocols by orders of magnitude.



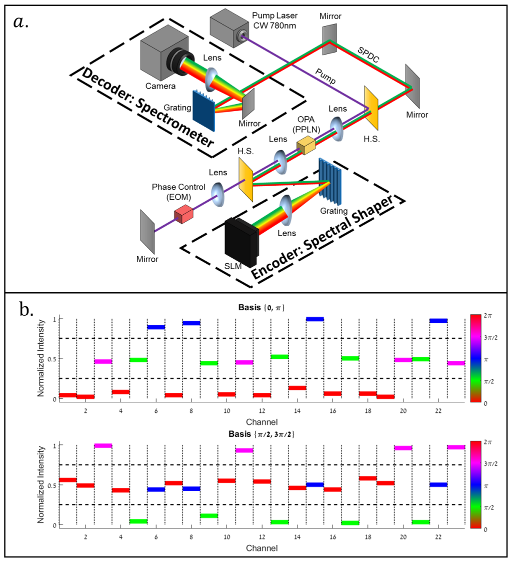
General building blocks.png



Qkd scheme.jpg



Quantum teleportation scheme.png



Setup and results.png

Experimental noiseless quantum amplification of coherent states of light by multiphoton addition and subtraction

Oral - Abstract ID: 31

Jiří Fadrný [1], *Michal Neset* [1], *Martin Bielak* [1], *Miroslav Ježek* [1], *Jan Bilek* [1], *Jaromir Fiurasek* [1]

1. *Department of Optics, Palacký University*

Introduction: Conditional addition and subtraction of photons represents a crucial tool for optical quantum state engineering and it forms a fundamental building block of advanced quantum photonic devices. To date, experimental photon addition was limited to one photon. Here we report experimental realization of conditional addition of up to three photons as well as combination of conditional addition of two photons followed by their conditional subtraction. We utilize these operations for approximate probabilistic noiseless amplification of coherent states.

Methods: Our experiment, see Fig. 1, is based on single-pass optical parametric amplification in a nonlinear crystal pumped by pulsed picosecond laser [arXiv:2405.10403]. The input signal mode is seeded with a coherent state while the idler mode is initially in vacuum state. Interaction in the nonlinear crystal generates correlated photon pairs in signal and idler modes. Detection of n photons in the output idler mode heralds the addition of n photons into the signal mode. To subtract m photons, we insert an unbalanced beam splitter into the path of the output signal beam and condition on detection of m photons in the auxiliary output port of that beam splitter. The experimentally generated states in signal mode are measured by a home-built balanced homodyne detector with 12 dB signal-to-noise ratio and 100 MHz bandwidth.

Results: We first demonstrate the experimental addition of one, two, and three photons to input coherent states with various amplitudes. The resulting highly nonclassical photon-added states are completely characterized with time-domain homodyne tomography. We experimentally show that the conditional addition of photons realizes approximate noiseless quantum amplification of coherent states with sufficiently large amplitude. We then experimentally implement combination of conditional addition and subtraction of two photons which realizes high-fidelity noiseless amplification of coherent states even for small coherent amplitudes. We compare the performance of our noiseless amplifier with an amplifier based on sequence of single-photon addition and subtraction, see Fig. 2.

Discussion: Our results significantly extend the range of experimentally accessible noiseless quantum amplifiers and pave the way towards the experimental realization of other complex optical quantum operations based on combination of multiple photon additions and subtractions.

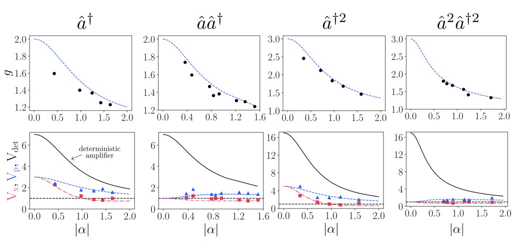


Figure 2 noiseless amplification experimental gains and quadrature variances.png

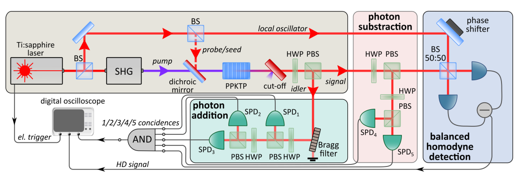


Figure 1 noiseless amplification experimental setup.png

Solving The Quantum Many-Body Hamiltonian Learning Problem with Neural Differential Equations

Oral - Abstract ID: 257

Timothy Heightman [1], *Edward Jiang* [2], *Antonio Acin* [3]

1. ICFO - The Institute of Photonic Sciences, 2. ICFO, 3. ICFO-The Institute of Photonic Sciences

Understanding and characterising quantum many-body dynamics remains a significant challenge due to both the exponential complexity required to represent quantum many-body Hamiltonians, and the need to accurately track states in time under the action of such Hamiltonians. This inherent complexity limits our ability to characterise quantum many-body systems, highlighting the need for innovative approaches to unlock their full potential. One approach to solve this problem is to formulate it in terms of Hamiltonian Learning (HL), defined as the task of inferring quantum dynamics from many-body state trajectories. State-of-the-art works have thus far solved the HL problem on quadratic Hamiltonians with at most a sub-linear number of coefficients. This limits their utility in settings such as device characterisation and optimal control, where Hamiltonians of higher complexity are often employed.

To address this challenge, we propose a novel method to solve the HL problem using neural differential equations combined with an Ansatz Hamiltonian. Our method is experimentally friendly, using bit-strings from marginal distributions of compatible observables as training data. Furthermore, our method allows for interpretability via a curriculum learning protocol, making it a stable solution for HL on a set of Hamiltonians previously unlearnable in the literature. We benchmark our method against state-of-the-art HL algorithms using a 1D spin-1/2 chain proof of concept, with results shown in Table 1. These results include Hamiltonians beyond quadratic, even probing non-ergodic systems, demonstrating that our method surpasses current techniques in HL, with results computed on a standard laptop. Figure 1 shows how the infidelity of our method changes in time compared to ground-truth dynamics. The boundary of the shaded region is the training data time, and to the right, the figure shows our method remaining above 99% accurate for around 10 times the simulated training time, on basis states never seen in training. Finally, Figure 2 compares how the loss landscape of our benchmarked Hamiltonians look around the global minimum, and how they look in the absence of a neural augmentation. This provides a deeper understanding of why certain Hamiltonians may be harder to learn than others in terms of their responsiveness to Pauli measurements.

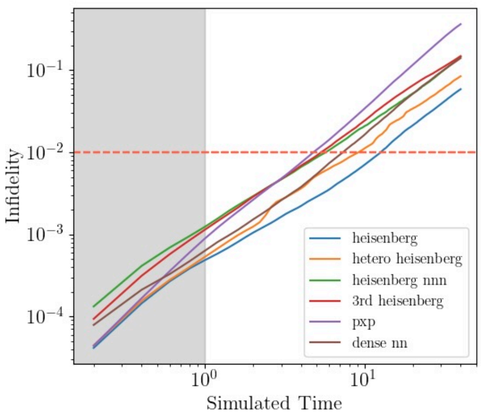


Fig1 extrapolation times.jpeg

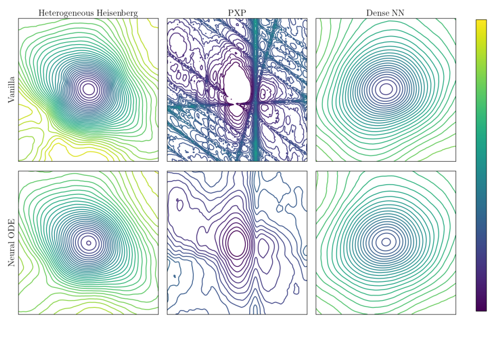


Fig2 loss landscape neural vs vanilla.png

Hamiltonian	N	Vanilla	Neural ODE
Heisenberg	3	66%	100%
	4	86%	100%
	5	94%	100%
	6	64%	100%
	7	52%	100%
	8	52%	100%
Anisotropic Heisenberg	3	28%	96%
	4	46%	96%
	5	34%	94%
	6	32%	96%
	7	18%	96%
	8	16%	96%
PXP	3	12%	100%
	4	12%	100%
	5	6%	100%
	6	2%	100%
	7	0%	98%
	8	0%	94%

Hamiltonian	N	Vanilla	Neural ODE
Dense NN	3	94%	100%
	4	98%	100%
	5	96%	98%
	6	98%	98%
	7	88%	98%
	8	98%	98%
Heisenberg NNN	3	18%	98%
	4	56%	100%
	5	48%	92%
	6	50%	86%
	7	46%	96%
	8	56%	94%
3rd order Heisenberg	3	54%	100%
	4	68%	100%
	5	70%	100%
	6	68%	86%
	7	78%	96%
	8	64%	94%

Table1 robustness hamiltonian learning.png

Qubit-efficient variational quantum algorithms

Oral - Abstract ID: 259

Adi Makmal [1]

1. *Bar Ilan University*

Despite being designed to address the limitations of the NISQ era, variational quantum algorithms (VQAs) have not yet proven useful. This is primarily due to the detrimental impact of current noise levels and the standard information encoding technique, which requires qubits number that scales linearly with problem size. Developing new information encoding schemes that are more qubit-efficient may offer solutions to both challenges. In this talk, I will describe some of our recent progress in developing qubit-efficient VQAs and discuss their potential usage within the NISQ era.

[1] Daniel Yoffe, Noga Entin, Amir Natan, and Adi Makmal. "*A Qubit-Efficient Variational Selected Configuration-Interaction Method*." arXiv preprint https://arxiv.org/abs/2302.06691 (2023).

[2] Yovav Tene-Cohen, Tomer Kelman, Ohad Lev, and Adi Makmal. "*A variational qubit-efficient maxcut heuristic algorithm*." arXiv preprint https://arxiv.org/abs/2308.10383 (2023).

Erbium doped silicon nanophotonics for scalable quantum networks

Oral - Abstract ID: 29

Kilian Sandholzer [1], ***Florian Burger*** [1], ***Johannes Früh*** [1], ***Andreas Gritsch*** [1], ***Adrian Holzäpfel*** [1], ***Jakob Pforr*** [1], ***Stephan Rinner*** [1], ***Jonas Schmitt*** [1], ***Alexander Ulanowski*** [1], ***Andreas Reiserer*** [1]

1. *Technical University of Munich, Max-Planck-Institute for Quantum Optics*

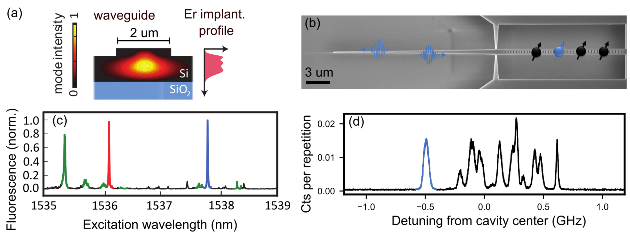
The creation of quantum links between individual units promises to enable secure communication channels and scalable quantum computation in networks [1]. Such a link is most practically realized with photons in the telecommunication regime, where transmission with minimal loss is achievable. This requires efficient photonic interfaces to local quantum devices. Long coherence times and optical transitions in the telecom regime make erbium ions integrated into solid state crystals a prime candidate [2].

To overcome the weak light-matter interaction of erbium ions, we directly implant erbium into silicon nanophotonic devices such as single-mode waveguides and photonic crystal resonators as shown in Figure (a) and (b), using tapered fiber connections to the nanostructures for efficient optical detection and control.

We achieve reliable integration of erbium in the silicon crystal at newly discovered sites, depicted in Figure (c), providing narrow inhomogeneous linewidths below 1 GHz and good optical coherence up to temperatures of several Kelvin [3]. These results have been reproduced in commercially fabricated silicon-on-insulator waveguides promising rapid transfer to technological applications [4]. In addition, we are able to resolve single ions spectroscopically by incorporating the ions into nanobeam cavities with quality factors close to 10^5 [5] as shown in Figure (d). In this structure, we observe Purcell enhancements of up to 177-fold and demonstrate coherent optical control with Rabi oscillations. Using external magnetic fields, we lift the spin-degeneracy of the ground state and find electronic spin lifetimes above one second for temperatures accessible by conventional ^{4}He cryocoolers. We initialize and read out the electronic spin state by optical means with fidelities approaching 90% [6].

Overall, these results establish erbium-doped silicon nanostructures as a promising platform for spin-photon interfaces that can be used as the basis for scalable quantum networks.

[1] S. Wehner, D. Elkouss, and R. Hanson, Science **362**, eaam9288 (2018).
[2] M. Rančić *et al.*, Nat. Phys. **14**, 50 (2018).
[3] A. Gritsch *et al.*, Phys. Rev. X **12**, (2022).
[4] S. Rinner *et al.*, Nanophotonics **12**, 3455 (2023).
[5] A. Gritsch *et al.*, Opt. Vol 10 Issue 6 Pp 783-789 **10**, 783 (2023).
[6] A. Gritsch *et al.*, arXiv:2405.05351 (2024).



Erbiumdopedsiliconnanostructures.png

Distribution of Quantum-Memory-Compatible Polarization Entanglement Over 140 km of deployed fiber

Oral - Abstract ID: 254

Eden Figueroa [1], ***Chase Wallace*** [1], ***Tsering Lodhen*** [1], ***Chi-Chih Chen*** [1], ***Leonardo Castillo*** [1], ***Anthony Del Valle*** [1], ***Dimitrios Katramatos*** [2], ***Julian Martinez*** [2]

1. Stony Brook University, 2. Brookhaven National Laboratory

Introduction. Quantum communication using entanglement promises to revolutionize current communication systems. Despite this potential, quantum networking is still in a nascent phase, and many challenges remain before the full potential of large quantum communication systems can be realized. One of the greatest challenges is the preservation of entanglement over inter-city distances while using current fiber infrastructure.

Methods. We use a multi-pronged approach to address this challenge. First, we have designed and constructed telecom entangled sources and single photon detection systems which are compatible with standard optical communication infrastructure. Second, we have developed quantum enabling technologies which allow us to manage and control the entanglement distribution process over a long-distance fiber network, including polarization compensation systems. Finally, we have established a fiber testbed that connects three laboratories in Long Island, at Brookhaven National Laboratory, Stony Brook University, and the RICOH USA Commack (CMK) co-location facility. This three-node quantum network (see Fig. 1) is our testbed to distribute entanglement over 140 kilometers of commercial fiber.

Results. We developed two-photon absorption spectroscopy setups to stabilize tunable lasers to rubidium atomic transitions in the telecom band at a wavelength of 1324 nm. Additionally, we developed a polarization entanglement source operational at telecom wavelengths. In this source, an input pump laser tuned to a wavelength of 622 nm is used to generate photon pairs centered around the 1324nm 5P1/2 to 6S1/2 transition of rubidium atoms. Entangled photon pair production is achieved with two PPLN non-linear Type-I crystals. We also developed portable on-line-controlled superconducting nanowire single photon detector systems, allowing for quantum state characterization for the transmitted entangled state over distantly located nodes. We will report on our current experiments aimed at characterizing the quality of the distributed entanglement over long distances. This includes measuring the non-local quantum state tomography of the transmitted state after real time polarization compensation and the demonstration of Bell Inequality violation by non-locally measuring the S parameter associated with the transmitted entangled state.

Discussion. Our long-term goal is to demonstrate entanglement swapping using four long distance quantum channels over 250km, paving the way for a quantum repeater.

A quantum network made of two dissimilar and independent cold atomic quantum nodes

Oral - Abstract ID: 157

Felix Hoffet [1], *Jan Lowinski* [1], *Lukas Heller* [1], *Auxiliadora Padron-Brito* [1], *Hugues de Riedmatten* [1]

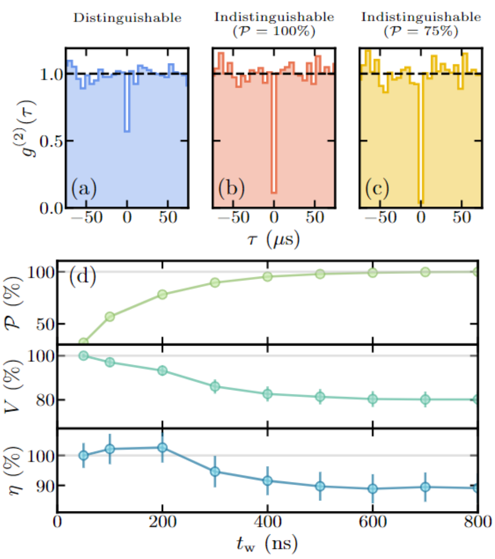
1. ICFO - The Institute of Photonic Sciences

In the field of quantum communication research, achieving indistinguishability of single photons emitted from independent quantum nodes is essential for long-distance entanglement distribution. Bell-state measurements, crucial for successful entanglement distribution, have their fidelity bounded by the visibility of two-photon interference. Given that different platforms excel at specific operations, quantum networks are anticipated to consist of heterogeneous nodes. Consequently, it is vital to develop the capability to interface these diverse nodes effectively.

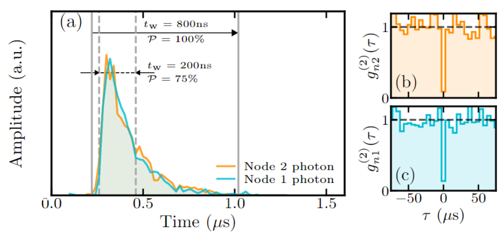
In this work, we demonstrate two-photon interference with an exceptionally high degree of indistinguishability using single photons emitted from two distinct and independent cold-atomic quantum nodes. The first node operates as a quantum repeater link, leveraging the probabilistic generation of atom-photon entanglement and featuring an in-built quantum memory for network synchronization. The second node, consisting of a fully-blockaded Rydberg cold atomic ensemble, serves as a deterministic photon source. We use specific techniques to shape our photons and mode-match them in all degrees of freedom for long periods of time.

Ultimately, we demonstrate an indistinguishability of 89% within a temporal window that includes all photon counts, without any noise subtraction. By reducing the temporal window to include only 75% of the photon counts, the indistinguishability increases to 95%. To our knowledge, these results set a new benchmark for hybrid networks.

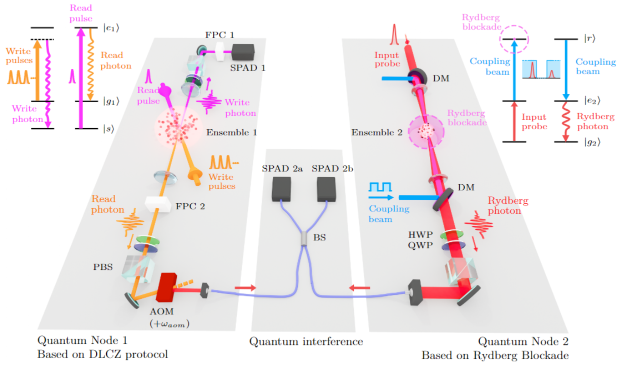
This experiment paves the way for interconnecting hybrid quantum nodes through entanglement. Notably, it demonstrates that high fidelities of Bell-state measurements between photons from different platforms can be achieved without compromising the efficiency of the measurement. This capability is essential for developing a scalable and fully functional quantum network.



Hom results.png



Photons.png



Dif setup.png

Multi-color continuous variables quantum teleportation: from near-infrared to telecommunications' L-band

Oral - Abstract ID: 208

Felipe Gewers [1], *Gabriel Borba* [2], *Beatriz Moura* [2], *Tulio Brito Brasil* [3], *Rayssa Andrade* [4], *Renné Araujo* [5], *Igor Koniecznia*k [6], *Paulo Nussenzveig* [2], *Marcelo Martinelli* [2]

1. Humboldt University of Berlin, 2. São Paulo University, Brazil, 3. University of Copenhagen, 4. Technical University of Denmark, 5. Federal University of Santa Catarina, 6. Federal University of Paraná

Quantum teleportation is the basis for numerous quantum applications, with the continuous variables (CV) protocol having the significant advantage of being unconditional and deterministic, allowing every input state to be teleported. Quantum channels connecting different wavelengths can be used in quantum hybrid networks, linking several quantum platforms with distinct purposes that interact with light at specific wavelengths.

Our approach to building these continuous variable quantum channels is through quantum teleportation between the fields' quadratures at different frequencies. For that, we used a triply resonant parametric optical oscillator (TROPO), in the above threshold regime, as a source of two-mode entangled states. Pumping with an Nd:YAG second harmonic laser (532nm), we generated intense beams at near-infrared (793nm) and telecommunications' L-band (1616nm), with a frequency separation of more than one octave. A scheme of the experimental setup is illustrated in Figure 1.

Here we report the first demonstration of a multi-color CV quantum teleportation protocol between intense beams sideband modes that violate the classical limit fidelity. Figure 2 presents the protocol results for a coherent input state with non-zero mean quadrature values, without the corrections for Alice and Victor's detection losses. We achieved a fidelity of 56.2(5)% for the protocol's gain of 0.970(3), indicating a violation of the classical limit of 50% by more than twelve standard deviations. We hope this demonstration will inspire the development of connecting devices in quantum hybrid systems.

1. A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble, and E. S. Polzik, "Unconditional quantum teleportation," science 282, 706–709 (1998).

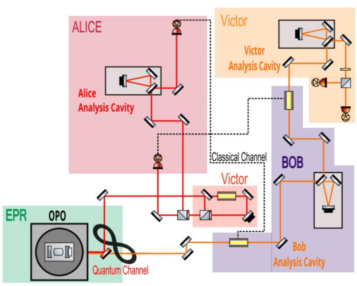


Fig. 1: Scheme of the multi-color unconditional teleportation experimental setup.

Figure 1 - setup scheme.jpg

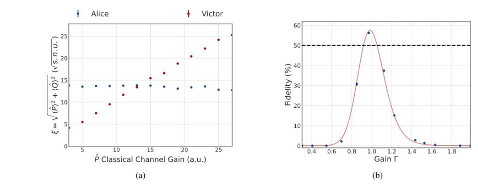


Fig. 2: a) The average value of the sideband states measured at the stations of Alice and Victor. b) The measured fidelity for the coherent input state without loss corrections. The fidelity closest to unitary gain is 56.2(5)% with a gain of $\Gamma = 0.970(3)$.

Figure 2 - teleportation results.jpg

Universal scheme to self-test extremal quantum measurements (and any mixed state)

Oral - Abstract ID: 71

Shubhayan Sarkar [1]**, *Alexandre Orthey*** [2]**, *Remigiusz Augusiak*** [2]

1. *Université libre de Bruxelles,* ***2.*** *Center for Theoretical Physics PAS*

The recent rapid development of quantum technologies has defined an extraordinary and urgent problem: how to certify correct functioning of quantum devices. A particular question that fits this general problem is how to certify that the devise operates on a particular quantum state and performs particular quatum measurements on it.

Among various approches that allow to tackle the above question is the device-independent certification, which does not require making any assumptions about the devices under study, except that they obey the rules of quantum theory. The main resource enabling device-independent certification is Bell nonlocality, which is revealed in quantum systems by violations of Bell inequalities. The strongest and most complete form of device-independent certification is self-testing which allows to almost fully (up to certain well-known equivalences) determine the underlying quantum state and measurements.

While schemes have been proposed to self-test all pure bipartite and multipartite entangled states, and real local rank-one projective measurements, little has been done to certify composite or non-projective measurements. On the other hand, it is not possible to certify mixed entangled quantum states based merely on violations of Bell inequalities. By employing the framework of quantum networks, we propose a scheme that can be used to self-test (up to complex conjugation) all extremal quantum measurements, including the projective ones. Interestingly, the scheme allows also for device-independent certification of mixed quantum states with postselection. The quantum network considered in our work is the simple star network, which is implementable using current technologies. For our purposes, we also construct a family of Bell inequalities that can be used to self-test the two-dimensional tomographically complete set of measurements with an arbitrary number of parties.

This presentation is based on the article [S. Sarkar, A. C. Orthey, Jr., R. Augusiak, A universal scheme to self-test any quantum state and measurement, arXiv:2312.04405].

Distributing quantum correlations through local operations and classical resources

Oral - Abstract ID: 90

Adam Hawkins [1], ***Mauro Paternostro*** [2]

1. *Queen's University Belfast,* ***2.*** *Universita degli Studi di Palermo*

Distributing quantum correlations to each node of a network is a key aspect of quantum networking. In most tasks, the resource we wish to distribute is quantum entanglement. However, measures of entanglement do not capture all the quantum correlations of a system. These can be characterised by other measures which may be non-zero in separable states. A popular measure is the quantum discord, which, in its original definition, arises due to the differing, classically equivalent definitions of the mutual information. The full usefulness of 'discordant' separable states remains to be seen, however so far discord has been shown to be a resource in bipartite entanglement activation, remote state preparation and quantum cryptography [1,2,3].

In a paper by A. Streltsov [4], it has been shown that certain local, non-unitary channels acting on a single qubit can generate discord in a multiqubit system. Here, we take this idea and introduce a protocol whereby these quantum correlations can be distributed to nodes of a network (initially in a pure, uncorrelated state) through local operations, namely unitary operations and projective measurements. Additionally, the resource state possesses only classical correlations, and the distribution of discord does not rely on postselection as the amount of discord relies only on the basis used, not the measurement outcomes. We have further shown that the discordant resource state of the B92 quantum key distribution protocol can be obtained with 100% probability, allowing the protocol to be performed in the case of Alice and Bob being supplied the state by a trusted third party, without the third party knowing which of the pure states they will obtain.

We also demonstrate that the protocol is robust to the noise applied to the initial state, as well as showing that the global quantum correlations scales very well with the number of nodes in the network.

[1] M. Piani *et al.*, Phys. Rev. Lett. **106** (2011)

[2] B. Dakić *et al.*, Nat. Phys. **8**, 666 (2012)

[3] S. Pirandola. Sci. Rep. **4**, 6956 (2014)

[4] A. Streltsov *et al.*, Phys. Rev Lett. **10**7, 170502 (2011)

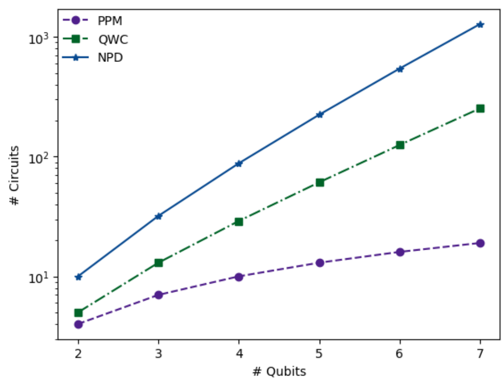
Towards enhancing quantum expectation estimation of matrices through partial Pauli decomposition techniques and post-processing

Oral - Abstract ID: 34

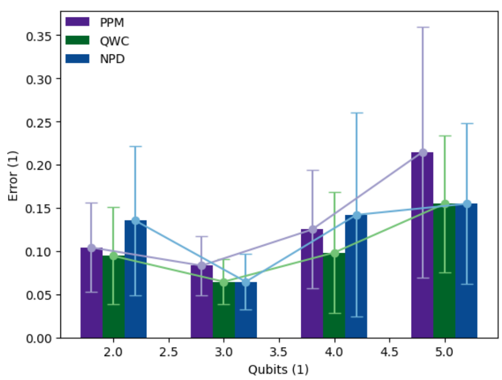
dingjie lu [1], *Yangfan Li* [1], *Dax Koh Enshan* [1], *Zhao Wang* [1], *Jun Liu* [1], *Zhuangjian Liu* [1]
1. *Institute of High Performance Computing*

We introduce an approach for estimating the expectation values of arbitrary \$n\$-qubit matrices \$M \in \mathbb{C}^{2^n\times 2^n}\$ on a quantum computer. In contrast to conventional methods like the Pauli decomposition that utilize \$4^n\$ distinct quantum circuits for this task, our technique employs at most \$2^n\$ unique circuits, with even fewer required for matrices with limited bandwidth. Termed the \textit{partial Pauli decomposition}, our method involves observables formed as the Kronecker product of a single-qubit Pauli operator and orthogonal projections onto the computational basis. By measuring each such observable, one can simultaneously glean information about \$2^n\$ distinct entries of \$M\$ through post-processing of the measurement counts. Our technique utilizes efficient binary arithmetic to derive the required quantum circuits, making the overall approach highly efficient in terms of term grouping and circuit construction. Our strategy is a universal and straightforward-to-understand approach for the expectation evaluation problem with at most \$n-1\$ CNOT gates required to construct the necessary quantum circuits, making the overall approach highly efficient in terms of quantum resources. This reduction in quantum resources is especially crucial in the current noisy intermediate-scale quantum era, offering the potential to accelerate quantum algorithms that rely heavily on expectation estimation, such as the variational quantum eigensolver and the quantum approximate optimization algorithm.

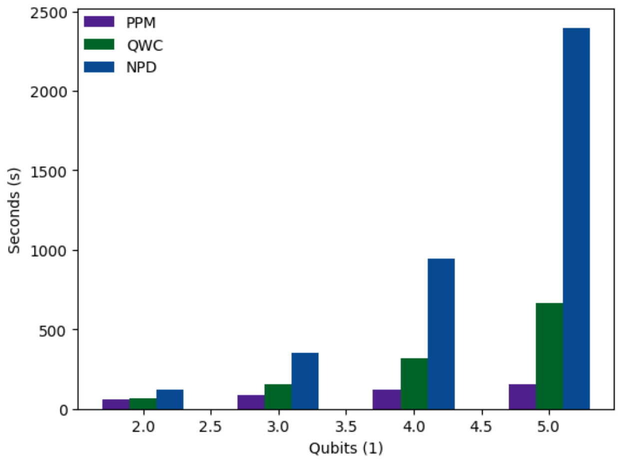
To validate the effectiveness of our approach, we tested the number of unique circuits needed for multiple cases, which agrees will with the theoretical bounds. More importantly, we have tested it extensively on real quantum hardware provided by IBM. This includes comprehensive test cases covering single qubit states with symmetrical matrices, \$\bra{\phi} M \ket{\phi}\$ as well as double qubit states with symmetrical matrices \$\bra{\phi} M \ket{\psi}\$, and the results obtained match the expected error margin, demonstrating the practical applicability of our method.



Qubits vs circuits.png



Qubits vs error.png



Qubits vs time.png

Dissipative variational quantum algorithms for Gibbs state preparation

Oral - Abstract ID: 213

Yigal Ilin [1], *Itai Arad* [2]

1. Electrical and Computer Engineering, Technion Israel Institute of Technology, 2. Centre for Quantum Technologies, National University of Singapore

In recent years, variational quantum algorithms (VQAs) have been the center of an extensive research effort due to their adaptability and efficiency on near-term quantum hardware. The variational framework leverages a significant part of the computation to a classical side, thereby allowing for a much shallower quantum circuits. Additionaly, their variational nature offers some resilience against coherent errors, which are prevalent in today's quantum hardware.

Here, we extend the toolbox of VQAs by considering *dissipative* operations such as probabilistic and RESET gates. Specifically, we study the performance of VQAs in which, in addition to unitary gates, one can apply the gate R(p,θ), which with probability p, resets qubit i to the state $|\theta\rangle\langle\theta|$. Our approach has two important advantages: 1) The inclusion of dissipative operations allows for the creation of mixed states, eliminating the need for ancilla qubits when targeting mixed states. 2) Dissipative variational circuits can mitigate non-coherent errors, similar to how unitary VQAs mitigate coherent errors, resulting in better performance in the presence of noise.

We demonstrate these advantages through classical simulations of variational Gibbs state preparation, a central problem in quantum computation and information of both theoretical and practical importance.

Focusing on periodic 1D models, we demonstrate that a simple brick-wall architecture with dissipative gates matches state-of-the-art results in the noiseless case and significantly outperforms other coherent variational algorithms in the noisy case [Y. Wang et al., Phys. Rev. Applied 16, 054035; M. Consiglio et al., arXiv:2303.11276]. In 'figure-1.jpg', we show the performance of our ansatz for the Ising model with transverse field values h=0.5,1,1.5, and for the XY model with anisotropy parameters γ=0.1,0.5,0.9 with n=2,4,6 qubits. In 'figure-2.jpg', we compare the performance of our architecture against the ansatz in Ref. [Y. Wang et al., Phys. Rev. Applied 16, 054035] for n=6 qubits for the XY model with γ=0.5. Both figures present noisy and noiseless cases.

Our work lays the foundation for future VQA algorithms that seamlessly integrate dissipative error mitigation, and can therefore take better advantage of current and near future hardware.

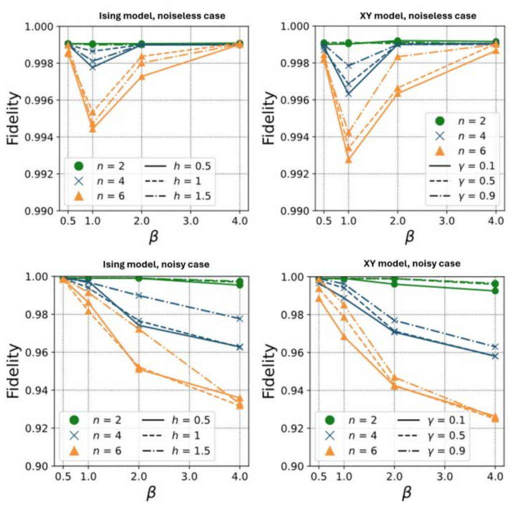


Figure-1.jpg

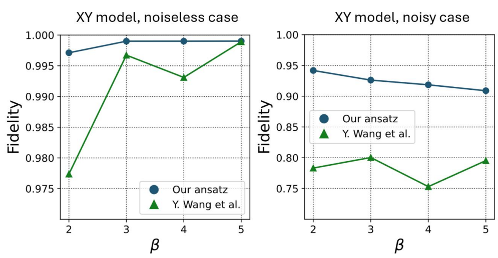


Figure-2.jpg

Quantum Enhanced Inference of Conditional Future Probabilities for Stochastic Processes

Oral - Abstract ID: 127

Jianjun Chen [1], *Chengran Yang* [1], *Ariel Neufeld* [1], *Jayne Thompson* [2], *Mile Gu* [1]

*1. Nanyang Technological University, 2. Institute of High Performance Computing, Agency for Science, Technology, and Research (A*STAR) Singapore*

Introduction

Analytical modeling, combined with Monte Carlo sampling, helps assess risks by quantifying probabilities of rare events like financial crashes and earthquakes. Ideal models should provide accurate predictions with minimal memory cost. Quantum models have shown superior memory efficiency compared to the best classical models, offering potential applications in various fields. This paper presents a novel end-to-end algorithm integrating quantum modeling with quantum amplitude estimation (QAE), improving performance, particularly for NISQ computers. Our algorithm achieves two key improvements: reduced systematic bias and statistical variance in probability estimations, surpassing classical limits.

Methods

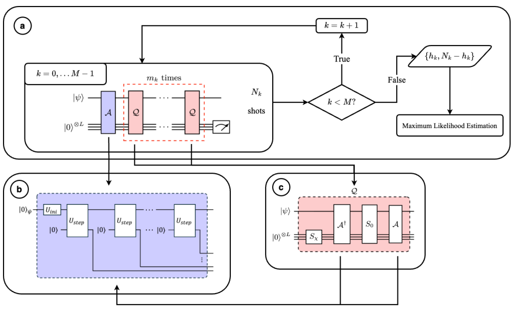
We model a stochastic time series process that produces a time series sequence of observables, which, given a present time, can be partitioned into past and future segments. The objective is to estimate the probability of a certain future given the past. The stochastic process is modelled by a finite state machine, which is converted to a quantum model with dynamics encoded by custom unitaries. The QAE method used is the Maximum Likelihood amplitude estimation (MLAE) method. We tested multiple schedules, including a new schedule, and evaluated the estimation accuracy using the root-mean-square error (RMSE).

Results

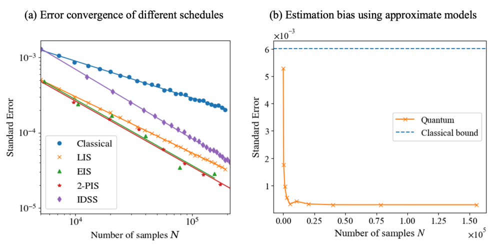
The proposed algorithm (see algorithm_illustration) reduces the gate cost from an exponential to linear dependence on the sequence length. It also achieves a quadratic scaling advantage in sample size for probability estimation (see simulation_results (a)) as compared to classical methods, in which a new schedule catered to NISQ computers is also used. We demonstrated a bias reduction in estimation results under restricted memory settings when using quantum models as compared to classical ones (see simulation_results (b)).

Discussion

Our new algorithm leverages both quantum models and QAE to offer several key benefits. By reducing the gate costs while still providing a quadratic speedup, the algorithm significantly enhances computational efficiency in probability estimation, making it suitable for near-term quantum computers. The bias reduction allows for further improvements in estimation accuracy, which is especially useful for small quantum computers. The end-to-end nature of our algorithm extends its benefit to industry and academia.



Algorithm illustration.png



Simulation results.png

Hardware-Tailored Circuits for Quantum Chemistry, Tomography, Stabilizer State Preparation, and Logical Clifford Gates for Quantum Error-Correcting Codes

Oral - Abstract ID: 91

Daniel Miller [1] ***, Kyano Levi*** [1] ***, Eric J. Kuehnke*** [1] ***, Jens Eisert*** [1]
1. *Freie Universität Berlin*

Introduction

Noise is the main obstacle hindering practical quantum advantage. While error correction may solve this problem eventually, large-scale fault-tolerant devices are decades away. This is why error mitigation techniques have recently attracted much attention; they can remove noise at the cost of an exponential sampling overhead.

When designing new quantum circuits, the main figure of merit predicting the cost is the number of CNOT gates. To limit the scope, researchers are mostly content with optimizing the **scaling** of the CNOT count, e.g., optimizing an n-qubit circuit with CNOT count from O(n^3) to O(n^2). Optimizing the constants, however, has not received enough attention.

Results

In this talk, I want to present our new research line "Hardware-Tailored Circuits", e.g., ArXiv:2203.03646, and three follow-up papers in progress. Our goal is to get rid of as many CNOTs as possible. As the fidelity of a quantum circuit is exponentially suppressed in the number of CNOT gates, improving this constant will make error mitigation techniques exponentially more efficient (which does not contradict the fact that error mitigation remains exponentially costly).
By exploiting application-specific freedoms (see below) and incorporating hardware-connectivity constraints into our method, we can often reduce the final number of CNOTs by many orders of magnitude.

Observables given as a linear combination of Pauli operators can be measured via a selection of readout circuits corresponding to a Pauli grouping into commuting subsets. While one often cannot remove CNOTs in a given readout circuit, one can replace the entire set of circuits with a new, better one.
For logical Clifford gates on quantum error-correcting codes, the physical circuit must map logical Pauli operators to the correct logical Pauli operators modulo stabilizers. This gauge freedom is naturally compatible with our approach.

Discussion
Our approach addresses a key challenge of practical quantum computing. It is compatible with most other methods, flexible, general, and honest.

Methods

We combine the stabilizer formalism, algebraic geometry, integer optimization (exploiting new functionalities of the Gurobi optimizer), and graph theory in a new way that enables the construction of ultra-short Clifford circuits. A core feature is to incorporate hardware connectivity constraints.

Two-cavity mediated photon-pair emission by a single atom

Oral - Abstract ID: 49

Pau Farrera [1], _Gianvito Chiarella_ [1], _Tobias Frank_ [1], _Gerhard Rempe_ [1]
1. *Max Planck Institute of Quantum Optics*

Cavity-QED provides a powerful platform for quantum information processing, including efficient photonic qubit generation, storage and processing. Recently the attention focusses in increasing both the number of emitters coupled to the cavity, and the number of cavity modes coupled to the emitter. Miniaturized fiber cavities allow having multiple independent resonators coupled to the same emitter in the high atom-photon cooperativity regime, and provide room for scalability. In addition one can independently tune each cavity to the desired resonant wavelength and cooperativity regime. Here we report on a source based on a single three-level atom coupled to two optical fiber-cavities in a ladder configuration. We efficiently generate in-fiber photon pairs and study their temporal correlation properties. We also study theoretically the regime where both cavities are strongly coupled to the atom. ln this parameter regime we observe that an atom in the upper state can be transferred to the ground state without populating the intermediate state, while generating photons in both cavities. Such a process is analogous to STIRAP but mediated by the vacuum field in both cavities. We finally consider parameters that allow to generate pairs of indistinguishable single photons.

Entanglement of spin-wave on-demand solid-state quantum memories for quantum repeater links

Oral - Abstract ID: 124

Félicien Appas [1], Jonathan Hänni [1], Alberto Rodriguez-Moldes Sebastian [1], Sören Wengerowsky [1], Dario Lago-Rivera [1], Markus Teller [1], Samuele Grandi [1], Hugues de Riedmatten [1]

1. *ICFO - The Institute of Photonic Sciences*

1. Introduction

Heralded entanglement of shared excitations between two remote matter nodes is a primitive for quantum repeater links. This type of architecture relies on quantum nodes consisting of sources of entanglement and quantum memories (QM). Entanglement is created by heralding at intermediate locations via the detection of a telecom photon, then stored in quantum memories and manipulated locally. Some of the main requirements for practical quantum links are high heralding rates with photons at telecom wavelength and multiplexed operation. Most importantly, the ability to retrieve stored excitations on-demand is a crucial feature for synchronization of repeater links across a network.

2. Methods

In this talk, we report on recent progress towards remote entanglement of two on-demand solid-state quantum memories using cavity-enhanced non-degenerate spontaneous parametric downconversion (cSPDC) sources and Pr^{3+} rare-earth doped QM. A sketch of the experimental setup is presented in Figure 1. The sources emit entangled photon pairs with one idler photon in the telecom band and one signal photon at 606 nm, that is stored in a Pr^{3+} QM. Upon detection of an idler click at one of the detectors of the central station, an entangled state is heralded at the memories. To verify entanglement, it is necessary to show that we operate in the single excitation regime and that the excitation is in a coherent superposition of the two memories

3. Results

By retrieving the excitations from the QMs and interfering the photons at a beam splitter, state tomography can be carried out. Figure 2. shows the conditional single-photon interference fringes measured at the signal detectors proving quantum coherence between the two spin-wave QM of Alice and Bob. The estimated concurrence of the detected heralded state is of $(4.95 \pm 2.12) \times 10^{-5}$ with single photon suppression $h_c = 0.295 \pm 0.028$ and associated total heralding rate of around 540 cps indicating the successful heralding of a genuinely entangled state at high rate.

4. Discussion

Together with the high multiplexing capability of Pr^{3+} QM, our system combines most requirements for efficient quantum repeater links thus paving the way towards real-world deployment of quantum networks.

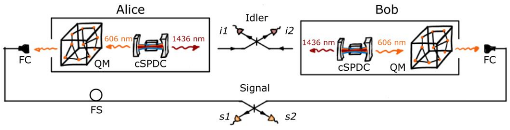


Figure 1.jpg

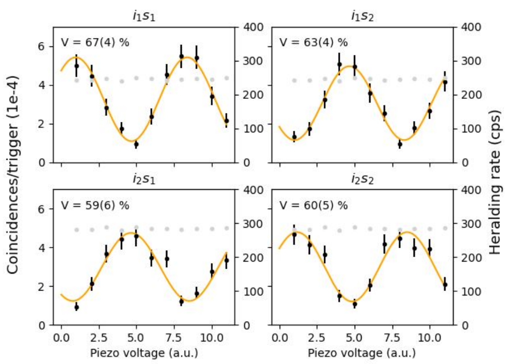


Figure 2.jpg

Experimental demonstration of frequency dependent Einstein-Podolsky-Rosen steering with a negative mass spin oscillator

Oral - Abstract ID: 147

Jun Jia [1], Valerii Novikov [1], Andrea Grimaldi [1], Maimouna Bocoum [1], Emil Zeuthen [1], Tulio Brito Brasil [1], Eugene Polzik [1]

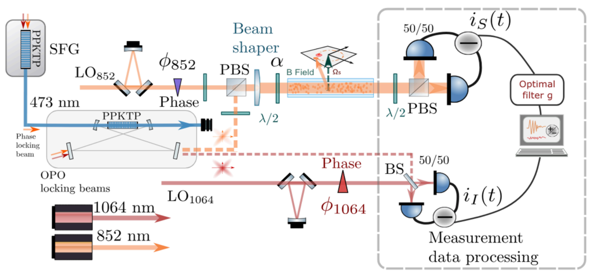
1. *University of Copenhagen*

Atomic systems offer unique advantages explored in quantum networks to store and process quantum information. On the other hand, one of the most practical applications of atom-light interaction is quantum sensing. In this talk, I will describe experimental results from integrating a macroscopic quantum atomic system with a two-color Einstein-Podolsky-Rosen (EPR) light state for quantum enhanced sensing. The experiment is grounded in a proposal for quantum enhancement of gravitational wave detectors [1].

The experimental setup (Fig 1) involves two systems. The atomic system, a room temperature quantum noise limited spin ensemble [2], prepared as a negative mass oscillator enables quantum back-action-evading measurements [3]. The EPR source, a nondegenerate parametric oscillator, generates high-purity EPR states at 1064 nm and 852 nm [4]. The protocol includes the EPR state preparation, interaction of the 852 nm beam with the spin oscillator, and subsequent homodyne detection for post-processing characterization.

Post-interaction with the atomic oscillator the 852 nm beam quantum state is modified. The state is rotated and carries the quantum back-action, depending on the oscillator frequency and interaction strength, parameters easily varied by the bias magnetic field and probe optical power. We demonstrate that a frequency dependent squeezed state emerges by conditioning the detection on the 1064 nm beam with information from the EPR correlated atom-light interaction. Scanning the 1064 nm homodyne detection angle reveals quantum state steering at different sideband frequencies near the spin Larmor frequency. This suggests the potential for quantum state manipulation transfer by atoms to another optical frequency, thereby extending quantum enhanced sensing to a variety of systems exhibiting similar oscillator dynamics.

[1] F. Ya. Khalili and E. S. Polzik. Phys. Rev. Lett. 121, 031101 (2018).
[2] J. Jia et al., Nat. Commun. 14, 6396 (2023).
[3] C. B. Møller et al., Nature 547, 191–195 (2017).
[4] T. B. Brasil et al., Nat. Commun.13, 4815 (2022).



Experimental setup.png

Interference of photons from independent hot atoms

Oral - Abstract ID: 182

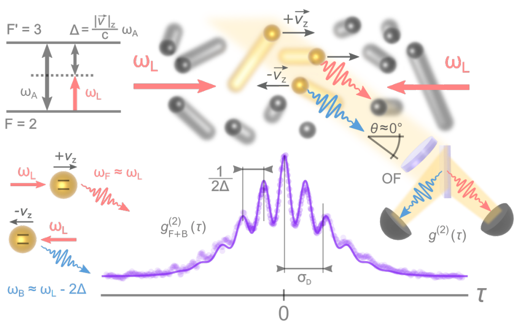
Jaromír Mika [1], *Stuti Joshi* [1], *Robin Kaiser* [2], *Lukáš Slodička* [1]

1. Department of Optics, Palacký University, 2. Université Cote d'Azur, CNRS, INPHYNI

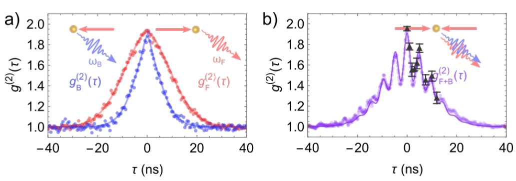
We propose and experimentally demonstrate the scheme for observation of interference of photons from independent warm atomic vapors. While the random phase fluctuations of the scattered light caused by a large thermal motion and Doppler broadening prevent direct observability of the phase coherence, the stable frequency difference between scattered photons provides strong periodic modulation in the temporal second order correlation function $g^{(2)}(\tau)$ with the period given by their relative frequency difference.

The scheme for observation of interference of light from warm atomic vapors is displayed in Figure 1. It depicts the elementary case of excitation of ensembles of two-level atoms and corresponding observable frequency shifts for forward (F) and backward (B) scattered photons. The excitation laser at the frequency ω_L detuned by Δ from the atomic transition scatters on the particular velocity class of atoms along its propagation direction. In the forward scattering, the corresponding Doppler shift Δ_D effectively compensates and photon frequency remains unchanged up to the residual Doppler broadening with a linewidth σ_D, given by the scattering angle θ. The scattered photons exhibit chaotic statistics characterized by near-ideal photon bunching $g^{(2)}(0) \approx 2$ (Figure 2 a). The retroreflected laser scatters on atoms with opposite directions of motion but with the same velocity magnitude. The corresponding backward-scattered photons are frequency-shifted by $\approx\Delta$ with respect to an observer in the frame moving with the atomic scatterer and by $\approx 2\Delta$ to the forward-scattered photons. The photons are collected in the same optical mode and measurement of the second-order correlations $g^{(2)}(\tau)$ provides observable coherent frequency beating with a period of $1/(2\Delta)$ (Figure 2 b).

Direct applicability for the estimation of the laser frequency detuning from the atomic transition resonance promises diverse adaptations in atomic and molecular spectroscopy, with the achieved frequency resolution reaching below 1 MHz. Modification to the interference of the back-scattered field with the excitation laser beam will allow for fast frequency stabilization schemes with an intrinsic offset tunability within the large Doppler-broadened spectra of hot atomic vapors.



1.png



2.png

Quantum Control via Enhanced Shortcuts to Adiabaticity

Oral - Abstract ID: 139

Andreas Ruschhaupt [1]
1. *School of Physics, University College Cork*

The fast and robust control of quantum states is of the utmost importance for all quantum technologies. Shortcuts to Adiabaticity (STA) [1] are such fast and robust quantum control protocols motivated by adiabatic processes and mainly derived using analytical techniques. However, there are still quantum systems where these STA methods cannot be applied. Therefore, I will present a new technique for such scenarios, called "Enhanced Shortcuts to Adiabaticity" (eSTA) [2-4]. This new method works for previously intractable Hamiltonians by providing an easy to calculate analytical correction to existing STA protocols. After giving some introductory overview about STA, I start with a presentation of the formalism of eSTA. I show then the applications of eSTA to the manipulation of an internal atomic state beyond the rotating-wave approximation, to the transport of a neutral atom in an anharmonic optical trap and to the transport of two trapped ions in an anharmonic trap [2,3]. Moreover, I discuss the application of eSTA to the expansion of both a Gaussian trap and accordion lattice potential [4] as well as applications of eSTA to spin squeezing in internal bosonic Josephson junctions [5,6]. Finally, I show the proposal of a novel quantum heat engine based on a spin-orbit- and Zeeman coupled Bose-Einstein [7,8] with the outlook to combine enhanced shortcuts-to-adiabaticy and quantum thermodynamics towards Shortcut-Enhanced Quantum Thermodynamics.

References:
[1] D. Guéry-Odelin, A. Ruschhaupt, A. Kiely, E. Torrontegui, S. Martínez-Garaot and J. G. Muga, Rev. Mod. Phys. 91, 045001 (2019)
[2] C. Whitty, A. Kiely and A. Ruschhaupt, Phys. Rev. Research 2, 023360 (2020)
[3] C. Whitty, A. Kiely and A. Ruschhaupt, Phys. Rev.A 105, 013311 (2022)
[4] C. Whitty, A. Kiely and A. Ruschhaupt, J. Phys. B: At. Mol. Opt. Phys. 55, 194003 (2022)
[5] M. Odelli, V. M. Stojanović and A. Ruschhaupt, Phys. Rev. Applied 20, 054038 (2023)
[6] M. Odelli, A. Ruschhaupt and V. M. Stojanović, Phys. Rev. A 110, 022610 (2024)
[7] J. Li, E. Ya Sherman and A. Ruschhaupt, Phys. Rev. A 106, L030201 (2022)
[8] J. Li, E. Ya Sherman and A. Ruschhaupt, New. J. Phys. 26, 053031 (2024)

Fig sta.png

Mirror-mediated ultralong-range dipole-dipole interactions for quantum sensing

Oral - Abstract ID: 26

Almut Beige [1], ***Nicholas Furtak-Wells*** [1], ***Benjamin Dawson*** [1], ***Gin Jose*** [1]

1. *University of Leeds*

In three dimensions, dipole-dipole interactions which alter atomic level shifts and spontaneous decay rates only persist over distances comparable to the wavelength of the emitted light. To provide novel tools for quantum technology applications, like quantum sensing, many attempts have been made to extend the range of these interactions. In this paper we show that such an extension can be achieved with the help of partially transparent asymmetric mirror interfaces. Suppose two atoms are placed on opposite sides of the interface, each at the position of the mirror image of the other. In this case, their emitted light interferes exactly as it would when the atoms are right next to each other. Hence their dipole-dipole interaction assumes an additional maximum, even when the actual distance of the atoms is several orders of magnitude larger than their transition wavelength.

Metrological approach to multipartite entanglement

Oral - Abstract ID: 129

Eloi Descamps [1], *Nicolas Fabre* [2], *Arne Keller* [1], *Perola Milman* [1]
1. Université Paris Cité, 2. Telecom Paris, Institut Polytechnique de Paris

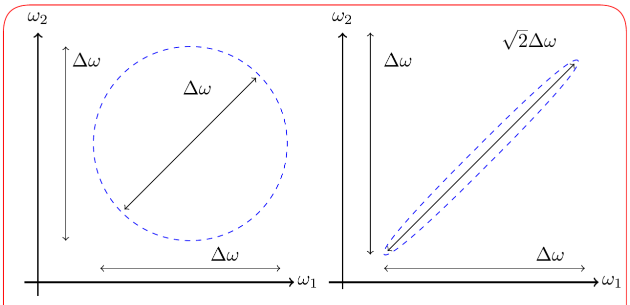
Entanglement is pivotal in quantum mechanics, offering profound implications for foundational studies and practical applications in quantum information science. While bipartite entanglement has been extensively explored, further studies, notably in the realm of multipartite entanglement, are essential for advancing our understanding of quantum systems.

Our research aims to study multipartite entanglement from a metrological perspective. Our approach's originality lies in using the time-frequency degree of freedom of single photons. Our initial study analyzes the role of the spectrum in enhancing the precision of time parameter estimation. We reveal that spectral entanglement can be leveraged beyond merely utilizing intensity resources to achieve quantum advantage. This contrasts with the conventional view in continuous variables, where spectral properties are typically regarded as classical resources. Our findings indicate that the spectral entanglement required for quantum advantage in parameter estimation can be described as entanglement along a collective variable, which can be intuitively understood through a graphical representation.

Building on these insights, we propose that this form of entanglement can be harnessed for additional applications. In subsequent work, we demonstrate the application of this perspective in constructing more robust error correction codes based on a time-frequency comb state, specifically enhancing the Gottesman-Kitaev-Preskill (GKP) code. Analogous to the metrological setting, where entanglement provides a quadratic improvement in measurement precision over separable states, we show that our approach can quadratically enhance the robustness of the GKP code against time-frequency shift errors concerning the number of photons used.

It turns out that similar types of entanglement have been investigated in other systems, such as finite-dimensional ones. To provide a more comprehensive understanding, we formulate a general unifying framework that introduces a new quantifier of multipartite entanglement. This general presentation and the geometrical picture inherent to the time-frequency setting illuminate existing results in a novel light. Additionally, this framework is particularly relevant for the concept of k-entanglement, a specific form of multipartite entanglement.

In conclusion, our work advances the theoretical understanding of multipartite entanglement and provides practical tools for enhancing precision in quantum measurements.



Schematics of different spectrums. The left one corresponds to a product state while the right one is distributed along a diagonal. One can observe that, at constant local variance, the right figure achieves a larger spectral variance in the diagonal direction than the left one.

Spectrum of different two photon states.png

Entanglement-preserving single-pair measurement of the Bell parameter

Oral - Abstract ID: 32

Salvatore Virzì [1], Enrico Rebufello [1], Francesco Atzori [2], Alessio Avella [1], Fabrizio Piacentini [1], Rudi Lussana [3], Iris Cusini [3], Francesca Madonini [3], Federica Villa [3], Marco Gramegna [1], Eliahu Cohen [4], Ivo Pietro Degiovanni [5], Marco Genovese [5]

1. INRIM - Istituto Nazionale di Ricerca Metrologica, strada delle Cacce, 91 10135 Torino, Italy, 2. INRIM - Istituto Nazionale di Ricerca Metrologica, strada delle Cacce, 91 10135 Torino, Italy; Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy, 3. Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Piazza Leonardo da Vinci 32, 20133 Milano, Italy, 4. Faculty of Engineering and the Institute of Nanotechnology and Advanced Materials, Bar Ilan University, Ramat Gan, Israel, 5. INRIM - Istituto Nazionale di Ricerca Metrologica, strada delle Cacce, 91 10135 Torino, Italy; INFN, sezione di Torino, via P. Giuria 1, 10125 Torino, Italy

Introduction

In 1964, J. S. Bell introduced the Bell inequalities, turning a philosophical debate into a physical experiment capable of extracting the true nature of correlations within physical systems, opening, in turn, several research fields spanning from quantum mechanics foundations to quantum technologies. Over the past decades, the scientific community has thoroughly investigated Bell inequalities, eventually achieving loophole-free tests. However, some issues persist. For instance, the wavefunction collapse and Heisenberg uncertainty principle forbid performing all the measurements needed for evaluating the entire Bell parameter on the same quantum system with the usual projective measurements.

To overcome these limitations, we demonstrate a method able to estimate the entire Bell parameter from each entangled pair while preserving entanglement, ensuring its availability for further applications.

Methods

This method relies on weak measurements, a measurement procedure in which a tiny coupling between the observed system and the measurement device allows estimating the observables of interest while preventing the state from collapsing. This allows to measure multiple observables on the same quantum state, extracting all the correlations needed to evaluate the full Bell parameter from each pair (although with a large uncertainty).

Results

Our results obtain an average Bell parameter in agreement with the Tsirelson bound and highlighting a violation of the classical bound above 5 sigmas. Furthermore, we show how our procedure preserves the entanglement between the two photons, leaving it available for other purposes.

Discussion

Our experiment provides new insights into understanding the foundations of quantum mechanics, such as the concept of counterfactual definiteness. Furthermore, the entanglement certification leaves the quantum state almost unaltered, ready to be exploited for other quantum information protocols or quantum foundations investigations, such as testing novel bounds intertwining local and nonlocal correlations.

Photonic quantum technologies: from integrated quantum devices to designing large complex system

Oral - Abstract ID: 271

Christine Silberhorn [1]

1. Paderborn University, Germany

Quantum technologies promise a change of paradigm for many fields of application. However, their implementation often requires advanced setups of high complexity, because scaling photonic quantum systems many controllable modes and input states with many photons.

Here we review different approaches for the experimental implementation of future multidimensional photonic quantum systems, including Gaussian Boson sampling and time frequency multiplexing. Our systems comprise non-linear integrated quantum devices, source engineering and pulsed temporal modes as well as time-multiplexed architectures.

Non-linear integrated quantum devices with multiple channels and tailored functionalities are required for implementation of suitable quantum circuits, which include high-performance quantum sources and fast electro-optic modulations on compact monolithic structures. We investigate the use of thin-film lithium niobate circuits together with new concepts to establish a toolbox of integrated devices tailored for quantum applications.

For the engineering of future-oriented quantum light structures, pulsed photon temporal modes are an attractive platform for advanced quantum information encoding. They are defined as field-orthogonal superposition states and constitute a high-dimensional quantum system, which is naturally present in current nonlinear quantum light sources. Here, the control of these temporal modes is key for the realization efficient quantum network architectures based on quantum inference.

Time-multiplexed quantum systems allow for the efficient implementation of scalable and configurable networks with many modes and dynamic control of the underlying graph structures. This enables, e.g. feed-forward operations and source multiplexing for realizing efficient entanglement generation as well as the realization of flexible advanced quantum circuits for future quantum computation and simulation.

Shedding Light on Nuclear Spins: Through the looking-glass

Oral - Abstract ID: 309

Mete Atature [1]

1. *University of Cambridge*

Optically active spins in solids are strong candidates for scalable devices towards quantum networks. Semiconductor quantum dots set the state-of-the-art as single-photon sources with high level tuneability, brightness, and indistinguishability. In parallel, their inherently mesoscopic nature leads to a unique realisation of a tripartite interface between light as information carrier, an electron spin as a proxy qubit, and an isolated nuclear spin ensemble. The ability to control these constituents and their mutual interactions create opportunities to realize an optically controllable ensemble of ~50,000 spins. In this talk, I will present a journey from treating the quantum dot nuclei as an uncontrolled noise source limiting spin coherence to the observation of their collective magnon modes and eventually to their function as a quantum register, all witnessed via a single electron spin driven by light.

Universal Quantum Computing with Field-Mediated Unruh–DeWitt qubits.

Oral - Abstract ID: 46

Eric Aspling [1], *Michael Lawler* [2]

1. *Air Force Research Lab,* **2.** *Binghamton University*

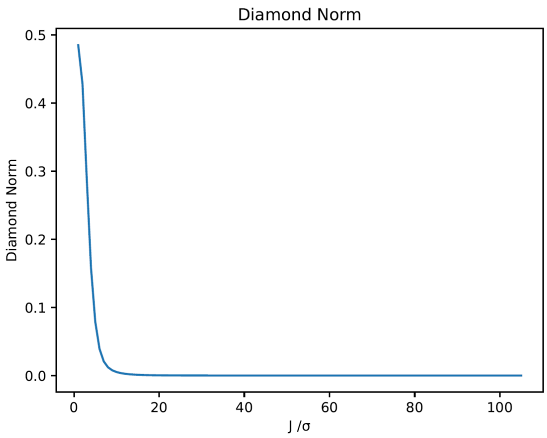
Introduction: Qubit-field quantum transduction is necessary to realize long-range field-mediated quantum computing. Yet little work has been done to demonstrate the limits of qubit-field transduction in Condensed Matter (CM) systems. On the other hand, the community of Relativistic Quantum Information (RQI) has been testing these limits using Unruh–DeWitt (UDW) detectors as qubits coupled to fields in curved spacetime. Quantum field theory and CM physics have blossomed in a combined effort over the last several decades. Therefore, a natural approach to understanding qubit-field transduction in CM systems would be to find the same marriage in the language of Quantum Information Sciences.

Methods and Results: In this talk, we will first discuss projective representations of quantum gates, such as the Pauli operators. Through this representation, we demonstrate the projector form of a Quantum State Transfer (QST) channel from two CNOTs and compare it to the field-mediated QST channel made with multiple controlled unitary gates of a similar projector form.

While similar in design, the operational effects of the two unitaries are quite different. It is only in the completely field-mediated process that we see an equivalence. This equivalence is demonstrated through the diamond distance by numerically comparing the diamond distance of the two QST channels with the coherent information through our field-mediated QST channel, a previously well-established result.

With the proof of concept in place, we develop a set of field-mediated unitaries that are known to allow universal quantum computing, namely the CNOT, H, T, and S gates. The distinguishability of the field-mediated CNOT channel and the canonical CNOT channel can be again demonstrated through the diamond distance as in Fig.1. We close by discussing applications of these unitaries to CM systems.

Discussion: Current investigations into qubit-field interactions in devices will aid development towards physically realizing quantum transduction for long-range quantum communication. Technologies that utilize qubit-field interactions, such as superconducting qubit interactions with Glauber states, could find parameterized fidelities and capacities through a UDW procedure. Numerical simulations, employing techniques in this work, can guide theoreticians and experimentalists toward efficient quantum communication systems.



Udw diamond distance cnot 2 qubits.png

Dimension reduction in quantum sampling of stochastic processes

Oral - Abstract ID: 177

Chengran Yang [1]***, Marta Florido-Llinàs*** [2]***, Mile Gu*** [1]***, Thomas Elliott*** [3]

1. Nanyang Technological University, 2. Technical University of Munich, Max-Planck-Institute for Quantum Optics, 3. Department of Physics and Astronomy, University of Manchester

Introduction – Quantum technologies offer a promising route to the efficient sampling and analysis of stochastic processes, with potential applications across the sciences. Known quantum advantages include quadratic speed-ups in analysing properties such as characteristic functions, pricing options, and enhanced expressivity. These advantages involve the preparation of quantum sample states that comprise of all possible strings of outputs in superposition. The preparation of a quantum sample state of the stochastic process requires a memory system to propagate correlations between the past and future of the process. However, as complex stochastic processes often exhibit strong temporal correlations, the requisite dimension of the memory system can grow quite large.
Methods – Here, we introduce a method of lossy quantum dimension reduction that allows this memory to be compressed, not just beyond classical limits, but also beyond current state-of-the-art quantum stochastic sampling approaches. Specifically, we develop a systematic approach whereby given a target q-sample circuit we determine a new circuit (see fig. 1) of fixed memory dimension that assembles an approximation to the original q-sample. Our approach exploits a correspondence between MPSs and q-samples.
Results – We investigate the trade-off between the saving in memory resources from this compression and the distortion it introduces. We have provided theoretical proof demonstrating that when the amount of information carried by the memory is much smaller than the capacity offered by the size of its memory, a significant reduction in memory size is possible without significant distortion to the resulting q-sample. We showcase that our approach of lossy dimension reduction can be highly effective in strongly non-Markovian processes alike. Furthermore, the compressed quantum model gains accuracy advantages over any classical counterpart with the same dimension (see Fig. 2).
Discussion – Our approach to quantum dimension reduction for quantum sampling and quantum stochastic modelling may provide a route to leveraging quantum approaches for more efficient feature extraction, a task of vital importance in a world that is becoming ever-increasingly data-rich and data-intensive. Moreover, by reducing the quantum resources required for such tasks, we bring them increasingly into reach of quantum processors of the near future.

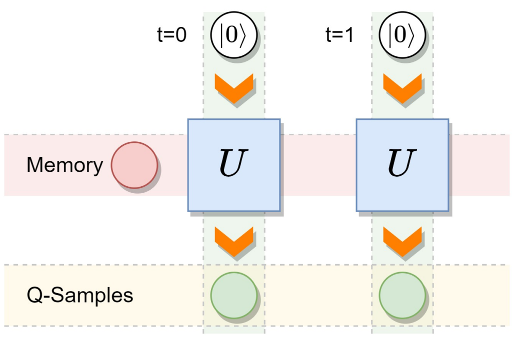


Fig1.jpg

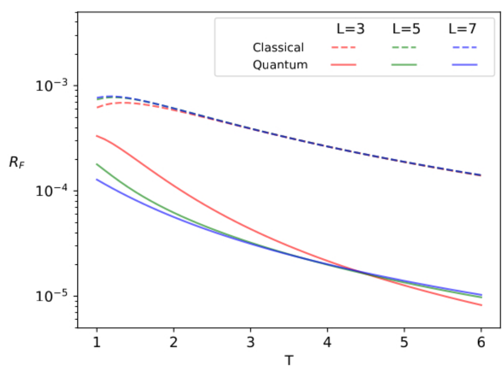


Fig2.jpg

Temporally correlated quantum noise in driven quantum systems

Oral - Abstract ID: 171

Balázs Gulácsi [1], ***Guido Burkard*** [1]

1. *University of Konstanz*

Introduction. The ubiquitous effects of the environment on quantum-mechanical systems generally cause temporally correlated fluctuations. This particularly holds true for systems of interest for quantum computation where such effects lead to correlated errors. Conventional theoretical methods make use of an approximation which treats these errors as uncorrelated, however, for practical settings this is often unjustified. The uncorrelated assumption is also persistently used for driven quantum systems, for which one, often unknowingly, describes the decay effects independently from the time-dependent control of the system.
Methods. We develop a quantum master equation for driven systems weakly coupled to quantum environments that avoids the uncorrelated approximation, as well as the Markovian approximation, and time coarse-graining. Our method makes it possible to track all occurring decay channels and their time-dependent generalized rates.
Results. We apply our method to a generally driven two-level system in the presence of both relaxation and dephasing noise. We illustrate the consequences of all the arising decoherence channels, including those that are ignored within the uncorrelated approximation. We also demonstrate that correlated effects can lead to an increase of the average fidelity of single-qubit gate operations.
Discussion. The presented framework can be generalized to include spatially correlated noise effects, which is the current focus of our research. We believe that the simplicity and applicability of our model can lead to significant advances in the understanding of both temporally and spatially correlated noise processes that plague the controlled evolution of quantum hardware.

Interacting circular Rydberg atoms trapped in optical tweezers

Oral - Abstract ID: 211

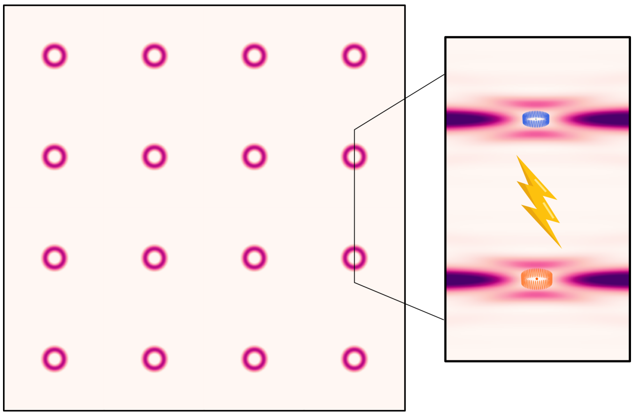
Paul Méhaignerie [1], Yohann Machu [1], Andrés Durán Hernández [1], Gautier Creutzer [1], Aurore Young [1], David Papoular [2], Jean-Michel Raimond [1], Clément Sayrin [1], Michel Brune [1]

1. Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-Université PSL, Sorbonne Université, 2. LPTM, UMR 8089 CNRS & CY Cergy Paris Université

Quantum simulators based on arrays of Rydberg atoms have produced impressive results in the recent years, in particular for their ability to emulate large systems of interacting spins in two dimensions. Nonetheless, a major limitation of these simulations is the number of measurable interaction cycles, because of the short lifetime of the commonly used low-angular momentum Rydberg states. Circular Rydberg atoms, namely Rydberg atoms with maximal angular momentum, typically have a hundred times longer natural lifetimes. This makes them well suited to the quantum simulation of the dynamics of interacting quantum systems [1].
In our setup, we laser-trapped individual circular Rydberg atoms in an array of optical bottle beams [2] based on the ponderomotive force. Here, we report on the first observation of the dipole-dipole interaction between two circular Rydberg atoms.
We characterize the dipole-dipole interaction between two circular Rydberg atoms in different geometrical configurations by microwave spectroscopy. We find an excellent agreement with the theory. In addition, we demonstrate the dynamical tuning of the interaction strength using the electric field. We then use this interaction to record the relative oscillations of the atoms inside their traps [3]. This movement is itself induced by the interaction between the two atoms. We thus demonstrate a coupling between spin and motional degrees of freedom in a Rydberg-atom system [4].
I will also discuss our latest results, in which we use the dipole-dipole interaction to locally control and measure the state of our interacting circular Rydberg atoms.

[1] T.L. Nguyen et al., Towards quantum simulation with circular Rydberg atoms, PRX 8, 011032 (2018).
[2] B. Ravon et al., Array of individual circular Rydberg atoms trapped in optical tweezers, PRL 131, 093401 (2023).
[3] P. Méhaignerie et al., Interacting circular Rydberg atoms trapped in optical tweezers, arXiv:2407.04109 (2024).

[4] P. Méhaignerie et al., Spin-motion coupling in a circular-Rydberg-state quantum simulator: Case of two atoms, PRA 107, 063106 (2023).



Qtech creutzer circular rydberg interactions.png

The Gibbs form and complexity of fixed points of local Kraus maps

Oral - Abstract ID: 234

Omer Gurevich [1], ***Raz Firanko*** [1], ***Itai Arad*** [2]

1. Technion - Israel Institute of Technology, 2. Centre for Quantum Technologies (CQT), National University of Singapore

Introduction and aim:

We study Markovian open systems governed by local dynamics - local Kraus maps or local Lindbladians. These systems are relevant for realistic scenarios (system-bath interactions), and for up-to-date quantum computation (circuits with non-unitary operations). Such systems are known to converge to a steady state.

The study of such steady states is essential and relevant for many reasons. One is that they can be used as a platform for quantum computation, e.g., dissipative quantum computation, dissipative state engineering, and quantum Boltzmann machines, which are algorithms based on Gibbs states. Another reason is understanding the effect of noise in quantum computers.

We ask the following question, motivated by quantum information and computation: what is the influence of noise on the structure and computational power of such steady states.

This question is crucial for determining whether we can use such systems for computational tasks. Can we simulate open systems on a quantum computer? Can we engineer them to efficiently produce steady states that are computationally significant?

Methods:

We use three principal techniques. The first is a multivariate perturbation theory used to analyze the Gibbs structure of the steady state with respect to the underlying noise-interactions interplay. The second is a standard single-parameter perturbation theory in the Heisenberg picture, exploited to understand the complexity of expectation value calculations of local observables. The third is a numerical (ED) demonstration.

Results: For a two-local Kraus map (interaction graph) subjected to independent noise, we show

1. The steady-state has an algebraic structure of a Gibbs state of an approximately local Hamiltonian. Perturbing on the amplitude of interactions, a radius k Hamiltonian term arises at k+1 perturbation order.

2. Below a certain noise threshold, a classical algorithm can efficiently calculate expectation values of local observables, with complexity depending on the graph's dimensionality. For instance, 1D graphs present polynomial complexity.

3. Numerical understanding of (1), analyzing decay rates of Gibbs Hamiltonian interactions.

Discussion:

1. Can we use this framework to prescribe dynamics to create a Gibbs-state of choice?
2. What exactly determines the decay rate of the Gibbs Hamiltonian?
3. Adapting the proof to other scenarios.

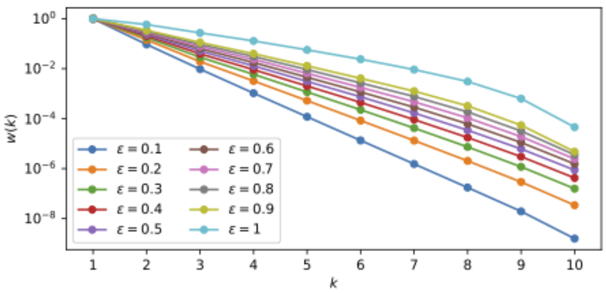


Fig b ti 1 .png

Rise of quantum non-Gaussian coherences in atoms

Oral - Abstract ID: 187

Radim Filip [1]
1. *Department of Optics, Palacký University*

The study of quantum non-Gaussian coherences in atoms and similar systems is crucial for the advancement of quantum technology. These coherences play a vital role in bosonic quantum sensors, quantum simulators of unexplored bosonic effects, bosonic quantum error correction, and quantum computation. They encompass a wide variety of states, processes, and effects, offering many unexplored areas and potential new applications.

Despite their significance, there are still open challenges in comprehending them deeply, generating and controlling them autonomously, detecting them reliably, and providing conclusive certification.

In an upcoming talk, new theories and experimental results concerning the qubit and quantum non-Gaussian coherence of atomic motion represented by off-diagonal elements on a Fock state basis will be briefly overviewed and summarized. The talk will highlight the emergence of large autonomous coherence through the cooling of interacting systems to the ground state and its significant sensing capability [1]. Additionally, it will illustrate that nonlinear motional couplings of atoms can give rise to quantum non-Gaussian coherences stimulated by small energy of a few thermal quanta [2]. Lastly, the talk will introduce a new, experimentally tested and unpublished rise and classification of quantum non-Gaussian coherence in the discrete and continuous variable picture, which is essential in understanding the aforementioned phenomena.

All these contributions are anticipated to have a cross-fertilizing effect on the field of quantum non-Gaussian coherence.

[1] M. Kolář, R. Filip, arXiv:2211.08851, accepted in Quantum Science and Technology (2024); M. Kolář, R. Filip, arXiv:2403.08474

[2] P. Laha, D.W. Moore, and R. Filip, Phys. Rev. Lett. 132, 210201 (2024)

Landau-Zener without a qubit: multiphoton sidebands interaction and signatures of dissipative quantum chaos

Oral - Abstract ID: 249

Leo Peyruchat [1], ***Fabrizio Minganti*** [1], ***Marco Scigliuzzo*** [1], ***Filippo Ferrari*** [1], ***Vincent Jouanny*** [1], ***Franco Nori*** [2], ***Vincenzo Savona*** [1], ***Pasquale Scarlino*** [1]

1. École Polytechnique Fédérale de Lausanne (EPFL), 2. RIKEN

Landau-Zener-Stückelberg-Majorana (LZSM) interference emerges when the parameters of a qubit are periodically modulated across an avoided level crossing. In this work [1], we investigate the occurrence of the LZSM phenomenon in nonlinear multilevel bosonic systems, where the interference pattern is determined by multiple energy levels and cannot be described by a level crossing between only two states. We fabricate two superconducting resonators made of flux-tunable Josephson junction arrays [Fig. 1]. The first device is weakly nonlinear (the nonlinearity is smaller than the photon-loss rate) and, when a low driving field is applied, it behaves as a linear resonator, yet shows the same LZSM interference as in a two-level system. Notably, here the interference originates from multiple avoided level crossings of the harmonic ladder. When subjected to a stronger drive, nonlinear effects start playing a role, and the interference pattern departs from the one observed in two-level systems. We demonstrate that, when two or more LZSM interference peaks merge, dissipative quantum chaos emerges [Fig 2. left]. In the second device, where the nonlinearity surpasses the photon-loss rate, we observe additional LZSM interference peaks due to Kerr multiphoton resonances [Fig 2. right]. When described under the light of the Floquet theory, these resonances can be interpreted as synthetic modes of an array of nonlinear coupled cavities. We derive a simple effective model highlighting the essential features of the entirety of these phenomena. As the control of LZSM in qubit systems led to the implementation of fast protocols for characterization and state preparation, our findings pave the way to better control of nonlinear resonators, with implications for diverse quantum technological platforms.

[1] L. Peyruchat et al., arxiv:2404.10051 (2024)

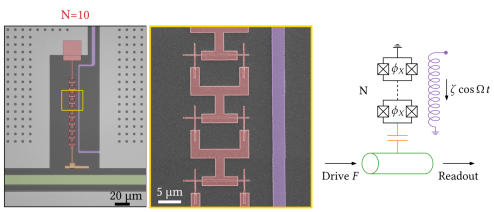


Fig 1 squid array circuit.png

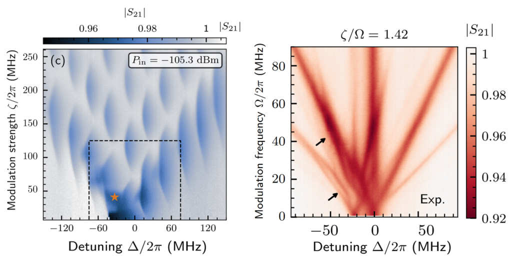


Fig 2 lz interference kerr regimes.png

Towards perfect spin projection in a QD-based spin-photon interface

Oral - Abstract ID: 219

Adrià Medeiros Garay [1], Vincent Vinel [1], Manuel Gundín [1], Elham Mehdi [1], Clément Millet [1], Niccolo Somaschi [2], Aristide Lemaitre [1], Isabelle Sagnes [1], Olivier Krebs [1], Dario Fioretto [3], Pascale Senellart [4], Loïc Lanco [1]

1. C2N, Université Paris Saclay, 10 Bd Thomas Gobert, 91120 Palaiseau, France, 2. Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France, 3. C2N, Université Paris Saclay, 10 Bd Thomas Gobert, 91120 Palaiseau & Quandela, 7 Rue Léonard de Vinci, 91300 Massy, 4. C2N, Université Paris Saclay, 10 Bd Thomas Gobert, 91120 Palaiseau

Charged quantum dots (QD) are promising candidate platforms for quantum information processing applications. Entanglement between the spin degree of freedom of a charged confined in the QD (acting as a stationary qubit) and the polarization of single photons (flying qubits) allows for deterministic spin-photon and photon-photon quantum gates [1]. However, this requires an efficient read-out of the matter qubit state. A promising strategy, in this respect, is to take advantage of the giant rotation induced by a single spin on the polarization state of single photons as in micropillar cavity-based spin-photon interfaces [2,3].

In our work, we explore an InAs negatively charged QD deterministically coupled to a microcavity [4]. An attenuated linearly polarized CW laser is sent to the cavity-QD system and tuned close to resonance from the trion transition. The output polarization of the reflected photons is rotated with respect to the incoming one, providing a spin-state dependent effect. In our protocol, the spin qubit is projected into one of its eigenstates by a projective measurement on a first photon reflected from the interface. We then perform time-resolved intensity measurements of the reflected photons polarization to track the spin evolution towards the steady state. Doing so, we can infer the state of the spin in the Bloch sphere and demonstrate efficient measurement induced back-action.

This work paves the way for novel entanglement schemes, where a single spin gets entangled with single incoming photons in QD-based systems, the next step towards deterministic spin-photon gates working at the single photon level.

[1] C. Y. Hu et al, Phys. Rev. B 78, 085307 (2008)
[2] C. Arnold et al, Nature Communications 6, 6236 (2015)
[3] E. Mehdi et al, Nature Communications 15, 598 (2024)
[4] N. Somaschi et al, Nature Photonics 10, 340-345 (2016)

Study of biphoton spatial correlations via single photons detection

Oral - Abstract ID: 101

Emma Brambila [1], *René Sondenheimer* [2], *Marta Gilaberte Basset* [1], *Valerio Flavio Gili* [1], *Markus Gräfe* [3]

1. Fraunhofer Institute for Applied Optics and Precision Engineering, Friedrich-Schiller-Universität Jena, 2. Institute of Condensed Matter Theory and Optics, Friedrich-Schiller-Universität Jena., 3. Institute of Applied Physics, Technical University of Darmstadt

Introduction

Most of the quantum imaging techniques nowadays rely on the characteristics of spatial correlations between the illumination and/or detected photons [1,2]. That is why, further improvement of these techniques and the development of new methods, require deeper understanding of this key property.

Spatial correlations have been analyzed previously by different groups, setting always equal wavelengths for both photons, and via complex coincidence measurements [3,4]. This work is about the characterization of nondegenerate pairs by detecting only one photon. Our technique is based on a detailed theoretical analysis of the imaging technique of undetected photons, and corresponding experiments are performed.

Methods

We investigate biphoton spatial quantum correlations as function of different parameters. The photon pair source is based on quasi-phase matched spontaneous parametric down conversion, whose spatial properties depend between others, on the pump waist and crystal length [5]. Under the assumption of paraxial regime, and thin crystal approximation, momentum correlations are expected to weaken when tightening the pump waist [5,6]. For position correlations, and a fixed pump waist, longer crystals produce similar effect of correlations degradation [5]. These tendencies are explored with our formalism, and a simplified experimental scheme of the undetected photons setup is used, to assure minimum alignment influence on the experimental correlation strength results.

The setup consists of a double-pass crystal nonlinear interferometer, with operating nondegenerate wavelengths in the near-infrared. A qualifier of a nonlinear interferometer is the visibility obtained by measuring maximally constructive and destructive interference. In this work, that attribute is measured to calculate the corresponding correlation strength as function of the mentioned different parameters.

References

1. P. A. Morris, et al. Nature Communications 6, 5913 (2015).
2. G. Barreto Lemos, et al. Nature 512, 409-412 (2014).
3. W. Zhang, et al. Optics Express 27, 15, 20745-20753 (2019).
4. H. Defienne, et al. Nature Communications 13, 3566 (2022).
5. M.P. Edgar, et al. Nature Communications 3,984 (2012).
6. A. Hochrainer, et al. PNAS 114 (7), 1508-1511 (2016).

Hong-Ou-Mandel interference of two photons of vastly different color

Oral - Abstract ID: 227

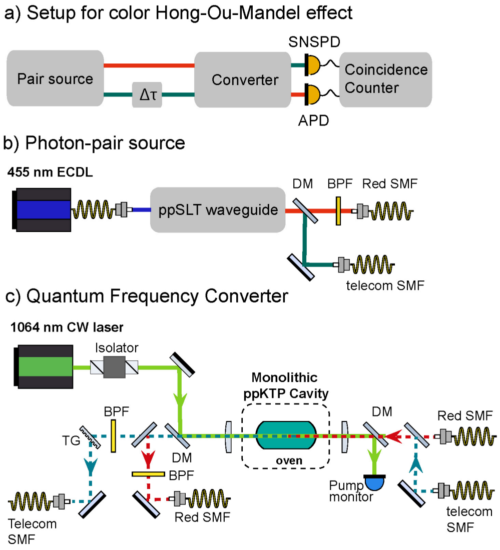
Felix Mann [1]***, Helen Chrzanowski*** [2]***, Felipe Gewers*** [1]***, Marlon Placke*** [1]***, Sven Ramelow*** [3]

***1.** Humboldt-Universität zu Berlin,* ***2.** Humboldt-University Berlin,* ***3.** Humboldt University of Berlin*

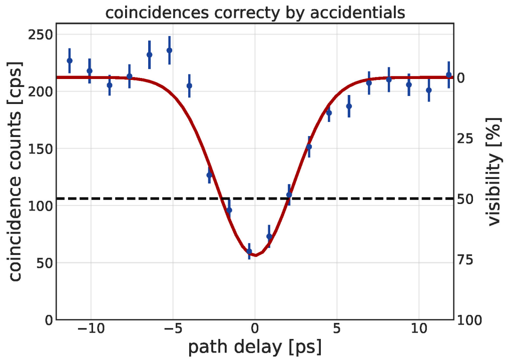
Hong-Ou-Mandel (HOM) interference [1] is a uniquely quantum mechanical effect that is central to tasks in photonic quantum information processing and sensing with quantum light [2]. HOM interference is typically realized with passive beam splitters like semi-transparent mirrors for two photons of the same color. Equally, by employing an active beam splitter, like a quantum frequency converter, photons of very different color can also demonstrate this effect [3,4,5].

The active beam splitter in this experiment is a quantum frequency converter realized as a monolithic cavity from bulk ppKTP pumped by a 1064 nm laser, designed to efficiently convert photons between 637 nm and 1587 nm [6]. The photon-pair source is a laser-written ppSLT waveguide pumped by a 455 nm external-cavity diode laser (ECDL), quasi-phasematched to produce a red photon (637 nm) and a corresponding photon at telecommunication wavelengths (1587 nm), which differ in frequency by more than an octave with a spacing of 282 THz. The photon pair is aligned into the converter, where each photon has a 50% chance of either remaining at its current color, or converting. Destructive interference between the amplitudes of both photons being converted and both photons remaining unconverted suppresses coincidence events at the two detectors at the output ports of the converter.
A visiblity of the HOM dip of (74 ± 3)% was measured, which is well above the classical limit of 50%.

[1] Hong, Chong-Ki ; OU, Zhe-Yu ; Mandel, Leonard: Measurement of subpicosecond time intervals between two photons by interference. In: Physical review letters 59 (1987), Nr. 18, S. 2044
[2] Pan, Jian-Wei, et al. "Multiphoton entanglement and interferometry."*Reviews of Modern Physics* 84.2 (2012): 777.APA
[3] MG Raymer et al. "Interference of two photons of different color". In: Optics Communications 283.5 (2010), pp. 747–752.
[4] Toshiki Kobayashi et al. "Frequency-domain hong–ou–mandel interference". In: Nature photonics 10.7 (2016), pp. 441–444.
[5] Hsuan-Hao Lu et al. "Frequency-bin photonic quantum information". In: Optica 10.12 (2023),pp. 1655–1671.
[6] Mann, Felix, et al. "Low-noise quantum frequency conversion in a monolithic cavity with bulk periodically poled potassium titanyl phosphate."*Physical Review Applied* 20.5 (2023): 054010.



Colorhom-setup.jpg



Coincsub s1.jpg

Quantum parameter estimation with many-body fermionic systems and application to the Hall effect

Oral - Abstract ID: 40

Olivier Giraud [1], ***Mark-Oliver Goerbig*** [2], ***Daniel Braun*** [3]

1. *University Paris-Saclay, CNRS, LPTMS, 91405 Orsay,* ***2.*** *Université Paris-Saclay, CNRS, Laboratoire de Physique des Solides, 91405 Orsay,,* ***3.*** *Institute for Theoretical Physics, Eberhard-Karls Universität Tübingen*

Introduction

The Hall effect offers a precise and economic way of measuring magnetic fields with small, integrated sensors. In the present work we investigate the ultimate sensitivity of such sensors based on the quantum Cram\'er-Rao bound (QCRB) in the integer-quantum-Hall regime.To this end, we first develop more generally the formalism of quantum parameter estimation with a system described by a fermionic quantum field theory. We consider three different ways by which a parameter dependence can be imprinted on the quantum state: via a parameter-dependent Hamiltonian evolution, via parameter-dependent fermionic many-particle basis states, or via a Bogoliubov transformation.

Methods

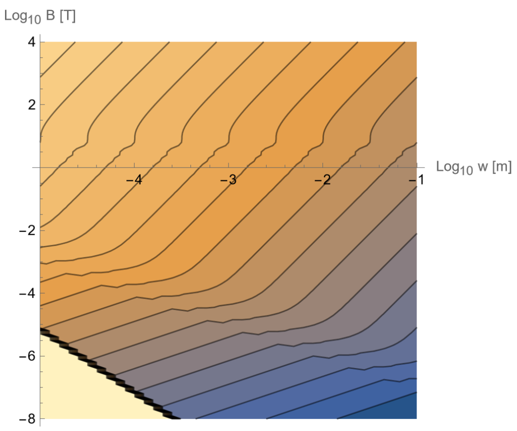
We derive several formulas for the quantum Fisher information (QFI) of many-fermion systems, including a chain rule for two successive unitary transformations. They lead us to variance-based formulas for the QFI that generalize previously known ones and allow us to express the QFI for arbitrary pure many-fermion states. These are applied then to Bogoliubov transformations.

Results

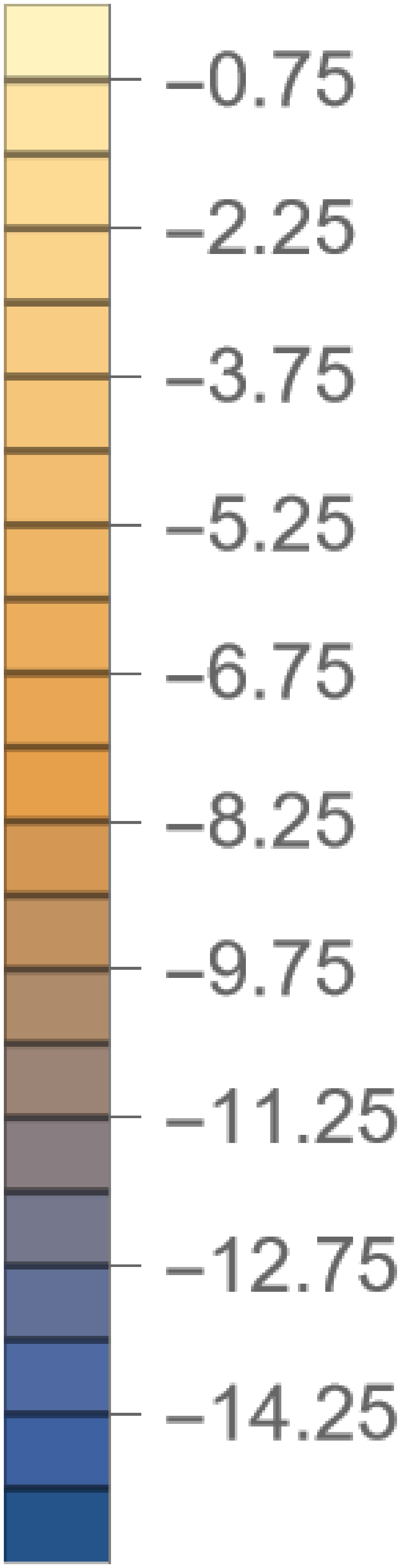
We find that the QFI for a not-completely-filled band of fermions depends not only on the occupied states but also on the un-occupied ones. The ultimate sensitivity of quantum-Hall-effect-based sensors depends on the aspect ratio of the sample. For large numbers N of electrons the QFI scales with a power (1+2p) of N, if the width of the sensor scales with a power p and the length with a power 1-p. Long, strip-like sensors are therefore preferable. For any p>1/2, one obtains a “super-Heisenberg scaling” of the sensitivity.

Discussion

“Super-Heisenberg scaling” of sensitivity without the need to actively entangle any particles is rather remarkable. The phenomenon can be traced back to the occupation of high-momenta single-electron states up to the Fermi-level that we get for free from the Pauli principle. Even though we did not include dissipation or decoherence, the universal validity of the Pauli principle and the resulting “particle-like” entanglement suggest that the results should be robust and achievable in the lab by simply reaching the quantum Hall regime, i.e. at low enough temperatures and high magnetic fields.



Contourplotsigmab10kt.png



Legendcontourplot.png

A radiofrequency superconducting qubit for quantum control of ultracoherent mechanical resonators

Oral - Abstract ID: 164

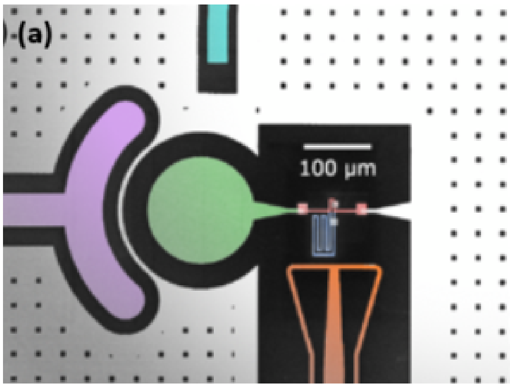
Baldo-Luis Najera Santos [1], Rémi Rousseau [2], Kyrylo Gerashchenko [1], Himanshu Patange [3], Zaki Leghtas [4], Emmanuel Flurin [5], Thibaut Jacqmin [1], Samuel Deléglise [1]

1. *Laboratoire Kastler Brossel, Sorbonne Universite,* ***2.*** *Laboratoire Kastler Brossel, Sorbonne Universite, Alice & Bob,* ***3.*** *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France,* ***4.*** *Laboratoire de Physique de l'Ecole Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université,* ***5.*** *Quantronics group, Université Paris-Saclay, CEA, CNRS, SPEC,*

Beyond their applications in quantum computing, superconducting qubits are a powerful platform to probe various quantum phenomena, when coupled to a different physical system, for instance a mechanical resonator mode [1]. The most popular superconducting qubit—the transmon—operates at a frequency of several GHz: a microwave signal at this frequency excites transitions between the two qubit states, and can be used to implement quantum logic gates. However, the fact that most of superconducting qubits operate in the GHz frequency domain limits the class of systems they can interact with. Building upon the heavy fluxonium qubit architecture [2], we have developed a superconducting qubit with an unprecedentedly low transition frequency of 1.8 MHz [3]. Notably, we have demonstrated a qubit with a coherence time exceeding 30 µs, the ability to prepare the qubit in a pure state with 97.7% fidelity, and single-shot readout capability. Moreover, by detecting a weak charge modulation by repeated qubit interrogation, we demonstrate the high-sensitivity of this qubit to a nearly resonant electric charge modulation, proving its potential in a hybrid quantum system. We will finally present our recent efforts to achieve the resonant (strong) coupling regime between this qubit and an ultra-coherent softly-clamped mechanical membrane mode. In this device, the mechanical mode is a defect mode of a high stress phononic crystal membrane, that we characterize with a motorized optical interferometer [4]. It has a frequency of a few MHz, matching that of the qubit, and a quality factor reaching hundreds of millions at cryogenic temperature. This hybrid quantum system could be used to observe macroscopic quantum phenomena.
Figures: (a) Colorized microscope image of the heavy fluxonium circuit, (b) Microscope image of the membrane resonator (size 1 mm x 1mm), (c) Microscope image of the hybrid system: membrane resonator on top, heavy fluxonium circuit 300 nm below.

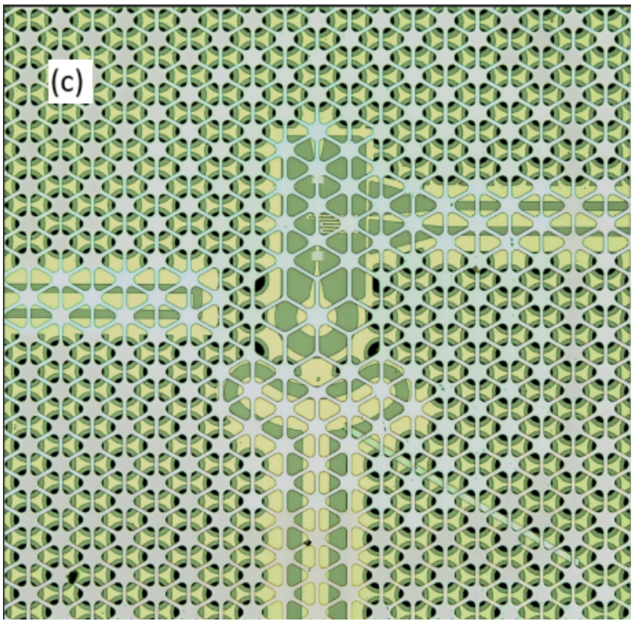
References :

[1] Y. Chu et al. *Nature* 563, 666 (2018).
[2] H. Zhang et al. *Physical Review X* 11, 011010 (2021).
[3] Najera-Santos et al. *Phys. Rev. X* 14, 011007 (2024)
[4] Ivanov et al. *Appl. Phys. Lett.* 117, 254102 (2020)



Sem image of circuit.png

Microscope image phononic crystal structure.png



Hybrid mecafluxonium.png

A cavity-enhanced solid-state spin wave quantum memory

Oral - Abstract ID: 181

Leo Feldmann [1], Sören Wengerowsky [1], Antariksha Das [1], Stefano Duranti [1], Hugues de Riedmatten [1]
1. ICFO - The Institute of Photonic Sciences

The realization of large scale quantum networks requires the distribution of entanglement over large distances. In this long-range regime, direct transmission is prohibitive due to losses in optical fibers. Quantum repeaters are predicted to overcome direct transmission and allow entanglement distribution at continental scales. However, most quantum repeater schemes rely on the storage of quantum states into quantum memories. In order for memories to be useful in practical implementations, they must exhibit several features including a long storage time, a high storage efficiency and a large multiplexing capability. Solid-state quantum memories based on rare-earth doped solids promise excellent performances in terms of storage time and multiplexing capability.
With longer storage time, the efficiency of many memory protocols decays exponentially due to the coherence time of the material. This severely limits the applicability of the memory. Storage in a spin-state has the advantage, that spin-rephasing techniques can be applied to mitigate this efficiency decay.
For rare-earth based memories, the efficiency for spin-wave storage at the single photon level was so far limited to around 31% using the spectral-hole memory protocol [10.1103/PhysRevA.93.040302] which does not allow for qubit storage without sacrificing efficiency. The highest efficiency using spin-wave-storage with the atomic frequency comb protocol (AFC) was reported by Jobez et al [10.1088/1367-2630/16/8/083005] with 12% for coherent states at the classical level.
Using the AFC protocol, we present a quantum memory implemented in an impedance-matched cavity [10.1103/PhysRevA.82.022310] built around the vacuum chamber of our cryostat [10.48550/arXiv.2307.03509]. We reached a device efficiency over 50% for storage of weak coherent states at the single photon level in the excited state for 8 µs and over 38% for storage in the spin-state for additional 5 µs. Maintaining a good signal-to-noise ratio (SNR) is more challenging for storage in the spin-state than in the excited state. We reached a SNR of about 16 with a mean input photon number of 0.44, making it feasible to store photons from SPDC sources. We characterized the efficiency and SNR with respect to photon bandwidth and storage time (see fig.1) and investigated the effect of the impedance-matched cavity on the noise level.

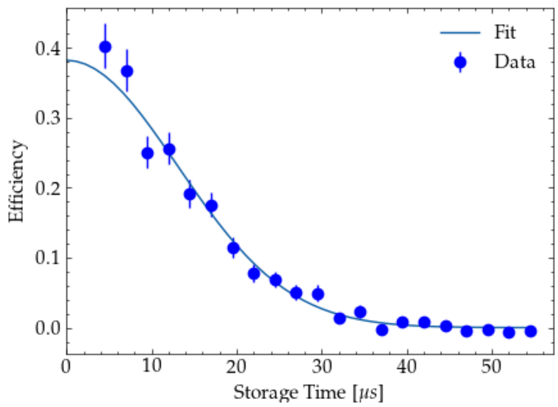


Fig1 - efficiency vs spin-state storage time.png

Near-coherent quantum emitters in hexagonal boron nitride with discrete polarization axes

Oral - Abstract ID: 191

Nathan Coste [1], ***Jake Horder*** [1], ***Dominic Scognamiglio*** [1], ***Ádám Ganyecz*** [2], ***Viktor Ivády*** [3], ***Mehran Kianinia*** [1], ***Milos Toth*** [1], ***Igor Aharonovich*** [1]

1. *University of Technology Sydney,* ***2.*** *Wigner Research Centre for Physics,* ***3.*** *Linköping University*

Hexagonal boron nitride (hBN) is a 2-dimensional material that has recently gained attention as a solid state host of quantum emitters. In particular, the recently discovered B centers show promise for integration in scalable photonic quantum technologies thanks to site-specific defect generation, reproducible wavelength and room temperature emission.
In this work[1], we employ spectral hole burning (SHB) spectroscopy and resonant polarization measurements to study the coherence properties of these emitters. The SHB technique allows to sidestep linewidth broadening due to spectral diffusion, revealing near lifetime-limited homogeneous linewidths as narrow as 150 MHz for individual emitters and ensembles. Absent spectral diffusion, the B center can be expected to source coherent single photons suitable for quantum photonics applications. In addition, resonant polarization measurements show that the B center emission has one of three discrete in-plane polarization axes separated by 60°. We discuss this result within the framework of the Jahn-Teller (JT) distortion of a split interstitial defect, yielding a C2v symmetry within the hBN crystal lattice. Our results constitute an important milestone towards the implementation of hBN quantum emitters in integrated quantum photonics.

FIGURE 1. a) Schematic of spectral hole detected by scanning a probe laser over an inhomogeneously broadened spectrum of width Γinhom, where a stationary pump laser creates a dip of width Γhole equivalent to twice the homogeneous linewidth Γhom. Inset : schematic representation of the technique on a defect state in the hBN lattice. b) Spectral hole burning measurement on a single emitter as a function of the pump laser power.

[1] J. Horder, D. Scognamiglio, Ganyecz, V. Ivády, N. Coste, M. Kianinia, M. Toth, and I. Aharonovich, "Near-coherent quantum emitters in hexagonal boron nitride with discrete polarization axes," (2024), arXiv :2402.11786

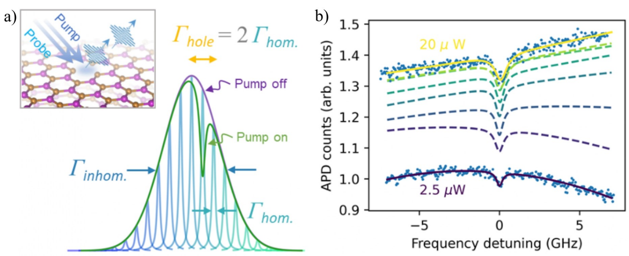


Fig coste hbn.jpg

Authors Index

Prem C

Conferences, Events & Workshops