QI 32: Quantum Sensing and Metrology

Time: Friday 9:30–13:30 Location: HFT-FT 131

Invited Talk QI 32.1 Fri 9:30 HFT-FT 131

Quantum levitodynamics: Harnessing quantum motion of levitated particles for fundamental and applied quantum research — •Sungkun Hong — Institute for Functional Matter and Quantum Technologies, University of Stuttgart, 70569 Stuttgart — Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart, 70569 Stuttgart, Germany

Quantum levitodynamics is a thriving new field in quantum science that aims to control the quantum motion of micro- and nanoparticles levitated, for example, in optical traps. In recent years, researchers have made rapid progress in achieving quantum control of optically levitated dielectric nanoparticles. This progress opens up exciting possibilities for the development of new quantum technologies and for testing quantum physics beyond the microscopic world. In this talk, I will give a brief overview of the field and discuss my group's research activities, in particular, our efforts to develop a novel nanophotonic platform for levitodynamics with ultrastrong quantum cooperativity.

QI 32.2 Fri 10:00 HFT-FT 131

Squeezed Superradiance Enables Robust Entanglement-Enhanced Metrology Even with Highly Imperfect Readout — •Martin Koppenhöfer[1,3], Peter Groszkowski[1,2], and Aashish A. Clerk[1] — [1]Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, USA — [2]National Center for Computational Sciences, Oak Ridge National Laboratory, Tennessee 37831, USA — [3]Fraunhofer-Institut für Angewandte Festkörperphysik IAF, Tullastraße 72, 79108 Freiburg, Deutschland

Quantum metrology protocols using entangled states of large spin ensembles attempt to achieve measurement sensitivities surpassing the standard quantum limit (SQL), but in many cases they are severely limited by even small amounts of technical noise associated with imperfect sensor readout. Amplification strategies based on time-reversed coherent spin-squeezing dynamics have been devised to mitigate this issue, but are unfortunately very sensitive to dissipation, requiring a large single-spin cooperativity to be effective. Here, we propose a new dissipative protocol that combines amplification and squeezed fluctuations. It enables the use of entangled spin states for sensing well beyond the SQL even in the presence of significant readout noise. Further, it has a strong resilience against undesired single-spin dissipation, requiring only a large collective cooperativity to be effective.

QI 32.3 Fri 10:15 HFT-FT 131

Ennhanced Raman Scattering with squeezed states of light — •Shahram Panahiyan[1,2] and Frank Schlawin[1,2] — [1]Max Planck Institute for the Structure and Dynamics of Matter, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Quantum sources of light are unique tools in metrology enabling pushing the limitations of the utilization of the classical light fields [1]. In our theoretical studies, we employ the squeezed state of light to improve the precision of multiphoton absorption [2,3] and stimulated Raman measurements. We derive bounds on the sensitivity that can be obtained for such measurements and propose optimal experimental setups. We compare our results with measurements using classical light and highlight the advantages of quantum light in nonlinear spectroscopy and imaging.

[1] M. Barbieri, PRX Quantum 3, 010202 (2022). [2] S. Panahiyan et al., Phys. Rev. Lett. 130, 203604 (2023). [3] S. Panahiyan et al., Phys. Rev. A 106, 043706 (2023).

QI 32.4 Fri 10:30 HFT-FT 131

Achieving heisenberg scaling via interacting many body dynamics — •Ricard Puig i Valls[1], Paolo Andrea Erdman[2], Pavel Sekatski[3], Paolo Abiuso[4], John Calsamiglia[5], and Martí Perarnau-Llobet[3] — [1]EPFL, Lausanne, Switzerland — [2]FU, Berlin, Germany — [3]UNIGE, Geneva, Switzerland — [4]IQOQI, Vienna, Austria — [5]GIQ, Barcelona, Spain

Theoretical models describing quantum metrology schemes and the corresponding experimental demonstrations have so far mainly described protocols that involve the preparation of the sensor into a carefully engineered quantum state; interaction of the sensor with an external (unknown) field and measurement of the sensor to retrieve information. However, the process of preparation can sometimes be lengthy, require fine tuning and be sensible to noise. The main goal of this project is to use many-body interactions to entangle the state while the field encodes information into it. Thus, we eliminate the preparation process and we add some dynamics that might counter the noise effect.

In this setting, we consider the estimation of a magnetic field by N spins whose interactions can be externally controlled. We derive an analytic expression for the Quantum Fisher Information and we show an idealized protocol that achieves Heisenberg Scaling via a N-body interaction. We achieve a quantum advantage by using 2-body interactions (numerically we can approach HS) and show that measuring the spin of the probe state suffices to saturate the QFI. Finally, preliminary results show that the noise resilience might be higher.

QI 32.5 Fri 10:45 HFT-FT 131

Activation of metrologically useful genuine multipartite entanglement — •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 Th. Phys., UPV, Bilbao, Spain — [2]DIPC, San Sebastián, Spain — [3]Wigner RCP, Budapest, Hungary — [4]Dept. of Math. Sci., Durh. Univ., UK — [5]Int. Cnt. for Theory of Quant. Tech., UG, Gdansk, Poland — [6]Fac. of Appl. Phys. and Math., Nat. Quant. Inf. Cnt., GUT, Gdansk, Poland — [7]Inst. for Nucl. Research, Debrecen, Hungary — [8]IKERBASQUE, Bilbao, Spain

Quantum states with metrologically useful genuine multipartite entanglement (GME) outperform all states without GME in metrology. States reaching the maximal utility in metrology all belong to this convex set of quantum states. With our proposed scheme, we can identify a broad class of practically important states that possess metrologically useful GME in the case of several copies, even though in the single copy case these states can be non-useful, i.e., not more useful than separable states. Thus, we essentially activate quantum metrologically useful GME. Moreover, the maximal metrological usefulness is reached exponentially fast with the number of copies and the necessary measurements are just simple correlation observables. We also provide examples of states not living in the above mentioned class that improve their usefulness. Our scheme can also be used to protect certain quantum states against certain types of errors without the use of full-fledged quantum error correction techniques.

15 min. break

QI 32.6 Fri 11:15 HFT-FT 131

Quantum metrology in the finite-sample regime — •Johannes Jakob Meyer[1], Sumeet Khatri[1], Daniel Stilck França[1,2,3], Jens Eisert[1,4,5], and Philippe Faist[1] — [1]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Berlin, Germany — [2]Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark — [3]Ecole Normale Superieure de Lyon, Lyon, France — [4]Helmholtz-Zentrum für Materialien und Energie, Berlin, Germany — [5]Fraunhofer Heinrich Hertz Institut, Berlin, Germany

In quantum metrology, the ultimate precision of estimating an unknown parameter is often stated in terms of the Cramér-Rao bound. Yet, the latter is no longer guaranteed to carry operational meaning in the regime of few measurement samples. We instead propose to quantify the quality of a metrology protocol by the probability of obtaining an estimate with a given accuracy. This approach, which we refer to as probably approximately correct (PAC) metrology, ensures operational significance in the finite-sample regime. The accuracy guarantees hold for any value of the unknown parameter, unlike the Cramér-Rao bound which assumes it is approximately known. We establish a strong connection to multi-hypothesis testing with quantum states, which allows us to derive an analogue of the Cramér-Rao bound which contains explicit corrections relevant to the finite-sample regime and apply our framework to phase estimation with an ensemble of spin-1/2 particles. Our operational approach allows the study of quantum metrology in the finite-sample regime and opens up new avenues for research at the interface of quantum information theory and quantum metrology.

QI 32.7 Fri 11:30 HFT-FT 131

Magnetometry with Driven Spin Systems — •Dhruv Deshmukh and Joachim Ankerhold — Institute for complex quantum systems, Ulm University, Germany

The dynamics of time-dependent two-level system is a well addressed problem in quantum physics that has spurred the development of many novel techniques and technologies due to its widespread applicability. Here, we focus on the problem of a two-level system driven linearly over the entire parameter space of amplitude and frequency of the classical drive. This problem does not have analytical solutions and has only been solved approximately, near resonance for a weak drive and, for high-frequency drives. Employing Floquet formalism, we have found special manifolds on the parameter space for which the entire Bloch Sphere exhibits period multiplicity. This treatment allows for a deeper understanding of the approximate solutions obtained before.

Understanding the Floquet dynamics has proved to be vital for applications in magnetometry. We found that setting drive parameters at the quasi-energy crossing manifolds in the parameter space, yields the highest quantum fisher information (QFI) for magnetic field oriented parallel to the drive. The Floquet dynamics of periodically driven multi-spin clusters, and spin-chains, were also investigated. In regard to magnetometry, we found (for some simple cases) that the QFI scales linearly with the number of spins (Heisenberg scaling) for suitable parameter choices.

QI 32.8 Fri 11:45 HFT-FT 131

Quantum sensing of RF signals with spin defects in a 2D material — •Roberto Rizzato[1,2], Martin Schalk[2,3], Stephan Mohr[1], Jens Hermann[1,2], Joachim Leibold[1], Fleming Bruckmaier[1], Giovanna Salvitti[1], Chenjiang Qian[3], Peirui Ji[3], Georgy Astakhov[4], Ulrich Kentsch[4], Manfred Helm[4], Andreas Stier[2,3], Jonathan Finley[2,3], and Dominik Bucher[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Department of Chemistry, 85748 Garching, Germany. — [2]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany. — [3]Technical University of Munich, Walter Schottky Institut, 85748 Garching, Germany — [4]Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Bautzner Landstraße 400, Dresden, 01328, Germany

Negatively-charged Boron Vacancy centers (VB-) in hexagonal Boron Nitride (hBN) are attracting increasing interest since they represent optically-addressable qubits in a 2D material. In particular, these spin defects have shown promise as sensors for temperature, pressure, and static magnetic fields. However, their short spin coherence time limits their scope for quantum technology. Here, we apply dynamical decoupling techniques to suppress magnetic noise and extend the spin coherence time by two orders of magnitude, approaching the fundamental T1 relaxation limit. Based on this, we demonstrate a set of quantum sensing protocols to detect RF signals with sub-Hz resolution. This work opens a promising path to the development of quantum technology integrated into ultra-thin structures.

QI 32.9 Fri 12:00 HFT-FT 131

Optimal Control for Quantum Technology with NV-Centers in Diamond — •Matthias Müller — Forschungszentrum Jülich GmbH, Institute for Quantum Control (PGI-8)

Diamond-based quantum technology is a fast-emerging field with both scientific and technological importance. The performance relies on unique features like superposition and entanglement and depends on sophisticated mechanisms of control to perform the desired tasks. Quantum Optimal Control (QOC) has proven to be a powerful tool to accomplish this task. I will give a brief overview on the use of QOC for NV-centers in diamond [1], the CRAB algorithm for Optimal Control [2], the optimal-control software QuOCS [3] and report on recent applications toward quantum sensing.

[1] P. Rembold et al., AVS Quantum Sci. 2, 024701 (2020) [2] M. M. Müller et al., Rep. Prog. Phys. 85 076001 (2022) [3] M. Rossignolo et al. Comp. Phys. Comm. 291, 108782 (2023) [4] N. Oshnik et al., Phys. Rev. A 106, 013107 (2022) [5] A. Marshall et al., Phys. Rev. Res. 4, 043179 (2022)

QI 32.10 Fri 12:15 HFT-FT 131

Toward probing thin films with quantum sensors in diamonds — •Martin Wanckel[1,2,3], Verena Streibel[2,3], Fabian Freire[1], Ian D. Sharp[2,3], and Dominik Bucher[1] — [1]Department of Chemistry ,TUM School of Natural Sciences, Technische Universität München, 85748, Garching, Germany — [2]Walter Schottky Institute, Am Coulombwall 4, 85748, Garching, Germany — [3]Department of Physics,TUM School of Natural Sciences, Technische Universität München, 85748, Garching, Germany

Nuclear magnetic resonance (NMR), one of the most powerful analytical techniques in chemistry and the life sciences, is typically limited to macroscopic volumes due to its inherently low sensitivity. This limitation excludes NMR spectroscopy from the analysis of planar surfaces or interfaces. In recent years, it has been shown that NMR signals can be detected from nanoscale volumes by a new sensor class - quantum sensors based on defects in the diamond lattice - nitrogen-vacancy (NV) centers [1]. In this contribution, we will present our recent results, where we used an ensemble of NV centers to detect the NMR signal of a self-assembled monolayer on an aluminum oxide layer. This discussion includes the detection of spatially resolved NMR signals and the monitoring of the layer formation in real-time at the solid-liquid interface. In the outlook, we will discuss possible further applications, such as probing thin film materials in catalysis and energy science. Reference: 1.Liu, Kristina S., et al. Surface NMR using quantum sensors in diamond. PNAS 2022 Vol. 119 No. 5 e2111607119.

QI 32.11 Fri 12:30 HFT-FT 131

Investigation of exotic phases in low-dimensional systems using nanoscale NMR with NV centres in diamond — •Marcel Martin[1], Yash Nitin Palan[2], Falko Pientka[2], and Nabeel Aslam[1] — [1]Felix-Bloch-Institut für Festkörperphysik, Universität Leipzig — [2]Institut für Theoretische Physik, Goethe-Universität Frankfurt am Main

Understanding exotic phases of matter such as unconventional superconductors, quantum spin liquids and topological insulators promises a deeper understanding of fundamental physics or even a new approach to technological challenges of our time. Especially in low dimensional systems, strong quantum effects can promote the occurrence of such phases. Conventional nuclear magnetic resonance (NMR) has proven to be a reliable and powerful method in the study of many such exotic phases in different materials but is limited to bulk samples.

Here, we present the novel approach of applying nanoscale NMR to low-dimensional solids and surfaces. Using nitrogen vacancy (NV) centres in diamond as local probes, we harness their ability to detect an NMR signal from thin layers even down to a single monolayer as well as from surfaces of bulk materials. This opens the door to the investigation of exotic phases in truly low-dimensional systems using NMR. In this talk, we will show first calculations for the study of induced superconductivity in one- and two-dimensional semiconductors. Other material classes of interest will also be discussed.

QI 32.12 Fri 12:45 HFT-FT 131

Measuring nuclear spin qubits by qudit-based spectroscopy in Silicon Carbide — •Erik Hesselmeier[1], Pierre Kuna[1], Istvan Takacs[2], Viktor Ivady[2,4], Wolfgang Knolle[3], Nguyen Tien Son[4], Misagh Ghezellou[4], Jawad Ul-Hassan[4], Durga Dasari[1], Florian Kaiser[5], Vadim Vorobyov[1], and Jörg Wrachtrup[1] — [1]3rd Institute of Physics, University of Stuttgart, Stuttgart, Germany — [2]Eötvös Loránd , Egyetem tér 1University-3, H-1053 Budapest, Hungary — [3]Department of Sensoric Surfaces and Functional Interfaces, Leibniz-Institute of Surface Engineering (IOM), Leipzig, Germany — [4]Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden — [5]Materials Research and Technology (MRT) Department, LIST, 4422 Belvaux, Luxembourg

Nuclear spins with hyperfine coupling to single electron spins are highly valuable quantum bits. In this work [1] we probe and characterise the particularly rich nuclear spin environment around single silicon vacancy color-centers (V2) in 4H-SiC. By using the electron spin-3/2 qudit as a 4 level sensor, we identify several sets of 29Si and 13C nuclear spins through their hyperfine interaction. We extract the major components of their hyperfine coupling via optical detected nuclear resonance, and assign them to shells in the crystal via the DFT simulations. We utilise the ground state level anti-crossing of the electron spin for dynamic nuclear polarization and achieve a nuclear spin polarization of up to 98(6)%. We show that this scheme can be used to detect the nuclear magnetic resonance signal of individual spins and demonstrate their coherent control. [1] Preprint Arxiv: 2310.15557

QI 32.13 Fri 13:00 HFT-FT 131

Wavelength Dependence of the Electrical and Optical Readout of NV Centers in Diamond — •Lina Maria Todenhagen[1,2] and Martin S. Brandt[1,2] — [1]Walter Schottky Institut, Technische Universität München, Am Coulombwall 4, 85748 Garching, Germany — [2]Physik-Department, School of Natural Sciences, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany

The nitrogen-vacancy (NV) center in diamond is one of the most attractive quantum systems used in practical applications, especially for quantum sensing. However, the miniaturization and integration of NV-based quantum technology is still challenging, as the conventional optical spin readout (optically detected magnetic resonance, ODMR) requires an extensive optical setup and is often limited by the inefficient outcoupling of photons. Alternatively, we can read out the spin state purely electrically by generating a spin-dependent photocurrent (electrically detected magnetic resonance, EDMR). To maximize the achievable spin contrast in both readout techniques, we investigate the influence of different optical excitation wavelengths and identify different spectral regimes that drive different excitation processes in both stable charge states of the NV center, NV^0 and NV^-. While ODMR works efficiently between 480 and 580 nm, we find that EDMR shows an additional strong dependence on the excitation dynamics, and is significantly enhanced by resonantly exciting the zero-phonon line of the NV neutral charge state.

QI 32.14 Fri 13:15 HFT-FT 131

Gradient Magnetometry with Bose-Einstein Condensates — •Iagoba Apellaniz[1,2,3] and Géza Tóth[1,2,4,5,6] — [1]Department of Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain — [2]EHU Quantum Center, University of the Basque Country UPV/EHU, Leioa, Spain — [3]Department of Applied Mathematics, University of the Basque Country UPV/EHU, E-48013 Bilbao, Spain — [4]Donostia International Physics Center (DIPC), P.O. Box 1072, E-20080 San Sebastián, Spain — [5]IKERBASQUE, Basque Foundation for Science, E-48013 Bilbao, Spain — [6]Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary

We study gradient magnetometry with BECs. We obtain the precision bounds for estimating the gradient of the magnetic field based on the quantum Fisher information [1]. For a single BEC the precision bound cannot surpass the so called shot noise limit. On the other hand, if one considers two spatially separated ensembles [2], the Heisenberg scaling can be achieved. We present a method to quantify these precision bounds based on the quantum states.

[1] I. Apellaniz et al., Phys. Rev. A, 97 053603 (2018)
[2] G. Vitagliano et al., Quantum 7, 914 (2023)