Symposium Quantum Limited Measurement: Applications in Metrology, Biology and Solid State Research (SYQM)

jointly organized by
the Quantum Optics and Photonics Division (Q) and
the Atomic Physics Division (A)

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Overview of Invited Talks and Sessions

(lecture room V47.01)

Invited Talks

SYQM 1.1	Fri	10:30–11:00	V47.01	**Overview of some recent "atomic-physics" experiments with nitrogen-vacancy centers in diamond** — •Dmitry Budker
SYQM 1.2	Fri	11:00–11:30	V47.01	**Quantum Limits and Quantum Enhancement in Magnetometry** — Federica Beduini, Naeimeh Behbood, Yannick de Icaza, Brice Dubost, Marco Koschorreck, Mario Napolitano, Ana Predojevic, Robert Sewell, Florian Wolfgramm, •Morgan Mitchell
SYQM 2.1	Fri	14:00–14:30	V47.01	**Nanoscale magnetic resonance imaging: Progress and challenges** — •Daniel Rugar
SYQM 2.2	Fri	14:30–15:00	V47.01	**Optical Far-Field Addressing of Single Spins Beyond the Diffraction Limit at Enhanced Collection Efficency** — •Dominik Wildanger, Jero Maze, Benno Koberstein-Schwarz, Jan Meijer, Sébastien Pezzagna, Brian Patton, Jason Smith, Stefan Hell

Sessions

SYQM 1.1–1.7	Fri	10:30–12:45	V47.01	**Quantum limited measurement applications 1**
SYQM 2.1–2.7	Fri	14:00–16:15	V47.01	**Quantum limited measurement applications 2**

SYQM 1: Quantum limited measurement applications 1

Time: Friday 10:30–12:45 Location: V47.01

Invited Talk SYQM 1.1 Fri 10:30 V47.01
Overview of some recent "atomic-physics" experiments with nitrogen-vacancy centers in diamond — •Dmitry Budker — University of California, Berkeley, USA 94720-7300

I will report on several recent measurements conducted by our group and our collaborators on NV-center ensembles, including a systematic study of spin-relaxation processes, pump-probe spectroscopy of singlet states, the "light-narrowing" effect, and optical polarization of large ensembles of nuclear spins. Up-to-date bibliography related to this work can be found at http://budker.berkeley.edu/PubList

Invited Talk SYQM 1.2 Fri 11:00 V47.01
Quantum Limits and Quantum Enhancement in Magnetometry — Federica Beduini, Naeimeh Behbood, Yannick de Icaza, Brice Dubost, Marco Koschorreck, Mario Napolitano, Ana Predojevic, Robert Sewell, Florian Wolfgramm, and •Morgan Mitchell — ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

Quantum Metrology uses entanglement and other quantum resources to improve the sensitivity of interferometric measurements. Strongly-interacting light-matter systems, or "quantum interfaces," offer several routes to improved sensitivity, including quantum non-demolition measurements, squeezing-enhanced optical readout of atomic sensors, and interaction-based measurements. I will describe recent experimental work that applies these quantum techniques in optical magnetometry, including sensitivity enhancements using optical entanglement, generation of squeezed states in magnetically-sensitive atomic ensembles, and interaction-based spin measurements that scale better than the so-called "Heisenberg limit" of sensitivity.

SYQM 1.3 Fri 11:30 V47.01
Differential Magnetometry using Singlets — •Iñigo Urizar-Lanz[1], Philipp Hyllus[1], Iñigo Egusquiza[1], and Géza Tóth[1,2,3] — [1]Department of Theoretical Physics, The University of the Basque Country, P.O. Box 644, E-48080 Bilbao, Spain — [2]IKERBASQUE, Basque Foundation for Science, E-48011 Bilbao, Spain — [3]Research Institute for Solid State Physics and Optics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary

The gradient of a magnetic field can be measured using a single cloud of non-interacting spins, prepared initially in a state with vanishing angular momentum. The magnetic field gradient can be estimated from a measurement of the square of the angular momentum operator $\hat{J}_x$. The measurement uncertainty can then be estimated by the error propagation formula if $\langle \hat{J}_x^2 \rangle$ and $\langle \hat{J}_x^4 \rangle$ are known as a function of the gradient. We show how these quantities can be computed for the ideal state. Finally, we discuss how the results can be applied to a state close to a singlet which can be realistically prepared experimentally with a cloud of cold atoms.

SYQM 1.4 Fri 11:45 V47.01
Ultimate quantum bounds on mass measurements with a nano-mechanical resonator — •Daniel Braun — Université de Toulouse, UPS, Laboratoire de Physique Théorique (IRSAMC), F-31062 Toulouse, France — CNRS, LPT (IRSAMC), F-31062 Toulouse, France

I establish the ultimate lower bound on the mass that can be measured with a nano-mechanical resonator in a given quantum state based on the fundamental quantum Cramér–Rao bound, and identify the quantum states of the oscillator which will allow the largest sensitivity for a given maximum energy. I show that with existing carbon nanotube resonators it should be possible in principle to measure a thousandth of the mass of an electron, and future improvements might allow to reach a regime where one can measure the relativistic change of mass due to absorption of a single photon, or the creation of a chemical bond.

[1] D. Braun, Eur.Phys.Lett. **94**, 68007 (2011)

SYQM 1.5 Fri 12:00 V47.01
Entanglement-Enhanced Interferometer on an Atom Chip — •Caspar Ockeloen, Roman Schmied, Max F. Riedel, and Philipp Treutlein — Departement Physik, Universität Basel, Switzerland

We experimentally realize a Ramsey interferometer operating beyond the standard quantum limit (SQL), using two internal spin states of a two-component Bose-Einstein condensate. We first produce spin-squeezed states by controlled collisional interactions between the atoms using a state-dependent microwave near-field potential. We observe spin noise reduction by up to 4.5 dB below the SQL with a spin coherence of $> 98\%$, corresponding to a depth of entanglement of at least 40 particles.

Using such spin-squeezed states as interferometer input states, we demonstrate performance beyond the SQL. Our interferometer outperforms an ideal classical interferometer with the same number of particles (≈ 1300) for interrogation times up to 5 ms.

These experiments are performed on a micro-fabricated atom chip providing small and well-localized trapped atomic ensembles. This makes our technique promising for high-precision measurements with micrometer spatial resolution, e.g. probing near-field magnetic or microwave fields close to the chip surface.

SYQM 1.6 Fri 12:15 V47.01
Heisenberg-limited metrology without entanglement — •Daniel Braun[1,2] and John Martin[3] — [1]Université de Toulouse, UPS, Laboratoire de Physique Théorique (IRSAMC), F-31062 Toulouse, France — [2]CNRS, LPT (IRSAMC), F-31062 Toulouse, France — [3]Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, 4000 Liège, Belgium

It is common experimental practice to improve the signal-to-noise ratio by averaging many measurements of identically prepared systems. If the systems are independent, the overall sensitivity of the measurement, defined as the smallest resolvable change of the quantity under consideration, improves as $1/\sqrt{N}$. Quantum enhanced measurements promise the possibility to improve this scaling behavior. Indeed, if the N systems are initially entangled, one may achieve in principle a $1/N$ scaling of the sensitivity, known as the "Heisenberg limit". Unfortunately, decoherence has so far limited the implementation of such "quantum enhanced protocols" to small values of N. Here we show that a setup in which N quantum systems interact with a $N+1$st system allows one to achieve Heisenberg limited sensitivity, without using or ever creating any entanglement. Local decoherence changes only the prefactor but not the scaling with N. We present a general theoretical framework for this new kind of measurement scheme, and propose a possible application in high precision measurements of the length of an optical cavity.

[1] Braun, D. & Martin, J., Nature Comm. **2**, 223, 2011.
[2] Braun, D. & Martin, J., arXiv:1005.4443.

SYQM 1.7 Fri 12:30 V47.01
Quantum logic readout and cooling of a single dark electron spin — Fazhan Shi[1,3], Boris Naydenov[2], Fedor Jelezko[2], Jiangfeng Du[3], •Friedemann Reinhard[1], and Jörg Wrachtrup[1] — [1]Universität Stuttgart und Forschungszentrum SCoPE — [2]Universität Ulm — [3]University of Science and Technology of China, Hefei/China

The electron spin of the NV center in diamond can be polarized and read out optically. These incidental features have spawned rapidly progressing efforts to use this center for quantum information processing and magnetic sensing. However, the NV center is only one of numerous electron spin defects in diamond, most of which do not feature these attractive properties and are hence refered to as dark spins.

In my talk I present techniques to implement optical initialization and readout on these dark spins by quantum logic control. We have successfully mapped the state of a dark spin to a nearby NV center where it can be read out optically. Using this technique, we have performed pulsed electron spin resonance experiments on a single dark spin. Moreover, we were able to cool a dark spin by swapping its state with a nearby polarized NV.

These two results allow to extend the NV center's two key properties - optical spin polarisation and readout - to any electron spin in its vicinity.

SYQM 2: Quantum limited measurement applications 2

Time: Friday 14:00–16:15 Location: V47.01

Invited Talk SYQM 2.1 Fri 14:00 V47.01

Nanoscale magnetic resonance imaging: Progress and challenges — •Daniel Rugar — IBM Research Division, San Jose, California, USA

Magnetic resonance imaging (MRI), based on the sensitive detection of nuclear spins, enables three dimensional imaging without radiation damage. Conventional MRI techniques achieve spatial resolution that is at best a few micrometers due to sensitivity limitations of conventional inductive detection. The advent of ultrasensitive nanoscale magnetic sensing opens the possibility of extending MRI to the nanometer scale. If this can be pushed far enough, one can envision taking 3D images of individual biomolecules and, perhaps, even solving molecular structures of proteins. In this talk we will discuss issues related to nanoscale magnetic resonance imaging, especially its implementation using magnetic resonance force microscopy (MRFM). MRFM is based on the detection of ultrasmall (attonewton) magnetic forces. While 3D spatial resolution below 5 nm has been demonstrated, further progress depends on overcoming poorly understood near-surface force noise effects. We will also consider the future possibility of using NV centers in diamond for detection of nanoMRI.

Invited Talk SYQM 2.2 Fri 14:30 V47.01

Optical Far-Field Addressing of Single Spins Beyond the Diffraction Limit at Enhanced Collection Efficency — •Dominik Wildanger[1], Jero Maze[2], Benno Koberstein-Schwarz[1], Jan Meijer[3], Sébastien Pezzagna[3], Brian Patton[4], Jason Smith[4], and Stefan Hell[1] — [1]MPI for Biophysical Chemistry, Göttingen, GER — [2]PUC, Santiago, Chile — [3]Ruhr-Universität, Bochum, GER — [4]University of Oxford, Oxford, UK

The electron spin associated with charged nitrogen-vacancy (NV) centres in diamond is optically addressable, because it can be polarised via an optical excitation, while its spin information is encoded in its fluorescence signal and can be read-out by using a fluorescence microscope. Till recently fluorescence microscopy was limited by diffraction and thus the spins of close-by NV- centres could not be addressed individually. Today techniques are available to fundamentally overcome the diffraction limit in fluorescence microscopy and some of them could be successfully applied on the NV- centre.

Here we show how to address single electron spins in diamond with single digit nanometre resolution by combining STED (Stimulated Emission Depletion) with ODMR (Optically Detectable Magnetic Resonance) techniques. Furthermore we overcome the limitations on fluorescence efficiency and focus quality caused by the high index of refraction of diamond by employing a solid immersion lens (SIL). We demonstrate that SIL enhanced STED-ODMR provides a spin addressing resolution potential of 1.6 nm. Concurrently the collection efficiency is increased by a factor of 5.

SYQM 2.3 Fri 15:00 V47.01

Beating the classical resolution limit via multi-photon interferences of independent light sources — Steffen Oppel[1], Thomas Büttner[1], Pieter Kok[2], and •Joachim von Zanthier[1] — [1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, Erlangen, Germany — [2]Department of Physics and Astronomy, University of Shefield, Shefield, UK

Multi-photon interferences with indistinguishable photons from independent light sources are at the focus of current research due to their potential in optical quantum computing, creating remote entanglement and quantum metrology. The paradigmatic states for multi-photon interference are the highly entangled NOON states which can be used to achieve enhanced resolution in interferometry and lithography [1]. Multi-photon interferences from independent, uncorrelated emitters can also lead to enhanced resolution [2]. So far, such quantum interferences have been observed with maximally two emitters. Here, we report multi-photon interferences with up to five independent emitters, displaying interference patterns equivalent to those of NOON states. Experimental results with independent thermal light sources confirm this NOON-like modulation. The experiment is an extension of the landmark measurement by Hanbury Brown and Twiss who investigated intensity correlations of second order. Here we go beyond this level by measuring spatial intensity correlations up to fifth order to further increase the resolution.

[1] A. N. Boto et al., Phys. Rev. Lett. 85, 2733 (2000).
[2] C. Thiel et al., Phys. Rev. Lett. 99, 133603 (2007).

SYQM 2.4 Fri 15:15 V47.01

High Dynamic Range Magnetometry with a Single Nuclear Spin in Diamond — •Gerald Waldherr[1], Johannes Beck[1], Philipp Neumann[1], Ressa S. Said[2], Matthias Nitsche[1], Jason Twamley[3], Fedor Jelezko[4], and Jörg Wrachtrup[1] — [1]3. Physikalisches Institut, Universität Stuttgart, 70569 Stuttgart — [2]Institut für Quanten-Informationsverarbeitung, Universität Ulm, 89081 Ulm — [3]Centre for Engineered Quantum Systems, Faculty of Science, Macquarie University, Sydney, Australia — [4]Institut für Quantenoptik, Universität Ulm, 89073 Ulm

Sensors based on the nitrogen-vacancy (NV) defect in diamond are being developed to measure weak magnetic and electric fields at nanoscale. However, such sensors rely on measurements of a shift in the Lamor frequency of the defect, so an accumulation of quantum phase causes the measurement signal to exhibit a periodic modulation. This means that the measurement time is either restricted to half of one oscillation period, which limits accuracy, or that the magnetic field range must be known in advance. Moreover, the precision increases only slowly, as $T^{-0.5}$, with the measurement time T. We implement a quantum phase estimation algorithm on a single nuclear spin in diamond to combine both high sensitivity and high dynamic range. By achieving a scaling of the precision with time to $T^{-0.85}$, we improve the sensitivity by a factor of 7.4, for an accessible field range of 16 mT, or alternatively, we improve the dynamic range by a factor of 130 for a sensitivity of 2.5 $\mu T/Hz^{0.5}$. These methods are applicable to a variety of field detection schemes, and do not require entanglement.

SYQM 2.5 Fri 15:30 V47.01

Enhancement of a single electron spin based magnetometer by utilizing a small nuclear spin quantum register — •Philipp Neumann[1], Gerald Waldherr[1], Matthias Nitsche[1], Sebastian Zaiser[1], Fedor Jelezko[2], and Jörg Wrachtrup[1] — [1]3. Physikalisches Institut, Universität Stuttgart — [2]Institut für Quantenoptik, Universität Ulm

The negatively charged nitrogen-vacancy (NV) center in diamond and its associated nuclear spins form a versatile small quantum register. Apart from its potential applications in quantum information processing the susceptibility of its quantum coherence to external stimuli like magnetic and electric fields render the NV center a tiny quantum sensor. Its high spatial confinement allows to build very small sensing devices which lead to a sample-probe distance of only a few nanometer potentially enabling the detection of single electron or even nuclear spins.

Here we show how a small quantum register of proximal nuclear spins around the NV center can be used to drastically increase the performance of the NV electron spin as a magnetic field sensor.

SYQM 2.6 Fri 15:45 V47.01

Sub shot-noise interferometry from measurements of the one-body density — Jan Chwedenczuk[1,2], •Philipp Hyllus[1,3], Francesco Piazza[1,4], and Augusto Smerzi[1,5] — [1]INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, 38123 Povo, Italy — [2]Faculty of Physics, University of Warsaw, ul. Hȯza 69, 00-681 Warsaw, Poland — [3]Department of Theoretical Physics, The University of the Basque Country, P.O. Box 644, E-48080 Bilbao, Spain — [4]Physik Department T34,Technische Universität München, James-Franck-Straße, 85747 Garching, Germany — [5]INO-CNR and LENS, 50125 Firenze, Italy

We show that a sub shot-noise sensitivity – associated with the quantum correlations present in the state entering the interferometer – can be achieved with particle-position measurements using a new phase estimator which does not require *any* knowledge about these correlations, and is based on the single-body density. For the case of the estimation of the relative phase θ between two interfering wave-packets we demonstrate that the sensitivity can scale as $\Delta^2\theta \propto N^{-1.33}$ with the total number of particles N when phase-squeezed states are used. The necessary amount of squeezing could be created using a Bose-Einstein Condensate trapped in a double-well potential, and we argue that even with finite detection efficiency/resolution, sub shot-noise sensitivity can be preserved.

SYQM 2.7 Fri 16:00 V47.01

Quantum State Tomography of Bipartite Bose Condensates

— •Roman Schmied, Caspar Ockeloen, and Philipp Treutlein — Departement Physik, Universität Basel, Schweiz

The quantum-mechanical states of large systems are difficult to measure experimentally because of the exponentially large number of variables involved. Yet in systems of indistinguishable bosons, this number is dramatically reduced, and a tomographic reconstruction of the exchange-symmetric density matrix is feasible even for thousands of particles. We present a practical method for experimentally performing this tomography for two-component Bose–Einstein condensates,* and extend it to the tomographic determination of *correlations* between small numbers of particles within a condensate: such correlations can be stable even when the total atom number fluctuates between experimental runs. The tomographic reconstructions of Wigner functions, Glauber–Sudarshan P-representations, and Husimi-Q distributions on the Bloch sphere are compared.

As an application we present the quantum-state tomography of spin-squeezed states of a two-component ^{87}Rb Bose–Einstein condensate (see also SYQM 1.5).

* R. Schmied and P. Treutlein, New J. Phys. **13**, 065019 (2011)