Multiparameter Quantum Sensing and Metrology

827. WE-Heraeus-Seminar

03 – 06 February 2025

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 827. WE-Heraeus-Seminar:

Quantum metrology is one of the three pillars of the emerging quantum revolution 2.0, along with quantum computing and quantum communication. It has already substantial impact in science and is considered one of the quantum technologies closest to applications. So far the field has mostly focused on quantum metrology for a single parameter, such as a component of a magnetic field or an acceleration, but with new applications such as quantum imaging, or quantum wave-form estimation, quantum parameter-estimation problems arise that are naturally multi-parameter.

Multi-parameter quantum estimation problems have been examined early on by the founding fathers of the field, but the situation is substantially more complex than for single-parameter estimation, because the corresponding Quantum Cramér-Rao bound can typically not be saturated. There is now a large community of researchers who use various tools of quantum parameter estimation over a broad range of fields in physics and the time is ripe to bring together experimental and theoretical scientists, for exchanging techniques and best practices, and discussing open problems. Five selected leading international experts will give tutorials with an introduction to their fields, and additional 14 invited leading international scientist will give an overview of their current research, guarantee a high scientific level, and structure the seminar. All other participants will be given the opportunity to present their current research work through posters. Five submissions for posters will be selected for contributed talks, and a prize for the best poster will be awarded.

Introduction

Scientific Organizers:

Prof. Gerardo Adesso
University of Nottingham
School of Mathematical Sciences
Nottingham, UK
E-Mail: gerardo.adesso@nottingham.ac.uk

Prof. Dr. Daniel Braun
Universität Tübingen
Institut für Theoretische Physik
Tübingen, Germany
E-Mail: daniel.braun@uni-tuebingen.de

Prof. Dr. Fedor Jelezko
Universität Ulm
Institut für Quantenoptik
Ulm, Germany
E-Mail: fedor.jelezko@uni-ulm.de

Administrative Organization:

Dr. Stefan Jorda
Marion Reisinger

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-18
Fax +49 6181 92325-15
E-Mail reisinger@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Introduction

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internetwww.pbh.de

Taxi Phone +49 2224 2222

Registration:

Marion Reisinger (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 02 February 2025

17:00 – 21:00	Registration	
18:30	*BUFFET SUPPER and informal get-together*	
19:30 – 20:20	Nicolas Treps	**Modal approach to multi-parameters estimation in optics and the example of incoherent sources**

Monday, 03 February 2025

08:00	*BREAKFAST*	
08:45 – 09:00	Gerardo Adesso, Daniel Braun, Fedor Jelezko	**Welcome words** **Video Wilhelm and Else Heraeus Foundation**
09:00 – 09:50	Rafal Demkowicz – Dobrzanski	**Quantum Metrological Theoretical Toolbox - all you need to know to find the optimal protocols!**
09:50 – 10:30	Abolfazl Bayat	**Overcoming Quantum Metrology Singularity**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:40	Jan Jeske	**Cavity-enhanced magnetometry with nitrogen-vacancy centres in diamond**
11:40 – 12:20	Javier Cerrillo	**Multiparameter NV Quantum Sensing at Low Frequency, Low Bias Magnetic Field or High Frequency**
12:20 – 12:25	***Conference Photo***	
12:30 – 14:30	*LUNCH*	

Program

Monday, 03 February 2025

14:30 – 15:10	Uwe R. Fischer	**Self-Consistent Many-Body Metrology**
15:10 – 15:30	Marta Maria Marchese	**Cascaded Optomechanical Sensing**
15:30 – 16:10	Dennis Rätzel	**Gravity sensing with quantum optomechanical systems**
16:10 – 16:40	*COFFEE BREAK*	
16:40 – 17:20	Javier Prior	**Sensing Inside Biological Systems: Nanodiamonds for Tracking Cellular Inflammation**
17:20 – 18:00	***Poster Flashes***	
18:30	*DINNER AND GET-TOGETHER*	

Program

Tuesday, 04 February 2025

08:00	*BREAKFAST*	
09:00 – 09:50	Valeria Cimini	**Adaptive multiphase estimation at the quantum bound with integrated photonics circuits**
09:50 – 10:30	Mankei Tsang	**Quantum estimation with infinitely many parameters**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:40	Emre Köse	**Multi-Parameter Quantum Imaging: From Passive Sensing to Mass Photometry**
11:40 – 12:20	Alexander Lvovsky	**Mankei's method in application to imaging**
12:30 – 14:30	*LUNCH*	
14:30 – 16:10	***Poster Session***	
16:10 – 16:40	*COFFEE BREAK*	
16:40 – 17:20	Arne Wickenbrock	**Searching for new physics with quantum sensors**
17:20 – 18:00	Renbao Liu	**Diamond sensors in complex environments**
18:30	*HERAEUS DINNER (social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 05 February 2025

08:00	*BREAKFAST*	
09:00 – 09:50	Paola Cappellaro	**Multiparameter sensing via control and entanglement**
09:50 – 10:30	Ugo Marzolino	**Quantum metrology assisted by quantum algorithms**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:40	Lorenzo Maccone	**Quantum optical classifier with superexponential speedup**
11:40 – 12:00	Jesus Rubio Jimenez	**Symmetry-informed global quantum metrology: towards a multiparameter formulation**
12:00 – 12:20	Salvatore Muratore	**Superresolution imaging of two incoherent sources via two-photon interference sampling measurements in the transverse momenta**
12:30 – 14:00	*LUNCH*	
14:00 – 16:30	*EXCURSION*	
16:40 – 17:20	Tuvia Gefen	**Quantum precision limits for waveform estimation and noise detection**
17:20 – 18:00	Madalin Guta	**Optimal estimation of quantum Markov chains using coherent absorbers and pattern counting estimators**
18:30	*DINNER AND GET-TOGETHER*	

Program

Thursday, 06 February 2025

08:00	*BREAKFAST*	
09:00 – 09:50	Luca Pezzè	**Role of entanglement in distributed quantum sensing**
09:50 – 10:10	Lorcan Conlon	**The role of entangling measurements in quantum multiparameter estimation**
10:10 – 10:30	Atmadev Rai	**Heisenberg-scaling sensitivity in the simultaneous estimation of multiple parameters using squeezed light**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:40	Michal Parniak	**Interaction-enhanced quantum sensing with Rydberg atoms**
11:40 – 12:20	***Panel Discussion***	
12:30 – 14:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Friday however, a self-service breakfast will be provided on Friday morning

Posters

Posters

Federico Belliardo	**Upper bounds on the precision of sensing correlated noise with quantum sensor networks**
Russell Brooks	**Quantum-private distributed sensing**
Domantas Burba	**Strong long-range interactions and geometrical frustration in subwavelength Raman lattices**
Maria Paz Camposano Moore	**Development of a microwave-free measurement protocol for quantum sensing**
Jyong-Hao Chen	**Bounds on quantum adiabaticity in driven many-body systems and applications to adiabatic quantum computation**
Jéssica Fernanda Da Silva Barbosa	**Towards fabrication of shallow NV centers with long coherence times**
Jacques Ding	**Quantum metrology in realistic bosonic systems: Theory and experiment**
Durgun Duran	**Non-Markovianity of the reduced dynamics of quantum systems under the unitary actions of Yang-Baxter matrices**
Kaoutar El Bachiri	**Fidelity and Quantum Distance: Theoretical Foundations and Applications in Quantum Measurement**
Demosthenes Ellinas	**Maximum likelihood parameter estimation with reluctant quantum walks: analytic results and operational methods**
Nicolas Fabre	**Estimation of time and frequency parameters with frequency entangled photons**
Michael Gaida	**Metrology for magnetic moments in transmission electron microscopes**

Posters

Edward Gandar	**Short-time metrology enhanced by non-linear interactions in a collective spin system**
Ana Teresa Gea Caballero	**Adiabatic preparation scheme for the AKLT state in a 1D Rydberg platform**
Romain Granier	**Metrology of microwave fields with cold Rydberg atoms**
Antonin Grateau	**Multiparameter approach to experimental separation estimation of unequally bright sources**
Shuaiwei Guo	**Quantum Coherence Control at Temperatures up to 1400 K**
Bartosz Kasza	**Atomic-optical interferometry in fractured loops: a general solution for Rydberg radio frequency receivers**
Stanislaw Kurdzialek	**Quantum metrology using quantum combs and tensor network formalism**
Carlos E. Lopetegui Gonzalez	**Metrology-inspired detection of mode-intrinsic quantum entanglement**
Alberto Lopez Garcia	**Robust arbitrary single qubit gates for nv centers: low-field or high-frequency regimes**
Luca Maggio	**Multiparameter quantum estimation based on two-photon interferometric techniques**
Carmen Maria Martinez Lopez	**Implementation of a microfluidic device to a quantum sensor based in Nitrogen-Vacancy centers in diamond**
Alejandro Martínez Méndez	**Characterization of the initialization of NV centers in highly populated systems.**
George Mihailescu	**Understanding Singularities of the Quantum Fisher Information Matrix using Bayesian Strategies**

Posters

Jesús Moreno Meseguer	**Quantum Sensing on cells using nanodiamonds**
Marcel Morillas Rozas	**Double Quantum Entanglement Generation Between Aligned NV Centers Using Global Addressing**
Quentin Muller	**Quantum inspired super-resolution of surface roughness**
Fabian Müller	**Pushing the Boundaries: Interferometric Mass Photometry at the Quantum Limit of Sensitivity**
Sofía Rodríguez Vidal	**Bipartite entanglement in one-dimensional Quantum Walks**
Mahdi Rouhbakhshnabati	**Semi-Classics for Quantum Fisher Information**
Anagha Shriharsha	**tbc**
Antoni Skoczypiec	**Design of fiber-based dispersive elements for quantum information science**
Giacomo Sorelli	**Quantum optimal discrimination of incoherent sources**
Danilo Triggiani	**Quantum optimal precision by resolving two-photon correlations**
Leah Turner	**All non-Gaussian states are advantageous for channel discrimination**
Denis Vasilyev	**Optimal Multi-Parameter Metrology: Vector Field Sensing with Two Qubits**
Antonio Verdú	**Sensing intramolecular interactions with nitrogen-vacancy centers**

Posters

Shuo Wang	**Optically Detected Magnetic Resonance with Light-sheet Microscopy**
Erik Weiss	**Pattern-based Quantum Functional Testing**
Jing Yang	**Optimal Measurements in Quantum Sensing**

Abstracts of Talks

(in alphabetical order)

Overcoming Quantum Metrology Singularity

Y. Yang[1], V. Montenegro[1] and A. Bayat[1]

[1] *Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Chengdu 611731, China*

The simultaneous estimation of multiple unknown parameters is the most general scenario in quantum sensing. Quantum multi-parameter estimation theory provides fundamental bounds on the achievable precision of simultaneous estimation. However, in multi-parameter sensing these bounds can become singular due to parameter interdependencies, limited probe accessibility, and insufficient measurement outcomes. Here, we address the singularity issue in quantum sensing through a simple mechanism based on sequential measurement strategy. This sensing scheme overcomes the singularity constraint and enables the simultaneous estimation of multiple parameters with a local and fixed measurement throughout the sensing protocol. This is because sequential measurements, involving consecutive steps of local measurements followed by probe evolution, inherently produce correlated measurement data that grows exponentially with the number of sequential measurements. Finally, through two different examples, namely a strongly correlated probe and a light-matter system, we demonstrate the practical implication of such singularities on inferring the unknown parameters through Bayesian estimation.

Multiparameter sensing via control and entanglement

P. Cappellaro[1]
[1]Massachusetts Institute of Technology, Cambridge, MA, USA

Sensing the vectorial components of a field or its spatial variations provides important information about the underlying processes that generate it. Performing such measurement in an efficient way, and ideally at the quantum limit, is still a challenge, especially in the presence of noise and control imperfection. Here we introduce protocols that can tackle such tasks by exploiting control, in the form of frequency modulation, and by leveraging the presence of additional qubits that expand the capability of the qubit sensor.

Multiparameter NV Quantum Sensing at Low Frequency, Low Bias Magnetic Field or High Frequency

J. Cerrillo

Universidad Politécnica de Cartagena, Cartagena, Spain

The use of conventional protocols for metrology and nano-NMR with NV centers limits the range of application to frequencies above the decohering rate of the probe and, at the same time, below the Zeeman splitting of the ground state. We explore two approaches that extend the operational regime of NV centers: correlated Ramsey and three-level control. By correlating the results of repeated Ramsey measurements at a rate larger than the decohering rate of the probe [1], it is possible to significantly lower the bound of detectable frequencies. Furthermore, phase and strength of the signal can be identified simultaneously. Concerning three-level control, we propose the NV-Effective Raman Coupling (NV-ERC) technique [2] that, by careful design of pulses addressing the zero-field transition, enables implementation of NMR sequences in the otherwise inaccessible low-magnetic-field regime [3]. NV-ERC is a versatile approach allowing for arbitrary qubit gates in the double-quantum transition [4] and the creation of two types of entangled pairs of NV centers with fourfold enhancement of the sensitivity to longitudinal magnetic fields or transverse electric fields respectively.

References

[1] S. Oviedo-Casado; J. Prior; J. Cerrillo. Low Field Nano-NMR via Three-Level System Control. J. Mag. Res. 126, 220402 (2024).
[2] J. Cerrillo; S. Oviedo-Casado; J. Prior. Low Field Nano-NMR via Three-Level System Control. Phys. Rev. Lett. 126, 220402 (2021).
[3] P. J. Vetter; A. Marshall; G. T. Genov; T. F. Weiss; N. Striegler; E. F. Großmann; S. Oviedo-Casado; J. Cerillo; J. Prior; P. Neumann; F. Jelezko. Zero- and Low-Field Sensing with Nitrogen-Vacancy Centers. Phys. Rev. Appl. 17, 044028 (2022).
[4] A. López García, J. Cerrillo. Full Qubit Control of NV Ground State for Low Field or High Frequency Sensing. arXiv:2407:17461 (2024).

Adaptive multiphase estimation at the quantum bound with integrated photonics circuits

V. Cimini[1], M. Valeri[1], E. Polino[1], S. Piacentini[2], F. Ceccarelli[2], G. Corrielli[2], R. Osellame[2], N. Spagnolo[1], and F. Sciarrino[1]

[1]Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy.

[2]Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche (IFN-CNR), Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy.

Quantum sensing stands as one of the most promising quantum technologies, intending to use quantum resources to improve measurement sensitivity beyond classical limits. In particular, the possibility to perform the simultaneous estimation of multiple parameters, beating the best possible precision achievable with classical resources represents an important step towards real-world applications. In practical scenarios, it becomes fundamental to optimally adjust the measurement settings through adaptive strategies [1]. These consist in adjusting the measurement settings after the interaction of each probe with the system under investigation, thus setting the quantum sensor in its optimal working point: fundamental condition to show quantum-enhanced performances in the whole range of the parameters values. In general, such optimization tasks are quite complex to solve and the situation gets even more intricate when dealing with multiparameter problems.

Experimental demonstration of quantum-enhanced multiparameter estimation relies on highly reconfigurable platforms that enable fine control over numerous parameters, including the ability to tune probe states and measurement settings as part of adaptive protocols. However, implementing these strategies in a scalable way also requires punctual characterization and precise control of the employed system, both of which are non-trivial to implement in actual quantum platforms.

In recent years, our research has focused on overcoming these challenges by developing efficient adaptive strategies making use of deep learning algorithms [2] and variational optimization techniques [3] applied to an integrated photonic circuit for the estimation of multiple optical phase shifts.

Variational techniques indeed offer a powerful solution to efficiently explore the high-dimensional parameter space typical of multiparameter optimization problems, consisting of a hybrid quantum-classical approach. The quantum circuit is directly employed to evaluate a meaningful cost function that is subsequently fed into a classical gradient-free optimization algorithm, making the procedure inherently resilient to noise and experimental imperfections that are in this way automatically considered during the cost function reconstruction. The key advantage of this approach lies indeed in its ability to tailor variational quantum circuits to the specific characteristics of the experimental setup enabling an inherent robustness against noise.

Our findings demonstrate the efficacy of adaptive techniques in advancing quantum sensing and quantum information processing with photonic circuits for use in Noisy Intermediate-Scale Quantum (NISQ) devices.

References

[1] M. Valeri et al., Experimental multiparameter quantum metrology in adaptive regime, Phys.Rev.Res. 5(1), 013138 (2023).

[2] V. Cimini, et al., Deep reinforcement learning for quantum multiparameter estimation, Advanced Photonics 5(1), 016005 (2023).

[3] V. Cimini, et al., Variational quantum algorithm for experimental photonic multiparameter estimation, npj Quantum Information 10(1), 26 (2024).

The role of entangling measurements in quantum multiparameter estimation

Lorcán O. Conlon,[1] Ping Koy Lam,[1,2] and Syed Assad[1,2,*]

[1] *Quantum Innovation Centre (Q.InC), Agency for Science Technology and Research (A*STAR), 2 Fusionopolis Way, Innovis 08-03, Singapore 138634, Republic of Singapore*

[2] *Centre for Quantum Computation and Communication Technology, Department of Quantum Science, Australian National University, Canberra, ACT 2601, Australia.*

Quantum multiparameter estimation showcases the full spectrum of quantum mechanical effects in metrology. Not only can the impact of quantum resources, such as squeezed light and entangled states, be observed, but fundamental limits set by the uncertainty principle and operator non-commutivity is also on display. Understanding the ultimate limits of quantum multiparameter estimation is therefore of both fundamental and practical importance. In this talk I discuss the role of entangling measurements in saturating these ultimate limits, set by the Holevo Cramér-Rao bound (HCRB) and quantum Fisher information (QFI). I shall discuss the major limitation of these bounds - saturating them can require entangling measurements on infinitely many copies of the quantum state, which is experimentally infeasible. To circumvent this problem we introduce a new Cramér-Rao bound (CRB) which applies when restricted to experimentally relevant separable measurements [npj Quant. Info. 7, 110 (2021)]. As this bound can be computed as a semi-definite program, it can also be applied when entangling measurements on a limited number of copies of the quantum state are allowed. To demonstrate the practical relevance of our new CRB compared to the HCRB and QFI, I shall then present recent experimental results showing the first demonstration of entangling measurements on two copies of a quantum system saturating the theoretical limits [Nat. Phys. 19, 351-357 (2023)]. Next, I shall present a no-go theorem on when the HCRB and QFI can be saturated. We prove that in many practical scenarios neither the HCRB or QFI can be saturated by any finite energy measurement [arXiv2208.07386v3 (2024)]. Finally, we address the question of whether the HCRB or QFI can be approximately saturated, i.e. does there exists a measurement which gets within a constant factor of either bound. We prove that when estimating the maximum number of independent parameters in a d dimensional Hilbert space the gap between our CRB and these bounds can scale linearly in d [arXiv2405.09622 (2024)].

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[*] There are too many collaborators for this series of papers to list here - instead we list the authors who have co-authored all the papers mentioned and acknowledge the full list of authors in the talk.

Abstract

Rafal Demkowicz – Dobrzanski
University of Warsaw, Poland

Identifying the optimal quantum metrological protocols in presence of realistic noise may be challenging. Brute force methods usually do not allow to study models in the regimes interesting from practical point of view. In this talk I will present the state-of-the-art (and even a bit beyond..) tools that allow for an efficient search of the optimal protocols even in asymptotic regime of infinite available resources (particles, time, etc..) as well as methods to derive fundamental bounds that can certify their optimality.

Self-Consistent Many-Body Metrology

Jae-Gyun Baak, Uwe R. Fischer

We investigate performing classical and quantum metrology and parameter estimation by using interacting trapped bosons, which we theoretically treat by a self-consistent many-body approach of the multiconfigurational Hartree type. Focusing on a tilted double-well geometry, we compare a self-consistently determined and monitored two-mode truncation, with dynamically changing orbitals, to the conventional two-mode approach of fixed orbitals, where only Fock space coefficients evolve in time.
We demonstrate that, as a consequence, various metrological quantities associated to a concrete measurement such as the classical Fisher information and the maximum likelihood estimator are deeply affected by the orbitals' change during the quantum evolution.
Self-consistency of the quantum many-body dynamics of interacting trapped ultracold gases thus fundamentally affects the attainable parameter estimation accuracy of a given metrological protocol.

References

Jae-Gyun Baak and Uwe R. Fischer: Self-Consistent Many-Body Metrology, Phys. Rev. Lett. 132, 240803 (2024).

Quantum precision limits for waveform estimation and noise detection

Tuvia Gefen[1], James W. Gardner[2,3], Simon A. Haine[4], Joseph J. Hope[4], John Preskill[3,5], Lee McCuller[3,5], Yanbei Chen[3]

[1] Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Givat Ram, Israel

[2] OzGrav-ANU, Centre for Gravitational Astrophysics, Research Schools of Physics, and of Astronomy and Astrophysics, The Australian National University, Canberra, ACT 2601, Australia

[3] Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA

[4] Department of Quantum Science and Technology and Department of Fundamental and Theoretical Physics, Research School of Physics, The Australian National University, Canberra, ACT 0200, Australia

[5] Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA

Estimating a weak waveform is a core task of various physical problems, such as gravitational waves detection, fundamental physics searches and nano-NMR. I will discuss quantum metrology bounds and protocols for these different estimation tasks. Improved protocols for gravitational waves detection in the detuned cavity case will be presented [1]. In this case, the relevant precision bounds correspond to the Holevo Cramer-Rao bounds and the optimal measurements turn out to be non-stationary quadrature measurements.

I will then discuss stochastic waveform estimation, a sensing task relevant for fundamental physics searches. We derive channel quantum Fisher information bounds for this problem and show that a significant improvement can be introduced using non-Gaussian states, such as GKP states, and non-Gaussian measurements [2]. Finally, we address the more general question of how well noise can be estimated in the presence of other nuisance noise processes. We derive a general criterion for evading the Rayleigh curse and find optimal input states and detection schemes for this problem [3].

[1] Achieving the fundamental quantum limit of linear Waveform Estimation. *Physical Review Letters* 132.13 (2024): 130801

[2] Stochastic waveform estimation at the fundamental quantum limit. *arXiv preprint arXiv:2404.13867* (2024)

[3] Lindblad estimation with fast and precise quantum control. *arXiv preprint arXiv:* 2501.03364 (2025)

Optimal estimation of quantum Markov chains using coherent absorbers and pattern counting estimators

Federico Girotti[1], Alfred Godley[2] and Madalin Guta[2]

[1]*Department of Mathematics, Polytechnic University of Milan, Italy*
[2] *School of Mathematical Sciences, University of Nottingham, United Kingdom*

In this presentation I will discuss the problem of estimating dynamical parameters of a quantum Markov chain. The key tool will be the use of a coherent quantum absorber which transforms the problem into a simpler one pertaining to a system with a pure stationary state at a reference parameter value. Motivated by the proposal in [1] I will consider counting output measurements and show how the statistics of the counts can be used to compute a simple, asymptotically optimal estimator of the unknown parameter. For this, I will introduce translationally invariant modes (TIMs) of the output and show that these modes are Gaussian in the limit of large times and capture the entire quantum Fisher information of the output. Moreover, the counting measurement provides an effective joint measurement of the TIMs number operators. The unknown parameter is estimated using a two stage estimation procedure. A rough estimator is first computed using a simple measurement, and is used to set the absorber parameter. Due to non-identifiability issues of the counting measurement the reference parameter needs to be shifted away from the initial rough estimator, as shown in the displaced-null measurements theory [2]. Finally, an optimal estimator is computed in terms of the total number of excitations of the TIMs, avoiding the need for expensive estimation procedures. Details can be found in [3].

[1] D. Yang, S. F. Huelga, and M. B. Plenio PRX Quantum 13, 031012 (2023)
[2] F. Girotti, A. Godley and M. Guta, J. Phys. A 57 245304 (2024)
[3] F. Girotti, A. Godley and M. Guta, arXiv: 2408.00626

Cavity-enhanced magnetometry with nitrogen-vacancy centres in diamond

Lukas Lindner[1], Florian Schall[1], Sebastian Heuft[1], Michael Kunzer[1] and Jan Jeske[1]

[1]*Fraunhofer Institut für Angewandt Festkörperphysik IAF, Freiburg, Germany*

Laser cavities are non-linear optical elements which can be used to significantly enhance small changes in brightness of a quantum emitter or absorber, particularly when operated near the threshold. In this way components of the magnetic field (or other quantities, such as temperature) can be measured more precisely and/or with improved dynamic range enabling also a path to improved vector magnetometry. I will present an overview of laser threshold magnetometry and show our recent advances: The first continuous-wave laser threshold as a function of pumping of NV diamond, realized by combining NV diamond with a second gain medium, emitting in the same wavelength range [1]. Furthermore, we have enhanced contrast up to 42% and measured optically detected magnetic resonance in a new wavelength regime via absorption: between 700nm and 1000nm [2]. These are important steps in realizing laser threshold magnetometry [3].

References

[1] Lindner et al. "Dual-media laser system: Nitrogen vacancy diamond and red semiconductor laser" *Science Advances* **10**, eadj3933 (2024)

[2] Schall et al. "High-contrast absorption magnetometry in the visible to near-infrared range with nitrogen-vacancy ensembles", *arXiv:* 2412.07798 (2024)

[3] Jeske et al. "Laser threshold magnetometry", *New J. Phys.* **18** 013015 (2016)

Multi-Parameter Quantum Imaging: From Passive Sensing to Mass Photometry

Emre Köse*

Abstract

We present two of our recent works in quantum-enabled optical technologies: the first explores super-resolution imaging for passive remote sensing, achieving quantum-enhanced spatial resolution beyond classical aperture synthesis for current satellite systems [1,2]; the second presents an innovative optical imaging system for measuring parameters of a small particle, such as a macromolecule or nanoparticle, at the quantum limit of sensitivity [3].

References:

1. E. Köse, G. Adesso, and D. Braun, Phys. Rev. A 106,012601 (2022).
2. E. Köse and D. Braun, Phys. Rev. A 107, 032607 (2023).
3. F. Müller, E. Köse, A. J. Meixner, E. Schäffer, and D. Braun, arXiv:2410.19417 (2024)

*Institute for Theoretical Physics , Tübingen, Germany

Diamond sensors in complex environments

Ren-Bao Liu

Department of Physics, Centre for Quantum Coherence, The Hong Kong Institute of Quantum Information Science and Technology, and New Cornerstone Science Laboratory, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China

Nitrogen-vacancy (NV) centers in diamond are versatile quantum sensors for biological and material studies. I will show examples of using nanodiamond orientation-sensors to measure the non-local deformation of materials and cells under nano-indentation [1-3]. For studies in live biological systems, it is highly desirable to track moving and rotating nanodiamond sensors in liquid [4] and to minimize the phototoxicity. We show two possible solutions. One is optical detection of magnetic resonance using light-sheet illumination, which allows for a wide-field, vertically scannable imaging and sensing in live cells with reduced phototoxicity. Another technique is the simultaneous fast tracking of multiple nanodiamonds in liquid using digital micro-mirror devices, which allow multi-focus random access of nano-sensors moving in liquid samples. We will also present examples of controlling quantum coherence of NV centers at high temperature [5,6], detection of magnetic transitions of single nanoparticles [7], measurement of magnetic fluctuations near Curie temperatures of magnetic nanoparticles, and methods for improving magnetometry sensitivity near zero magnetic fields (which is important for non-invasive study of magnetic properties of materials).

This work was supported by the Innovation Program for Quantum Science and Technology Project 2030ZD0300600, the Hong Kong RGC/CRF Project C4007-19G, the Hong Kong RGC/GRF Project 14301722, and the Hong Kong RGC/SRFS Project SRFS2223-4S01. I acknowledge collaborations with Quan Li, Y. Cui, W. H. Leong, S. Wang, J. Ye, M. Ai, X. Wang, K. C. Cheung, K. Liu, X. Chen, S. Guo, X.i Liu, Y. Gao, Z. Li, G. Zhu, H. Zeng, N. Wang, G. Liu, S. Li, M. H. Kwok, T. Zhang, Z. Chu, S. Zhang, K. Xia, C. Liu, X. Feng, J. Fan, R. Dou, H. Cheng F. Dolde, A. Finkler, A. Denisenko, S. Yang, J. Wrachtrup, X. D. Cui, T. Ngai, and H. Fedder.

References

[1] K. Xia, et al., Nat. Commun. **10**, 3259 (2019)
[2] Y. Cui, et al., Nano Lett. **22**, 3889 (2022)
[3] Y. Cui, et al., arXiv:2406.18577 (2024)
[4] X. Feng, et al., Nano Lett. **21**, 3393 (2021)
[5] G. Q. Liu, et al., Nat. Commun. **10**, 1344 (2019)
[6] J.-W. Fan, et al, Nano Lett. **24**, 14806 (2024)
[7] N. Wang, et al., Phys Rev X **8**, 011042 (2018)

Mankei's method in application to imaging

A. Duplinskiy, J. Frank, K. Bearne, L. Gong and A. I. Lvovsky

Department of Physics, University of Oxford, Oxford, OX1 3PU, UK

In the last decades, a number of techniques for circumventing the diffraction limit in microscopy have been proposed, defining a field called superresolution imaging. However, these approaches involve active interaction with the sample: they are either operational in the near-field only, or rely on nonlinear probing, which makes them expensive, invasive, and not universally applicable. But can we achieve superresolution by observing light coming from an object without any active interaction with it?

Although the diffraction limit had been known for 150 years and appeared unsurmountable, a recent theoretical breakthrough by Tsang et al. showed that it can in fact be beaten by treating imaging as a quantum sensing problem [1]. In practice, this involves demultiplexing the incoming field into an orthonormal basis of spatial modes (e.g., Hermite-Gaussian), measuring the amplitude or intensity of each basis component and subsequently reconstructing the image from these data.

The advantage of this approach over direct imaging was experimentally tested in recent years. Our group has proposed [2] and realized [3,4,5] a proof-of-concept experiment on SpaDe imaging, achieving a resolution enhancement by more than a factor of two compared to the diffraction limit. We will discuss these results and perspectives of developing then into a revolutionary imaging technology applicable in realistic conditions and at all scales, and hence capable of revolutionizing microscopy and opening new avenues for scientific and industrial applications of imaging, ranging from nanotechnology and life sciences to environmental sciences and astronomy.

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Quantum optical classifier with superexponential speedup

Simone Roncallo1, Angela Rosy Morgillo1, Chiara Macchiavello1, Lorenzo Maccone1, and Seth Lloyd2

1. Dipartimento di Fisica, UniversitÃ degli Studi di Pavia, INFN Sezione di Pavia, Via Agostino Bassi 6, I-27100, Pavia, Italy.

2.Massachusetts Institute of Technology, Cambridge, MA 02139, USA

We present a quantum optical pattern recognition method for binary classification tasks. Without direct image reconstruction, it classifies an object in terms of the rate of two-photon coincidences at the output of a Hong-Ou-Mandel interferometer, where both the input and the classifier parameters are encoded into single-photon states. Our method exhibits the same behaviour of a computa- tional neuron of unit depth. Once trained, it shows a constant O(1) complexity in the number of computational operations and photons required by a single classification. This is a superexponen- tial advantage over a classical neuron, that is at least linear in the image resolution. We provide simulations and analytical comparisons with analogous neural network architectures.

Cascaded Optomechanical Sensing

M. M. Marchese[1], S. Nimmrichter[1], D. Braun[2], D. Rätzel[3,4]

[1] Universität Siegen, Germany – [2] Universitz Tübingen, Germany – [3] ZARM University of Bremen, Germany – [4] Humboldt Universität zu Berlin, Germany

Coherent averaging schemes have been introduced as a method to achieve the Heisenberg limit in parameter estimation. Typically, these schemes involve multiple probes in a product state interacting with a quantum bus, with parameter estimation performed via measurements on the bus. We propose a coherent averaging scheme for force sensing applied to optomechanical detectors. A bus-laser pulse sequentially passes through several optomechanical cavities, accumulating signal-induced phase shifts, before being read out. The potential enhancement in sensitivity makes this scheme suitable for many weak sensing applications, such as the detection of the gravitational fields at the Large Hadron Collider, dark matter signatures, and effects predicted by hypothetical collapse models.

Quantum metrology assisted by quantum algorithms

U. Marzolino[1]

[1] University of Trieste, Strada Costiera 11, 34151 Trieste, Italy

I will discuss metrological schemes based on quantum algorithms consisting of the phase estimation and the amplitude amplification algorithms and sampling. The quantum phase estimation algorithm allows for the measurement of a phase of a unitary operator, assuming that the probe is prepared in the corresponding eigenstate of the unitary. This assumption is relaxed by using sampling, amplitude amplification and prior shot-noise limited estimations, and these schemes are generalised to the estimation of several phases or several parameters of the phases. I will focus on the scaling of the accuracy (bias) and the precision (statistical fluctuations) with the time and the number of particles, and show that the above schemes can achieve Heisenberg limited errors in both time and particle number. Phase unwrapping techniques are presented in order to avoid the ambiguities that, due to the signal periodicity, are enhanced for precise estimations. I will also discuss the role of measurement incompatibility and entanglement which is not always needed if prior shot-noise limited estimations are available. As concrete examples, I will consider the estimation of the components of a magnetic field, and the estimation of Hamiltonian parameters. The latter example provides Heisenberg limited estimation of Hamiltonian parameters without the need to prepare the probe close to a phase transition.

Superresolution imaging of two incoherent sources via two-photon interference sampling measurements in the transverse momenta

Salvatore Muratore[1], **Danilo Triggiani**[1,2], **and Vincenzo Tamma**[1,3]

[1] School of Mathematics and Physics, University of Portsmouth, Portsmouth PO1 3QL, UK

[2] Dipartimento Interateneo di Fisica, Politecnico di Bari, Bari 70126, Italy

[3] Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth PO1 3FX, UK

The ability to estimate efficiently the position of two close incoherent sources beyond the classical Rayleigh limit has a profound importance in quantum optics and quantum technologies including biomedical imaging, nanoscopy and astronomy.

Our work demonstrates the emergence of quantum beats from the interference between a reference photon created in lab and a photon coming from a pair of incoherent thermal sources at any relative transverse distance.

Furthermore, it introduces for the first time a sub-Rayleigh imaging technique enabling to estimate such a distance by sampling the transverse momenta of the two photons after they interfere at a beam splitter. Through Fisher information analysis, we show that this technique can be employed to estimate the separation between the two incoherent sources independently of the value of the separation, hence including the sub-Rayleigh regime, by employing a relatively low number of sampling measurements. This feature renders our technique particularly desirable when tracking efficiently a variable distance between the two incoherent sources. Remarkably, being our technique only based on transverse momenta samplings, it overcomes demultiplexing the optical modes and the associated drawbacks in previous schemes, such as mode crosstalk, which affects substantially the precision even for a few numbers of modes preventing any sub-Rayleigh resolution for smaller and smaller distances. Our work not only sheds new light on the physics and quantum metrological power of multiphoton interference in quantum optics with incoherent sources but can also pave the way to the near future development of experimentally feasible sub-Rayleigh imaging technologies.

Interaction-enhanced quantum sensing with Rydberg atoms

Michał Parniak[1,2]

[1] Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland
[2] Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

Rydberg atoms can interact strongly with each other, which is the basis for their applications in quantum computing and simulation. The very same property allows them to also act as exceptional sensors. In my talk I will describe our story of developing new microwave and mm-wave sensors based on Rydberg atoms. In particular, I will describe two unconventional approaches we have undertaken.

First, in a hot atom system we employ a complex loop of transitions to achieve sensing via transduction, which has allowed us to receive thermal radiation [1]. In the most recent experiment, with the goal to reach more fundamental limits than available in hot-atom systems, we tried to use a cold-atom system along with the most-standard Ramsey-sequence protocol to combine optimized signal collection with photon-counting detection. Here, we have observed atomic interaction effects which suggest a collective gain can be achieved in the understanding of quantum metrology, even though the interaction caused collective dephasing. This surprising result, with losses leading to enhancement in sensitivity, provides a strong argument for rigorous quantum-metrological analysis in practical sensing scenarios. I will also consider simultaneous estimation of microwave power and frequency via the Rabi oscillation/Ramsey interferometry in the Rydberg ensemble.

Overall, the exploration of Rydberg sensing stems from the simple observation of exceptional sensitivity to microwaves, but rapidly leads to both fascinating applications for example in space technologies, as well as interesting fundamental metrological questions.

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Role of entanglement in distributed quantum sensing

L. Pezzè

Instituto Nazionale di Ottica – consiglio Nazionale delle Ricerche (INO-CNR) and European Laboratory for Nonlinear Spectroscopy (LENS), Largo Enrico Fermi 6, Firenze

Distributed quantum sensing is at the forefront of multiparameter quantum metrology, offering a powerful framework where quantum states are spatially distributed among multiple sensing nodes to enable the simultaneous estimation of several parameters. This paradigm has the potential to revolutionize key technologies, ranging from precision measurements to imaging, clock synchronization, differential inertial sensing and quantum-enhanced navigation. Despite significant progress, a clear consensus on the advantages of quantum resources—such as entanglement and squeezing—over standard single-parameter schemes remains elusive.
In this talk, I will address the fundamental sensitivity bounds in distributed quantum sensing by analyzing a sensor composed of an array of spatially distributed Mach-Zehnder interferometers (MZIs) [1,2,3]. The model provides a fully analytical playground for optimizing and understanding distruibuted sensing. I will demonstrate that local, independent measurements on each MZI can achieve sensitivity levels that saturate the quantum Cramér-Rao bound, reaching the Hesienberg limit for the estimation of any linear combinations of the multiple interferometric phase shifts. Furthermore, I will provide a thoughtful comparison with separable schemes using independent MZIs, which will highlight the tangible advantages of entanglement under different resource constraints. These results offer new insights into the role of quantum resources in distributed sensing and their potential to enhance practical multiparameter metrology.

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Sensing Inside Biological Systems: Nanodiamonds for Tracking Cellular Inflammation

Javier Prior Arce

Universidad de Murcia

Nanodiamonds (NDs) doped with nitrogen-vacancy centers are emerging as powerful tools for biological applications, enabling precise nanoscale sensing within biological systems. Their unique capabilities allow for the detection of local changes in cellular environments that are otherwise undetectable by traditional methods. In this talk, the biocompatibility of NDs within various cell types will be explored, demonstrating that they can be safely integrated without causing toxicity still maintaining strong sensing capabilities. Using confocal microscopy, we will show for real-time tracking and nanoscale sensing that the nanoparticles remain stable allowing us to implement accurate protocols. Finally, HEK-293 cells results where inflammation mechanisms have been induced will be shown. From a theoretical point of view, we will show results using tensor network state to simulate a bath of nuclear spins coupled to the NC center.

Gravity sensing with quantum optomechanical systems

Dennis Rätzel

ZARM – University of Bremen, Am Fallturm 2, 28359 Bremen, Germany

Quantum optomechanical systems are mechanical resonators in the quantum regime controlled and read out by light fields. Due to their mass, they are ideal sensors for gravitational effects. In this talk, I will present quantum metrological aspects of quantum optomechanics, in particular fundamental precision bounds for measuring oscillating gravitational fields. I will also discuss implications for tests of gravitational theory, including Newton's force law, the gravitational field of ultra-relativistic matter at the Large Hadron Collider and quantum properties of gravity.

Heisenberg-scaling sensitivity in the simultaneous estimation of multiple parameters using squeezed light

Atmadev Rai[1], **Danilo Triggiani**[1,2], **Paolo Fachhi**[3,4], **and Vincenzo Tamma**[1,5]

[1] School of Mathematics and Physics, University of Portsmouth, Portsmouth PO1 3QL, UK

[2] Dipartimento Interateneo di Fisica, Politecnico di Bari, Bari 70126, Italy

[3] Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy

[4] INFN, Sezione di Bari, I-70126 Bari, Italy

[5] Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth PO1 3FX, UK

Achieving the ultimate quantum scaling precision, given by the Heisenberg-scaling, in the simultaneous estimation of multiple physical parameters is a difficult but sought after challenge in quantum metrology due to fundamental limitations found in multiparameter quantum metrology and experimental challenges in harnessing the necessary quantum resources.

We have demonstrated for the first time the ultimate quantum sensitivity, in the simultaneous estimation of multiple unknown parameters with a relatively low number of experimental iterations and scalable experimental resources. In particular, we have proposed an experimentally feasible scheme to reach Heisenberg-scaling sensitivity in simultaneously estimating two unknown phase parameters in a Mach-Zehnder interferometer using a squeezed and coherent state of light and homodyne detections [1]. Moreover, we have introduced a novel scheme that simultaneously estimates three unknown parameters consisting of two-phase and a reflectivity parameter in a two-channel optical network. We demonstrate that this methodology not only reaches the Heisenberg-scaling multiparameter Cramer-Rao bound for all unknown parameters but is also experimentally scalable.

Harnessing the quantum advantage of simultaneous Heisenberg-scaling estimation of multiple parameters opens a new frontier in quantum metrology. It can pave the way for the development of scalable quantum technologies for distributed multiparameter quantum metrology with pivotal applications across multiple fields, including quantum imaging, biological sensing, distributed networks, quantum process tomography, estimation of gravitational wave parameters, and inhomogeneous forces and gradients.

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Symmetry-informed global quantum metrology: towards a multiparameter formulation

Jesús Rubio*

School of Mathematics and Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

High-precision measurements are essential for probing the extreme regimes required for progress in fundamental physics. Symmetries are central to this task, and symmetry-informed approaches to global quantum metrology, combined with Bayesian principles, have recently been shown to offer significant precision gains for finite sample sizes and prior information.[1,2]

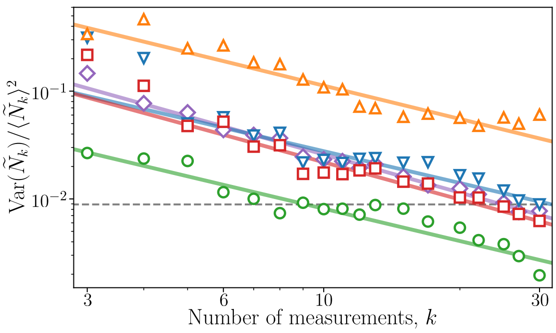

Figure 1: Noise-to-signal ratio (NSR) for two frequentist methods (triangles, squares) and three Bayesian techniques (inverted triangles, rhombuses, circles). The dashed line shows that the NSR for best standard method (squares) with 30 shots is achieved by the adaptive strategy (circles) with only 9 shots.[1]

However, symmetry-informed estimation has mostly been limited to single-parameter scenarios, and its generalisation to more complex, multiparameter problems remains a significant challenge. This work presents a symmetry-informed error bound for the estimation of multiple parameters, which is shown to recover global bounds previously found in the literature. One is the bound for quantum imaging and sensing networks,[3]

$$\bar{\epsilon}_{\mathrm{mse}} \geq \frac{1}{d}\sum_{i=1}^{d}\left[\int d\boldsymbol{\theta} p(\boldsymbol{\theta})\theta_i^2 - \mathrm{Tr}(\rho_{0,i}S_{i,\mathrm{lin}}^2)\right],$$

where $p(\boldsymbol{\theta})$ denotes a prior probability, $S_{i,\mathrm{lin}}$ solves

$$S_{i,\mathrm{lin}}\rho_0 + S_{i,\mathrm{lin}} = 2\rho_{1,i,\mathrm{lin}},$$

$\rho_{k,i,\mathrm{lin}} = \int d\boldsymbol{\theta} p(\boldsymbol{\theta})\rho(\boldsymbol{\theta})\theta_i^k$, and $\rho(\boldsymbol{\theta})$ is the probe state. Another one is a bound for estimation of multiple scale parameters,[4]

$$\bar{\epsilon}_{\mathrm{mle}} \geq \frac{1}{d}\sum_{i=1}^{d}\left[\int d\boldsymbol{\theta} p(\boldsymbol{\theta})\log^2\left(\frac{\theta_i}{\theta_u}\right) - \mathrm{Tr}(\rho_{0,i}S_{i,\log}^2)\right],$$

where $S_{i,\log}$ is similarly defined but using $\rho_{k,i,\log} = \int d\boldsymbol{\theta} p(\boldsymbol{\theta})\rho(\boldsymbol{\theta})\log^k(\theta_i/\theta_u)$, and θ_u neutralises the units within the logarithm.

Finally, experimental validation of symmetry-informed strategies for atom number estimation on a cold atom platform is reported,[1] demonstrating a five-fold precision increase in the presence of a nuisance parameter.

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*j.rubiojimenez@surrey.ac.uk

Modal approach to multi-parameters estimation in optics and the example of incoherent sources

Nicolas Treps

Sorbonne Université, Paris, France

Quantum optical metrology aims at identifying the ultimate sensitivity bounds for the estimation of parameters encoded into an optical field. In many practical applications, such as imaging, microscopy, and remote sensing, the parameter of interest is encoded not only in the quantum state of the field but also in its spatio-temporal distribution, i.e., in its modal structure. In this context, we propose both a theoretical framework and an experimental approach to derive bounds and perform measurements that are quantum-optimal, either in the single or in the multi parameter settings. We illustrate this with the example of multi-parameter estimation on two incoherent sources..

Quantum estimation with infinitely many parameters

Mankei Tsang[1,2,*]

[1]*Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117583*

[2]*Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117551*

(Dated: November 19, 2024)

This talk will cover two theoretical advances in quantum metrology, as motivated by our recent work on superresolution imaging:

1. Quantum semiparametric estimation: a generalization of the quantum Cramér-Rao lower error bound when the unknown parameter θ is infinite-dimensional while the parameter of interest $\beta(\theta)$ is a functional of θ [1]. For example, in optical imaging, θ may be the unknown object intensity function in some infinite-dimensional function space, while the parameter of interest $\beta(\theta)$ may be the centroid or variance of the intensity function.

2. Poisson quantum information: a significant simplification of quantum information quantities, such as the Uhlmann fidelity and the quantum Fisher information, when a Poisson limit is taken for a stream of rare quantum particles, such as photons from weak thermal sources [2].

Applications of the theory to imaging problems will also be discussed [3–6].

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* mankei@nus.edu.sg; https://blog.nus.edu.sg/mankei/

Searching for new physics with quantum sensors

Arne Wickenbrock[1,2,3]

[1]Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
[2] Helmholtz Institute Mainz, 55099 Mainz, Germany
[3]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

The Standard model of physics is extremely successful in describing the universe. However, there are several hints that it might not be complete. Quantum sensors are powerful tools to search for physics beyond the standard model. I am going to illustrate this with our most recent search for galactic axion-like particles (ALPs) [1]. ALPs arise from well-motivated extensions to the Standard Model and could account for dark matter. The quantum sensor in the search was an interferometer composed of two atomic alkali-nuclear comagnetometers. I will discuss the working principles of the sensor, discuss the measurement and illustrate what other quantities it could probe.

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Abstracts of Posters

(in alphabetical order)

Upper bounds on the precision of sensing correlated noise with quantum sensor networks

Federico Belliardo

February 2025

In this work, we consider the estimation of correlated noise acting on a network of quantum sensors. We study the case of vanishingly small noise and derive two semidefinite programs to upper bound the quantum Fisher information of the estimation task. One of these programs is independent of the initial quantum state of the network, is computationally efficient in the number of probes in the network, and provides a bound based entirely on the characteristics of the classical correlations in the noise. Interestingly, we observe that different regimes of noise correlation, such as exponential or polynomial correlations, lead to different asymptotic scalings of the precision and determine whether the standard quantum limit can be surpassed. The results presented in this paper are applicable to the detection of all physical phenomena that can be transduced into phases θ_i in a quantum-mechanical system.

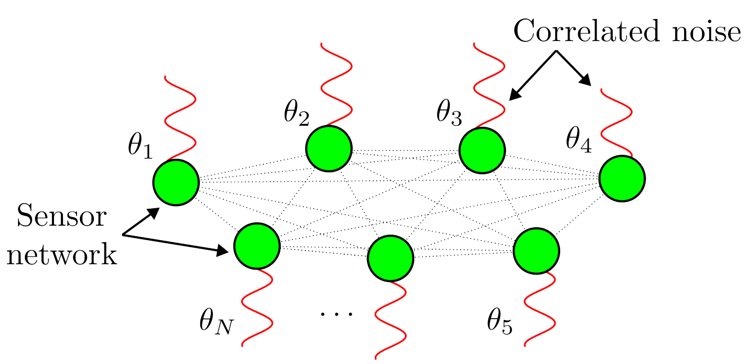

Figure 1: Quantum sensor network of multiple probes, each subject to a different noise, which is correlated through the network.

Quantum-secure distributed sensing

Jonathan W. Webb[1], Joseph Ho[1], Russell Brooks[1], Federico Grasselli[2], Eric Gauger[1], and Alessandro Fedrizzi[1]

[1]Institute of Photonics and Quantum Sciences, Heriot Watt University, Edinburgh EH14 4AS, United Kingdom

[2]Institute de Physique Theoriqué, Université Paris-Saclay, CEA, CNRS, 91191 Gif-sur-Yvette, France

Quantum networks allow connected quantum devices to perform advanced communication tasks such as multi-user secure communication, distributed sensing and computing. Recently, there has been interest in coupling quantum cryptography and quantum metrology to realise so-called quantum-secure network sensing, which introduces a new framework of security, privacy and sensitivity conditions. One such scheme is called private parameter estimation (PPE) [1]

The goal of PPE is for a group of users to perform distributed quantum sensing without revealing the local sensor values, for which the GHZ state is well-suited. To achieve this, the users request a number of copies of the resource state over a quantum network and perform a verification protocol [2] on a subset of the copies to guarantee they are sharing a GHZ state. In this work, we follow the protocol that makes use of stabiliser generator measurements to lower-bound the fidelity of the state, establishing the security and privacy when performing the quantum sensing task, i.e., parameter estimation, using the remaining copy of the states.

We prepare a three-photon GHZ state using parametric down-conversion sources and a linear-optic gate to investigate the PPE protocol. Polarisation analysers are set to measure each photon and perform full quantum state tomography to establish the fidelity of the states we prepare in the lab. The reconstructed state fidelities are compared to the estimated fidelity established by the verification protocol. We find that the verification protocol always provides a lower estimate on the fidelity of the GHZ state, ensuring robustness in the security guarantees.

To evaluate the privacy, the quantum Fisher information (QFI) for the local and global phases is calculated. For the states prepared in the lab, we demonstrate asymmetric information gain between the local and the global phases by one order of magnitude, meaning very little information is leaked from the local sensors while the global phase is estimated with a precision at the standard quantum limit. PPE could find applications in a healthcare scenario where medical testing equipment is outsourced to a quantum network and privacy of patient data is of the highest importance.

(a) (b)

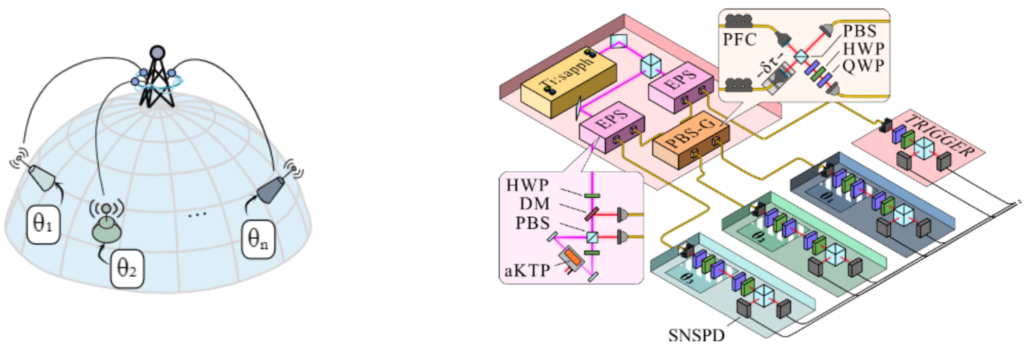

Fig. 1 (a) PPE: A central server distributes a quantum resource to each of the sensing nodes for verification. The local information θ_i is encoded onto the verified state for parameter estimation. (b) Experimental setup preparing a three-qubit GHZ state (pink box) and implementing PPE (green boxes).

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Strong long-range interactions and geometrical frustration in subwavelength Raman lattices

Domantas Burba[1], Gediminas Juzeliūnas[1], Ian B. Spielman[2], Luca Barbiero[3]

[1]Institute of Theoretical Physics and Astronomy, Vilnius, Lithuania
[2]Joint Quantum Institute, Maryland, USA
[3]Institute for Condensed Matter Physics and Complex Systems, Turin, Italy

Non-local interactions are the key building block to allow for a spontaneous breaking of the translational symmetry. The latter represents one of the most fundamental symmetries in physics as it reflects the formation of periodic structures of mass and electric charge. Quantum matter with such a feature falls in the class of spontaneously symmetry broken (SSB) many-body phases with broken translational invariance. Their ubiquity in nature has made the investigation and creation of such states of matter of central importance. In this respect, quantum simulators made of ultracold magnetic atoms with large magnetic dipolar momentum (e.g., erbium) represent a promising and powerful resource. However, current setups only explore frustrated regimes with weak local interactions or regimes where quantum fluctuations are suppressed. To the best of our knowledge, there are no experimental schemes able to simultaneously realize long-range interactions and geometrical frustration.

Here we consider a possible alternative to current setups - a recently realized subwavelength lattice formed by a pair of counter-propagating lasers driving two photon Raman transitions in an ensemble of ultracold atoms. It was shown that one may precisely control the tunneling amplitude, range, and phase by tuning the detunings. One also achieves significantly stronger interactions in the proposed scheme due to its subwavelength nature. Thus, one may realize intriguing phases of matter, such as density waves and chiral superfluids. Our results show several possible scenarios may occur, depending on the lattice depth and detunings.

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Development of a microwave-free measurement protocol for quantum sensing

M. P. Camposano Moore[1,2], O. Dhungel[1,2], A. Ermakova[3] and D. Budker[1,2,4]

[1]Helmholtz-Institut Mainz, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 55128 Mainz, Germany
[2] Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
[3] Hasselt University, Diepenbeek, Belgium
[4] Department of Physics, University of California, Berkeley, California 94720-300, USA

Current methods for studying defects in soft matter primarily use optical techniques (like widefield and fluorescence microscopy) or electron and X-ray imaging. These techniques mainly focus on structural imaging and defect localization, rather than dynamic processes such as the migration or transformation of soft matter defects. Nanoscale magnetometry using Nitrogen-Vacancy (NV) color centers in nanodiamond can bridge this gap, providing better insights into the dynamic processes in soft matter, including biosystems.

Typically, sensing with NV centers relies on optically detected magnetic resonance (ODMR).). However, this technique requires external microwaves, which can serve as an external heater and can negatively influence the properties of soft matter, especially biological systems. The newly developed microwave-free technique enables sensing protocols without delivering microwaves[1]. In this work, we address essential steps for performing microwave-free magnetometry with NV centers in nanodiamond and discuss the current applications we are developing.

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TITLE Bounds on quantum adiabaticity in driven many-body systems and applications to adiabatic quantum computation

Presenter Jyong-Hao Chen,
Department of Physics, National Central University, Chungli, Taiwan

Abstract:

The ability to prepare desired quantum states with high precision is essential in developing contemporary quantum science and technology. To this end, various approximations based on the quantum adiabatic theorem are widely used. However, determining the optimal rate of adiabatic evolution for approaching desired target states is generally a challenging task, particularly in quantum many-body systems. In this presentation, I will first explain how one can estimate the quantum fidelity of adiabatic evolution in quantum many-body systems using two more handily calculated quantities: generalized orthogonality catastrophe and quantum speed limit [1, 2]. The proposed approach allows us to establish stronger bounds on adiabatic fidelity than those previously obtained in the literature. I will then demonstrate how these new bounds can be applied to adiabatic quantum computing [3]. Notably, our method can provide lower bounds for the runtime of an example of adiabatic quantum algorithms with undetermined quantum speedups (where the traditional approach based on calculating spectral gaps is ineffective).

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Towards fabrication of shallow NV centers with long coherence times

J.F. Da Silva Barbosa [1], A. Kaiser [1], A. B. Sergi [1], M. Mohr [1]

[1]German Aerospace Center, Institute of Quantum Technologies, Ulm, Germany

Nitrogen-Vacancy (NV) centers in diamond are well known as a robust quantum system that have been widely studied in the last decades due to its Optically Detected Magnetic Resonance (ODMR) at room temperature, which provides very sensitive magnetometry with nanometric resolution [1].

Although deeply implanted NVs into CVD diamonds have long coherence times and are very robust quantum systems, enhancing their inductive coupling with a desired species on the diamond surface remains a challenge. Bringing the NV closer to the diamond surface is a good strategy to overcome this difficulty. Long coherence times shallow NVs are promising candidates for experimental studies of multi-parameter quantum problems, helping to validate theory and simulations. However, shallow NV become more susceptible to any kind of decoherence sources (charge fluctuation and magnetic impurities, for instance)[2].

To address this problem, our project aims at engineering the diamond surface at atomic level to guarantee the stability and long coherence times for shallow NV centers. In order to do so, we develop new methods for surface cleaning and termination, combining surface etching and coating at atomic resolution for defect reduction, termination and passivation of the surface. We aim to minimize the non-diamond surface carbon and spins from the surface atoms as well as the surface roughness. The surface treatment is validated by comparing the spin coherence times before and after the treatment.

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Quantum metrology in realistic bosonic systems: Theory and experiment

Jacques Ding[1]

[1] *Laboratoire AstroParticule et Cosmologie, Université Paris Cité, France*

Recent advancements in quantum technologies have enabled breakthroughs in quantum metrology, such as frequency-dependent quantum squeezing in gravitational wave detectors [1], now operating below the standard quantum limit [2]. However, experimentally reaching the Heisenberg limit in optical phase estimation [3] remains a challenge. Additionally, many quantum estimation theories rely on assumptions—such as well-defined temporal modes and white noise quantum fluctuations—that fail in real systems. This creates a gap between theoretical quantum metrology advances and practical engineering tools like control theory and signal processing.

I will address both experimental and theoretical perspectives.

1. I discuss our recent theory [4] of Quantum Linear Time Invariant systems, which quantizes classical multimode systems with minimal assumptions. We establish tighter spectral bounds, identify the group structure of transformations, and optimize tomography for frequency-dependent states. Our work unifies the tools developed in quantum control theory, gaussian quantum information, and integrated quantum photonics.
2. I report on the status of an experimental realization of a Heisenberg-limited Mach-Zehnder interferometer using two-mode squeezed states at MIT LIGO Lab [5], towards achieving the Quantum Cramer Rao bound for continuous optical phase estimation via spectral analysis of photocurrents and monitor degradation parameters (loss, phase noise).

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Non-Markovianity of the reduced dynamics of quantum systems under the unitary actions of Yang-Baxter matrices

D. Duran[1], **A. Türkmen**[2], **G. Çelebi**[3] **and B. Dernek**[3]
[1]Yozgat Bozok University, Department of Physics, 66200, Yozgat, Türkiye
[2]Ordu University, Department of Mathematics, 52200, Ordu, Türkiye
[3]Yozgat Bozok University, Department of Mathematics, 66200, Yozgat, Türkiye
[3]Yozgat Bozok University, Department of Mathematics, 66200, Yozgat, Türkiye

Exploring open quantum systems from various perspectives has been an intensive research topic in recent years due to key questions and their important role in realizing quantum information protocols in real-world applications. An interesting approach to address open quantum systems is to investigate the information flow between the components of composite quantum systems, or in particular to explore the exchange of information between the system and its surrounding environment. We focus on the dynamical evolution of quantum Fisher information (QFI) to distinguish the process of Markovianity and non-Markovianity by adopting the flow of QFI as the quantitative measure of the information flow. For this purpose, we investigate the QFI's behavior for the quantum systems' reduced dynamics under the unitary actions of different Yang-Baxter matrices on the various two and three-qubit input states. In certain ranges of parameters, we observe that dynamical evolutions of the systems show non-Markovian behavior in which the information flows from the environment to the system.

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Fidelity and Quantum Distance: Theoretical Foundations and Applications in Quantum Measurement

K. El Bachiri[1] and Y. Hassouni[2]

[1]ESMAR Team, University Mohammed V ,Faculty of Sciences, Rabat, Morocco
[2]Institute of Quantum Science, Rabat, Morocco

Quantum measurement plays a fundamental role in quantum mechanics and its applications, particularly in quantum information processing, quantum cryptography, and quantum metrology. Fidelity and quantum distances, such as the Bures distance and trace distance, have emerged as essential tools for evaluating the precision and robustness of quantum measurement protocols.

This work delves into the theoretical underpinnings of fidelity as a measure of similarity between quantum states, providing insights into its mathematical properties and physical interpretations. We explore the role of quantum distances in capturing the geometry of the quantum state space and their relevance in quantifying errors and imperfections in quantum measurements. The connections between fidelity, quantum distances, and the quantum Fisher information are highlighted, emphasizing their implications for enhancing sensitivity in parameter estimation tasks.

To illustrate the practical utility of these concepts, we present a series of examples and numerical simulations. These include scenarios where quantum distances are employed to optimize measurement strategies in noisy environments, improving the detection of weak signals and reducing the impact of decoherence. Moreover, we discuss the potential applications of these tools in advanced quantum technologies, such as quantum sensors and quantum communication systems.

This study provides a unified framework linking mathematical formalism with practical applications, offering a foundation for the design of robust quantum measurement protocols. By leveraging fidelity and quantum distances, our work contributes to advancing the understanding and implementation of high-precision quantum technologies.

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Maximum likelihood parameter estimation with reluctant quantum walks: analytic results and operational methods

D. Ellinas

Technical University of Crete, School of ECE QLab, Chania, Greece

The parametric maximum likelihood (ML) estimation problem is addressed in the context of quantum walk theory for walks on the line, l-QW, or on a finite ring r-QW. Two different coin reshuffling actions are presented, with the real parameter theta to be estimated being identified, either with the angular argument of an orthogonal reshuffling matrix, or the phase of a unitary reshuffling matrix, acting in coin space, respectively. We provide analytic results for the probability distribution for a quantum walker in terms of quantum channels with generators constructed by Euclidean algebra E(2) [ISO2)] and by Weyl algebra of clock-shift matrices, for l-QW and r-QW respectively. In the estimation scenario a l-QWer displaced by d units from its initial position after k steps is considered. For k large, the likelihood is sharply peaked at a displacement determined by the d/k ratio, which correlates with the reshuffling parameter theta. We suggest that this `reluctant walker' behavior provides the framework for maximum likelihood estimation analysis, allowing for robust parameter estimation of theta via measurement of the walker `reluctance index' r = d/k. ML condition induces derivatives on the probability distribution function wrt the unknown parameter theta the implementation of which is an open question in current quantum NN theory, treated by e.g. parameter-shift rule methods. In the present problem the similar question is addressed by putting forward an operational method that introduces quantum channels and their unitary dilations.

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Estimation of time and frequency parameters with frequency entangled photons

Nicolas Fabre[1], **Eloi Descamps[2], Simone Felicetti[3], Arne Keller[2], Pérola Milman[2]**
[1] *Télécom Paris, Institut Polytechnique de Paris, 91120 Palaiseau France*
[2] *Université Paris Cité, CNRS, Laboratoire Matériaux et Phéomènes Quantiques, 75013 Paris, France*
[3] *Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche (CNR-IFN), Via Cineto Romano 42, I-00156 Rome, Italy*

Hong-Ou-Mandel interferometry takes advantage of the quantum nature of two-photon interference to increase the resolution of precision measurements of time delays. Relying on few-photon probe states, this approach is applicable also in cases of extremely sensible samples and it achieves attosecond-scale resolution, which is relevant to cell biology and two-dimensional materials. Here, we theoretically analyze how the precision of Hong-Ou-Mandel interferometers can be significantly improved by engineering the spectral distribution of two-photon probe states. In particular, we assess the metrological power of different classes of biphoton states with non-Gaussian time-frequency spectral distributions, considering the estimation of both time and frequency shifts. We find that grid states, characterized by a periodic structure of peaks in the chronocyclic Wigner function, can outperform standard biphoton states in sensing applications [1].

After discussing how engineer the spectral distribution of photon pairs for measuring time and frequency delays, we will mention the use of more general quantum states possessing a higher number of photons for estimating time shifts using the presented intrinsic multimode quantum metrology approach [2]. We will show that the particle-number and time-frequency degree of freedom are intertwined for quantifying the ultimate precision achievable by quantum means. Increasing the number of photons of a large entangled EPR probe state actually increases the noise coming from the frequency continuous variable hence deteriorating the precision over the estimation of a time shift.

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Metrology for magnetic moments in transmission electron microscopes

Santiago Steven Beltrán Romero,[1,2] Michael Gaida,[3] Stefan Nimmrichter,[3] Philipp Haslinger,[1,2] and Dennis Rätzel[4]

[1] *Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria*
[2] *University Service Centre for Transmission Electron Microscopy, TU Wien, Wiedner Hauptstraße 8-10/E057-02, 1040 Wien, Austria*
[3] *Naturwissenschaftlich–Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany*
[4] *ZARM, Unversität Bremen, Am Fallturm 2, 28359 Bremen, Germany*

In transmission electron microscopy (TEM), an electron beam passes through a thin sample layer, producing an interference pattern that reveals atomic-scale structures. While TEM is well-established, quantum metrology offers potential enhancements.

Building on the experimental proposal in reference [1], which aims to detect individual quantum spins' magnetic moments using electron beams, we extend the analysis to include scattering dynamics in the paraxial high-energy regime. We calculate the quantum Fisher information for estimating magnetic moments using analytical and numerical methods, comparing it to classical methods with position-resolving electron detectors. Our goal is to determine the experimental conditions required to detect a single Bohr magneton with focused electron beams.

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Short-time metrology enhanced by non-linear interactions in a collective spin system

Edward Gandar[1], Stefan Nimmrichter[2], and Luis A. Correa[3, 1]

[1]Department of Physics and Astronomy, University of Exeter, United Kingdom

[2]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany

[3]Departamento de Física, Universidad de La Laguna, Spain

Standard equilibrium thermometry relies on waiting for a probe to fully thermalize with a bath before measuring its state to estimate the temperature. However, this approach is highly susceptible to experimental challenges such as decoherence, particle loss, temperature fluctuations, and unknown quantum noise channels that can disrupt the dynamics. In this work, we explore a short-time metrological scheme using a collective spin system with non-linear interactions, coupled to a thermal bath and described by a weak-coupling Lindblad master equation. Leveraging phase-space techniques [1,2], we derive an analytical expression for the system's evolution, valid for times shorter than the thermalisation timescale. We see that the bath induces spin diffusion, which, when combined with non-linear spin-spin interactions, leads to a pronounced "shearing" effect in the state's distribution, visualised on the (generalised) Bloch sphere. By employing a Ramsey interferometry scheme and carrying out photon counting measurements, we demonstrate that this shear amplifies the system's sensitivity, enabling the simultaneous estimation of coupling rate and temperature with equilibrium-level precision in a fraction of the time typically required.

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Adiabatic preparation scheme for the AKLT state in a 1D Rydberg platform

A.T. Gea-Caballero*[1], J. Prior[1], H. P. Büchler[2], J. Mögerle[2]

[1] *Departamento de física - CIOyN, Universidad de Murcia, Murcia E-30071, Spain*
[2] *Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany*

There has been a growing interest in topological phases in recent years. In one-dimensional systems, we have symmetry-protected topological phases. An example is the AKLT state [2]. Realizing such phases in artificial matter would allow us to better understand the nature of such states. To do so, Rydberg atoms are a promising platform.

In the present work, we study the preparation process of the AKLT state using a Rydberg platform of effective spin $S = 1$ particles [3]. This study consists of the search for an adiabatic path from the ground state of a trivial product state to the ground state of the AKLT state, which would allow for a preparation scheme in real experiments. To do so, we review a different and successful adiabatic preparation scheme for the ferromagnetic SSH [1], considering instead an antiferromagnetic SSH chain. The similarities between this antiferromagnetic chain and the AKLT state lead us to find a successful AKLT preparation scheme.

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Metrology of microwave fields with cold Rydberg atoms

Romain Duverger, Alexis Bonnin, Romain Granier, Quentin Marolleau, Cédric Blanchard, Nassim Zahzam, Yannick Bidel, Malo Cadoret, Alexandre Bresson and Sylvain Schwartz

DPHY, ONERA, Université Paris Saclay, F-91123 Palaiseau, France

Rydberg atoms are highly promising for microwave electric field sensing owing to their large dipole matrix elements. While most experimental developments have focused on room-temperature vapors so far, utilizing cold atoms in this context could open new possibilities for applications where accuracy, long term stability and high-resolution at large integration times are required, such as calibrating blackbody shifts in state-of-the-art optical clocks [1] or measuring the cosmic MW background.

Here, we demonstrate a novel approach [2] for the metrology of microwave fields with cold 87 Rubidium Rydberg atoms based on trap-loss-spectroscopy in a magneto-optical trap (MOT). This technique stands out for its simplicity, relying solely on fluorescence measurements. By using a two-photon transition highly-detuned from the intermediate state, we realize a situation where the frequencies of the spectral lines are well-described by a coupled two-level system (quasi-ideal Autler-Townes configuration), which is particularly favorable for the linearity of the sensor in the resonant case. With a scale factor linearity at the 1% level and a long-term frequency stability equivalent to a resolution of $5\ \mu V/cm$ at $2500\ s$ and no noticeable drift over this time period, this new measurement technique appears to be particularly well-suited for metrology experiment. This method will allow in principle to reconstruct the amplitude and the frequency of the microwave field simultaneously without the need for an external reference field.

A mid-term perspective of this project is the implementation of an experimental setup for trapping and manipulating cold atoms in optical tweezers. Then, we will be able to characterize the properties of the resulting sensor in different operating regimes: single atoms vs atom ensembles, utilizing trap position control for spatial or frequency resolution, leveraging atom-atom interactions to generate and investigate metrological useful quantum states and reduce sensor noise.

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Multiparameter approach to experimental separation estimation of unequally bright sources

BAD HONNEF, Poster Abstract

Antonin Grateau

Due to the wave nature of light, optical imaging is inherently subject to diffraction, which typically dictates the resolution limit for two point sources. A practical way to describe this phenomenon is through Rayleigh’s criterion, which states that two sources are barely resolvable when the minimum of one source's diffraction pattern coincides with the maximum of the other’s. However, recent advances in optical quantum metrology have shown that this classical limit can be surpassed by leveraging the spatial correlations within the light field. Specifically, decomposing the light into a Hermite-Gauss mode basis provides substantially more information on the separation between the sources than traditional direct imaging, which measures local intensity.

In this work, we implement this spatial demultiplexing technique and propose an experimental framework for estimating the separation of unequally bright light sources, where the unknown intensity imbalance adds complexity to the task. By optimizing the measurement basis and applying advanced machine learning estimation strategies, we aim to measure separations beyond the diffraction limit. While still in progress, our approach holds promise for advancing optical resolution, with impactful applications in high-resolution imaging, microscopy, and astronomy.

Quantum Coherence Control at Temperatures up to 1400 K

Jing-Wei Fan[1,2,#], Shuai-Wei Guo[1,3,#], Chao Lin[1], Ning Wang[1,4], Gang-Qin Liu[5], Quan Li[1,6,7], Ren-Bao Liu[1,3,6,7]

[1] *Department of Physics, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China*
[2] *School of Physics, Hefei University of Technology, Hefei, Anhui 230601, China*
[3] *New Cornerstone Science Laboratory, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China*
[4] *School of Physics, Hubei Key Laboratory of Gravitation and Quantum Physics, Institute for Quantum Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China*
[5] *Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[6] *Centre for Quantum Coherence, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China*
[7] *The Hong Kong Institute of Quantum Information Science and Technology, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China*
 # These authors contribute equally.

Coherent quantum control at high temperatures is important for expanding the quantum world and is useful for applying quantum technologies to realistic environments. Quantum control of spins in diamond has been demonstrated near 1000 K, with the spins polarized and read out at room temperature and controlled at elevated temperatures by rapid heating and cooling [1]. Further increase of the working temperature is challenging due to fast spin relaxation in comparison with the heating and cooling rates. Recently we significantly improve the heating and cooling rates by using reduced graphene oxide as the laser absorber and heat drain and hence realize coherent quantum operation at up to 1400 K [2], which is higher than the Curie temperatures of all known materials. This work facilitates the use of diamond sensors to study a wide range of magnetic effects in the high-temperature regime, such as thermoremanent magnetism and magnetic shape memory effects.

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Atomic-optical interferometry in fractured loops: a general solution for Rydberg radio frequency receivers

Bartosz Kasza[1,2], *Sebastian Borówka*[1,2], *Wojciech Wasilewski*[1,2] *and Michał Parniak*[1,2]

[1]Centre for Quantum Optical Technologies, Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland

[2]Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

Multi-level atoms, e.g. excited to Rydberg states, present many unique opportunities, but present several challenges for numerical treatment of their interaction with multiple laser fields. In hot-atom systems this is further aggravated by the necessity to include Doppler broadening. Further challenges arise if the system is time-dependent, as the system then doesn't have a strict steady-state solution. Our study presents a numerically efficient approach to solving non-equilibrium steady states, focusing on fractured atomic loops, as exemplified by Rydberg-atom microwave sensing protocols. By manipulating terms within the master equation and applying Fourier expansion of Floquet-Lindblad modes, we uncover new insights into the control and coherence of atomic states under periodic driving, resulting from fracture [1]. The results are particularly relevant for superheterodyne Rydberg sensors [2], where the main question is the efficient transfer of modulation from a weak microwave signal field to light. These findings enhance our understanding of quantum dynamics in Floquet systems and offer potential applications in modelling quantum communication, sensing and transduction protocols [3].

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Quantum metrology using quantum combs and tensor network formalism

S. Kurdziałek[1], P. Dulian[1,2], J. Majsak[1,3], S. Chakraborty[1,4], R. Demkowicz-Dobrzański[1]

[1] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warszawa, Poland*

[2] *Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warszawa, Poland*

[3] *Quantum Research Center, Technology Innovation Institute, Abu Dhabi, UAE*

[4] *Departamento de Física Teórica, Facultad de Ciencias Fısicas, Universidad Complutense, 28040 Madrid, Spain*

We develop an efficient algorithm for determining optimal adaptive quantum estimation protocols with arbitrary quantum control operations between subsequent uses of a probed channel.We introduce a tensor network representation of an estimation strategy, which drastically reduces the time and memory consumption of the algorithm, and allows us to analyze metrological protocols involving up to $N=50$ qubit channel uses, whereas the state-of-the-art approaches are limited to $N=5$. The method is applied to study the performance of the optimal adaptive metrological protocols in presence of various noise types, including correlated noise.

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Metrology-inspired detection of mode-intrinsic quantum entanglement

C. E. Lopetegui[1], M. Isoard[1], N. Treps[1] and M. Walschaers[1]

[1]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, 4 Place Jussieu, F-75252 Paris, France

In the context of continuous variable quantum information, identifying and characterizing the necessary resources for computational advantage remains a challenging task. Entanglement is clearly a necessary resource, but on itself it is not enough. It is known that a non-Gaussian statistic with a negative Wigner function [1], is also necessary to develop protocols that cannot be simulated efficiently with classical resources.
Moreover, in Ref. [2] it was shown that in a certain family of sampling protocols a strong form of quantum entanglement is required: not passive separability, i.e., the fact that entanglement cannot be undone with optical passive transformations (beamsplitters and phase shifters).
In this work [3], we propose a witness, based on previously known relations between metrological power and quantum correlations [4], to detect such a strong form of entanglement, i.e. entanglement in all mode bases, that only non-Gaussian states can possess. The strongest form of the witness is based on the quantum Fisher information matrix, which typically can only be computed after performing full tomography of the quantum state. For that reason, we propose relaxations of the witness by relying on the classical Fisher information associated to a specific kind of measurements easily accessible in continuous variable quantum optics: homodyne detection.
Furthermore, our method has a more practical experimental application beyond the detection of mode-intrinsic entanglement. In quantum optics experiments that use multiplexing in time and/or frequency, some mode bases are experimentally inaccessible for direct measurements with state-of-the-art techniques. Our new method allows to nevertheless access entanglement between such inaccessible modes.
The strength of our witness is two-fold: it only requires measurements in one basis to check entanglement in any arbitrary mode basis; it can be made applicable experimentally using homodyne measurements and without requiring a full tomography of the state.

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Robust Arbitrary Single Qubit Gates for NV Centers: Low-Field or High-Frequency Regimes

Alberto López-García[1] **and Javier Cerrillo**[1]

[1]*Área de Física Aplicada, Universidad Politécnica de Cartagena, Cartagena 30202, Spain*

Microwave control of the negatively charged nitrogen-vacancy (NV) defect in diamond is usually based on a two-level approximation of its ground state that is only valid in the regime of high bias magnetic fields or low microwave power. We present the NV-ERC technique, which has demonstrated efficient initialization and readout of the double quantum transition with no leakage to any third level, thanks to an effective Raman coupling. The protocol may be used in the low-field regime and for high-frequency sensing applications. Based on this mechanism, we propose a scheme to perform fast single-qubit gates in the double quantum transition. We analyze its robustness with respect to pulse-timing errors resulting from inaccurate identification of system parameters or phase-control limitations. We also demonstrate that the technique can be implemented in the presence of unknown electric or strain fields.

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Multiparameter quantum estimation based on two-photon interferometric techniques

Luca Maggio[1], Danilo Triggiani[1,2], Paolo Fachhi[3,4], and Vincenzo Tamma[1,5]

[1] School of Mathematics and Physics, University of Portsmouth, Portsmouth PO1 3QL, UK

[2] Dipartimento Interateneo di Fisica, Politecnico di Bari, Bari 70126, Italy

[3] Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy

[4] INFN, Sezione di Bari, I-70126 Bari, Italy

[5] Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth PO1 3FX, UK

When two nonidentical photons impinge on a balanced beam splitter, the probability of them reaching two different output ports is not zero and depends on the overlap between the two single-photon states. Thus, it is possible to retrieve the value of a physical property encoded in such overlap by measuring the coincidence rate. Indeed, this interference effect has several applications in quantum metrology, and it has been used for single parameter estimation, e.g. to evaluate time delays of photons [1], frequency [2], and polarization [3].

Here, we show a protocol based on the same two-photon interference, that can estimate multiple relative photonic parameters achieving the ultimate precision even with a limited number of experimental runs. These parameters can be, for example, both the polar angle and the difference in relative phase of a two-photon polarization state [4], or both the time delay and the transverse displacement. The ultimate precision is achieved under the assumption of unit detector efficiency and perfect overlap of all the photonic degrees of freedom except the ones to measure. The efficiency and scalability of these protocols make them ideal for several applications, e.g. in quantum imaging, quantum communication, and quantum computing.

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Implementation of a microfluidic device to a quantum sensor based in Nitrogen-Vacancy centers in diamond

C.M. Martínez-López[1] and **J. Prior[1]**

[1]*Departmento de Física-CIOyN, Universidad de Murcia, Murcia, Spain*
cm.martinezlopez1@um.es

We are witnessing a revolution led by quantum technologies, which are expanding and evolving into other fields of science. Among them, the area of quantum sensors stands out, with the Nitrogen-Vacancy defects in diamonds being one of the most promising and widely used. Specifically, in the lab we manipulate the electronic spin's quantum state with the use of pulsed laser and pulsed microwaves, collecting the fluorescence emitted with a confocal microscope. One of the many possible applications for quantum sensors is to combine them with the field of microfluidics and biomedicine. Our group aims to develop a microfluidic device suitable with our current confocal microscope which would allow us to dig into new ways of disease detection and intracellular studies, together with biochemical research and other investigations still under construction.

In this work, we focus on the design and implementation of three types of microchannels: one fabricated through polydimethylsiloxane (PDMS) (Figure 1a.) printing from a silicon mold and two designs in silica glass (the second of which was designed to address the complications of the first) (Figure 1b.). We also count with a set up that allows us to control the passage of fluids through these channels. The first objective of the study is to identify the basic requirements that the configurations need to fulfill to be used with the confocal microscope, as well as find solutions to the possible problems encountered. We will discuss how better the silica design is compared to the PDMS-based one, and the specific characteristics used to enhance the chip to create the second microchannel. Secondly, we introduce the possible measurements that can be performed on the channels, along with their applications, to explore an alternative nanoscale approach for quantifying fluid dynamics and characteristics. In particular, we distinguish static-fluid measurements and dynamic-fluid measurements. Finally, we realize static measurements and expose the results obtained, comparing them to other works. In addition, we make an approach on how to achieve the dynamic-fluid measurements for future works.

(a.) (b.)

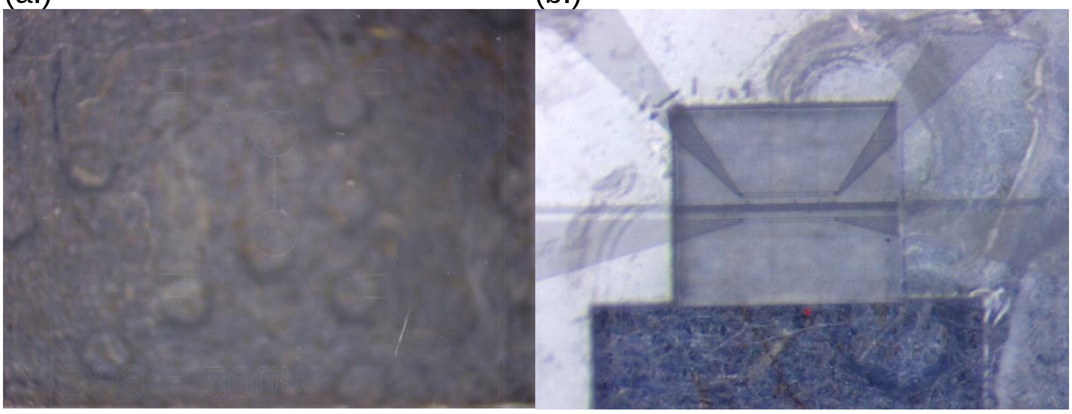

Figure 1: Microchannels made of PDMS (a.) and silica glass (b.).

Characterization of the initialization of NV centers in highly populated systems.

Alejandro Martínez-Méndez[1], Javier Prior[1].

[1] *Departamento de Física - CIOyN, Universidad de Murcia, Murcia E-30071, Spain*

alejandro.martinezm3@um.es

Nitrogen Vacancy centers (NV centers) in diamond have shown to be remarkable candidates for room temperature sensing of chemical and biological systems due to their long coherence times and accessibility. The spin information of the color defect is encoded in its fluorescence response to laser irradiation, which is also responsible for the reinitialization of the spin state. Ensuring correct readout and polarization is critical for any protocol as insufficient energies can lead to incorrect readout signals. In this work, we show how this can be an issue when working with highly populated samples. We use both a nitrogen-rich bulk diamond as well as nanodiamonds with high NV content to examine the response of initialization curves as a function of laser power, pulse duration and dark times preceding the measurements. All parameters show to have an effect on the initialization of the NV, making it critical to characterize the window of operation for sensing experiments. We also examine the behavior of T_1 measurements, one of the most commonly used protocols for biological systems, under these effects. We show how the loss of polarization can be inferred by the contrast of the obtained signals and how the independent behavior of each spin suggests dynamics not associated to relaxation in play [1].

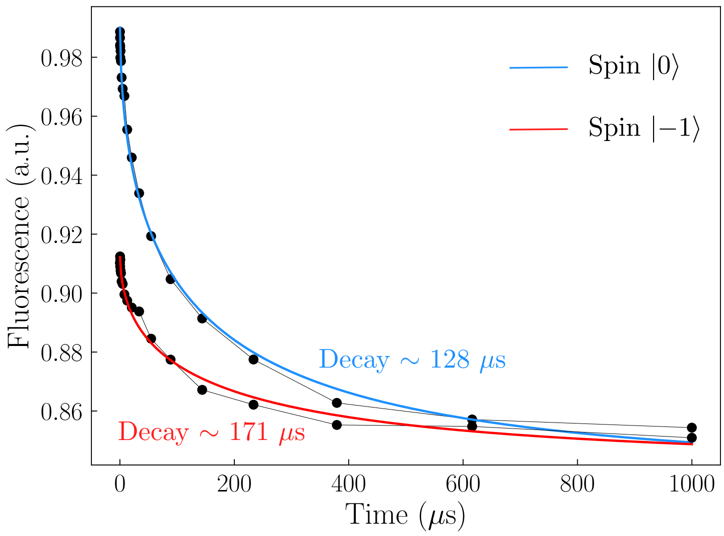

Figure 1: Depolarization dynamics for a 140 nm nanodiamond with a 3 ppm concentration of NV centers. A longer decay for the $|-1\rangle$ state, indicating spin-dependent polarization mechanisms.

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Understanding Singularities of the Quantum Fisher Information Matrix using Bayesian Strategies

George Mihailescu[1,2], Saubhik Sarkar[3,4], Steve Campbell[1,2], Andrew K. Mitchell[1,2], and Abolfazl Bayat[3,4]

[1] School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
[2] Centre for Quantum Engineering, Science, and Technology, University College Dublin, Dublin 4, Ireland
[3] Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Chengdu 611731, China
[4] Key Laboratory of Quantum Physics and Photonic Quantum Information, Ministry of Education, University of Electronic Science and Technology of China, Chengdu 611731, China

Quantum sensing can be approached from the perspective of either frequentist or Bayesian frameworks. Within the former, estimates for unknown parameters are built up from sample data via an estimator, where the estimation precision is controlled by the quantum Fisher information (QFI) through the Cramér-Rao bound (CRB). In the latter case, the probabilistic interpretation of parameter estimates comes from successively updating prior knowledge from information gained by repeated measurements. These approaches are connected via the Bernstein–von Mises theorem and can be generalized to the multiparameter case. When QFI matrix is *singular* however, the frequentist approach breaks down and *nothing* can be said within this framework about the precision of parameter estimation. In this paper we analyze the origin of QFI singularities, and show that Bayesian estimation still provides rich information when the frequentist approach fails. Singularities appear in the Bayesian posterior distribution maps as lines of high likelihood, which indicate implicit relations or constraints between unknown parameters. The precision of estimation along these lines is characterized by a variance following an effective CRB determined by an effective single-parameter (non-singular) QFI. The QFI matrix singularity can be interpreted as an ambiguity about where the true value of the parameters lie on this line.

Quantum Sensing on cells using nanodiamonds

Jesús Moreno-Meseguer[1] and Javier Prior[1]

[1] Departamento de Física - CIOyN, Universidad de Murcia, Murcia E-30071, Spain

j.morenomeseguer@um.es

Fluorescent nanodiamonds have emerged in the last decade as a powerful platform to enable quantum measurements in the field of Biology, making possible studies involving free radical detection and high-accurate thermometry, to cite a few. NV centers are highly sensitive to local magnetic field fluctuations, enabling the detection of unpaired electrons in free radicals, which generate magnetic noise. Moreover, apart from FR detection, these color defects can be used to identify the presence of other molecules in certain ranges such as protein complexes that can induce inflammatory responses on sub-cellular environments. Its ODMR-temperature dependency also allows to identify regions of cells that may have a higher level of activity. Nanodiamonds allow us to collect data from a lot of dynamical processes that occur inside the cell and may not accesible using other sensing techniques. In the poster we show our nanodiamond samples and their characteristic coherence times, together with some thermometry measurements and relaxometry studies that allow us to indentify NLP3 protein complexes inside our cell samples. We also show the future perspective of our studies targeting free radical detection, nanoNMR and development of new sensing protocols for three-level systems in the low field regime.

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Double Quantum Entanglement Generation Between Aligned NV Centers Using Global Addressing

Marcel Morillas-Rozas[1] and Javier Cerrillo[1]

[1]Área de Física Aplicada, Universidad Politécnica de Cartagena, Cartagena, 30202, Spain

A key quantum feature is entanglement, which enables quantum sensors to improve their sensitivity, reaching the Heisenberg limit. Previous works have demonstrated entanglement between two NV centers using individually tailored microwave (MW) fields [1], as well as between electronic and nuclear spins within a single nitrogen-vacancy (NV) center [2]. Here, we propose a novel mechanism to prepare entangled states based on the NV-Effective Raman Coupling protocol [3-5]. Our approach utilizes the double quantum transition of two aligned NV centers, addressed globally with a single MW field, simplifying the experimental setup. The entangled states generated through this mechanism offers a fourfold improvement in sensitivity compared to a single NV center in the single quantum transition. Moreover, the protocol can prepare a variety of states that are responsive to specific external field types, including magnetic fields in the axial direction and transverse electrical fields.

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Pushing the Boundaries: Interferometric Mass Photometry at the Quantum Limit of Sensitivity

Fabian Müller[1], Emre Köse[1], Alfred J. Meixner[2], Erik Schäffer[3], and Daniel Braun[1]

[1]Institut für Theoretische Physik, Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany
[2]Institut für Physikalische und Theoretische Chemie, Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany
[3]Cellular Nanoscience (ZMBP), Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany

We present an innovative optical imaging system for measuring parameters of a small particle such as a macromolecule or nanoparticle at the quantum limit of sensitivity. In comparison to the conventional confocal interferometric scattering (iSCAT) approach, our setup adds a second arm to form a Michelson interferometer that allows us to tune a relative phase. We evaluate the quantum Cramér-Rao bound (QCRB) for different quantum states, including single-mode coherent states, multi-frequency coherent states, and phase-averaged coherent states. Our results show that the proposed setup can achieve the QCRB of sensitivity and outperform iSCAT for all considered quantum states for mass and phase estimation of a particle.

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Quantum inspired super-resolution of surface roughness

Quentin Muller, Tommaso Tufarelli, Katherine Inzani, Samanta Piano and Gerardo Adesso

School of Mathematical Sciences and Centre for the Mathematical and Theoretical Physics of Quantum Non-Equilibrium Systems, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

Recent developments in quantum imaging have shown that resolution limits, previously thought to be fundamental to the specific optical system considered, are largely due to the suboptimal measurement scheme used[1]. Moreover, surface roughness is a critical parameter in many disciplines, particularly engineering where its accurate measurement is required to determine a manufactured part's tribological, contact resistance or contact stiffness properties.

In this work, we develop a theoretical framework for describing rough surfaces and calculate bounds on the amount of information that can be gathered about the surface roughness. We also consider two optical measurement schemes and compare their abilities to saturate these bounds. The first of these is direct imaging, whereby the intensity of the field propagating from the surface is measured at the image plane. The second, more sophisticated measurement scheme is known as "mode sorting" or "spatial mode demultiplexing". Here the optical state is first decomposed into a spatial basis and the individual modes are then measured via intensity measurements or homodyne detection. We demonstrate in particular the superiority of mode sorting over direct imaging to extract information about relevant surface parameters in the regime of small roughness. This paves the way for more accurate quantum-inspired optical techniques for quality inspection of manufactured surfaces at the submicrometre scale.

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Bipartite entanglement in one-dimensional Quantum Walks

S. Rodríguez-Vidal[1, 2], D. Goyeneche [2] and O. Bourget [3]

[1] *Institut für Theoretische Physik, Universität Tübingen, Tübingen, Germany*
[2] *Instituto de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
[3] *Facultad de Matemáticas, Pontificia Universidad Católica de Chile, Santiago, Chile*

Due to the interest of the quantum walk model for various applications in quantum computing and information, we attempt a new study to approach the property of entanglement from a stability point of view. The present work focuses on understanding bipartite entanglement in quantum walks with an analytical component. We consider the entanglement between a particle of spin 1/2 and position through a discrete-time evolution. In particular, we analyse this property on a specific one-dimensional quantum walk model, the discrete-time quantum walk on a line. For this, we address bipartite entanglement through the negativity measure. We show the results of an original simulation for negativity in quantum walks, and draw conclusions regarding the behaviour of negativity under evolution for several configurations of the initial state and a coin parameterised by one and three variables. We find that under symmetric initial conditions, the entanglement is maximal after one step, independently of the coin choice, for a coin parameterised by a single variable, which is not the case for an asymmetrical initial state. Also, we consider 3 degrees of freedom for the coin and analyse the influence of different parameter choices on the evolution of the system.

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Semi-Classics for Quantum Fisher Information

Mahdi Rouhbakhshnabati[1]

Henning Schomerus[2]

Daniel Braun[1]

[1]Department of Physics, Eberhard Karls Universität Tübingen, Germany

[2]Department of Physics, Lancaster University, United Kingdom

Abstract:

Quantum sensors that are driven to the quantum chaotic regime have been shown to lead to enhanced sensitivity in certain parameter regimes. In order to study precisely the impact of classical phase space structures, here we develop an accurate semi-classical approximation of the quantum Fisher information, the central quantity that quantifies the ultimate achievable sensitivity. Applied to a paradigmatic system of quantum chaos, the kicked top, we show that the semi-classical approximation leads to excellent numerical precision in the calculation of the QFI even for modest quantum numbers, and allows one to reach extremely high quantum numbers, beyond the reach of other methods. Using the semi-classical method we then show that the QFI as function of position of the initial state in phase space, develops features that correlate closely with classical phase space structures when the phase space is mixed, and develops universal behaviour in fully chaotic systems.

Keywords: Semi-Classics of Quantum Fisher Information, Quantum Fisher Information, Kicked Top, Phase Space

Design of fiber-based dispersive elements for quantum information science

A. Skoczypiec and **M. Karpiński**

Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warszawa, Poland

Fiber Bragg gratings (FBGs) are fiber-based dispersive elements that have a range of applications in telecommunication and sensor construction. Modifications to uniform FBGs result in different phase and spectral responses, allowing for the construction of dispersion-compensating filters, pulse shapers and multiplexers. At the same time, high sensitivity to external conditions – temperature and stress – makes them perfect to use as temperature, strain, acceleration or magnetic field sensors [1]. In each of these applications, certain grating properties are desirable, such as low dispersion, high reflectance at the maximum, absence of sidebands, or particular dispersion profile for pulse shaping [2]. This is not always easy to achieve, so it is crucial to understand characteristics and develop methods to design FBGs with the desired parameters.

In this work I present a genetic algorithm which can design a Bragg grating, given its parameters, such as length, spectrum and wavelength-dependent phase response. In particular, the algorithm can improve desired parameters starting from already known grating designs. I show several examples of algorithmically synthesized designs, which turn out to have better performance than filters with known apodization profiles. To verify the validity of the algorithm, we also measured spectrum and index modulation of a chirped FBG fabricated at University of Southampton [3].

This shows that the developed algorithm can be used to design Bragg gratings with desirable parameters for sensing and as a part of larger photonic systems, such as a high-resolution single-photon spectrometer [4] or an interface between quantum light pulses with different timescales or spectral-temporal profiles [2, 5].

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Quantum optimal discrimination of incoherent sources

K. Schlichtholz[1], T. Linowski[1], and G. Sorelli[2]

[1] *International Centre for Theory of Quantum Technologies, University of Gdansk, 80-309 Gdańsk, Poland*

[2] *Fraunhofer Institute of Optronics, System Technologies and Image Exploitation, Gutleuthausstr. 1, 76275 Ettlingen, Germany*

We are interested in the quantum-optimal discrimination between one and two closely separated light sources. Optimality in this contest can be defined eithre in the framework of simmetric or asymetric hypothesis testing. In the former, one minimizes the average error probability. In the latter, instead one fixes an acceptable treshold for the false detection probability an minimize the miss probability. This second scenario is particularly relevant for the study of rare events, e.g. in exoplanet detection. In both these frameworks optimality can be theoretically achieved by ideal spatial-mode demultiplexing, simply monitoring whether a photon is detected in a single antisymmetric mode. Unfortunately, things changes abruptely in presence of imperfections.

We demonstrate that for symmetric hypothesis testing the simple statistical test described above becomes as good as flipping a coin in presence of imperfections of the demultiplexer, no matter how small. To remedy this, we insvestigate both symetric and and asymmetric hypothesis testing, and we propose semi-separation-independent tests that provides a reliable method to design experiments with arbitrary control over the maximal probability of error. Our results for symmetric hypothesis testing habe been published in [1].

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Quantum optimal precision by resolving two-photon correlations

Danilo Triggiani[1,2,3*], L. Maggio[3], S. Muratore[3], Vincenzo Tamma[3,4†],

[1]Dipartimento Interateneo di Fisica, Politecnico di Bari, 70126, Bari, Italy
[2]INFN, Sezione di Bari, 70126 Bari, Italy
[3]School of Mathematics and Physics, University of Portsmouth, PO13FX, Portsmouth, UK
[4]Institute of Cosmology and Gravitation, University of Portsmouth, PO13FX, Portsmouth, UK
*danilo.triggiani@poliba.it

Two-photon interference plays an important role in modern high-precision measurement techniques. As the second-order correlations between two photons impinging on the two faces of a beam-splitter are highly sensitive to the differences between the photons, and are not affected by changes in their relative phases, these techniques are routinely employed for the measurement of differences in the values of given photonic parameters, such as colours, arrival times, polarisations, and transversal positions. However, despite recent advances, these techniques are still fundamentally hindered by the distinguishability of the photons at the detectors caused by the difference in the physical parameters we wish to estimate: the less the wavepackets of the two photons overlap, the more the photons become distinguishable at the detectors, the less visible is their interference, and thus the less sensitive is the technique.

Here, we present a two-photon interference approach based on inner-variable resolved correlation measurements that overcomes the limitation of overlapping wavepackets. In particular, we show with Fisher information analysis that this approach achieves the quantum optimal precision, that is independent on the overlap between their wavepackets. We will show that the origin of such a quantum advantage resides in the observation of beating oscillations that are normally averaged out when performing a standard two-photon coincidence experiment. We discuss how such an approach can be applied to disparate domains, e.g. estimation of time delays [1], transverse separations [2, 3], multi-parameter polarization sensing [4], and sub-Rayleigh imaging [5], finding applications in bio-imaging, nano-imaging, single-molecule localization microscopy and exoplanet localization [6].

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All non-Gaussian states are advantageous for channel discrimination

Leah Turner, Mădălin Guţă, and Gerardo Adesso

School of Mathematical Sciences and Centre for the Mathematical and Theoretical Physics of Quantum Non-Equilibrium Systems, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

Gaussian states are widely used within continuous variable quantum information, due to the relative ease with which they can be created and manipulated experimentally and their elegant mathematical formalism. Staying purely within this Gaussian regime, however, sets limitations on the achievable tasks, and it is therefore natural to ask what advantages we gain when going beyond the Gaussian framework.

We consider the task of channel discrimination, in which the aim is to correctly guess which channel, chosen from a known ensemble, is being applied to a probe state. The advantage of using resource states as probes in such tasks is, in many resource theories, quantified by the generalized robustness monotone [1]. Previous analysis of this monotone, however, does not trivially extend to the study of non-Gaussianity as a resource.

In this work, we investigate the advantage given by non-Gaussian states in the channel discrimination setting. We show that for any non-Gaussian state, there always exists a channel discrimination task in which it outperforms all Gaussian states. Further, we define the generalized robustness of non-Gaussianity, and show it has two operational interpretations within the context of channel discrimination: firstly, it provides an upper bound on the maximal advantage in a multi-copy channel discrimination task. Secondly, it exactly quantifies the worst-case advantage in single-copy channel discrimination when considering comparisons to each Gaussian state. Our results show that all non-Gaussian states can provide an advantage for channel discrimination, even those that are simply mixtures of Gaussian states.

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Optimal Multi-Parameter Metrology: Vector Field Sensing with Two Qubits

Denis V. Vasilyev[1] and Peter Zoller[1,2]

1 Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria
2 Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria

We explore optimal local estimation of multiple physical parameters, focusing on the fundamental limits set by the Fisher information framework. While these limits are well-defined, identifying the states and measurements that achieve them remains a challenge. To address this, we developed a systematic method [1] combining Fisher information and Bayesian approaches to quantum metrology. This approach identifies input states and measurements meeting dual criteria: saturating the fundamental precision limit and providing unambiguous estimation of unknown parameters.
We refer to the resulting optimal sensor as a '*quantum compass*' solution, which serves as a direct multiparameter counterpart to the Greenberger-Horne-Zeilinger state-based interferometer, renowned for achieving the Heisenberg limit in single-parameter metrology. I will demonstrate this method by deriving quantum circuits for optimal simultaneous estimation of three parameters (vector field) with two qubits. This scenario highlights the role of quantum non-commutativity, where the Holevo-Cramér-Rao bound, not the Quantum Cramér-Rao bound, sets the ultimate precision. Finally, I will present preliminary data from a proof-of-principle experiment using two trapped ions as a programmable quantum sensor for optimal *simultaneous* estimation of three parameters.

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Sensing intramolecular interactions with nitrogen-vacancy centers

A. Verdú, J. Prior

Departamento de Física, Universidad de Murcia, 30071 Murcia, Spain

Low-frequency signals play a central role in our understanding of nature. Their presence in several scenarios, from both fundamental and applied problems, has compelled the scientific community to develop various techniques to characterize such signals. A family of signals with special interest in chemistry, biology and biomedicine comes from weak intramolecular interactions, such as the *J*-coupling. In this work, we study the signal received by a solid-state quantum sensor, namely a nitrogen-vacancy center, under dipolar interaction with a set of interacting atoms placed on top of it. We propose a method for the exact calculation of sensor dynamics, accounting for all of the system interactions. Additionally, we explore the potential enhancement of signal detection by introducing multiple copies of interacting spin pairs, presenting exact numerical simulations using Tensor Networks.

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Optically Detected Magnetic Resonance with Light-sheet Microscopy

Shuo Wang[1], Ming-Zhong Ai[1], Jing-Wei Fan[1,3], Jun-Chen Ye[1], Chao Lin[1], Quan Li[1,4,5,*] and Ren-Bao Liu[1,2,4,5,*]

[1] Department of Physics, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China
[2] New Cornerstone Science Laboratory, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China
[3] School of Physics, Hefei University of Technology, Hefei, Anhui 230009, China
[4] Centre for Quantum Coherence, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China
[5] The Hong Kong Institute of Quantum Information Science and Technology, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China

Nanodiamonds (NDs) containing nitrogen-vacancy (NV) centers are promising quantum sensors for biological studies for their good spin coherence under ambient conditions, versatile multi-modal responses, good biocompatibility and sub-micron spatial resolution. However, the optically detected magnetic resonance (ODMR) measurement of NV center spins involves intense laser irradiation and can cause inevitable damage to live cells. To overcome the phototoxicity in diamond-based bio-sensing, we applied light sheet microscopy (LSM) to ODMR measurement. Compared to traditional widefield ODMR, the optical sectioning ability of LSM can significantly reduce the phototoxicity. Compared to the widefield ODMR in the total-internal-reflection-fluorescence (TIRF) mode, the light sheet is movable in the vertical direction so 3D sensing can be realized. Using the LSM-ODMR setup, we realize nano-thermometry with a sensitivity about 3 $\mathrm{K}/\sqrt{\mathrm{Hz}}$. $\mathrm{T_1}$ relaxation measurement with high sensitivity ($\mathrm{T_1}$ = 196.2 ± 24.7 μs with a measurement time about 60 s) is also achieved. We also demonstrate three-dimensional imaging of Hela cells and intracellular NDs. Our LSM-based widefield nanodiamond quantum sensing system, by solving the bottleneck issue of phototoxicity in bio-applications, provides a new approach to exploring machineries in live cells, with high time and spatial resolution, capability of three-dimensional and even four-dimensional (space and time) sensing, and multi-modal sensitivity.

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Pattern-based Quantum Functional Testing

Erik Weiss[1], Marcel Cech[1], Stanislaw Soltan[1], Martin Koppenhöfer[2], Michael Krebsbach[2], Thomas Wellens[2], and Daniel Braun[1]

[1]Institute for Theoretical Physics, University of Tübingen, 72076 Tübingen, Germany
[2]Fraunhofer Institute for Applied Solid State Physics IAF, Tullastr. 72, Freiburg 79108, Germany

Abstract

With the growing number of qubits in quantum information processing devices, fully characterizing these processors becomes increasingly unfeasible. From a practical perspective, it is essential to identify potential errors in the functioning of the device quickly or establish its correct operation with high confidence. In response to these challenges, we propose a pattern-based approach inspired by classical memory testing algorithms to evaluate the functionality of quantum memory based on plausible failure mechanisms. We demonstrate the method's capability to extract pattern dependencies of important qubit characteristics such as T_1 and T_2 times and to identify interactions between adjacent qubits. Additionally, our approach enables the detection of various crosstalk effects and signatures indicating non-Markovian dynamics in individual qubits.

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Optimal Measurements in Quantum Sensing

Jing Yang [1]

1. Nordita, KTH Royal Institute of Technology and Stockholm University, Hannes Alfvéns vag 12, 106 91 Stockholm, Sweden

* Email: jing.yang@su.se

Abstract: Saturating the quantum limits is an important task in quantum sensing. We first present the results on the optimal measurements that saturate the multi-parameter quantum Cramer-Rao bound. Next, we discuss the optimal measurements in many-body metrology, where the measurements are restricted to local ones with or without classical communications.

References:

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