Control of Quantum Dynamics of Atoms, Molecules and Ensembles by Light

Sol Marina Palace Hotel, Nessebar, Bulgaria, June 16 – June 20, 2025

CAMEL XX

Twentieth International Workshop

BOOK OF ABSTRACTS

Edited by
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Programme

Monday, June 16

Morning Session chaired by **Nikolay Vitanov**

09:00-09:45 **Markus Hennrich**, *Trapped Rydberg ions*

09:45-10:30 **Ana Predojevic**, *Correlations and statistics of quantum dot sources of quantum light*

10:30-11:00 **Coffee break**

Noon Session chaired by **Markus Hennrich**

11:00-11:45 **Thomas Walther**, *Full implementation of a quantum key distribution network in a city*

11:45-12:30 **Felix Motzoi**, *Quantum logical gates with DRAG formalism*

Lunch

16:30-17:00 **Coffee break**

Evening Session chaired by **Felix Motzoi**

17:00-17:30 **Stancho Stanchev**, *Multipass quantum process tomography*

17:30-18:00 **Hristo Tonchev**, *Robust, fast and high-fidelity composite single-qubit gates for superconducting transmon qubits*

18:00-18:20 **Simona Grigorova**, *Quantum error correction: bit-flip and repetition code on IBM Quantum*

18:20-18:40 **Kremena Parashkevova**, *Efficient quantum control by composite ultrastrong field*

Tuesday, June 17

Morning Session chaired by **Roberto Grimaudo**

09:00-09:45 **Genko Genov**, *Quantum technologies with color centers in diamond*

09:45-10:30 **Kaloyan Zlatanov**, *Composite modulated Mølmer-Sørensen gate*

10:30-11:00 **Coffee break**

Noon Session chaired by **Genko Genov**

11:00-11:45 **Roberto Grimaudo**, *Qua and counter-intuitive effects in a two-qubit and a two-qutrit quantum Rabi model*

11:45-12:30 **Georgi Bebrov**, *Long-distance quantum secure communication model based on quantum teleportation*

Lunch

15:00-18:00 **Boat trip**

Wednesday, June 18

Morning Session chaired by **Thomas Zanon-Willette**

09:00-09:45 **Winfried Hensinger**, *Developing trapped-ion quantum computing technology for the million-qubit scale*

09:45-10:30 **Hardik Mendpara**, *Progress towards a fault-tolerant, microwave-driven quantum processor with trapped ions*

10:30-11:00 **Coffee break**

Noon Session chaired by **Ana Predojevic**

11:00-11:45 **Germano Montemezzani**, *Tailoring vectorial optical waves by conical diffraction in cascade*

11:45-12:30 **Thomas Zanon-Willette**, *Dynamically-decoupled hyper-Ramsey spectroscopy of optical transitions*

Lunch

16:30-17:00 **Coffee break**

Evening Session chaired by **Kaloyan Zlatanov**

17:00-17:30 **Artem Kovalenko**, *Interference-controlled photon statistics in mesoscopic ion chains*

17:30-18:00 **Nayden Nedev**, *Robust dynamical decoupling approach for quantum sensing*

18:00-18:20 **Vasil Vasilev**, *Householder reflections in quantum informatics*

18:20-18:40 **Julian Dimitrov**, *Optimization of STIRAP by pulse shaping*

20:00 **Conference dinner**

Thursday, June 19

Morning Session chaired by **Patrick Cheinet**

09:00-09:45 **Jyrki Piilo**, *Overcoming noise in quantum teleportation with multipartite hybrid entanglement*

09:45-10:30 **Andreas Ruschhaupt**, *Shortcuts to adiabaticity and CAMEL*

10:30-11:00 **Coffee break**

Noon Session chaired by **Germano Montemezzani**

11:00-11:45 **Patrick Cheinet**, *Rydberg thermometry for atomic clocks*

11:45-12:30 **Ivo Mihov**, *Pulse-shape effects and Delos-Thorson equivalence with phase-modulated pulses on IBM Quantum*

Lunch

16:30-17:00 **Coffee break**

Evening Session chaired by **Ivo Mihov**

17:00-17:30 **Adrien Amour**, *Cavity assisted ion-photon entanglement*

17:30-18:00 **Branislav Ilich**, *Quantum teleportation across four qubit graphs on IBM Quantum*

18:00-18:20 **Aida Shiroyan**, *The Davies-Pechukas method for qubit dynamics*

18:20-18:40 **Petar Chernev**, *Complete and robust population transfer between the two ground states of a three-state loop quantum system by amplitude composite pulse control*

List of Abstracts

CAVITY ASSISTED ION-PHOTON ENTANGLEMENT

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Combining trapped atomic ions with photons is currently the most promising approach for building distributed quantum computers and large-scale quantum networks. The highest-fidelity single- and two-qubit gates demonstrated to date have been achieved using trapped ions. Trapped ions also allow for high-fidelity state preparation and measurement. Photons, in contrast, are the most reliable carriers of quantum information over long distances. By coupling ions to optical cavities, it is possible to leverage the advantages of both systems, enabling the generation of remote entanglement — a prerequisite for quantum networking and distributed quantum computing. Previous research within the group has demonstrated schemes for producing photons with greater indistinguishability and improved robustness against birefringence-induced decoherence, using state selection and time-bin encoding, respectively [1,2]. The aim of this project is to build on this research by producing ion-photon entanglement.

[1] T. Walker et al., Phys. Rev. A, **102**, 032616 (2020).
[2] T. Ward and M. Keller, New J. Phys., **24**, 123028 (2022).

LONG-DISTANCE QUANTUM SECURE COMMUNICATION MODEL BASED ON QUANTUM TELEPORTATION

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The talk is concerned with introducing a long-distance quantum secure communication model based on the quantum teleportation. The model demonstrates a data rate that scales with the square root of the channel transmittance. This is achieved by utilizing weak-coherent-state interference and performing a distant CNOT gate in the course of establishing EPR channel (teleportation channel) that is required for securely teleporting data. The security of this quantum secure communication model is proved against CNOT gate attack as well as coherent-state channel attack.

RYDBERG THERMOMETRY FOR ATOMIC CLOCKS

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Optical Lattice Clocks present nowadays the best performances but are mainly limited by the AC-Stark shift induced by Black-Body Radiation (BBR) on the clock levels. Promoting the

atoms into a Rydberg state allows to increase greatly the sensitivity to BBR and obtain an in-situ temperature measurement. I will present a new proposed method, relying on specific properties of atoms with 2 valence electrons, allowing to improve significantly the expected sensitivity.

COMPLETE AND ROBUST POPULATION TRANSFER BETWEEN THE TWO GROUND STATES OF A THREE-STATE LOOP QUANTUM SYSTEM BY AMPLITUDE COMPOSITE PULSE CONTROL

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This study introduces a technique for achieving complete, robust, and efficient population transfer between the two ground states of a three-state loop quantum system. The method employs composite sequences of pulses by effectively reducing the three-state system to an equivalent two-state system. This reduction enables the application of broadband composite pulses initially developed for standard two-state quantum systems. However, in the three-state quantum system, the proposed composite pulses do not use phases as control parameters; instead, they are implemented through an amplitude ratio between the Rabi frequencies.

OPTIMIZATION OF STIRAP BY PULSE SHAPING

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We present a comparative study of various approaches toward high-fidelity Stimulated Raman adiabatic passage (STIRAP) using pulse shaping of the driving fields. This technique for population transfer in a three-state quantum system is widely used because of its robustness to errors in the driving fields and the fact that the intermediate state is unpopulated in the adiabatic limit. Its main drawbacks are the large pulse areas needed to achieve adiabaticity and the necessity for a two-photon resonance between the two end states, which make it difficult to achieve very high population transfer efficiency. Here we compare four approaches that allow us to use pulse shaping of the driving fields in STIRAP. One of them is new, two are known in the literature and the other one is partially new. We assume that only two fields are present and discard the often used third field, which introduces unnecessary redundancy.

QUANTUM TECHNOLOGIES WITH COLOR CENTERS IN DIAMOND

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Color centers in diamond are promising for quantum technologies but decoherence remains a major challenge. We introduce continuous phased dynamical decoupling for robust quantum sensing [1]. We also develop multipoint correlation spectroscopy, combining the advantages of correlation spectroscopy and quantum heterodyne detection, to enable temporally efficient measurements of statistically polarized samples at the nanoscale with spin ensembles [2]. We demonstrate a robust two-qubit gate between nitrogen-vacancy (NV) electron spins of in diamond, reaching a record gate fidelity of $96.0 \pm 2.5\%$ under ambient conditions [3]. Finally, we demonstrate coherent control of a carbon-13 nuclear spin, coupled to a germanium-vacancy center. We reach coherence times beyond 2.5 s at mK temperatures, the longest reported for group-IV defects, and an achievable quantum memory time of 18.1 s [4].

[1] D. Louzon, G. Genov, N. Staudenmaier, F. Frank, J. Lang, M. L. Markham, A. Retzker, and F. Jelezko, Phys. Rev. Lett., 134:120802 (2025).
[2] T. Spohn, N. Staudenmaier, P. J. Vetter, T. Joas, T. Unden, I. Schwartz, P. Neumann, G. Genov, and F. Jelezko, arXiv 2503.18930 (2025).
[3] T. Joas, F. Ferlemann, R. Sailer, P. J. Vetter, J. Zhang, R. S. Said, T. Teraji, S. Onoda, T. Calarco, G. Genov, M. M. Müller, and F. Jelezko. Phys. Rev. X, 15:021069 (2025).
[4] N. Grimm, K. Senkalla, P. J. Vetter, J. Frey, P. Gundlapalli, T. Calarco, G. Genov, M. M. Müller, and F. Jelezko. Phys. Rev. Lett., 134:043603 (2025).

QUANTUM ERROR CORRECTION: BIT-FLIP AND REPETITION CODE ON IBM QUANTUM

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I present implementations of the repetition and bit flip codes on IBMś superconducting qubit platforms. This work demonstrates effective error detection and correction, significantly mitigating bit-flip errors. The study outlines the experimental setup, key challenges, and results, emphasizing the potential for scalable, fault-tolerant quantum computation on current hardware.

QUA AND COUNTER-INTUITIVE EFFECTS IN A TWO-QUBIT AND A TWO-QUTRIT QUANTUM RABI MODEL

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The quantum Rabi model with two interacting qubits is studied. Using an exact approach, the model's integrability is demonstrated, and exact solutions are found in specific cases. The analysis also reveals level crossings and a quantum phase transition, the latter requiring a newly defined thermodynamic limit tailored to the two-qubit system. Finally, the study highlights unexpected and intriguing effects arising from the collective dynamics driven by the qubit-qubit interaction.

TRAPPED RYDBERG IONS

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Trapped Rydberg ions are a novel approach for quantum information processing [1,2]. This idea joins the advanced quantum computing toolbox of trapped ions with strong dipolar interaction between Rydberg atoms. For trapped ions, this method can speed up entangling interactions and enables such fast operations in larger ion crystals. In this presentation, I will first introduce the novel experimental platform of trapped Rydberg ions [2]. I will describe the specific physics involved when exciting ions into Rydberg states, the effects on the trapping potential due to the strong polarizability of Rydberg ions, and the controllable strong interaction between ion and motion. Moreover, I will summarize methods and results in speeding up trapped ion entanglement operations via the strong dipolar Rydberg interaction [3].

[1] M. Müller, L. Liang, I. Lesanovsky, and P. Zoller, Trapped Rydberg Ions: From Spin Chains to Fast Quantum Gates, New J. Phys. **10**, 093009 (2008).
[2] A. Mokhberi, M. Hennrich, and F. Schmidt-Kaler, Trapped Rydberg Ions: A New Platform for Quantum Information Processing, in Advances In Atomic, Molecular, and Optical Physics, Vol. 69 (Elsevier, 2020), pp. 233—306.
[3] C. Zhang, F. Pokorny, W. Li, G. Higgins, A. Pöschl, I. Lesanovsky, and M. Hennrich, Submicrosecond Entangling Gate between Trapped Ions via Rydberg Interaction, Nature **580**, 345 (2020).

DEVELOPING TRAPPED-ION QUANTUM COMPUTING TECHNOLOGY FOR THE MILLION-QUBIT SCALE

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I will give an overview of our work in developing technologies aiding the construction of quantum computers at the million qubit scale. I will also discuss a spin-off result in which we have realized a new electric field quantum sensor with unprecedented measurement sensitivity at low frequencies.

QUANTUM TELEPORTATION ACROSS FOUR QUBIT GRAPHS ON IBM QUANTUM

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We demonstrate different routing strategies for two-qubit quantum teleportation on four-qubit graph channels, establishing that gate routing order significantly impacts fidelity. Using stabilizer formalism, graph channels are generated through local complementation (H gates) and edge operations (CZ gates). Three teleportation protocols were evaluated on IBM Quantum processor `ibm_sherbrooke` with different hopping configurations: star graphs with asymmetric (1,3) hopping and chain graphs with symmetric (2,2) and asymmetric (1,3) hopping distances. Each protocol was tested with multiple routing approaches to identify optimal gate sequences. After initial CX gates couple input qubits to the graph channel, routing methods consist of using distinct CZ gate sequences to implement deferred measurements. The IBM transpiler generates different physical-level implementations based on the QPU connectivity constraints, introducing different circuit depths for each routing method. Optimal routing strategies achieved teleportation fidelities of $95 \pm 2\%$ across different two-qubit input states measured with tomography, while suboptimal approaches yield 5-10% lower performance. This establishes the first experimental comparison of routing strategies for two-qubit quantum teleportation on IBM hardware, providing practical guidelines for enhanced quantum information transfer.

INTERFERENCE-CONTROLLED PHOTON STATISTICS IN MESOSCOPIC ION CHAINS

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Controlling the quantum properties of light at the single-photon level is a central goal in modern quantum optics, with broad implications for quantum communication, sensing, and com-

putation. While photon antibunching has long served as a hallmark of single-emitter sources, engineering light statistics from many-emitter systems remains a key challenge—especially in free space, where decoherence and disorder typically obscure quantum signatures. In this work, we demonstrate experimentally that spatially modulated photon correlations can be achieved in free space using mesoscopic chains of trapped ions, without requiring inter-emitter interactions or entanglement.

By probing light scattered from up to 18 individually trapped and coherently driven $^{40}Ca^{+}$ ions, we show that the second-order photon autocorrelation function g(2)(0) exhibits a pronounced spatial structure, strongly anticorrelated with the scattered light intensity. In small ion crystals (e.g., four ions), we observe transitions between antibunching and bunching purely due to interference effects. This is achieved by tuning the inter-ion spacing and driving strength, which controls the balance between coherent (elastic) and incoherent (spontaneous) scattering. Even as the system scales up, these interference effects persist, indicating a robust mechanism for modulating photon statistics in mesoscopic ensembles.

Our results establish that coherent scattering from multiple independent emitters can serve as a powerful tool for tailoring quantum light. This provides a new pathway for realizing tunable photon sources and paves the way toward manipulating higher-order correlations in scalable free-space quantum platforms.

PROGRESS TOWARDS A FAULT-TOLERANT, MICROWAVE-DRIVEN QUANTUM PROCESSOR WITH TRAPPED IONS

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One of the central challenges in quantum information science is to achieve scalable, fault-tolerant quantum computation. The quantum charge-coupled device (QCCD) architecture is a leading approach to overcoming this challenge [1]. This architecture physically separates the memory, interaction, and detection zones, enabling parallel operations and modular scaling, both of which are essential for quantum processors. In the Quantum Valley Lower Saxony collaboration(QVLS), our goal is to build a 50-qubit quantum processor following this QCCD architecture. Here we report on our current progress towards building this small-scale quantum processor based microwave near-field approach [2] and outline planned experimental milestones. We further report on recent enhancements to our existing experimental platform, for quantifying and analyzing gate errors within the computational zones of the QVLS machine [3]. This will provide us with more insights into the fidelity and reliability of gate errors within a computational context.

[1] D. Kielpinski et al., Nature **417**, 709 (2002).
[2] C. Ospelkaus et al., Nature **471**, 7337 (2011).
[3] N. Pulido-Mateo et al., Physical Review Research **6**, 2 (2024).

PULSE-SHAPE EFFECTS AND DELOS-THORSON EQUIVALENCE WITH PHASE-MODULATED PULSES ON IBM QUANTUM

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Traditional pulse shapes, such as constant pulses, often induce power broadening in the excitation spectrum of qubits, limiting the precision of spectroscopic methods. Hyperbolic secant pulses, known for maintaining a constant transition linewidth, have been widely used to address this limitation. In this study, we introduce Lorentzian-based pulses, which demonstrate a remarkable new phenomenon: power narrowing [1]. This counterintuitive phenomenon reverses the conventional power broadening effect, causing the transition line to shrink, rather than broaden, as confirmed through IBM Quantum hardware experiments. By extending the truncation point further from the pulse midpoint and involving the heavy tails of the Lorentzian shape, we observe a transition from power broadening to strong power narrowing, culminating in a tenfold reduction in the width of the 7π-pulse area peak. Theoretical predictions suggest an additional reduction by two orders of magnitude, realized by truncating even further from the central part of the pulse.

In an effort to complete the linewidth control toolkit, this study also examines two novel pulse families—quadratic and even-exponent pulses—designed to enhance the opposite effect—power broadening—and find that the increased-power transition lines delocalize even further in what we call "power superbroadening." By amplifying non-adiabaticity at the pulse edges, these pulse shapes enable more sensitive interactions for applications such as EIT, quantum tomography, and nonlinear optics. The broadening capabilities of these pulse shapes, confirmed on IBM's quantum processors, offer new tools for optimizing quantum state manipulation, broadening interaction frequencies, and improving spectroscopy techniques.

Another part of our study explores the Delos-Thorson postulate—the principle that numerous coupling-detuning pairs can share the same transition probability landscape. This equivalence principle was verified by applying three distinct coupling-detuning combinations of the LMSZ, AEH and hAEH models on an IBM quantum processor, showing that different members of two families of quantum control models produce identical physical outcomes. The experimental demonstration was performed by making use of the equivalence of detuning control and phase modulation, whereby Rabi frequency phase modulation can replace time-dependent detuning. This technique exploits the mathematical relationship stating that detuning is simply the time derivative of any complex phase on the coupling, illustrated by a transformation of the two-level Hamiltonian from the Schrödinger to the interaction picture.

[1] I. S. Mihov and N. V. Vitanov, "Defying Conventional Wisdom in Spectroscopy: Power Narrowing on IBM Quantum", Phys. Rev. Lett. **132**, 020802 (2024).

TAILORING VECTORIAL OPTICAL WAVES BY CONICAL DIFFRACTION IN CASCADE

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Internal conical diffraction (CD) is a linear optical effect observable when focused light traverses an optically biaxial crystal (BC) along one of its optic axes. In the usual configuration involving a unique BC and uniformly polarized input wave, CD creates a double circular ring with spatially varying linear polarization (vector wave), two diametrically opposite points always have orthogonal linear polarizations. CD beams have shown compelling capabilities for various photonics applications, such as optical trapping, free-space optical communication, super-resolution imaging, or polarimetry. In this context, novel cascaded configurations where the optical wave traverses several aligned BCs play an important role. They lead to versatile methods for the tailoring of multiple-ring-shaped vector waves and their optical angular momentum, up to the case where the intrinsic circular symmetry is lost in conjugate cascades. Here we discuss our recent works in this context, where transformations in wave-vector and/or polarization spaces between the cascaded BCs can lead to highly peculiar vector waves. The resulting light patterns can be excellently predicted by a Fourier space paraxial model considering the effects of the individual BCs and of the intermediate transformations. We will also illustrate an unfolding procedure for double-pass semi-cavities containing a BC, as well as the marriage of CD with in-situ holography with crystals showing appropriate nonlinear optical effects.

QUANTUM LOGICAL GATES WITH DRAG FORMALISM

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The calibration of logical quantum computing gates can vary drastically between the optimal achievable fidelity and the practical achievable performance given limited available uptime as well as drifting system parameters. Thus, near-optimal control strategies with a minimal number of free parameters can significantly enhance usability of quantum information processors. We discuss the DRAG formalism for reducing certain typical off-resonant error transitions that often hamstring operations in most quantum computing platforms. After a brief overview of the analytical expansion method, we discuss some applications in entangling gates, dispersive measurement operations, Raman transitions, tunable interactions, Rydberg blockade gates, rotating-wave approximations, and qudit gates.

ROBUST DYNAMICAL DECOUPLING APPROACH FOR QUANTUM SENSING

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Dynamical decoupling (DD) is one of the simplest and least resource-intensive methods for decoherence suppression and has proven to be an essential tool on today's noisy intermediate-scale quantum (NISQ) devices. In this work, we derive general formulas for two new classes of DD sequences that are robust against detuning and pulse area errors. Experimental results are presented from the 127-qubit open-access IBM Quantum processors, showing excellent agreement with theoretical predictions.

In the presence of a weak ambient external electric or magnetic field, the ensuing Stark or Zeeman shift leads to an energy level shift and hence a static detuning. The same idea used for constructing robust sequences is applied in the reverse manner to constructing quantum sensing sequences that can be used for measuring small energy level shifts.

The optimal choice of pulse phases to maximize sensitivity is studied. We show that the best choice appears to be the alternating sequence $(0, \pi, 0, \pi, \ldots)$ [1]. Next, we investigate the effect of the separation between the pulses. We demonstrate that by introducing free evolution time intervals of equal duration between pulses, we achieve a small improvement in sensitivity for sequences with zero phases and slightly worse results for sequences with alternating phases. We have shown that the best option is time intervals with unequal duration, for which conditions maximizing sensitivity are derived.

[1] N. V. Vitanov, "Quantum sensing of weak electric and magnetic fields by coherent amplification of energy-level-shift effects," Phys. Rev. A **103**, 063104 (2021).

EFFICIENT QUANTUM CONTROL BY COMPOSITE ULTRASTRONG FIELD

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We present a study on coherent quantum control of a qubit by an ultrastrong driving field in the regime where the rotating-wave approximation cannot be applied. The resulting counter-rotating term makes traditional quantum control methods, such as resonant, adiabatic and shortcut techniques, unable to achieve high control accuracy. We identify the recently developed universal composite pulses as the only quantum control method which successfully maintains very high accuracy even in this ultrastrong coupling regime.

OVERCOMING NOISE IN QUANTUM TELEPORTATION WITH MULTIPARTITE HYBRID ENTANGLEMENT

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Any realistic quantum system interacts with its environment leading to the concept of open quantum system including decoherence and loss of quantum properties. Within this framework, it is possible to control the transition between memoryless Markovian dynamics and non-Markovian dynamics featuring memory effects [1]. Indeed, the characterization on non-Markovianity and memory effects in quantum dynamics has been very actively debated within the last ten years [2]. Moreover, it has become possible to fully control the pure decoherence caused by dephasing [3]. Recently, the focus has shifted to frameworks including quantum protocols [4]. In general, quantum entanglement and decoherence are the two counterforces of many quantum technologies and protocols. For example, while quantum teleportation is fueled by a pair of maximally entangled resource qubits, it is vulnerable to decoherence. Here, we propose an efficient quantum teleportation protocol in the presence of pure decoherence and without entangled resource qubits entering the Bell-state measurement. Instead, we use multipartite hybrid entanglement between the auxiliary qubits and their local environments within the open-quantum system context. With a hybrid-entangled initial state, it is the decoherence that allows us to achieve high fidelities. We demonstrate our protocol in an all-optical experiment [4].

[1] B.-H. Liu, L. Li, Y.-F. Huang, C.-F. Li, G.-C. Guo, E.-M. Laine, H.-P. Breuer, and J. Piilo. Nature Physics **7**, 931 (2011).
[2] H.-P. Breuer, E.-M. Laine, J. Piilo, and B. Vacchini. Reviews of Modern Physics **88**, 021002 (2016).
[3] Z.-D. Liu, H. Lyyra, Y.-N. Sun, B.-H. Liu, C.-F. Li, G.-C. Guo, S. Maniscalco, and J. Piilo. Nature Communications **9**, 3453 (2018).
[4] Z.-D Liu, O. Siltanen, T. Kuusela, R.-H. Miao, C.-X. Ning, C.-F. Li, G.-C. Guo, and J. Piilo. Science Advances **10**, eadj3435 (2024).

CORRELATIONS AND STATISTICS OF QUANTUM DOT SOURCES OF QUANTUM LIGHT

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Single quantum dots coupled to photonic cavities are established emitters of single photons and entangled photon pairs. The cascaded generation of photon pairs intrinsically contains temporal correlations that negatively affect the ability of such sources to perform two-photon interference, hindering applications. Our study identifies crucial parameters of the source and shows the way to achieve optimal performance. I will show that pairs of photons exhibit strongly non-classical properties that can be quantified. Our result is applicable to a wide

range of quantum light sources and measurement methods. Also, I will introduce novel methods to characterize sources of entangled photons.

SHORTCUTS TO ADIABATICITY AND CAMEL

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As this is the 20th CAMEL anniversary, I will use this opportunity to give an overview about all the topics which I have presented since I have attended my first CAMEL workshop. Of course, this will also include new developments on these topics as well as recent results following from them. Most of these topics have been centered around quantum control via Shortcuts to Adiabaticity (STA). I will start reviewing briefly Shortcuts to Adiabaticity; these are fast and robust quantum control protocols motivated by adiabatic processes and mainly derived using analytical techniques. I will also review some first STA applications which have been also presented in the earlier CAMEL workshops. However, there are still quantum systems where these STA methods cannot be applied. Therefore, I will then present a new technique for such scenarios, called "Enhanced Shortcuts to Adiabaticity" (eSTA), also presented in the last CAMEL workshops. This new method works for previously intractable Hamiltonians by providing an easy to calculate analytical correction to existing STA protocols. I will also show recent applications of eSTA. In the last part, I will switch to quantum thermodynamics and asymmetric quantum devices and I will give an overview about the different topics in these fields presented also in previous CAMEL workshops including recent updates.

THE DAVIES-PECHUKAS METHOD FOR QUBIT DYNAMICS

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In this work, we investigate the method developed by Davis and Pechukas, which is grounded in the semiclassical limit $\hbar \to 0$. In this regime, quantum dynamics approximate classical behavior, and for slowly varying Hamiltonians, the limit becomes equivalent to the adiabatic approximation. The method provides asymptotic expressions for the quantum evolution by analyzing the system in the basis of adiabatic eigenstates. Particular attention is given to nonadiabatic transitions induced by the time dependence of the Hamiltonian. For analytic time-dependent Hamiltonians, such transitions are localized near complex crossing points of the adiabatic potential curves. Remarkably, the corresponding transition amplitude is independent of the specific form of the nonadiabatic coupling and is described by a simple and elegant formula, originally derived by A. M. Dykhne and later generalized within the framework of semiclassical theory by Davis and Pechukas. The primary objective of this study is to explore the applicability of the method to various physical models, with special emphasis on the Demkov-Kunike model.

MULTIPASS QUANTUM PROCESS TOMOGRAPHY

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We introduce a method to enhance the precision and accuracy of Quantum Process Tomography (QPT) by mitigating the errors caused by state preparation and measurement (SPAM), readout and shot noise [1]. Instead of performing QPT solely on a single gate, we propose performing QPT on a sequence of multiple applications of the same gate. The method involves the measurement of the Pauli transfer matrix (PTM) by standard QPT of the multipass process, and then deduce the single-process PTM by two alternative approaches: an iterative approach which in theory delivers the exact result for small errors, and a linearized approach based on solving the Sylvester equation. We examine the efficiency of these two approaches through simulations on IBM Quantum using IBMQ_QASM_SIMULATOR. Compared to the Randomized Benchmarking type of methods, the proposed method delivers the entire PTM rather than a single number (fidelity). Compared to standard QPT, our method delivers PTM with much higher accuracy and precision because it greatly reduces the SPAM, readout and shot noise errors. We use the proposed method to experimentally determine the PTM and the fidelity of the CNOT gate on the quantum processor ibmq manila (Falcon r5.11L).

[1] Stanchev, S.G., Vitanov, N.V. Multipass quantum process tomography. Sci Rep **14**, 18185 (2024). doi.org/10.1038/s41598-024-68353-3

ROBUST, FAST AND HIGH-FIDELITY COMPOSITE SINGLE-QUBIT GATES FOR SUPERCONDUCTING TRANSMON QUBITS

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We introduce a novel quantum control method for superconducting transmon qubits that significantly outperforms conventional techniques in precision and robustness against coherent errors. Our approach leverages composite pulses (CP) to effectively mitigate system-specific errors, such as qubit frequency and anharmonicity variations. By utilizing CP, we demonstrate both complete and partial population transfers between qubit states, as well as the implementation of two essential single-qubit quantum gates. Simulations reveal substantial reductions in common error rates and gate durations. The effectiveness of our method is validated through four independent verification techniques, underscoring its potential for advancing quantum computing with superconducting qubits.

HOUSEHOLDER REFLECTIONS IN QUANTUM INFORMATICS

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Householder reflections are known method for QR decomposition of matrices. Here we investigate the applicability of this mathematical tool to quantum informatics. One of the research directions is how householder reflections can be applied in chain model. A sample circuit relying on householder reflections was created for generation of W4 states. It was shown that every unitary transformation can be decomposed into series of householder reflections, where each reflection requires a vector, which on its turn can be created with unitaries of smaller dimension and so on until the whole transformation is built. Exploration of Householder reflections is done on ion trap-based systems – starting from general treatment and considering special systems like Mølmer-Sørensen gate. Investigation was done on the applicability of Householder reflections for generation of random matrices. Comparison was done with methods based on Givens rotations and Spengler parametrization.

FULL IMPLEMENTATION OF A QUANTUM KEY DISTRIBUTION NETWORK IN A CITY

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Quantum key distribution (QKD) is one of the possible solutions to maintain data privacy when quantum computers will render todayś public-key cryptography insufficient. For a broad deployment of QKD, scalable and robust systems are necessary. Scalability can be achieved by using star-shaped networks in combination with entanglement-based QKD protocols. A single untrusted source in the center serves all connected network parties to exchange a key. We implemented a time-bin variant of the BBM92 protocol and demonstrated simultaneous pairwise QKD between four users while maintaining a principal scaling to up to 100 users. The critical components are interferometers in the source and each receiving party. Long- and short term stabilization of our interferometers is achieved by controlling the interferometer temperature with sub-millikelvin resolution. Based on our prior works [1-3], we implemented further improvements and then distributed our receiver units among four labs within Darmstadt and connected them via deployed fibers operated by Deutsche Telekom and TU Darmstadt. Furthermore, we implemented post-quantum secure authentication schemes for the public channel as well as full error correction, privacy amplification and software based clock recovery. In our talk, we discuss our results and give an outlook on future work, where we plan to switch to a Photonic Chip based light source.

[1] E. Fitzke et al., PRX **3** (2022) 020341;
[2] T. Dolejsky et al. Europ. Phys. J. Spec. Top. **232** (2023) 3553;

[3] J. Kaltwasser et al., Physical Review A **109** (2024) 012618.

DYNAMICALLY-DECOUPLED HYPER-RAMSEY SPECTROSCOPY OF OPTICAL TRANSITIONS

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Hyper-Ramsey protocols have been successfully implemented on ultra-narrow optical clock transitions to reduce systematic frequency-shifts induced by AC-Stark shift and amplitude pulse variation. However, the compensation remains imperfect against laser probe intensity fluctuation, decoherence and unsuited for external quasi-static or low frequency noise perturbations. Here, we address these limitations by employing dynamical-decoupling methods composed by multiple rotary Hahn-echo pulses toggling probe frequency detunings between opposite signs during interrogating laser pulses. Time-optimized Uhrig sequences of refocusing pulses produce highly contrasted and robust hyper-Ramsey interferences against low-frequency noise distortions caused by environmental factors and imperfections in the probe parameters. Dynamically-decoupled SU(2) hyper-clocks pave the way to universal noise-resilient quantum sensors, unveiling fault-tolerant quantum metrology to track fundamental symmetries and search for new physics beyond the Standard Model.

COMPOSITE MODULATED MOLMER-SORENSEN GATE

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The Mølmer-Sørensen (MS) gate is a two-qubit controlled-phase gate in ion traps that is highly valued due to its ability to preserve the motional state of the ions. However, its fidelity is obstructed by errors affecting the motion of the ions as well as the rotation of the qubits. In this work, we propose an amplitude-modulated composite MS gate which features high fidelity robust to gate timing, static and drifting detuning, coupling errors as well as a.c Stark shift.

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CAMEL XX Programme

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09:00-09:45	Hennrich	Genov	Hensinger	Piilo
09:45-10:30	Predojevic	Zlatanov	Mendpara	Ruschhaupt
10:30-11:00	coffee	coffee	coffee	coffee
11:00-11:45	Walther	Grimaudo	Montemezzani	Cheinet
11:45-12:30	Motzoi	Bebrov	Zanon-Willette	Mihov
15:00-16:30		**BOAT**		
16:30-17:00	coffee		coffee	coffee
17:00-17:30	Stanchev		Kovalenko	Amour
17:30-18:00	Tonchev		Nedev	Ilich
18:00-18:20	Grigorova		Vasilev	Shiroyan
18:20-18:40	Parashkevova		Dimitrov	Chernev
20:00			**DINNER**	

* Registration is available on June 15 between 18:00 - 19:00 and on June 16 between 08:00 - 09:00 in the conference room