QI 8: Quantum Sensors and Metrology

Time: Wednesday 15:00–17:45 Location: H9

Invited Talk QI 8.1 Wed 15:00 H9

Exploring Quantum Materials with Quantum Sensors — •Uri Vool — Max Planck Institute for Chemical Physics of Solids, Dresden, Germany

In recent years, improvements in crystal growth and sample fabrication have given us access to an expanding variety of quantum materials which exhibit exotic macroscopic phenomena directly tied to the strong quantum effects in their microscopic structure. These are exciting for basic research and potential technology applications, but there are still fundamental open questions about the structure of such systems, and the ability to control their quantum effects.

Meanwhile, there has been rapid growth in the ability to control coherent quantum effects in various solid state systems, from atomic defects to macroscopic electromagnetic circuits. These quantum systems can be efficiently manipulated and tuned while maintaining high coherence, making them leading quantum computing platforms. These advantages also make them excellent quantum sensors, and their operation at cryogenic temperatures and material compatibility make them especially suited for exploring quantum materials.

This talk will present several recent and ongoing experiments using coherent quantum systems for material exploration. We will focus on two experimental techniques: 1. Nitrogen-vacancy centers as cryogenic scanning probes for imaging hydrodynamic electron flow. 2. Hybrid superconducting circuits as probes of the superconducting structure in novel materials. Finally, we will discuss the prospective of this approach for material exploration and quantum technology.

QI 8.2 Wed 15:30 H9

Fractional Josephson effect induced by weak measurement — •Mohammad Atif Javed, Jakob Schwibbert, and Roman-Pascal Riwar — Forschungszentrum Jülich, Peter Grünberg Institute (PGI-2), 52425, Jülich, Deutschland

The fractional Josephson effect is commonly directly linked to the presence of Majorana- and parafermions, which are important candidates to implement (universally) protected quantum gates in superconducting quantum hardware. However, these exotic particles still seem notoriously challenging to realize in experiment, and difficult to unambiguously identify via transport measurements. Moreover, a proper understanding of the topological transport properties requires a generalization to an open quantum system context.

Here, we study a standard quantum dot in proximity to two conventional superconducting contacts, including a weak transport measurement and a nonequilibrium quasiparticle source. The non-hermitian system dynamics are analysed by means of exceptional points, leading to a braiding of the complex eigenspectrum. Based on this analysis, we show that this system exhibits an open system version of a fractional Josephson effect, in spite of using only conventional materials.

QI 8.3 Wed 15:45 H9

Defects in semi-conductors for Quantum Applications — •SAJID ALI, Fabian Bertoldo, Simone Manti, and Kristian Thygesen — CAMD, Computational Atomic-Scale Materials Design, Department of Physics, Technical University of Denmark, 2800 Kgs. Lyngby Denmark

Discovery of single photon emission (SPE) from 2D materials has opened a new arena of research because of the unique electric, magnetic and optical properties possessed by these SPE*s systems. Based on these superiror properties, such systems provide very attractive platform that can help to realize, control, manipulate and measure individual quantum states. The defect systems with similar properties must be explored in other 2D materials, as this will broaden the range of materials available for such applications, consequently revolutionising this field. In the present work we have shortlisted/ the defect systems with optimal properties for various quantum applications e.g. qubits, quantum key distribution, brain magnetometers etc., based on our screening study of intrinsic point defects in dynamically and thermodynamically stable and non-magnetic host systems from C2DB database . We study various aspects and properties of these defect systems e.g. photoluminescence (PL) line shape, Transition dipole moment, Radiative recombination rates, Inter-system crossing rates, Hyperfine coupling parameters, Zero field splitting, Spin-Coherence times etc. We identify a set of defect systems, with ideal properties, which can be exploited for various quantum technologies.

QI 8.4 Wed 16:00 H9

Iterative adaptive spectroscopy with a two-level nanomechanical platform — •Avishek Chowdhury[1], Anh Tuan Le[1], Hugo Ribeiro[3], and Eva M. Weig[1,2] — [1]Department of Electrical and Computer Engineering, Technical University of Munich, 85748 Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, 80799, Munich, Germany — [3]Department of Physics and Applied Physics,University of Massachusetts Lowell, Lowell, MA 01854, USA

We develop an iterative, adaptive frequency sensing protocol based on Ramsey interferometry of a two-level system. Our scheme allows one to estimate unknown frequencies with a high precision from short, finite signals. It avoids several issues related to processing of decaying signals and reduces the experimental overhead related to sampling. High precision is achieved by enhancing the Ramsey sequence to prepare with high fidelity both the sensing and readout state and by using an iterative procedure built to mitigate systematic errors when estimating frequencies from Fourier transform. Furthermore, we implement the protocol to demonstrate a proof-of-principle study on a classical two-level nanomechanical platform. We demonstrate that the protocol can detect the coupling between two normal modes with an accuracy higher than their individual dissipation rate. Moreover, the protocol can detect small DC fluctuation of the surrounding electrical field around our nanomechanical oscillator.

QI 8.5 Wed 16:15 H9

Quantum enhancement of multiphoton absorption signals in nonlinear interferometers — •Shahram Panahiyan[1,2] and Frank Schlawin[1,2] — [1]Max Planck Institute for the Structure and Dynamics of Matter, Center for Free Electron Laser Science, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany

SU(1,1)-interferometers are novel nonlinear interferometers [1] in which optical parametric amplifiers create quantum states of light by squeezing and anti-squeezing the light fields [2]. By taking advantage of these quantum states of light, SU(1,1)-interferometers have been employed for spectroscopy [3], imaging [4], quantum state engineering, and quantum information purposes.

Motivated by these applications, we study the precision of multiphoton absorption measurements in a nonlinear SU(1,1)-interferometer. We analyze multiphoton absorption signals, characterize the absorption as a function of nonlinear order, and derive sensitivity bounds from the Fisher Information. We show that the precision of multiphoton absorption measurements can be enhanced compared to classical measurement strategies. Finally, we highlight that this enhancement is robust against experimental imperfections in detection devices.

[1] M. V. Chekhova and Z. Y. Ou, Adv. Opt. Photon. 8, 104 (2016).
[2] S. Panahiyan, C. S. Muñoz, M. V. Chekhova, F. Schlawin, [arXiv:2205.10675].
[3] K. E. Dorfman, Light: Science & Applications 9, 123 (2020).
[4] M. Manceau et al., Phys. Rev. Lett. 119, 223604 (2017).

15 min. break

QI 8.6 Wed 16:45 H9

Multicopy metrology with many-particle quantum states — •Róbert Trényi[1,2,3], Árpád Lukács[1,4,3], Paweł Horodecki[5,6], Ryszard Horodecki[5], Tamás Vértesi[7], and Géza Tóth[1,2,8,3] — [1]Dept. of Theoretical Physics, U. of the Basque Country UPV/EHU, Bilbao, Spain — [2]DIPC, San Sebastián, Spain — [3]Wigner Research Centre for Physics, Budapest, Hungary — [4]Dept. of Mathematical Sciences, Durham University, United Kingdom — [5]International Centre for Theory of Quantum Technologies, University of Gdansk, Gdansk, Poland — [6]Faculty of Applied Physics and Mathematics, National Quantum Information Centre, Gdansk University of Technology, Gdansk, Poland — [7]Institute for Nuclear Research, Debrecen, Hungary — [8]IKERBASQUE, Bilbao, Spain

We consider quantum metrology with several copies of bipartite and multipartite quantum states. We characterize the metrological usefulness by determining how much the state outperforms separable states.

We identify a large class of entangled states that become maximally useful for metrology in the limit of infinite number of copies. The maximally achievable metrological usefulness is attained exponentially fast in the number of copies. We show that, on the other hand, pure entangled states with even a small amount of white noise do not become maximally useful even in the limit of infinite number of copies. We also make general statements about the usefulness of a single copy of pure entangled states. We show that the multiqubit states presented in Hyllus et al. [Phys. Rev. A 82, 012337 (2010)], which are not useful, become useful if we embed the qubits locally in qutrits.

QI 8.7 Wed 17:00 H9

Quantum metrology in the non-asymptotic regime — •Johannes Jakob Meyer[1], Sumeet Khatri[1], Philippe Faist[1], Daniel Stilck-França[2], Giacomo Guarnieri[1], and Jens Eisert[1,3,4] — [1]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [2]Univ Lyon, ENS Lyon, UCBL, CNRS, Inria, LIP, F-69342, Lyon Cedex 07, France — [3]Fraunhofer Heinrich Hertz Institute, 10587 Berlin, Germany — [4]Helmholtz-Zentrum Berlin für Materialien und Energie, 14109 Berlin, Germany

The main concern of quantum metrology is to determine how we can achieve the best possible precision in estimating parameters of physical processes. One of the main tools used in the field is the Quantum Cramér-Rao bound. However, it is a relation that is only tight and meaningful asymptotically and, conversely, too optimistic for finite numbers of experimental repetitions. We analyze how a change of perspective to an operationally motivated measure of estimation success can be used to achieve more meaningful bounds. We show that the measure can be evaluated using a semidefinite program and detail how it can be used to establish minimax guarantees against any prior distribution of the underlying parameter. We focus on the analysis of group-covariant estimation on pure states, which is relevant because of its relation to phase estimation. We prove that the optimal measurement in this setting is given by the pretty good measurement and exhibit a construction of a probe state that numerically saturates the optimal asymptotic minimax rate.

QI 8.8 Wed 17:15 H9

Gradient Magnetometry with Atomic Ensembles — •Iagoba Apellaniz[1], Iñigo Urizar-Lanz[1], Zoltán Zimborás[1,2,3], Philipp Hyllus[1], and Géza Tóth[1,2,4] — [1]Department of Physics, University of the Basque Country UPV/EHU, P. O. Box 644, E-48080 Bilbao, Spain — [2]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [3]Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary — [4]IKERBASQUE, Basque Foundation for Science, E-48013 Bilbao, Spain

We study gradient magnetometry with ensembles of atoms with arbitrary spin. We calculate precision bounds for estimating the gradient of the magnetic field based on the quantum Fisher information. For states that are sensitive to homogeneous fields, a simultaneous measurement is needed, as the homogeneous field must also be estimated.

We present a method to calculate precision bounds for gradient estimation with two spatially separated atomic ensembles. We also consider a single atomic ensemble with an arbitrary density profile, where the atoms cannot be addressed individually, and which is a very relevant case for experiments.

[1] I. Apellaniz *et al.*, Phys. Rev. A, **97** 053603 (2018)
[2] G. Vitagliano *et al.*, arXiv:2104.05663 (2021)

QI 8.9 Wed 17:30 H9

Ultra-low perturbation quantum measurements via random-time sampling — •Markus Sifft and Daniel Hägele — Ruhr University Bochum, Faculty of Physics and Astronomy, Experimental Physics VI (AG), Germany

Random-time sampling of a quantum system is introduced as a new approach to continuous quantum measurements with prospects for ultra-low-perturbation measurements [1]. Random sampling is, e.g., naturally realized in an optical spin noise experiment when weak probe-laser light exhibits random single-photon events in the detector [2]. Our theory shows that a direct evaluation of these detector click events yields power spectra that are equivalent but not identical to those of the usual Gaussian continuous measurement regime [3]. Surprisingly, this holds true even for average sampling rates much lower than the typical frequency range of the measured quantum dynamics. The third-order quantum polyspectrum (bispectrum) also contains the same information as its continuous counterpart. System characterization can, therefore, be performed using the analytic form of the quantum polyspectra [4]. Many applications of random- time sampling are envisioned for high-resolution spectroscopy, circuit quantum electrodynamics, quantum sensing, and quantum measurements in general.

[1] https://arxiv.org/abs/2109.05862, [2] G. M. Müller et al., Physica E 43, 569 (2010), [3] M. Sifft et al., Phys. Rev. Res. 3, 033123 (2021) [4] D. Hägele et al., Phys. Rev. B 98, 205143 (2018)