Quantum Sensing & Magnetometry
– from the nanoscale to geological explorations –

701. WE-Heraeus-Seminar

August 12 – 14, 2019
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 701. WE-Heraeus-Seminar:

The impact of quantum sensing technologies ranges from ultra-high-precision spectroscopy and microscopy, positioning systems, clocks, gravitational, electrical and magnetic field sensors, to optical resolution beyond the wavelength limit.

Today, magnetometry is one of the most advanced quantum sensing technologies. Its application spans the detection of biological, medical, geological and environmental magnetic fields, as well as its use as a research tool in fundamental physics. Currently, three different quantum technology based magnetic sensor types are in a mature state of development, enabling ultra-sensitive measurements over a wide range of length and frequency scales:

- SQUIDs – Superconducting QUantum Interference Devices
- OPMs – Optically Pumped Magnetometers
- NV- – Nitrogen-Vacancy-centers

The aim of the seminar is bringing together the makers and the users of novel magnetometry. Furthermore to identify novel methods of quantum sensing and envision what would be implementable by such novel sensitivities, precisions and accurracies.

Scientific Organizers:

Dr. Lutz Trahms	PTB, Berlin, Germany E-mail: lutz.trahms@ptb.de
Prof. Dr. Fedor Jelezko	Universität Ulm, Germany E-mail: fedor.jelezko@uni-ulm.de
Dr. Ilja Gerhardt	Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany E-mail: ilja@quantumlah.org

Program

Sunday, 11 August 2019

17:00 – 21:00	Registration	
from 18:00	*BUFFET SUPPER / Informal get together*	

Monday, 12 August 2019

07:30	*BREAKFAST*	
Session 1		
08:20 – 08:30	Lutz Trahms	**Opening and welcome**
08:30 – 09:15	Dmitry Budker	**Making (quantum) sense of dark particle-waves**
09:15 – 10:00	Timothy Chupp	**Applications of Noble Gas Magnetometry**
10:00 – 10:30	*COFFEE BREAK*	
Session 2		
10:30 – 11:15	Jörg Wrachtrup	**Multiparameter quantum sensing with nanoscale resolution**
11:15 – 12:00	Liam Hall	**Spin probes for hyperpolarization and beyond**
12:00 – 12:45	Christof Wunderlich	**Ultrasensitive magnetometer using a single trapped atomic ion**
12:45	*LUNCH*	

Monday, 12 August 2019

Session 3

14:00 – 14:45	Svenja Knappe	**Magnetic imaging with microfabricated optically-pumped magnetometer arrays**
14:45 – 15:30	Erling Riis	**Miniaturisation of optically pumped magnetometers**
15:30 – 16:00	Kasper Jensen	**Optically pumped magnetometer for biomedical applications**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 16:45	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

Session 4

16:45 – 17:45	**Poster flash**
17:45 – 18:00	*BREAK*
18:00 –19:30	*HERAEUS DINNER at the Physikzentrum (cold & warm buffet, free beverages)*
19:30	**Poster session**

Tuesday, 13 August 2019

07:45	*BREAKFAST*	

Session 5

08:45 – 09:30	Michael Romalis	**Atomic magnetometry with dense alkali-metal vapors**
09:30 – 10:00	Kiwoong Kim	**Hyperpolarized Imaging Applications based on Ultra-sensitive Magnetometry**
10:00 – 10:30	Arne Wickenbrock	**Towards biomagnetic measurements with a diamond endoscope**
10:30 – 11:00	*COFFEE BREAK*	

Session 6

11:00 – 11:45	Ronny Stolz	**High resolution magnetic field sensing for geoscientific applications**
11:45 – 12:30	Roland Lammegger	**A Coupled Dark State Magnetometer developed for Space Missions**
12:30 – 12:35	**Conference Photo**	
12:35	*LUNCH*	

Session 7

13:45 – 14:30	Georg Bison	**Magnetometry challenges in fundamental science**
14:30 – 15:00	Szymon Pustelny	**Searches for dark matter with a global network of optical magnetometers**
15:00 – 15:30	Alex Sushkov	**Fundamental physics with ensembles of spins**
15:30 – 16:00	*COFFEE BREAK*	

Tuesday, 13 August 2019

Session 8

16:00 – 16:20	Short talk 1 Patrick Bevington	**Non-Destructive Defect Imaging with a Radio-Frequency Optically Pumped Magnetometer**
16:20 – 16:40	Short talk 2 Sylvain Karlen	**Functionalized MEMS vapor cells for chip-scale magnetometery**
16:40 – 17:00	Short talk 3 Anne Fabricant	**Biomagnetism of Venus flytrap plants**
17:00 – 17:20	Short talk 4 Yongqi Shi	**GHz microwave field imaging with atomic vapor cells**
17:20 – 17:40	Short talk 5 Peter Schwindt	**Optical Beat Note Readout of a Magnetic Gradient**
17:40	*BREAK*	
18:00	*DINNER*	
19:30	**Poster session**	

Program

Wednesday, 14 August 2019

07:45	*BREAKFAST*	
Session 9		
08:45 – 09:30	Morgan Mitchell	**On energy resolution limits in magnetic field sensing**
09:30 – 10:15	Piet Schmidt	**Quantum logic spectroscopy and sensing with trapped ions**
10:15 – 10:45	*COFFEE BREAK*	
Session 10		
10:45– 11:30	Rainer Körber	**SQUID systems for ultra-sensitive magnetometry**
11:30 – 12:15	Justin Schneiderman	**High-T_c SQUID based on-scalp MEG**
12:15 – 12:45	Elena Boto	**A wearable multi-channel OPM-MEG system with lifetime compliance**
12:45 – 13:00	Lutz Trahms Fedor Jelezko Ilja Gerhardt	**Poster awards and closing remarks**
13:00	*LUNCH*	

End of the seminar *and Farewell Coffee* / **14:30 Departure**

Posters

1	Seyed Khalil Alavi	**Graphene nanoribbons: potential 2D materials for sensing applications**
2	Guzhi Bao	**Enhancement of the signal-to-noise ratio of an atomic magnetometer by 10 dB**
3	Andreas Blug	**Optically pumped magnetometers for material research applications**
4	Sven Bodenstedt	**Wide field range studies of nuclear magnetic relaxation using optically pumped magnetometers**
5	Ruth Corkill	**A proposed Interdisciplinary Approach to Advance Magnetomyography Techniques for Magnetic Field Recordings of Skeletal Muscles**
6	Anna Ermakova	**Perspectives of nanodiamonds with color centers for bio applications**
7	Michael Faley	**High-T_c SQUIDs for different applications**
8	Tino Fremberg	**An optically pumped magnetometer for counting magnetotactic bacteria**
9	Zoran Grujić	**Accurate magnetometry for nEDM (neutron Electrical Dipole Moment) searches**
10	Stefan Hartwig	**SQUID based ultra-low field NMR spectroscopy and relaxometry**
11	Sophia Haude	**Cancellation of the Earth Rotation Frequency Offset in Co-Magnetometry due to B-field Reversal**
12	Niall Holmes	**A multi-channel OPM-MEG system: from construction to application**

Posters

13	Dominic Hunter	**Waveform Reconstruction with a Cs Based Free-Induction-Decay Magnetometer**
14	Joonas Iivanainen	**Active shielding system for multichannel OPM arrays**
15	Stuart Ingleby	**Field demonstrations of double-resonance magnetometry**
16	Andrey Jarmola	**Nuclear magnetic resonance spectroscopy on a diamond chip**
17	Aaron Jaufenthaler	**OPM magnetorelaxometry in the presence of a DC bias field**
18	Patrick Kaspar	**An optogalvanic flux sensor for trace gases**
19	Vinaya Kavatamane	**Probing phase transitions in a soft matter system using defects in diamond**
20	Christopher Kiehl	**Vector magnetometry with atomic vapor self-calibrated with microwave polarization**
21	Wolfgang Kilian	**Side Band Detection of $^{3}He/^{129}Xe$ Nuclear Spin Precession for Dark Matter Sensing**
22	Jia Kong	**Towards quantum enhanced sensing in SERF-regime ensembles**
23	Tom Kornack	**A Simple 100 G Reference Magnetometer**
24	Peter Koss	**Optically pumped magnetometers for industrial applications**
25	Hannes Kraus	**SiCMAG - the Silicon Carbide Solid State Quantum Magnetometer**

26	Damian Kwiatkowski	**Sensing the environment with two NV centers**
27	Victor Lebedev	**Fast unshielded optical magnetometer for magnetic nanoparticles metrology**
28	Qiang Lin	**Measurement of human weak magnetic field by high sensitivity multi-channel quantum magnetometer**
29	Jonas Meinel	**Frequency shifts in noble-gas comagnetometers**
30	Thomas Middelmann	**Stress MCG during exercise with Optically Pumped Magnetometers**
31	Jiang Min	**Magnetic Gradiometer for the Detection of Zero- to Ultralow-Field Nuclear Magnetic Resonance**
32	Kostas Mouloudakis	**Open Quantum Systems description of spin-noise in single and multi-species alkali vapors**
33	Matthias Niethammer	**Room-temperature photo-current detected coherent spin motion of V_{Si} in 4H-SiC**
34	Carolyn O'Dwyer	**Noise suppression techniques in atomic magnetometry for portable sensors**
35	Gregor Oelsner	**Optically pumped magnetometer for ultrasensitive measurements of Earth's magnetic field**
36	Agustin Palacios-Laloy	**Helium-4 optically pumped magnetometers for medical imaging**
37	Chris Perrella	**High-bandwidth optical magnetometry**

Posters

38	Rebecca Rodrigo	**NanoSQUIDs based on Nb nanobridges**
39	Natasha Sachdeva	**A new measurement of the permanent electric dipole moment of ^{129}Xe using ^{3}He comagnetometry and SQUID detection**
40	Igor Savukov	**Atomic magnetometer research at Los Alamos**
41	Petr Siyushev	**Towards integrated diamond sensors for biomedical application**
42	Reza Tavakoli Dinani	**Current Monitoring System based on Cesium Magnetometry**
43	Michael Tayler	**Ultralow-field NMR of liquids confined in ferromagnetic and paramagnetic materials**
44	Charikleia Troullinou	**Squeezed light enhanced magnetometer with high density alkali vapor**
45	Stoyan Tsvetkov	**Bright and dark coherent resonances in potassium**
46	Jens Voigt	**Status of the heavily magnetic shielded Room BMSR-2.1 including an active stabilized B0-field**
47	Matthias Widmann	**Silicon Vacancies in Silicon Carbide for Quantum Sensing**
48	Florian Wittkämper	**Challenges of fabricating fully integrated alkali vapour cells**
49	Janik Wolters	**Rb vapor cell quantum memory for SPDC photons**

50	Peng Xinhua	**Experimental Benchmarking of Quantum Control in Zero-Field Nuclear Magnetic Resonance**
51	Rasmus Zetter	**Coil design framework for atomic sensors**

Abstracts of Lectures

(in chronological order)

Making (quantum) sense of dark particle-waves

D. Budker[1,2]

[1]*Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany*
[2]*Department of Physics, University of California, Berkeley, USA*

Ultralight (10^{-22} eV < m < 20 eV) bosonic particles are among prominent candidates for galactic dark matter. We will discuss the reason why such particles necessarily have to be bosons and various other properties that follow from their galactic association. It follows from the observed dark-matter density that the number density of the bosons is so high that their collective field could be a more convenient description. We will discuss the properties of this field, including its coherence time, coherence length, as well as its characteristic velocity with respect to the galactic frame [1]. These are important for the interpretation of dark-matter searches, including the recent results of the cosmic axion spin precession experiments (CASPEr) [2,3].

References

[1] Gary P. Centers, John W. Blanchard, Jan Conrad, Nataniel L. Figueroa, Antoine Garcon, Alexander V. Gramolin, Derek F. Jackson Kimball, Matthew Lawson, Bart Pelssers, Joeseph A. Smiga, Yevgeny Stadnik, Alexander O. Sushkov, Arne Wickenbrock, Dmitry Budker, and Andrei Derevianko, Stochastic amplitude fluctuations of bosonic dark matter and revised constraints on linear couplings, arXiv:1905.13650 (2019)

[2] Antoine Garcon, John W. Blanchard, Gary P. Centers, Nataniel L. Figueroa, Peter W. Graham, Derek F. Jackson Kimball, Surjeet Rajendran, Alexander O. Sushkov, Yevgeny V. Stadnik, Arne Wickenbrock, Teng Wu, and Dmitry Budker, Constraints on bosonic dark matter from ultralow-field nuclear magnetic resonance, arXiv:1902.04644

[3] Teng Wu, John W. Blanchard, Gary Centers, Nataniel L. Figueroa, Antoine Garcon, Peter W. Graham, Derek F. Jackson Kimball, Surjeet Rajendran, Yevgeny V. Stadnik, Alexander O. Sushkov, Arne Wickenbrock, and Dmitry Budker, Search for axionlike dark matter with nuclear spins in a single-component liquid, Phys. Rev. Lett. **122**, 191302 (2019); arXiv:1901.10843

Applications of Noble Gas Magnetometry

Timothy Chupp
University of Michigan
Ann Arbor, Michigan, USA
chupp@umich.edu

The spin-1/2 noble gases ^{3}He and ^{129}Xe provide nearly perfect two-state quantum systems for magnetometry. Spins are also sensitive to a number of non-magnetic couplings. For example, the electric dipole moment (EDM), a separation of charge along the atom's angular momentum vector is due to elementary particle forces that polarize the nucleus or atom that reveal something new about nature's and relate to the interactions that should have produced the baryon asymmetry in the early universe. Other couplings to spin, may include cosmic fields that violate local Lorentz Invariance by affecting nuclear energy levels that would be revealed in a system with spin greater than ½, for example ^{21}Ne (I=3/2). Because any system with angular moment has a magnetic moment, we developed the comagnetometer technique with ^{3}He to essentially measure the difference of exotic-physics effects between two species, while mitigating magnetic-field related systematic effects[1]. Over the course of several investigations[2,3,4] limitations of comagnetometry have been recognized. In parallel we have developed techniques of absolute magnetometry with ^{3}He, which requires corrections for a variety of systematic effects currently understood at the 10's of ppb level at ~1.45 T and relate to some comagnetometry limitations. In this talk, I will describe the fundamental motivations for EDM measurements and absolute magnetometry, and discuss technical details.

References

1. *Precision Frequency Measurements with Polarized ^{3}He, ^{21}Ne and ^{129}Xe,* T.E. Chupp, et al., **Phys. Rev. A 38**, 3998 (1988).
2. *Results of a New Test of Local Lorentz Invariance: A Search for Mass Anisotropy in ^{21}Ne,* T.E. Chupp et al., **Phys. Rev. Lett. 63**, 1541 (1989).
3. *Coherence in Freely Precessing ^{21}Ne and a Test of Linearity in Quantum Mechanics,* T.E. Chupp and R.J. Hoare, **Phys. Rev. Lett. 64**, 2261 (1990).
4. *Atomic Electric Dipole Moment Measurement Using Spin Exchange Pumped Masers of ^{129}Xe and ^{3}He,* M.A. Rosenberry and T.E. Chupp, **Phys. Rev. Lett. 86,** 22 (2001).
5. *A New Measurement of the permanent electric dipole moment of 129-Xe using 3-He comagnetometry and SQUID detection*, N. Sachdeva, I. Fan, E. Babcock, M. Burghoff, T. E. Chupp, S. Degenkolb, P. Fierlinger, E. Kraegeloh, W. Kilian, S. Knappe-Grueneberg, F. Kuchler, T. Liu, M. Marino, J. Meinel, Z. Salhi, A. Schnabel, J. T. Singh, S. Stuiber, W. A. Terrano, L. Trahms, and J. Voigt, arXiv 1902.02864 (2019).
6. *Frequency shifts in noble-gas magnetometers ,* W. A. Terrano, J. Meinel, N. Sachdeva, T. Chupp, S. Degenkolb, P. Fierlinger, F. Kuchler, and J.T. Singh, arXiv: 1807:11119. Submitted to Phys. Rev. Lett. (July 2018).

Multiparameter quantum sensing with nanoscale resolution

Jörg Wrachtrup, 3rd Institute of Physics and Centre for Applied Quantum Physics, University Stuttgart, Stuttgart

Spin defects in wide band gap semiconductors enable quantum sensing with a spatial accuracy of a few nano meters. This leads to a variety of intriguing applications in material- as well as bio science. It turns out, that the sensor spin is sensitive to a number of external parameters and that dedicated Hamiltonian engineering renders the system sensitive to a particular quantity, like e.g. electric fields, temperature, pressure or magnetic fields [1]. The talk will demonstrate sensing of various quantities and discuss the enhancement of sensor performance using dedicated readout schemes [2,3] as well as quantum algorithms [4,5].

[1] C.L. Degen, R. Reinhard, P. Cappelaro Rev. Mod. Phys. 89, 035002 (2017)

[2] D.A. Hopper et al. Micromachines, 9, 437 (2018)

[3] J.F. Barry et al. arXiv:1903.08176v1 (2019)

[4] N. Aslam et al. Science 357, 67 (2017)

[5] M. Pfender et al. Nature Com. 10, 594 (2019)

Spin probes for hyperpolarization and beyond

Liam Hall[1]

[1]*School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia*

Quantum sensing techniques using spin probes such as the nitrogen-vacancy (NV) in diamond [1] present a promising approach to performing magnetic resonance imaging and spectroscopy at the nanoscale. In this talk I will summarize some of our recent work [2-7], with focus on hyperpolarization of nuclear spins external to the diamond substrate based on controlled cross-relaxation [8], and concepts for single molecule imaging using other spin probes of interest.

References

[1] M. Doherty et al, *The nitrogen-vacancy colour centre in diamond*, Physics Reports **528** 1 (2013)

[2] J-P. Tetienne et al, *Quantum imaging of current flow in graphene*, Science Advances **3** e1602429 (2017)

[3] D. Simpson et al, *Electron paramagnetic resonance microscopy under ambient conditions,* Nature Communications **8** 458 (2017)

[4] J. Wood et al, *Microwave-free nuclear magnetic resonance at molecular scales,* Nature Communications **8** 15950 (2017)

[5] D. Simpson et al, *Non-Neurotoxic Nanodiamond Probes for Intraneuronal Temperature Mapping,* ACS Nano **11** 12077 (2018)

[6] A. Wood et al, *Quantum measurement of a rapidly rotating spin qubit in diamond*, Science Advances **4** 7691 (2018)

[7] J-P. Tetienne et al, *Spatial mapping of band bending in semiconductor devices using in-situ quantum sensors,* Nature Electronics **1** 502 (2018)

[8] D. Broadway et al, *Quantum probe hyperpolarisation of molecular nuclear spins,* Nature Communications **9** 1246 (2018)

Ultrasensitive magnetometer using a single trapped atomic ion

I. Baumgart[1], J.M. Cai[2], A. Retzker[3], M.B. Plenio[4], Ch. Wunderlich[1]

[1]*Department of Physics, Siegen University, 57068 Siegen, Germany*
[2] *School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China*
[3]*Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Givat Ram, Israel*
[4]*Institut für Theoretische Physik, Ulm University, 89069 Ulm, Germany*

The precision, and thus the sensitivity of magnetometry scales as $1/\sqrt{T_2}$ with the phase coherence time T_2 of the sensing system. Typical quantum sensing protocols prolong T_2 of the quantum states used for sensing by using dynamical decoupling (DD), that is, applying a continuous or pulsed electromagnetic driving field. In the case of pulsed DD, the required repetition rate of pulses -- with each pulse having a well defined pulse area -- is proportional to the frequency of the field to be detected with high sensitivity, thus effectively limiting the frequency range of the sensor. To achieve a long coherence time T_2 using continuous DD, the amplitude of the driving field has to be kept highly stable for time T_2, another technologically challenging problem.

Here, we implement a decoupling scheme using two continuous decoupling fields in an atomic 4-level scheme. Thus, fluctuations of the amplitude of the decoupling fields no longer limit the coherence time. Instead, T_2 is determined by the frequency stability of the driving fields which is straight forward to maintain with high precision using, for instance, a commercial atomic clock. Using a single trapped $^{171}Yb^+$ ion as a sensor, we experimentally attain a sensitivity of 4.6 pT/√Hz, to our knowledge an unprecedented value realized with a single atom. The detected magnetic field is an alternating-current (AC) magnetic field near 14 MHz. Based on the principle demonstrated here, the sensitivity together with its tuneability from nearly direct-current to the gigahertz range could be used for magnetic imaging in as of yet inaccessible parameter regimes.

References

[1] I. Baumgart, J.M. Cai, A. Retzker, M.B. Plenio, Ch. Wunderlich, Phys. Rev. Lett. **116**, 240801 (2016).

Magnetic imaging with microfabricated optically-pumped magnetometer arrays

V. Gerginov[1], N. Nardelli[1], B. Korenko[1], G. Romanov[1], M. Gerginov[1], O. Alem[1,2], J. Hughes[1,2] and S. Knappe[1,2]

[1]Mechanical Engineering Department, University of Colorado, Boulder CO, USA
[2] FieldLine Inc., Boulder CO, USA

We present our ongoing effort in developing imaging systems with microfabricated optically-pumped magnetometers (μOPMs). Through the use of microfabrication technologies and simplification of optical setups, we aim to develop manufacturable sensors of small size and weight, and low power. Our zero-field μOPMs require a shielded environment but reach high sensitivities of less than 10 $fT/Hz^{1/2}$. Target applications lie in the field of non-magnetic brain imaging, specifically magnetoencephalography (MEG). The attraction of using these sensors for non-invasive brain imaging stems from the possibility to place them directly on the scalp of the patient, as close as possible to the brain sources. The MEG test system we present consists of 48 μOPMs. They are integrated into pairs on small flying lead sensor heads, such that they form 24 first-order gradiometers with a baseline of 2 cm. The gradiometer and magnetometer data can be read out simultaneously. All μOPMs operate under negative feedback at the zero-field point [1]. The sensors are assembled on a conformal 3D printed helmet with spokes that can be adjusted in the radial direction. The helmet is attached to a wooden bed, which can be inserted into a set of shield cans, big enough to hold an adult subject, and is open on one side. The residual field inside the shield is around 5 nT. Shimming coils are installed to reduce the fields and gradients further. The magnetic field in the direction radial to the head is recorded with the magnetometers and radial gradiometers. We present MEG recordings of resting-state measurements and evoked responses used to characterize the system.

References

[1] D. Sheng, A. Perry, S. Krzyzewski, S. Geller, J. Kitching, and S. Knappe, Appl. Phys. Lett. **110**, 0031106 (2017)

Miniaturisation of optically pumped magnetometers

Erling Riis

Strathclyde University, Department of Physics, Glasgow, UK

Miniaturisation of optically pumped magnetometers (OPMs) have been made possible through the integration of compact laser sources and detectors with microfabricated MEMS vapour cells. In addition to this physics package development, the adoption of digital control and signal processing techniques has made further simplification possible as well as allowed for the inclusion of additional functionality.

Progress is reviewed on miniaturised and portable OPMs for total field sensing in an unshielded environment demonstrating both high bandwidth and sensitivity and with applications outside a lab environment. Two separate configurations are considered based on the rf-optical double resonance technique and a free-induction decay scheme respectively.

Optically pumped magnetometer for biomedical applications

K. Jensen[1,2], M. Zugenmaier[2], H. Stærkind[2], J. Arnbak[2], M. V. Balabas[2,3], and E. S. Polzik[2]

[1] School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, England, United Kingdom
[2] Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark
[3] Department of Physics, St Petersburg State University, Universitetskii pr. 28, 198504 Staryi Peterhof, Russia

Optically pumped magnetometers (OPMs) are highly sensitive quantum devices which can detect tiny magnetic fields from the human body, for instance, OPMs have detected brain activity and the adult and fetal heartbeat. Our magnetometer is based on room-temperature cesium atomic vapor and we have previously demonstrated sub-fT/sqrt(Hz) sensitivity and entanglement-assisted magnetometry [1]. More recently, we have detected bio-magnetic signals from animal nerve impulses [2] and the heartbeat of a guinea-pig heart [3] with our magnetometer.

OPMs can potentially also be used to non-invasively image the electrical conductivity of the heart using a technique called magnetic induction tomography (MIT) [4]. In MIT of the heart, one or more coils are used to induce eddy currents in the heart and an image of the heart is constructed from measurements of the associated induced magnetic field. This is a challenging task for several reasons, with the main one being the low conductivity $\sigma < 1$ S/m of the heart. As a step towards imaging the heart, we have detected low-conductivity objects with our magnetometer using a differential technique which increased the signal-to-noise ratio (SNR) by more than three orders of magnitude [5]. We detected small containers with a few mL of salt-water with conductivity ranging from 4—24 S/m with a good SNR. Our work opens up new avenues for using OPMs to image low-conductivity biological tissue including the human heart which would enable non-invasive diagnostics of heart diseases.

References

[1] W. Wasilewski et al. Phys. Rev. Lett. **104**, 133601 (2010).
[2] K. Jensen et al. Sci. Rep. **6**, 29638 (2016).
[3] K. Jensen et al. Sci. Rep. **8**, 16218 (2018).
[4] L. Marmugi and F. Renzoni. Sci. Rep. **6**, 23962 (2016).
[5] K. Jensen et al., arXiv:1905.01661 (2019)

Atomic magnetometry with dense alkali-metal vapors

M. Romalis

Princeton University, Princeton, USA

I will review recent progress in the development of high sensitivity atomic magnetometers using dense alkali metal vapors. By using a large number of atoms one can realize both high bandwidth and sensitivity, allowing many practical and fundamental applications of atomic magnetometers. Our current work is focused on several practical challenges, such as realizing high sensitivity in the presence of ambient magnetic fields and taking advantage of non-linear relaxation properties of dense alkali-metal vapors.

Hyperpolarized Imaging Applications based on Ultra-sensitive Magnetometry

Kiwoong Kim[1,2], Jeong Hyun Shim[1,2], Seong-Joo Lee[1], Seong-Min Hwang[1,2], Sangwon Oh[1], Keunhong Jeong[3], Ingo Hilschenz[1]

[1]Korea Research Institute of Standards and Science, Daejeon 34113, KOREA
[2]University of Science and Technology Daejeon 34113, KOREA
[3]Korea Military Academy, Seoul 01805, KOREA

Currently, quantum spin based imaging applications get attention from many research groups who have been dealing with various magnetometry. Especially, there were lots of efforts to find novel contrasts or applications in nuclear magnetic resonance imaging with sensitive magnetic field sensors such as superconducting quantum interference devices (SQUID), optically pumped magnetometer (OPM), and diamond nitrogen vacancy (DNV) centers. In such trials, the polarization of a sample is generally not enough due to the limitation in use of a strong polarization magnetic field under an operation condition of a sensitive sensor and in field cycling interference with shielding structure in micro-tesla applications.

Hyperpolarization can be an effective solution in order to increase the signal and spatial resolution in the imaging technology. In this presentation, we introduce hyperpolarization techniques and applications in ultra-low field nuclear magnetic resonance imaging (ULF-MRI). The scope of talk consists of Overhauser dynamic nuclear polarization (O-DNP), the signal amplification by reversible exchange (SABRE) technique with para-hydrogen, and optical DNP.

O-DNP can significantly enhance the intensity of the MRI signal in comparison to the thermal magnetization. Even in a zero magnetic field, there is a finite hyperfine energy splitting with a radical, which guarantees a certain level of polarization and numerically infinite enhancement factor at zero field through the cross relaxation between electron spins and nuclear spins. However, in practice, an overlap of opposite absorption lines cancels out the enhancement. By applying circularly polarized magnetic field, we could make a selective excitation and achieved a sub-millimeter resolution even in ULF-MRI.

Meanwhile we demonstrate real-time SQUID-based MRI in the micro-Tesla range magnetic field using the SABRE technique after designing a separated bubbling phantom. A maximum enhancement of 2,650 for ^1H was achieved for pyridine in Methanol. A clear SABRE-enhanced MR image of the phantom was successfully obtained at 34.3 μT and the enhanced polarization accelerated the acquisition time drastically. The results show that SABRE can be successfully incorporated into an ultralow-field MRI.

Finally, we introduce several applications with nano-diamonds and DNV nano NMR microscopy.

Towards biomagnetic measurements with a diamond endoscope

H. Zheng[1], G. Chatzidrosos[1], A. Wickenbrock[1] and D. Budker[1,2]

[1]*Johannes Gutenberg Universität, Helmholtz Institut, Mainz, Germany*
[2] *Department of Physics, University of California at Berkeley, California, USA*

The detection of feeble biomagnetic fields requires sensitive and robust magnetic field sensors deployable in a clinical environment. Ensembles of nitrogen-vacancy (NV) centers in diamonds are widely utilized for magnetometry, magnetic field imaging and magnetic-resonance detection.
I am going to give an overview of the diamond activity in the Matter-Antimatter Asymmetry section of the Helmholtz Institut Mainz focusing on our efforts to come up with novel microwave-free magnetometry methods and their recent inclusion of vector capability [1], demonstrate how to detect the conductivity of a material using diamonds [2] and show results of our efforts to extend the measurement range of NV centers into the zero-field regime [3]. Especially the last result might become important to allow diamonds to sense biomagnetic DC fields in a shielded environment. Commonly NV center magnetometers are deployed with a background magnetic field of several millitesla, which is not trivial within a magnetic shield and can also result in substantial technical noise.
Ultimately our hope is to deploy the developed sensors and techniques in a miniaturized endoscope allowing minimal distance to the biomagnetic source and therefore improved signal-to-noise as a novel tool in clinical diagnostics.

References

[1] H. Zheng et al. arXiv:1904.04361 (2019)
[2] G. Chatzidrosos et al., Phys. Rev. Applied **11**, 024005 (2019)
[3] H. Zheng et al., Phys. Rev. Applied **11**, 064068 (2019)

High resolution magnetic field sensing for geoscientific applications

R. Stolz[1] and the teams at Leibniz-IPHT and Supracon AG[2]

[1] Leibniz Institute of Photonic Technology (Leibniz-IPHT), Research group Magnetometry, Albert-Einstein Str. 9, D-07745 Jena, Germany
[2] Supracon AG, An der Lehmgrube 11, D-07751 Jena, Germany

Quantum magnetometers, magnetic field sensors with quantum limited resolution, have the potential to develop significant impact on applications in geo- and environmental science such as mineral exploration, geo-engineering and technical tasks like pipe or unexploded ordnance detection and archaeometry.
In this work, we will give a short and limited introduction on the methods which make use of highly sensitive magnetometers and the according specific demands on them. In order to make use of their extreme resolution, the magnetometers themselves have to overcome two main challenges – they must be operable at Earth's magnetic field without degradation of their resolution and, often for active methods, have to be able to track fast changing signals with large amplitude.
There are different ways to extract the information from very weak signals within large-amplitude signals of a disturbed surrounding. We will discuss two methods: one is the well-known gradiometry - the signal extraction is achieved by making use of reference sensors. The second method uses time or frequency domain signal extraction such as averaging for uncovering weak magnetic signals in large amplitude disturbances.
We will introduce instruments which are able to map magnetic field anomalies as well as electromagnetic signals using Superconducting Quantum Interference Devices (SQUID) and Optically Pumped Magnetometers (OPM) in order to derive 3D distributions of magnetization or conductivity of sub-surface geological structures. Examples for the exploration of mineral deposits e.g. [1] or archaeological remainders such as in [2] will be shown.

References

[1] R. Stolz et al., The Leading Edge 25, 178 (2006).
[2] M. Schneider et al., IEEE Trans. Magn. 50, 6000704 (2014).

A Coupled Dark State Magnetometer developed for Space Missions

Roland Lammegger[1], Michaela Ellmeier[1,2], Christoph Amtmann[1], Andreas Pollinger[2], Werner Magnes[2], Christian Hagen[2], Irmgard Jernej[2]

[1] *Institute of Experimental Physics, Graz University of Technology, Petersgasse 16, 8010 Graz, Austria*

[2] *Space Research Institute, Austrian Academy of Sciences, Schmiedlstraße 6, 8042 Graz, Austria*

The Coupled Dark State Magnetometer (CDSM) is a scalar magnetometer based on two-photon spectroscopy of free alkali atoms. Coherent Population Trapping (CPT) leads to narrow optical resonance features, which enable a precise determination of the magnetic field dependent Zeeman energy level shifts. Systematic errors which usually degrade the accuracy of single CPT magnetometers are cancelled or at least minimized by the use of several CPT resonances in parallel. CPT inherently enables omni-directional measurements. This leads to a moderately complex, all-optical sensor design without double cell units, excitation coils or electro-mechanical parts.

The measurement principle was discovered in 2008 [1] and since then the instrument has been developed by the two involved institutes for future space missions [2]. The first demonstration in space take place aboard the China Seismo-Electromagnetic Satellite (CSES) mission. The flight model was launched into a low Earth orbit in January 2018. Furthermore, the CDSM is baseline instrument for the JUpiter ICy Moon Explorer (JUICE) mission of the European Space Agency (ESA) to visit the Jovian system.

The presentation includes an introduction of the measurement principle. The instrument designs are introduced for the CSES mission (successful operation in space) and the JUICE mission. The performance characteristics of both designs are presented, and -in general- the challenging demands on the instrument design of a magnetometer suited for space operation are discussed.

References

[1] Roland Lammegger, *Method and device for measuring magnetic fields*, WIPO, Patent **WO/2008/151344** (2008).

[2] Andreas Pollinger, Michaela Ellmeier, Werner Magnes, Christian Hagen, Wolfgang Baumjohann, Erich Leitgeb, Roland Lammegger, *Enable the inherent omni-directionality of an absolute coupled dark state magnetometer for e.g. scientific space applications*, IEEE Instrumentation and Measurement Technology Conference (I2MTC) Proceedings, **33** (2012).

Magnetometry challenges in fundamental science

G.Bison[1]

[1] *Paul Scherrer Institut, Villigen, Switzerland*

Many experiments designed to test our understanding of the Universe at a fundamental level (see e.g. [1]), especially those searching for electric dipole moments (EDM) [2], require stable and homogeneous magnetic fields. Statistical and systematic uncertainties in such experiments depend on temporal and spatial variations of the magnetic field and can be the limiting factor in the overall experimental sensitivity. Improving the precision at which such fundamental physics tests can be performed thus poses increasingly demanding challanges for the creation and measurement of highly stable and homogeneous magnetic fields.
Taking the neutron EDM experiment at PSI as an example, the presentation will introduce fundamental physics tests and show how the relevant aspects of the magnetic field can be monitored by a variety of special magnetometer systems based on optically-pumped Cs [3], ^{199}Hg [4], and ^{3}He [5]. The used magnetometer techniques include multi-beam vector readout [6], accurate all-optical field readings, and the readout of precessing ^{3}He spins with Cs OPM [7]. The measurement of magnetic field gradients requires a large number of Cs sensors similar to arrays previously designed for bio-magnetometry [8].

References

[1] C. Abel et al., Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields, Phys. Rev. X 7.4, (2017).

[2] J.M. Pendlebury et al., Revised Experimental Upper Limit on the Electric Dipole Moment of the Neutron, Phys. Rev. D 92, 092003 (2015).

[3] A. Weis, G. Bison and Z. D. Grujic, Magnetic Resonance Based Atomic Magnetometers, in A. Grosz et al. (Eds.), High Sensitivity Magnetometers, Springer International Publishing, ISBN 978-3-319-34068-5, (2016).

[4] G. Ban et al., Demonstration of sensitivity increase in mercury free spin precession magnetometers due to laser-based readout for neutron electric dipole moment searches, NIM A 896 (2018).

[5] H.-C. Koch et al., Investigation of the intrinsic sensitivity of a ^{3}He/Cs magnetometer. Eur. Phys. J. D 69(11), 262 (2015).

[6] G. Bison et al., Sensitive and stable vector magnetometer for operation in zero and finite fields, Opt. Exp. 26, 17350-59, (2018).

[7] Z.D. Grujic et al., A sensitive and accurate atomic magnetometer based on free spin precession. In: European Physical Journal D 69.5 (2015).

[8] G. Lembke, et al. Optical multichannel room temperature magnetic field imaging system for clinical application. Biomed. Opt. Exp. 5(3), 62–65 (2014).

Searching for dark matter with a global network of optical magnetometers

S. Pustelny

Institute of Physics, Jagiellonian University, Lojasiewicza 11, 30-368 Krakow

Astronomical observations provide some of the greatest mystery of modern science. The questions: Why motion of galaxies is different from expected? Why seemly empty space is bending rays of light? Why does the Universe expansion accelerate? are some of the most important puzzles in our understanding of Nature.

A commonly accepted hypothesis, explaining the puzzling astronomical observations, is existence of dark matter and dark energy. Through gravitational interaction, the electrically neutral and electromagnetically "immune" dark matter would modify motion of astrophysical objects. In a similar manner the accelerating expansion of the Universe could be explained by repulsive long-range interactions associated with dark energy.

Despite many sophisticated experiments, hitherto dark-matter searches failed to provide noncontroversial proof of dark-matter existence. This null result of the search not only triggered activities in development of yet more sensitive experiments but also generated activity on theoretical (development of new theoretical theories) and experimental (development of new methodologies) fronts.

A particular reason for dark-matter-search fails is its different from expected nature of dark matter – ordinary matter interaction. In particular, transient or oscillatory character of the interaction would make most of the experiments insensitive. To address this issue, several years ago, we proposed construction of a global network of atomic sensors that would search for dark matter. Our network called the Global Network of Optical Magnetometers for Exotic physics searches (GNOME) [1] aims at the detection of dark matter, manifesting through temporarily modification of a spin state of atoms. To do we proposed to use optical magnetometers, as this is exactly this type of interaction, the sensors are sensitive to. However, in order to perform such measurement unambiguously, we correlate readouts of many geographically separated experiments. This not only allows to reduce the experimental noise, often significantly exceeding signal of interest in a single experiment, but also allows to triangulate the source of the spin perturbation (arising due to a collision with dark-matter planet [2]). Thereby, the GNOME is sensitive to global, exotic spin interactions.

During the talk, basics of the GNOME will be provided. Next, current experimental efforts will be discussed [3]. We will present results of first joint runs of the network identifying requirements for atomic sensors and challenges associated with measurements as well as data analysis. The talk will be concluded with discussion of plans for the future GNOME.

References:

[1] S. Pustelny *et al.*, *The Global Network of Optical Magnetometers for Exotic physics (GNOME): A novel scheme to search for physics beyond the Standard Model,* Ann. Phys. **525**, 659 (2013).

[2] D. F. Jackson Kimball *et al.*, *Searching for axion stars and Q-balls with a terrestrial magnetometer network,* Phys. Rev. D **94**, 043002 (2018).

[3] S. Afach et al., *Characterization of the global network of optical magnetometers to search for exotic physics,* Phys. Dark Universe **22**, 162-180 (2018).

Fundamental physics with ensembles of spins

A. O. Sushkov[1]

[1]*Boston University, Boston MA, USA*

Sensitive magnetometry is the key technology that enables a broad range of technologies and discovery-oriented experiments. This talk focuses on magnetic resonance with spin ensembles. Macroscopic spin ensembles are used to search for axion dark matter - I will focus on the Cosmic Axion Spin Precession Experiment (CASPEr). On the nanometer scale, I will describe how spin ensembles in diamond are used to explore the dynamics of many-body quantum systems with long-range interactions.

Non-Destructive Defect Imaging with a Radio-Frequency Optically Pumped Magnetometer

P. Bevington[1,2], **R. Gartman[1]**, **W. Chalupczak[1]**

[1] National Physical Laboratory, Hampton Rd, Teddington, TW11 0LW, United Kingdom
[2] Department of Physics, University of Strathclyde, 107 Rottenrow East, G4 0NG, Glasgow, United Kingdom

Non-destructive testing is a cost-effective option for the detection of structural defects, particularly, when there is no direct access to the surface of the studied sample. One method involves monitoring the sample's response (secondary field) to the inductive coupling of an oscillating magnetic field (primary field) [1]. Traditionally this is achieved with a pick-up coil, however, their instrumentation simplicity is outweighed by the degradation of their signal sensitivity at low frequencies. An interesting alternative is the use of an rf optically pumped magnetometer (OPM) [2, 3].
Structural defects can be imaged by recording the amplitude and phase of the OPMs atomic rf excitation spectrum at different points across the sample. We demonstrate the previously undiscussed semi vector nature of this measurement, enabling the 2D reconstruction of the measured secondary field with an unshielded, room temperature rf OPM with a sensitivity of ~50 $fT/Hz^{1/2}$ [3].

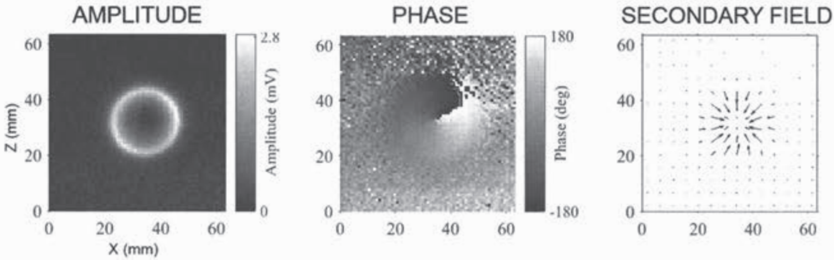


Figure 1 Measured change in the amplitude and phase of the magnetometer signal recorded over a 2.4 mm deep, 24 mm diameter recess in a 6 x 150 x 150 mm^3 Aluminum plate. The measured amplitude and phase represent the magnitude and direction of the secondary field projected on to a 2D plane. Careful selection of this projection axis enables the enhancement of the measured image contrast [3].

References

[1] L. Ma and M. Soleimani, Meas. Sci. Technol., **28**, 072001 (2017).
[2] A. Wickenbrock, et. al., Opt. Lett. **39**, 6367 (2014).
[3] P. Bevington, R. Gartman and W. Chalupczak, J. Appl. Phys. **125**, 094503 (2019);

Functionalized MEMS vapor cells for chip-scale magnetometery

S. Karlen[1], **T. Overstolz**[1], **J. Gobet**[1], **J. Haesler**[1], **F. Droz**[1], **D. Hunter**[2], **M. Tayler**[2], **S. Bodenstedt**[2], **S. Lecomte**[1] **and M. W. Mitchell**[2,3]

[1]*CSEM SA, Time & Frequency, Systems, Rue Jaquet-Droz 1, CH-2002 Neuchâtel, Switzerland*
[2] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain*
[3] *ICREA – Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain*

MEMS atomic vapor cells have applications in miniature atomic sensors including chip-scale atomic clocks (CSACs) [1], atomic magnetometers [2] and atomic gyroscopes [3]. They consist of a microfabricated cavity sealed by transparent windows and containing an alkali metal and an optional buffer gas. Here, we review the recent developments at CSEM in term of design, fabrication, filling, sealing and functionalization of MEMS atomic vapor cells, with particular attention to the needs of optically-pumped magnetometers (OPM).

Recent works on lifetime assessment of cells coated with Al_2O_3 and filled with the CSEM-patented method of RbN_3 UV decomposition [4] will be presented [5]. Integrated functionalities (heating and temperature sensing) will also be described [6] as well as CSEM patent-pending gold microdiscs technology which enables the preferential condensation of rubidium droplets at defined locations inside the cell volume. A particular focus will then be given to the effect on thermal magnetic noise [7] for OPM applications.

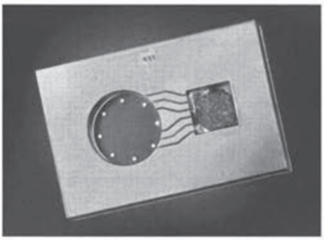


Figure 1: left: Cell filled by dispensing micropill and containing Au microdiscs - right: Cell filled by RbN_3 UV decomposition with integrated functionalities.

References

[1] L. Liew et al., APL 84(14) (2004)
[2] P. Schwindt et al., APL 85(26) (2004)
[3] E. Donley, proceedings of SENSORS 2010 (2010)
[4] S. Karlen et al., Opt. Express 25(3) (2017)
[5] S. Karlen, PhD Thesis (2018) http://doc.rero.ch/record/308907
[6] T. Overstolz et al., proceedings of MEMS'14 (2014)
[7] W. C. Griffith et al., Opt. Express 18, 27167 (2010)

Biomagnetism of Venus flytrap plants

A. Fabricant[1,2], G. Iwata[1], L. Bougas[1], K. Rolfs[3], A. Jodko-Władzińska[3], J. Voigt[3], and D. Budker[1,2,4]

[1] Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
[2] Helmholtz-Institut Mainz, 55128 Mainz, Germany
[3] Physikalisch-Technische Bundesanstalt, 10587 Berlin, Germany
[4] University of California, Berkeley, California 94720, USA

In this experiment, we aim to detect the magnetic fields produced by living plants. Our group previously conducted atomic-gradiometry measurements of a blooming titum arum, also known as the "corpse flower", at the Berkeley Botanical Garden in California [1]. As far as we know, the only reported successful detection of magnetic fields produced by intact plants occurred in 2000 [2]—an array of SQUID magnetometers was used to measure signals from wounded bean plants in a magnetically shielded room at Physikalisch-Technische Bundesanstalt (PTB) Berlin.

We chose to launch a new biomagnetism experiment using the Venus flytrap, *Dionaea muscipula*. This carnivorous plant is relatively easy to stimulate mechanically, and one can generate action potentials (APs) consistently. In our lab we set up surface-electrode measurements for AP monitoring, and we conducted preliminary magnetometry measurements in a small magnetic shield using QuSpin optically pumped magnetometers (OPMs). However, our measurements were dominated by mechanical noise due to the stimulation method. Therefore we have carried out two data runs in the shielded room at PTB, where we are able to conduct measurements without spatial constraints and with more sensors simultaneously.

Our first PTB data run, in December 2018, took place in the 3-layer magnetically shielded room using 8 OPMs. Promising initial results were presented at the Today's Noise Tomorrow's Signal workshop at PTB in February of this year. Based on our gained experience, we carried out an improved measurement run this March in the newly upgraded BMSR-2, using both OPMs and the SQUID system. Data analysis from these experiments is currently underway.

Beyond proof of principle, the long-term goal of the project is to develop a novel and robust system for measuring biomagnetic signals from a variety of living plants (e.g. agricultural species), ideally based on compact atomic sensors. Such measurements will pave the way for understanding current (ionic-flow) distributions in plants, as well as investigation of signaling pathways in response to various external stimuli.

References

[1] E. Corsini, V. Acosta, N. Baddour, J. Higbie, B. Lester, P. Licht, B. Patton, M. Prouty, and D. Budker, J. Appl. Phys. **109**, 074701 (2011).

[2] V. Jazbinsek, G. Thiel, W. Müller, G. Wübbeler, and Z. Trontelj, Eur. Biophys. J. **29**, 515-522 (2000).

GHz microwave field imaging with atomic vapor cells

Y. Shi[1], R. Mottola[1], A. Horsley[2], and P. Treutlein[1]

[1]Department of Physics, University of Basel, 4056 Basel-Stadt, Switzerland
[2]Laser Physics Centre, Research School of Physics and Engineering, Australian National University, 2601 Canberra, Australia

Microwave devices and circuits are the core parts of modern communication technology and precision instrumentation, with applications ranging from wireless networks, satellite communication, navigation systems to precision measurement. To perform the function and failure analysis of various microwave devices, a calibrated technique for high-resolution non-perturbative imaging of microwave fields is needed. Microwave detectors with high spatial resolution and low crosstalk are also essential for emerging applications of microwaves in medical imaging.

Our group developed a calibration-free technique for high-resolution imaging of microwave fields using atoms in miniaturized vapor cells as sensors [1]. In this technique, the microwave field to be measured drives Rabi oscillations on atomic hyperfine transitions. The oscillations are recorded in a spatially resolved way by absorption imaging with a laser and a camera. From the measured distribution of Rabi frequencies, we obtain an image of the microwave field distribution. All vector components of the microwave magnetic field can be imaged and the technique is intrinsically calibrated because the properties of the atomic transitions are precisely known. Using a custom vapor cell with thin walls and a proper amount of buffer gas our technique provides a spatial resolution of <100um [2].

In order to make our GHz microwave imaging technique frequency-tunable, we applied a static magnetic field (up to Tesla level), where the Zeeman splittings are larger than the hyperfine splitting (hyperfine Paschen-Back regime), and microwave magnetic fields from a few GHz to a few tens of GHz can be detected [3]. For a more homogenous DC magnetic field, we use a pair of permanent magnets and elevate the cell temperature to get sufficient optical depth. To achieve high spatial resolution, we use microfabricated cells with thin walls. We will present our latest results on frequency-tunable microwave field imaging and sensing.

References

[1] P. A. Böhi and P. Treutlein, Simple microwave field imaging technique using hot atomic vapor cells, Appl. Phys. Lett. 101, 181107 (2012).
[2] A. Horsley, G.-X. Du and P. Treutlein, Widefield microwave imaging in alkali vapor cells with sub-100 um resolution, New J. Phys. (Fast Track Communication) 17, 112002 (2015).
[3] A. Horsley and P. Treutlein, Frequency-tunable microwave field detection in an atomic vapor cell, Appl. Phys. Lett. 108, 211102 (2016).

Optical Beat Note Readout of a Magnetic Gradient

P.D.D. Schwindt,[1] K. Campbell[1], Igor Savukov[3], Y.J. Wang[2], and V. Shah[2]

[1]Sandia National Laboratories, Albuquerque, NM, USA
[2] QuSpin Inc., Louisville, CO, USA
[3]Los Alamos National Laboratories, Los Alamos, NM, USA

Typical gradient measurements using optically pumped magnetometers consist of making two independent measurements and then subtracting the results electronically. We present a technique where the gradient of the magnetic field is derived directly from the optical signal [1]. Using two ^{87}Rb vapor cells, the atoms are pumped into the |F = 2, m_F = 2> stretched state. Then, a resonant microwave pulse is applied to make a superposition between the |2,2> and |1,1> levels, and a resonant 780-nm probe beam is passed through the two vapor cells. With the atomic superposition precessing at the hyperfine splitting frequency, the probe laser will be modulated, parametrically generating an optical sideband [2]. If there is a magnetic field gradient between the two vapor cells, the sidebands will have a frequency difference and generate a beat note. Thus, the beat note frequency will be proportional the magnetic gradient. We will present an experimental implementation of this technique and describe efforts to improve the sensitivity and to eliminate dead zones of the gradiometer.

References

[1] Vishal Shah, System and Method for Measuring a Magnetic Gradient Field. Patent. US10088535 (2018).

[2] Tang, H. Parametric Frequency Conversion of Resonance Radiation in Optically Pumped Rb^{87} Vapor. Phys. Rev. A, **7**, 2010–2032 (1973).

On energy resolution limits in magnetic field sensing

Morgan W. Mitchell[1, 2]

[1] ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain.

[2]ICREA -- Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain.

We describe a class of quantum sensing limits that – unlike the standard quantum limit and Heisenberg limit – make no reference to particle number [1]. Rather, these "energy resolution limits" constrain E_R, the *energy resolution per bandwidth*, a figure of merit that combines the measurement noise, duration or bandwidth, and size of the sensed region. Technology-specific energy resolution limits have been derived for a number of important sensing modalities [2,3] and seem to converge near a limiting value of $E_R = \hbar$. We review the state of knowledge about such limits, and consider the possibility that a more general, technology-spanning limit constrains energy resolution. Possible sources include the Margolus-Levitin bound on the speed of quantum evolution and the Bremermann-Beckenstein bound on the entropy of a space-time region of given energy and volume.

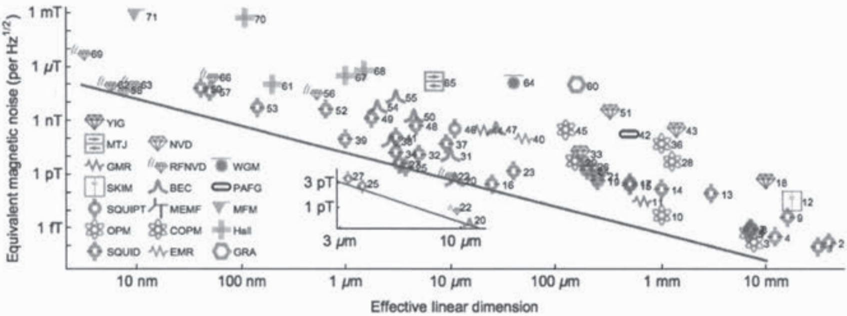


Figure 1. Reported low-frequency magnetic sensitivity versus size of the sensed region for several high-performance magnetic sensor types. MTJ - magnetic tunnel junction; GMR - giant magneto-resistance; SKIM - superconducting kinetic impedance magnetometer; SQUIPT - superconducting quantum interference proximity transistor; SQUID superconducting quantum interference device; OPM optically-pumped magnetometer; NVD - nitrogen-vacancy center in diamond (including RF sensors below 10 um); BEC Bose-Einstein condensate; MEMF - magnetoelectric multiferroic; COPM - cold-atom OPM; EMR extraordinary magneto-resistance; YIG yttrium-aluminum-garnet; GRA - graphene, MFM - magnetic force microscope, PAFG - parallel gating fluxgate, WGM - whispering-gallery mode magnetostrictive. Green line shows an energy resolution per bandwidth of $\hbar$.

[1] M. W. Mitchell, "Number-Unconstrained Quantum Sensing" Quantum Science and Technology 2, 044005 (2017).

[2] M. W. Mitchell, "Sensor self-interaction, scale-invariant spin dynamics, and the $\hbar$ limit of magnetic field sensing" arXiv:1904.01528 (2019).

[3] M. W. Mitchell and S. Palacios "Quantum limits to the energy resolution of magnetic field sensors" arXiv:1905.00618 (2019).

Quantum logic spectroscopy and sensing with trapped ions

Piet O. Schmidt[1,2]

[1]*QUEST Institut, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*
[2]*Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany*

The exquisite control achieved over internal and external motional degrees of freedom in trapped and laser-cooled ions makes them ideal candidates for optical clocks and other precision measurements, such as electric and magnetic field sensors. I will provide an introduction into quantum logic techniques that enable this control and demonstrate several applications. In the first application, we use motional state engineering to measure forces from oscillating electric fields and the oscillation frequency of the ion in the trap with a sensitivity beyond the classical limit. Specifically, motional Fock states allow improved measurements of displacement and phase evolution using the same quantum mechanical resource [1].

In optical clocks, external electric and magnetic fields shift the resonance frequency and need to be carefully evaluated. In particular, when increasing the number of trapped ions in an optical clock to improve the signal-to-noise ratio, additional shifts arising from position-dependent oscillating electric fields and field gradients, lead to inhomogeneous broadening of the clock transition to several tens of Hertz. We employ dynamical decoupling techniques to suppress magnetic field shifts by six orders of magnitude with the potential to eliminate inhomogeneous broadening in large (tens to hundreds of ions) Coulomb crystals of Ca^+ ions to the Hertz level [2]. This may allow for a multi-ion frequency reference with low statistical uncertainty.

In the last example, a so-called logic ion is co-trapped with a spectroscopy ion to provide sympathetic cooling, state preparation and state readout using quantum logic operations. We use this quantum logic spectroscopy technique to perform the first high precision spectroscopy on a highly charged ion (HCI), specifically $^{40}Ar^{13+}$. Owing to their special electronic properties, HCI are sensitive probes for QED and dark matter [3]. At the same time they are much less sensitive to external electric fields, suggesting them as candidates for high-accuracy optical clocks to test fundamental physics [4].

References

[1] F. Wolf, C. Shi, J. C. Heip, M. Gessner, L. Pezzè, A. Smerzi, M. Schulte, K. Hammerer, and P. O. Schmidt, ArXiv:1807.01875 (2018).
[2] N. Aharon, N. Spethmann, I. D. Leroux, P. O. Schmidt, and A. Retzker, ArXiv:1811.06732 (2018).
[3] M. S. Safronova, D. Budker, D. DeMille, D. F. J. Kimball, A. Derevianko, and C. W. Clark, Rev. Mod. Phys. **90**, 025008 (2018).
[4] M. G. Kozlov, M. S. Safronova, J. R. Crespo López-Urrutia, and P. O. Schmidt, Rev. Mod. Phys. **90**, 045005 (2018).

SQUID systems for ultra-sensitive magnetometry

J.-H. Storm[1], O. Kieler[2], and R. Körber[1]

[1]Physikalisch-Technische Bundesanstalt, Berlin, Abbestrasse 2-12, 10587 Berlin
[2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig

More than fifty years after its invention in the 1960's, the low-T_c Superconducting QUantum Interference Device (SQUID) remains the most sensitive detector for magnetic flux and it has been used, amongst other, in fundamental science, material characterisation, metrology and biomagnetism. Apart from the exquisite sensitivity it also features an enormous bandwidth, for instance, in flux locked loop (FLL) mode bandwidths of 300 MHz have been demonstrated. Frequently, a current sensor configuration is used where a pick-up coil is inductively coupled to the current sensor SQUID via an on-chip input coil. Accordingly, the resolution depends on the flux noise $\sqrt{S_\Phi}$ and on the coupling coefficient k between input coil and SQUID with inductance L. A common figure of merit is the coupled energy resolution $\varepsilon_c = \varepsilon/k^2$, where $\varepsilon = S_\Phi/2L$ is the energy resolution of the uncoupled SQUID.

When used as a sensor of magnetic fields originating from macroscopic objects at room temperature operation in a non-magnetic, non-metallic liquid Helium (LHe) dewar is required. Here, the system noise is typically limited to the low fT $Hz^{-1/2}$-range due to thermal noise in the superinsulation and heat shields. However, LHe dewars with negligible noise have been constructed and our SQUID system with a 45 mm pick-up coil reaches a measured ε_c of <40 h corresponding to a white noise below 200 aT $Hz^{-1/2}$ with an FFL bandwidth of 2.5 MHz [1]. The system is also robust to pulsed magnetic fields up to 50 mT and mainly used for biomagnetic measurements.

An improvement in sensitivity can be achieved by cooling the SQUID to lower temperatures T, reducing the SQUID inductance L or decreasing the Josephson Junction (JJ) capacitance C. As a small L impedes the coupling to the SQUID, we focussed on reducing the size of the JJ from 2.5 µm to below 1 µm. For the evaluation of the Nb-AlOx-Nb process miniature SQUID magnetometers were fabricated. For a device with square junctions of 800 nm, the measured white flux noise was about 330 $n\Phi_0$ $Hz^{-1/2}$ corresponding to an ε of 5 h at 4.2 K. The noise increases at lower frequencies with a typical value of 900 $n\Phi_0$ $Hz^{-1/2}$ (ε ~40 h) at 1 Hz. For integrated current sensors with $k = 0.75$ the expected ε_c is 10 h at 4.2 K corresponding to an equivalent field noise of ~90 aT $Hz^{-1/2}$ for a 45 mm diameter 1st order gradiometric pick-up coil coupled to a 400 nH input coil.

The current sensor configuration allows flexibility in the pick-up coil design and enables the optimization for individual experiments e.g. in fundamental physics.

References

[1] J.-H. Storm, et al., Applied Physics Letters **110**, 072603 (2017)

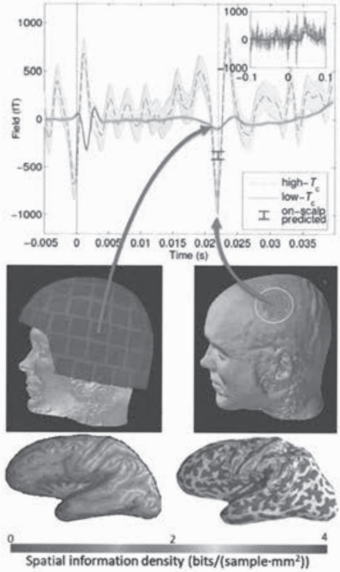
High-T_c SQUID based on-scalp MEG

C. Pfeiffer[1], S. Ruffieux[1], A. Kalaboukhov[1], L.M. Andersen[2], K. Westin[2,3], D. Lundqvist[2], D. Winkler[1], and J.F. Schneiderman[4]

[1]Chalmers University of Technology, Gothenburg, Sweden
[2]The Karolinska Insititute, Stockholm, Sweden
[3]Karolinska University Hospital, Stockholm, Sweden
[4]The University of Gothenburg, Gothenburg, Sweden

Accurate tracking of brain function in space and time with magnetoencephalography (MEG) has traditionally been performed with low critical-temperature superconducting quantum interference devices (low-T_c SQUIDs). While highly sensitive, the extreme cryogenic operating temperature of such SQUIDs necessitates rigid helmet dewars wherein the sensors are a few cm from the scalp surface. Our group is developing an approach for utilizing high-T_c SQUIDs for MEG because their less extreme operating temperature enables sampling at the scalp surface [1]. This is advantageous because improved proximity between the sensors and brain leads to stronger signal levels and higher spatial resolution. As such, we have shown how a full-head on-scalp MEG system can theoretically extract more information about brain activity—especially in children—than low-T_c SQUID-based systems despite the lower field sensitivity of high-T_c SQUIDs [2]. A newly developed seven-channel high-T_c SQUID based on-scalp MEG system reaches close scalp proximity and high sampling density. We have used it for a variety of neuroimaging investigations including somatosensory evoked fields, visual gamma-band neural oscillations, and epilepsy.

In this talk, I will provide an overview of our contributions to the field of on-scalp MEG. This includes theoretical motivation for this approach as well as experimental evidence for the advantages of on-scalp MEG via direct comparisons to a state-of-the-art (low-T_c SQUID-based) MEG system.



Experimental (top) and theoretical (bottom) demonstrations of the advantages of high-T_c SQUID-based on-scalp MEG (adapted from [2,3]).

References

[1] F. Öisjöen et al, *Applied Physics Letters* **100**(13), 132601 (2012)

[2] B. Riaz et al, *Scientific Reports* **7**(1), 6974 (2017)

[3] M. Xie et al, *IEEE Trans. on Biomed. Eng.* **64**(6), 1270-1276 (2016).

A wearable multi-channel OPM-MEG system with lifetime compliance

E. Boto[1], N. Holmes[1], J. Leggett[1], R.M. Hill[1], G. Roberts[1], T.M. Tierney[2], S. Mellor[2], V. Shah[3], G.R. Barnes[2], R. Bowtell[1] and M.J. Brookes[1]

[1]Sir Peter Mansfield Imaging Centre, School of Physics and Astronomy, University of Nottingham, UK
[2]Wellcome Centre for Human Neuroimaging, Institute of Neurology, University College London, UK
[3]QuSpin Inc., Louisville, CO, USA

Magnetoencephalography (MEG) is a non-invasive measure of brain function with high spatial and temporal resolution. Current devices based on a fixed array of superconducting quantum interference devices require participants to remain very still during measurements to avoid loss of data quality. This limits utility in some experimental cohorts that can be scanned, particularly children and adults with movement disorders, and the experimental questions that can be addressed.

Advances in quantum sensing has raised an interest in developing the next generation of MEG systems. Optically-pumped mangetometer (OPM) based MEG systems would allow for a more flexible, user-friendly, less restrictive and non-cryogenic brain imaging tool as well as potentially higher signal-to-noise (SNR) recordings [1,2].

We have developed a wearable MEG system [3] using QuSpin OPMs [4] which can be mounted on the scalp and if background fields are appropriately nulled [5], MEG data can be acquired even when individuals make natural head motions. This system provides a more comfortable experience than in traditional neuroimaging systems, like MRI. Using a generic, modified bike helmet that can securely house the sensors, we can perform MEG measurements in individuals across the lifespan: we demonstrate recordings in individuals as young as 3-years-old.

References

[1] E. Boto et al., PLoS One **11**(8):e0157655 (2016)
[2] Iivanainen et al., NeuroImage **147**, 542-553 (2017)
[3] E. Boto, N. Holmes, J. Leggett, G. Roberts et al., Nature **555**, 657-661 (2018)
[4] J. Osborne et al., Proc. SPIE **10548** (2018)
[5] N. Holmes, NeuroImage **181**, 760-774 (2018)

Abstracts of Posters

(in alphabetical order)

Graphene nanoribbons: potential 2D materials for sensing applications

Seyed Khalil Alavi[1,2], Boris V. Senkovskiy[3], Markus Pfeiffer[1], Danny Haberer[4], Felix R. Fischer[4,5,6], Alexander Grüneis[3], and Klas Lindfors[1]

[1] *Department of Chemistry, Universität zu Köln, Luxemburger Str. 116, 50939 Köln, Germany*

[2] *Institut für Angewandte Physik der Universität Bonn, Wegelerstr. 8, 53115, Bonn, Germany*

[3] *II. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany*

[4] *Department of Chemistry, University California, Berkeley, Tan Hall 680, Berkeley, CA 94720, USA*

[5] *Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

[6] *Kavli Energy NanoSciences Institute, University of California Berkeley, Berkeley, CA 94720, USA*

Graphene nanoribbons (GNRs) are novel 2D materials with interesting properties. Having a band gap, which can be tuned by the changing the width of the ribbon, makes them a promising candidate for a variety of optoelectronic applications. The sensitivity of their properties to environmental changes suggest the potential to use them in sensing applications on the molecular scale [1]. Our recent observation of single-emitter type of emission from GNRs at room temperature hints at the possibility to study and apply them even at the single ribbon level [2].

Here we present optical properties of 7-atom wide armchair-edge GNRs (7-AGNRs). We observe that 7-AGNRs have intrinsically low photoluminescence (PL) emission. However, GNRs can be rendered bright by inducing defects into their lattices. To induce the defects, we expose the ribbons to blue laser light for several minutes in ambient conditions [1]. We probe the modification of defects in emission by measuring the extinction for a single atomic layer of GNRs. Results suggest that defects boost PL emission in GNRs via suppressing quenching dark states that are energetically close to the bright emissive states [3].

As a first step towards applications of GNRs, we demonstrate a nanoscale photodetector based on GNRs. Due to its small size and low dark current, such detectors may in the future offer high-speed response and low power consumption with nanoscale dimensions.

References

[1] B. V. Senkovskiy, M. Pfeiffer, S. K. Alavi, *et al.*, Nano Letters **17**, 4029-4037 (2017).

[2] M. Pfeiffer, *et al.*, Nano Letters **18**, 7038-7044 (2018).

[3] S. K. Alavi, *et al.*, 2D Materials **6,** 035009 (2019).

Enhancement of the signal-to-noise ratio of an atomic magnetometer by 10 dB

Guzhi Bao [1], Shuhe Wu [1], Shuqi Liu [1], Wenfeng Huang [1], Ziran Li [1], L. Q. Chen [1], Chun-Hua Yuan [1], and Weiping Zhang [2,3]

[1]*State Key Laboratory of Precision Spectroscopy, Quantum Institute for Light and Atoms, Department of Physics, East China Normal University, Shanghai 200062, China.*

[2] *School of Physics and Astronomy, and Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China.*

[3] *Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, China.*

Nonlinear magneto-optical rotation (NMOR) is a sensitive technique for measuring magnetic fields [1]. The polarization self-rotation (PSR) effect is a fundamental source of excess quantum noise that limits the sensitivity of this technique [2]. In a typical polarimeter, the rotation angle is measured with the maximum signal, and the corresponding noise quadrature due to the PSR effect is not squeezed or anti-squeezed but always above the shot noise level. At a near-zero magnetic field, while change the quadrature phase the signal decreases with noise, thus making the signal-to-noise ratio (SNR) practically independent of quadrature phase in the experiment [3]. In this paper, we study the influence of the PSR effect on the signal-to-noise ratio (SNR) of an NMOR magnetometer in the Earth-field range and find that the SNR highly depends on the quadrature phase of light with a magneto-optical rotation. We introduce a phase shift before the polarimeter to improve the SNR by controlling the phase. The implementation of the phase shifter results in an improvement in the SNR up to 10 dB, achieving a best sensitivity of 8pT/√Hz with an ordinary cell (without a paraffin coating or buffer gas). Our research should be useful for high-sensitivity magnetic field measurements in a real geomagnetic environment.

References

[1] D. Budker, W. Gawlik, D. Kimball, S. Rochester, V. Yashchuk, and A. Weis, Reviews of modern physics. 74, 1153 (2002).

[2] E. E. Mikhailov and I. Novikova, Optics letters. 33, 1213 (2008).

[3] I. Novikova, E. E. Mikhailov, and Y. Xiao, Phys. Rev. A. 91, 051804 (2015).

Optically pumped magnetometers for material research applications

A. Blug[1] and A. Bertz[1]

[1]Fraunhofer Institute IPM, Freiburg, Germany

Optically pumped magnetometers (OPMs) offer a unique combination of high sensitivity, miniaturization and simplicity of operation paired with high sensitivity in the range of 15 fT/√Hz at room temperature [1]. These are good preconditions to expand state-of-the-art optical or magnetic methods in materials research towards smaller microstructural defect analysis. The QMAG project aims to build a first demonstrator for materials research applications using OPMs to detect and analyze material defects in the micrometer range as they are caused by hydrogen embrittlement in steel [2]. The sensor development and data evaluation will be accompanied by numerical solid mechanics simulation at the Materials Design department of Fraunhofer IWM [3].

.

References

[1] https://quspin.com/

[2] Di Stefano, D.; Nazarov, R.; Hickel, T.; Neugebauer, J.; Mrovec, M.; and Elsässer, C.: First-principles investigation of hydrogen interaction with TiC precipitates in α-Fe. PHYSICAL REVIEW B93, 184108 (2016).

[3] Fraunhofer Institute for Mechanics of Materials IWM, https://www.iwm.fraunhofer.de/en/services/materials-design.html

Wide field range studies of nuclear magnetic relaxation using optically pumped magnetometers

Sven Bodenstedt[1], **Michael C.D. Tayler**[1] **and Morgan Mitchell**[1]

[1]ICFO – The Institute of Photonic Sciences, The Barcelona Institute of Science and Technology, Castelldefels (Barcelona), Spain

Recently, spin-exchange relaxation free (SERF) alkali-vapor magnetometers have been applied as detectors of nuclear magnetic resonance (NMR) in the zero to ultralow field (ZULF) regime [1]. In ZULF the reduction of spectral line broadening due to field gradients as well as the possible existence of long-lived coherences [2] may lead to spectra with high resolution. These can provide new chemical and physics insight into the sample, beyond the capability of existing analytical techniques. In recent work the technique has been used to provide chemical-specific insight into liquid mixtures after being imbibing into porous catalytic materials [3].

In this presentation, we discuss new methodology that extends the scope of ZULF NMR to study multi-phase materials, including liquids in porous catalytic materials and metals. One aim is to measure ^1H NMR relaxation rates T_1 and T_2 at magnetic fields between a few nanotesla and several hundred microtesla, to interrogate slow dynamics associated with surface-site diffusion. These methods are applicable even to materials that cannot be studied with conventional magnetic resonance, including highly paramagnetic, disordered materials.

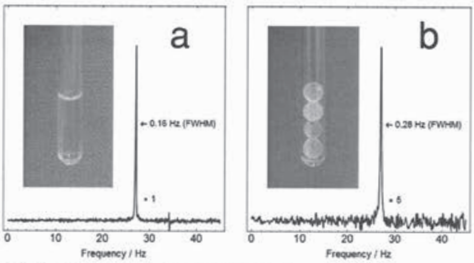


Fig.1. Detection of ^1H Larmor precession in bulk liquid (a) and porous silica (b). Both Fourier-transformed time-domain signals were measured with an optically pumped magnetometer. The low-field environment only leads to a slight increase in the resonance linewidth and allows detailed analysis of relaxation processes.

References

[1] M. C.D. Tayler, Review of Scientific Instruments **88**, 091101 (2017)

[2] M. Emondts, Physical Review Letters **112**, 077601 (2014)

[3] M. C.D. Tayler, Journal of Magnetic Resonance **297**, 1-8 (2018)

Poster: A proposed Interdisciplinary Approach to Advance Magnetomyography Techniques for Magnetic Field Recordings of Skeletal Muscles

Ruth Corkill[1], Prof. Oliver Röhrle[1] and Prof. Jörg Wrachtrup[2]

[1] *Institut für Modellierung und Simulation Biomechanischer Systeme, University of Stuttgart, Germany*

[2] *3. Physikalisches Institut, University of Stuttgart, Germany*

Recording and evaluating the electrical activity produced by skeletal muscles is an important medical diagnostic tool, which enables detailed studies of the neuromuscular system, and empowers many applications. For example, the rapidly developing field of neuroprosthetics depends on techniques that allow these electrical signals from the patient's body to be recorded, evaluated, and interpreted in a reliable way. However, existing measurement techniques face fundamental physical constraints and a radical new approach will be required to advance our capabilities.

Electromyography (EMG) techniques measure the electrical activity stemming from muscular contractions. Unfortunately, the fact that electrical signals decay as they propagate through biological tissue limits the accuracy of electrical-potential-based methods. In addition, standard EMG measurements on the skin record only a two-dimensional projection of the field. All current developments in the study of the neuromuscular system are based on improving the recording, evaluating and interpretation of EMG data, while virtually no work addresses the above-mentioned insurmountable physical limitations of EMG-based methods.

A fundamental paradigm shift in skeletal muscle studies is required to overcome hindrances of such a fundamental nature. We intend to initiate this shift by examining the potential of a new type of quantum magnetometer called the nitrogen vacancy (NV) centre. Our interdisciplinary approach will combine expertise in simulation technology, quantum physics and ethics to develop this project from proof of concept measurements through to device prototype testing.

Magnetic measurements offer significant advantages over EMG, including improved accuracy when estimating the location and magnitude of bioelectric sources. In particular, the 3D spatial resolution benefits from vector magnetometry, a technique in which more than one component of the magnetic field is measured, which allows the direction of the field to be determined. Biomagnetic field measurements have been made using technologies such as neuromagnetic current probes, Üptically Pumped Magnetometers (OPMs) or Superconducting Quantum Interference Device (SQUID) magnetometers. While these technologies have validated the concept of MMG and provided some interesting insights, they cannot compete with EMG across the large range of clinical settings that utilise EMG based techniques.

NV centre magnetometry has already demonstrated single-neuron sensitivity and intact organism applicability in close proximity to biological samples. Unlike many quantum sensing systems, the NV centre has demonstrated sustained fluorescence, long coherence times and is able to operate under ambient conditions. As a vector magnetometer, the NV system can provide three-dimensional magnetic field data. The NV centre's sensitivity, nanoscale resolution, and demonstrated biocompatibility means that it is ideally suited to applications in biological nanoscale sensing and imaging.

We expect that as NV magnetometer technology continues to improve over the next few years that it will be possible to measure the magnetic fields generated by neuromuscular recruitment in human subjects outside of a laboratory setting, and that these fields can be analysed in a similar way as for surface high density EMG. The key to success is the fact that human tissues do not attenuate magnetic fields. Hence, we can expect high quality signals from deep within the muscle – something not possible with EMG. Studies utilising this new technology will have an unprecedentedly detailed information, enabling researchers to pursue novel methodologies with the potential to revolutionise our understanding of the neuromuscular system.

Perspectives of nanodiamonds with color centers for bio applications

A. Ermakova[1], S. Harvey[1], M. Raabe[1] and T.Weil[1]

[1]*Max-Planck Institute for Polymer Research, Mainz, Germany*

Nanodiamonds with color centers are promising material for in vivo applications [1]. Especially, nanocrystals with Nitrogen-Vacancy (NV) defects can be used not only as optical markers but also like nanosized sensors of magnetic and electrical fields and temperature with high sensitivity [2]. Surface functionalization plays important role for nanodiamonds. First of all it defines hydrodynamic properties of nanocrystals, which are crucial for in vivo applications. Second, charge localized at the surface affects charge state of NV defects and as the result color centers can be active or inactive (efficient or inefficient) for all kind of sensing. In current work we discuss surface functionalization of nanodiamonds for magnetic sensing and other medically related applications.

References

[1] K. Turcheniuk et al, Nanotechnology **28**, 252001 (2017)
[2] R. Schirhagl et al, Annu.Rev.Phys.Chem. **65**, 83-105 (2014)

High-T_c SQUIDs for different applications

M. I. Faley

Peter Grünberg Institute 5, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

We have developed high-T_c dc SQUIDs for various applications from SQUID microscopy to biomagnetometry and geophysics. The SQUIDs demonstrate magnetic field resolution down to approximately 2 fT/√Hz at 77 K [1]. High-T_c SQUID microscope with ferromagnetic flux antenna was used for non-destructive evaluation of miniature room-temperature objects with positional resolution better than 1 µm over a scan range of more than 15 cm [2]. MCG and MEG measurements with 16-mm high-T_c SQUID magnetometers demonstrated sufficient signal-to-noise ratio for medical diagnostics and research [3] (see Fig.1). An 8-element tensor array made from 8-mm high-T_c SQUID magnetometers was implemented in an airborne system for magnetic anomaly detection [4]. The developed high-T_c superconductor technology was recently used for preparation of π-loops for their study by a SQUID microscope [5].

References

[1] M. I. Faley et al., *IEEE TAS* **28**, 1600505 (2018)
[2] M. I. Faley et al., *IEEE TAS* **27**, 1600905 (2017)
[3] M. I. Faley et al., *SuST* **30**, 083001 (2017)
[4] R. L. Fagaly, *Rev.Sci.Instrum.* **77**, 101101 (2006)
[5] M. I. Faley et al., *IEEE TAS* **29**, 1100405 (2019)

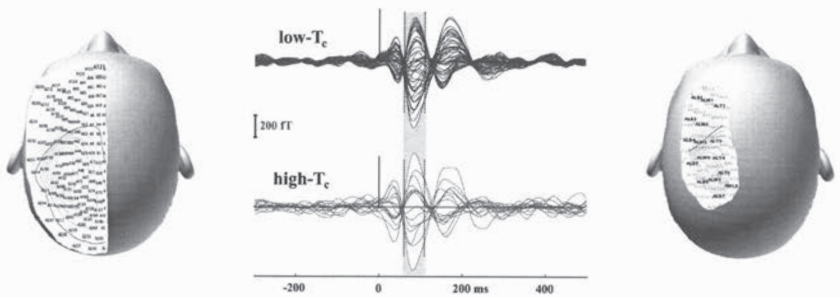


Fig. 1: Comparison of auditory evoked MEG averaged signals acquired at a similar location over the left hemisphere using low-T_c (50 positions, blue, upper curve) and high-T_c (16 positions, red, lower curves) SQUID systems [3].

An optically pumped magnetometer for counting magnetotactic bacteria

T. Fremberg, V. Schultze, F. Wittkämper, M. Kielpinski, T. Henkel, and R. Stolz

Leibniz Institute of Photonic Technology, P.O. Box 100239, D-07702 Jena, Germany

Magnetotactic bacteria (MTB) are aquatic bacteria with the ability to grow single domain magnets, so called magnetosomes. They contribute significantly to the micro-biotic biomass of our planet and are involved in environmental cycles of iron, sulfur, nitrogen and carbon [1]. After their death, the MTB remain magnetic, so their remainders can be used as markers for paleomagnetics and archaeology. In order to gain more information about their abundance and distribution on planet Earth, we want to examine water samples via automated single detection of MTB by means of microfluidics and optically pumped magnetometers (OPM).
The very small magnetic moment of the bacteria (10^{-15} Am^2) leads to challenging demands on our OPM, such as high sensitivity, small volume, and close proximity to the measurement object.
We present parameter studies of cell geometry as well as of a pump-probe scheme, in order to gain the best suited OPM for the goal of detecting single MTB.

References

[1] Araujo et al., Mar. Drugs **13**, 389-430 (2015)

Accurate magnetometry for nEDM (neutron Electrical Dipole Moment) searches

Z.D. Grujić[1]

[1]*Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia*

In last decades, FRAP (Fribourg Atomic Physics) has developed two generations of high sensitivity Cs (cesium) magnetometers to be used on the experiment with a goal to measure the nEDM - neutron Electric Dipole Moment [1]. At the end of its existence, the FRAP group was working on the third generation of Cs magnetometers with focus on accuracy of the magnetic field B_0 estimation, rather than on the sensitivity, in agreement with the nEDM experiment [1] requirements. Understanding and control of systematic effects for the nEDM experiment is crucial. So called false nEDM could be caused by a gradient of the magnetic field B_0 inside of the neutron precession volume due gravitational center-of-mass separation of cold neutrons and hot Hg co-magnetometer gas. The gradient was estimated by array of 16 Cs magnetometers placed in three planes above and below the neutron precession volume. But use of so called Mx PLL-locked magnetometers, does not warrant accurate estimation of the absolute B_0 value, as every magnetometer has its own readout offset due PLL (Phase Sensitive Loop) initial work point settings [2]. For example, if the work point of the PLL phase is set with error of 500 μrad the resulting offset will be 1 pT. Moreover, spin precession in the Mx magnetometer is driven by weak rf magnetic field at Larmor frequency. This leads to crosstalk between neighboring magnetometers affecting their performance even more.

To overcome these limitations in the next generation of the nEDM experiment, that is currently built in the PSI (Paul Scherrer Institute, Switzerland), FRAP group started development of the FSP (Free Spin Precession) [3]. The findings were promising until a heading error, of to our best knowledge unknown physical origin, was discovered. In collaboration with team of Prof. N. Severjins from Leuven Belgium, this effect was confirmed and measured in case of FAP (Free Alignment Precession). In case of FAP the heading error was still present but smaller making it best up to now candidate for use in the new nEDM experiment. Advantages of FSP and FAP is in fact that this are all-optical magnetometers where rf driving field and its influence on the environment is absent, plus there is no work point to be set - atoms perform free precession in the B_0 field.

References

[1] J. M. Pendlebury, et al., Phys. Rev D **92**, 092003 (2015).

[2] A. Weis, G. Bison, Z. Grujic, ′ "Magnetic Resonance Based Atomic Magnetometers", in "High Sensitivity Magnetometers", Springer, Berlin, (2017)

[3] Z.D. Grujic, P.A. Koss, G. Bison, A. Weis, Eur. Phys. J. D **69**, 135 (2015)

SQUID based ultra-low field NMR spectroscopy and relaxometry

S. Hartwig, H.-H. Albrecht and L. Trahms

Physikalisch Technische Bundesanstalt, Berlin, Germany

NMR measurements at ultra-low magnetic fields (ULF-NMR) are usually characterized by very low field gradients opening the way towards a direct measurement of T2 relaxation time. We will demonstrate this by measurements with our improved ULF-NMR setup, in which the magnetic sensor as well as the detection field generation have been optimized. Now we obtain a system noise level of about 800 $aT/Hz^{1/2}$ at 1 kHz. The good matching of T2* with the T1 relaxation time of benzene at magnetic fields below 7 µT demonstrates a negligible contribution of the field inhomogeneity on the T2 relaxation time. This enables the direct determination of the T2 relaxation time with only a small systematic deviation. Further we show investigations of T1 dispersion of copper sulfate-water solutions over a field range from 25 nT to 7 mT, demonstrating the setup's outstanding measurement range across seven orders of magnitude.

Cancellation of the Earth Rotation Frequency Offset in Co-Magnetometry due to B-field Reversal

S. Haude, S. Knappe-Grüneberg and L. Trahms

Physikalisch-Technische Bundesanstalt, Berlin, Germany

Earthbound laboratories are not inertial systems due to the earth's rotation. For this reason, the precession frequency of nuclear magnetic moments in earthbound magnetic fields is shifted with respect to the Larmor frequency in an inertial system. The shift depends on the cosine of the angle between the earth's axis and the applied magnetic field. This effect is of the order of a few microhertz and cannot be neglected in high-precision spin precession measurements where frequency deviations in the nanohertz level become meaningful.

This effect is also present in co-magnetometry data, where the weighted frequency difference of two noble gas nuclei is studied. Here, we evaluate the impact of a deflection of the B-field on the co-magnetometer frequency for the field vector pointing in two opposite directions. We show that the major part of this effect can be canceled by a B-field reversal. This result is meaningful for many fundamental studies, such as, e.g., the reduction of systematic errors in co-magnetometer studies on the ^{129}XeEDM.

A multi-channel OPM-MEG system: from construction to application

Niall Holmes[1], Elena Boto[1], James Leggett[1], Ryan M Hill[1], Gillian Roberts[1], Tim M Tierney[2], Stephanie Mellor[3], Vishal Shah[3], Gareth R Barnes[2], Richard Bowtell[1] and Matthew J Brookes[1]

[1] Sir Peter Masfield Imaging Centre, School of Physics and Astronomy, University of Nottingham, NG7 2RD, UK

[2] Wellcome Centre for Human Neuroimaging, Institute of Neurology, University College London, WC1N 3AR, UK

[3] QuSpin Inc., 331 South 104th Street, Suite 130, CO 80027, USA

Magnetoencephalography (MEG) is a non-invasive measure of brain function with high spatial and temporal resolution. Current devices use superconducting quantum interference devices (SQUIDs) which require subjects to remain still inside a fixed sensor array. This restricts the subject groups which can be studied (a child's head will be far from the sensor array resulting in weak signals, patients with disorders such as Tourette's syndrome will be unable to remain still during a scan) and neuroscientific questions which can be addressed (experiments involving social interactions and spatial navigation are difficult to perform).

Recently we have developed a wearable MEG system using QuSpin optically pumped magnetometers (OPMs) [1, 2]. High-quality data can be collected with participants free to make natural head motions, providing a more comfortable experience than in traditional neuroimaging systems (e.g. MRI).

Using our system we have measured brain activity arising from natural tasks. These include bouncing a ping-pong ball on a bat [1]; measurements in children as young as 3 years old; language lateralisation measurements to aid pre-surgical planning [3]; experiments using an Occulus Rift virtual reality headset to provide an immersive and realistic environment [4]; investigations of motor learning and measurements of deep brain structures such as the cerebellum [5]. Here, we present the development of the system and outline key results.

References

[1] E. Boto, N. Holmes, J. Leggett, G. Roberts et al., Nature **555**, 657-661 (2018)

[2] J. Osborne et al., Proc. SPIE **10548** (2018)

[3] T. Tierney et al., Neuroimage **181**, 513-520 (2018)

[4] G. Roberts et al.,Neuroimage **199**, 408-417 (2019)

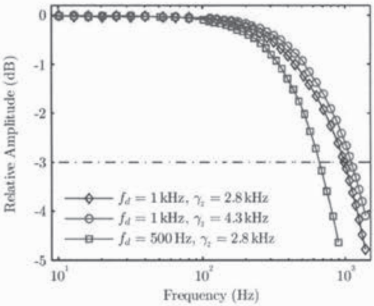
[5] C. Lin et al., The Journal of Physiology, Accepted Article (2019)

Waveform Reconstruction with a Cs Based Free-Induction-Decay Magnetometer

D. Hunter[1], **R. Jiménez-Martínez**[2], **J. Herbsommer**[3], **S. Ramaswamy**[3], **W. Li**[3], **and E. Riis**[1]

[1]University of Strathclyde, Glasgow, UK
[2]ICFO−Institut de Ciencies Fotoniques, Barcelona, Spain
[3]Texas Instruments Incorporated, Dallas, USA

We report the frequency response behaviour of an optically pumped magnetometer (OPM) based on a MEMS Cs cell, using the free-induction-decay (FID) technique[1]. The sensor bandwidth is characterised by observing how the system reacts to various stimuli; primarily dictated by spin relaxation comprising of numerous contributions that are intrinsic to the vapour cell, and induced externally through operational factors such as magnetic gradients and optical power broadening. Additionally, the Nyquist frequency determines the sampling bandwidth for the FID implementation[2]. The pump-probe repetition rate and vapour cell temperature are adjusted to investigate the impact these mechanisms impose on the sensor's frequency response.



Frequency response curves for different relaxation rates γ_2, and pump-probe repetition rates f_d. The test signal amplitude was set to 7 nT. Signals above the Nyquist frequency are folded into the detectable bandwidth through aliasing.

Frequency modulation sidebands present in the FID spectrum at high modulation depths are modelled using Bessel functions of the first kind. The ensuing distorted magnetic resonance lineshapes increase the complexity of the readout process, thus precedent is placed on understanding the nature of these signals in attempt to ensure an accurate sensor output.
The design simplicity, scalability, and all-optical nature of this OPM is attractive for numerous applications, including MCG that requires a flat response in the low frequency range. It also benefits from minimal cross-talk, which is essential in applications that demand magnetic source localisation with sensor networks.

References

[1] D. Hunter, R. Jiménez-Martínez, J. Herbsommer, S. Ramaswamy, W. Li, and E. Riis, Opt. Express **26**, no. 23, 30523-30531 (2018).

[2] D. Hunter, S. Piccolomo, J. D. Pritchard, N. L. Brockie, T. E. Dyer, and E. Riis, Phys. Rev. Appl. **10**, 014002 (2018).

Active shielding system for multichannel OPM arrays

Joonas Iivanainen[1], Rasmus Zetter[1], Mikael Grön[1], Karoliina Hakkarainen[1] and Lauri Parkkonen[1,2]

[1]*Department of Neuroscience and Biomedical Engineering, Aalto University, Espoo, Finland*
[2]*Aalto Neuroimaging, Aalto University, Espoo, Finland*

We have developed an active shielding system that can be used to shield multichannel OPM arrays from ambient magnetic noise [1]. Specifically, the system was designed to provide additional low-frequency shielding for OPM-based MEG (magnetoencephalography) arrays acting inside magnetically shielded rooms (MSRs).

The system comprises three homogeneous and five gradient coils which provide field homogeneity and linearity of roughly 5% in a (20-cm)^3 volume. The system uses same sensors for measuring the brain and shielding. The shielding algorithm is based on inversion of coupling matrix that describes the fields that the coils produce to the sensor array. The algorithm is automated and can be run with flexible sensor configuration. For dynamic zeroing, the system employs high bandwidth negative feedback (10 kHz) implemented with digital PI controllers. The feedback loops include low-pass filters so that the signal of interest and field drifts can be separated at sensor level.

Shielding provided by the system enabled the sensitive operation of commercial OPMs (QuSpin Inc.) in a two-layer MSR by reducing the remanent DC field from 70 to <1 nT. The dynamic compensation kept the sensors in their dynamic range and reduced OPM calibration drift due to ambient field drift. Low-frequency shielding factors of 43 and 22 dB were achieved without and with (<4 Hz) band-limiting the compensation.

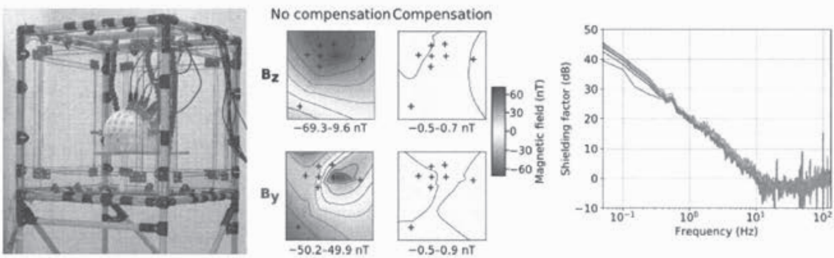


Fig. 1. Left: Picture of the system. Center: DC compensation of two field components in an array of eight OPMs. Right: Shielding factor for eight OPMs. [1]

References

[1] J. Iivanainen, NeuroImage **194**, 244 (2019)

Field demonstrations of double-resonance magnetometry

S. J. Ingleby[1], C. O'Dwyer[1], I. C. Chalmers[1], T. Dyer[1], P. F. Griffin[1] and E. Riis[1]

[1]Department of Physics, SUPA, University of Strathclyde, 107 Rottenrow East, Glasgow

Wide dynamic range and kHz+ bandwidth make double-resonance OPMs an attractive technology for unshielded measurements, where pT-range sensitivity is highly competitive with existing sensor types. Double-resonance OPMs in compact packages offer precise measurement in numerous applications where inductive magnetometers are currently commonplace [1,2].

The development of laboratory double-resonance OPMs [3,4] into portable systems for collaborative field trials in defence and geophysics applications is discussed. Details of sub-component design and characterisation, including microfabricated alkali vapour cells, compact laser drivers and embedded signal processing, are presented, along with the results and discussion of portable system performance.

This work is supported by the EPSRC Quantum Technology Hub in Sensors and Metrology and Innovate UK.

References

[1] J. W. Mooney, S. Ghasemi-Roudsari, E. Reade Banham, C. Symonds, N. Pawlowski and B. T. H. Varcoe, Biomed. Phys. Eng. Express **3** 015008 (2017)

[2] C. D. Beggan and M. Musur, J. Geophys. Res: Space Physics, **123**, 4202–4214 (2018)

[3] S. J. Ingleby, C. O'Dwyer, P. F. Griffin, A. S. Arnold, and E. Riis, Phys. Rev. Applied **10**, 034035 (2018)

[4] S. J. Ingleby, C. O'Dwyer, P. F. Griffin, A. S. Arnold, and E. Riis, Phys. Rev. A **96**, 013429 (2017)

Nuclear magnetic resonance spectroscopy on a diamond chip

A. Jarmola[1,2]

[1]Department of Physics, University of California, Berkeley, 94720 CA, USA
[2]ODMR Technologies Inc., El Cerrito, 94530 CA, USA

Nuclear magnetic resonance (NMR) is a powerful technique for determining the composition, structure, and function of a variety of molecules, but the sensitivity is presently limited for sub-nanoliter volumes. An emerging alternative approach is to replace inductive coils with non-inductive magnetometers based on Nitrogen Vacancy (NV) centers in diamond. In a first step, we used few-nm thick layers of NV centers doped into high-surface area nanostructured diamond to perform diamond NMR spectroscopy on ~1 pL of analyte [1]. I will present our recent work [2] to improve the sensitivity and spectral resolution of diamond NMR by separating the polarization and detection steps. Analyte is prepolarized in a larger magnetic field (1.5 T) and then adiabatically flowed to a microfluidic diamond NMR detector at 14 mT. Separating the polarization and detection enabled an order-of-magnitude improvement in spectral resolution (0.65 Hz) over previous diamond NMR studies. We used the platform to perform two-dimensional NMR on fluid analytes and observed the transfer of magnetization mediated by heteronuclear *J*-coupling.

References

[1] P. Kehayias, A. Jarmola, N. Mosavian, I. Fescenko, F. M. Benito, A. Laraoui, J. Smits, L. Bougas, D. Budker, A. Neumann, S. R. J. Brueck, V. M. Acosta, Nature Communications **8**, 188 (2017)

[2] J. Smits, J. Damron, P. Kehayias, A. F. McDowell, N. Mosavian, I. Fescenko, N. Ristoff, A. Laraoui, A. Jarmola, V. M. Acosta, arXiv:1901.02952 (2019)

OPM magnetorelaxometry in the presence of a DC bias field

A. Jaufenthaler[1], T. Scholtes[2], G. Oelsner[2], V. Schultze[2], R. Stolz[2] and D. Baumgarten[1]

[1]Private University for Health Sciences, Medical Informatics and Technology, Hall in Tirol, Austria
[2]Leibniz Institute of Photonic Technology, Jena, Germany

Magnetic nanoparticles (MNP) offer a large variety of promising applications in medicine, for which it is crucial to quantify the amount of MNP and to detect their binding state. This information can be gathered by magnetorelaxometry (MRX), where the response of the magnetization of the MNP to sudden changes of an external magnetic field is measured. It has been shown before, that optically pumped magnetometers (OPM) may be used in MRX [1,2]. Our intensity modulated OPM [3] may be operated in earth's magnetic field, potentially allowing OPM-MRX in an unshielded environment. Before analyzing unshielded measurements, it is fundamental to investigate the influence of DC bias magnetic fields on MNP relaxation curves experimentally, which to our knowledge has only been investigated before theoretically [4]. Thus, we show that OPM-MRX can be performed in the presence of DC bias magnetic fields with an intensity modulated OPM. Further, we show and discuss how DC bias magnetic fields (parallel or perpendicular to the excitation field) influence the relaxation process of MNP, especially the relaxation time constant.

References

[1] V. Dolgovskiy, Journal of Magnetism and Magnetic Materials, **379**, 137 (2015)
[2] O. Baffa, Journal of Magnetism and Magnetic Materials **475**, 533 (2019)
[3] V. Schultze, Optics Express **20**, 14201 (2012)
[4] V Rusakov, Sensors **18**, 1661 (2018)

An optogalvanic flux sensor for trace gases

Patrick Kaspar[1], Johannes Schmidt[1,2,4], Fabian Munkes[1,4], Denis Djekic[3,4], Daniel Krüger[3,4], Patrick Schalberger[2,4], Holger Baur[2,4], Robert Löw[1,4], Tilman Pfau[1,4], Jens Anders[3,4], Norbert Frühauf[2,4], Edward Grant[5], and Harald Kübler[1,4]

[1] *5th Institute of Physics, Stuttgart, Germany*
[2] *Institute of Large Area Microelectronics, Stuttgart, Germany*
[3] *Institute of Smart Sensors, Stuttgart, Germany*
[4] *University of Stuttgart, Center for Integrated Quantum Science and Technology (IQST), Stuttgart, Germany*
[5] *Department of Chemistry, University of British Columbia, Vancouver, Canada*

We demonstrate the applicability of a new kind of gas sensor based on Rydberg excitations. From a gas mixture the molecule in question is excited to a Rydberg state, by succeeding collisions with all other gas components this molecule gets ionized and the emerging electron and ion can then be measured as a current, which is the clear signature of the presence of this particular molecule. As a first test we excite Alkali Rydberg atoms in an electrically contacted vapor cell [1,2] and demonstrate a detection limit of 100 ppb to a background of N_2. For a real life application, we employ our gas sensing scheme to the detection of nitric oxide at thermal temperatures and atmospheric pressure [3]. We are planning to reduce the detection limit to 1 ppb using state of the art cw lasers for the Rydberg excitation of NO.

References

[1] D. Barredo, et. al., Phys. Rev. Lett. **110**, 123002 (2013)
[2] J. Schmidt, et. al., **SPIE** 10674 (2018)
[3] J. Schmidt, et. al., Appl. Phys. Lett. **113**, 011113 (2018)

Probing phase transitions in a soft matter system using defects in diamond

V. K. Kavatamane[1], D. Duan[1], S. R. Arumugam[1], N. Raatz[2], S. Pezzagna[2], J. Meijer[2] and G. Balasubramanian[1]

[1]MPRG-Nanoscale Spin Imaging, Max Planck Institute for Biophysical Chemistry, Am Fassberg 11, 37077, Göttingen, Germany

[2]Felix Bloch Institute for Solid State Physics, University of Leipzig, Linnéstraße 5, 04103 Leipzig, Germany

Soft matter systems encompass several areas including polymers, liquid crystals, gels, emulsions, colloids, surfactant assemblies, granular and many biological materials. In general, phase transitions of matter reveal some of the interesting phenomena at the level of individual entities that make up these systems. Understanding the nanoscopic origins of bulk phase transitions in the ordered soft matter has a profound impact on fundamental science and modern technologies. Typical energy scales equal to room temperatures energies (~25 meV) in these systems allows one to observe important structural dynamics at ambient conditions. Conventional nuclear magnetic resonance (NMR) measurement provides a non-invasive tool in studying such properties. However, its extension to the nanoscale is hindered due to the large number (10^{12}) of spins required to produce sufficient signal-to-noise ratio. Nitrogen-Vacancy (NV) centers in diamond have now been shown to be potential quantum sensors capable of performing nanoscale-NMR with ~10^3 spins at ambient conditions. Here, we employ such a sensing method to obtain information about controlled phase changes in a standard soft matter material as a function of temperature. Individual NV centers at a few nm depths are used as a probe to study a few molecular layers of sample on the surface of the diamond. The organization and collective dynamics of sample molecules in nanoscopic volumes are discussed. Our study aims to extend the areas of application of quantum sensing using NV centers to probe the soft matter systems, particularly those exhibiting mesophases and interesting interfacial properties.

References

[1] V. K. Kavatamane, D. Duan, S. R. Arumugam, N. Raatz, S. Pezzagna, J. Meijer and G. Balasubramanian, Probing phase transitions in a soft matter system using a single spin quantum sensor. (under journal review)

Vector magnetometry with atomic vapor self-calibrated with microwave polarization

C. Kiehl[1], T. Thiele[1], D. Wagner[1], T.-W. Hsu[1], M. O. Brown[1], S. Knappe[2], C. A. Regal[1]

[1] *JILA, National Institute of Standards and Technology and University of Colorado, and Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[2] *Department of Mechanical Engineering, University of Colorado, Boulder, CO 80309 USA*

Many of the applications of sensitive magnetometers, ranging from precision measurements, dark matter searches and timekeeping to biological imaging, navigation and exploration, can benefit from full vector detection. Several options have been explored to extend atomic magnetometers based on hot vapor cells, which are the most sensitive scalar magnetometers, to the vector domain. These sensors, however, are limited by the lack of a stable and precise reference to calibrate drifts in relative axes orientation that are often defined by bias coil or beam progation directions.

By exploiting the 3D structure of a microwave field as a stable reference, we will show our path to accurate vector measurements from a proof-of-concept experiment with optically trapped atoms [1] to a sensitive sensor using a hot-vapor cell.

In our technique, we first map the full polarization ellipse of a microwave field from the Rabi oscillations observed between hyperfine magnetic sublevels driven with different microwave polarization components. Importantly, we show that all relevant systematics in the direction of an applied bias field, for example non-orthogonal coil orientations, can be (self-)calibrated based on the fundamental atomic response and electro-magnetic field structure. With the ellipse acting as a calibrated reference, we can then determine the direction of an unknown magnetic field. In combination with one's favorite method for determining the scalar magnetic field, we explore using this technique to achieve full, self-calibrated vector magnetometry with atoms.

References

[1] T. Thiele, Y. Lin, M. O. Brown, and C. A. Regal, Phys. Rev. Lett. **121** 153202 (2018)

Side Band Detection of $^3He/^{129}Xe$ Nuclear Spin Precession for Dark Matter Sensing

S. Knappe-Grüneberg, W. Kilian, H.-H. Albrecht, D. Stollfuß, J. Voigt, S. Haude, I. Fan and L. Trahms

Physikalisch-Technische Bundesanstalt (PTB), Abbestr.2-12, 10587 Berlin, Germany

The postulation of dark matter born from the mismatch between potential and kinetic energy determined from inter- and intra-galactic velocity measurements lead to various theoretical models with the postulation of axions in high favor. These hypothetical ultra-light particles not only would solve the strong CP problem in QCD but also should lead to an additional spin interaction alike a classical oscillating magnetic field does. Several experimental approaches (CASPER [1], ARIADNE [2]) try to probe this effect in the way as a classical B_1-field acts in NMR on spins. We propose another technique being sensitive to very low modulation frequencies which we name **S**ideband **I**n **L**armor **F**requency **I**nduced by **A**xions (SILFIA) and try to give its sensitivity limits. We plan to implement this technique to probe for light axions in the mass range of 10^{-19} to 10^{-13} eV applying our measurements of hyperpolarized ^3He or ^{129}Xe nuclear spin precession within the shielded room BMSR-2 at the PTB.

[1] A. Garcon et al., Quantum Sci. Technol., **3** (2017) 14008,

[2] A. Arvanitaki and A. A. Geraci, Physical Review Letters, **113** (2014) 161801

Towards quantum enhanced sensing in SERF-regime ensembles

Jia Kong[1], Ricardo Jiménez-Martínez[1], Charikleia Troullinou[1], Vito Giovanni Lucivero[2], Géza Tóth[3,4], and Morgan W. Mitchell[1,5]

[1] ICFO–Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain

[2] Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

[3] Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain

[4] IKERBASQUE, Basque Foundation for Science, E-48011 Bilbao, Spain

[5] ICREA – Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain

Quantum enhanced sensing is often pursued using low-entropy methods, while there are important sensing technologies that operate in a high-entropy environment. Specifically, vapor-phase spin-exchange-relaxation-free (SERF) techniques are used for magnetometry, and give unprecedented sensitivity [1]. Here we study the nature of spin entanglement in this hot, strongly-interacting atomic medium, using techniques of direct relevance to extreme sensing. We produce and detect 1.9 dB spin squeezing, and at least 1.5×10^{13} of the 5.3×10^{13} measured atoms form singlets with entanglement bonds extending thousands of times the nearest-neighbor distance. The results show that the SERF-regime media can operate beyond the standard quantum limit.

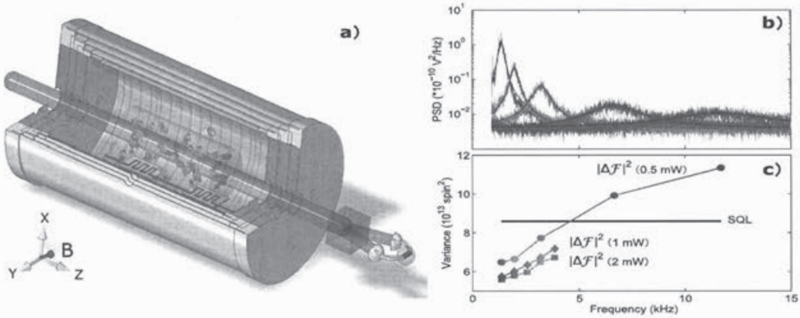


Figure 1: Experimental Principle. **a)** Experimental setup. A vapor of ^{87}Rb contained in a glass cell with buffer gas to slow diffusion, which is housed in magnetic shielding and field coils to control the magnetic environment, and the magnetic field is applied along the [1, 1, 1] direction. **b)** Spin noise spectra [2] with different bias field strengths characterizes the vapor enters the so-called spin-exchange-relaxation-free (SERF) regime. The density is maintained at $n_{Rb} = 3.6 \times 10^{14}$ atoms/cm^3. **c)** The total spin variance $|\Delta\mathcal{F}|^2$ including a transition to squeezed/entangled states as the system enters the SERF regime. The total spin variance is estimated by Kalman filter (KF) technique [3], and compared against spin squeezing inequalities [4] to detect and quantify entanglement. Black solid-line shows the standard quantum limit (SQL). Round, diamonds and squares symbols show $|\Delta\mathcal{F}|^2$ measured with 0.5 mW, 1 mW and 2 mW probe light, respectively.

References

[1] I. Kominis, T. Kornack, J. Allred, M. Romalis, *Nature* **422**, 596 (2003).

[2] V. G. Lucivero, R. Jiménez-Martínez, J. Kong, M. W. Mitchell, *Phys. Rev. A* **93**, 053802 (2016).

[3] R. Jiménez-Martínez, *et al.*, *Phys Rev Lett* **120**, 040503 (2018).

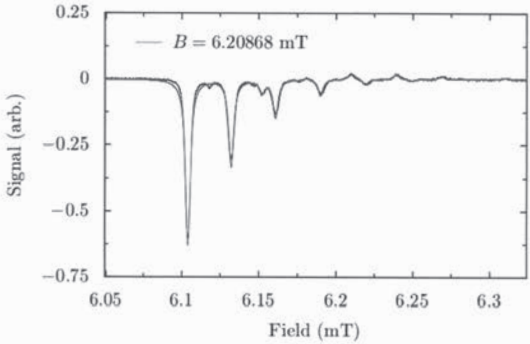
[4] G. Vitagliano, P. Hyllus, I. L. Egusquiza, G. Tóth, *Phys. Rev. Lett.* **107**, 240502 (2011).

A Simple 100 G Reference Magnetometer

D. Newby, M Limes, E Foley, and T. Kornack[1]

[1]*Twinleaf, Plainsboro, NJ USA*

We report on the development of a simple, high accuracy magnetometer designed for use in the range 10-100 G. This fills a need for measurements above typical total field optical magnetometers and below typical NMR probes. The sensor acquires a resonance frequency spectrum with the nonlinear Zeeman structure fully resolved. The field value is obtained by analyzing the spectrum using the Breit-Rabi formula. The sensor is highly integrated and uses low cost, microfabricated components.



Optically pumped magnetometers for industrial applications

P. A. Koss[1] **and F. Kühnemann**[1]

[1]*Fraunhofer Institute IPM, Freiburg, Germany*

Optically pumped magnetometers (OPMs) offer a unique combination of high sensitivity, miniaturization and simplicity of operation. This combination makes OPMs an interesting candidate for wider industrial application. The first commercial laser pumped OPMs have appeared a few years ago. These sensors yield a sub 15 fT/√Hz sensitivity without the need for cryogenic temperatures like SQUID sensors [1]. We propose to use these solutions and build custom systems in the industrial areas of process analytics and material research. There we will exploit the high sensitivity of OPMs and combine them with methods like NMR [2]. Thus, low field NMR could be used for multiphase flow metering where OPMs measure an NMR signal in a pipe flow setup [3].

References

[1] https://quspin.com/

[2] Savukov, I. M., and Michael V. Romalis. "NMR detection with an atomic magnetometer." *Physical review letters* 94.12 (2005): 123001.

[3] Bilgic, A. M., et al. "B6. 2-Multiphase flow metering with nuclear magnetic resonance spectroscopy." *Proceedings SENSOR 2015* (2015): 292-297.

SiCMAG - the Silicon Carbide Solid State Quantum Magnetometer

H. Kraus[1], J. Ashton[1,2], I. Cisneros[1], K. Wang[1], D. Spry[3], P. Neudeck[3], S.-I. Sato[4], Y. Yamazaki[4] T. Ohshima[4], C. Cochrane[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[2]Pennsylvania State University, University Park, PA, USA
[3]NASA Glenn Research Center, Cleveland, OH, USA
[4]National Institutes of Quantum and Radiation Science and Technology, Takasaki, Gunma, Japan

Magnetometry has a lot of tradition in space and planetary science. Most scientific exploration missions have the telltale magnetometer boom; one of the more prominent recognizable features of an exploration spacecraft. These nowadays carry the spaceflight state-of-the-art fluxgate and vector helium magnetometers. These well-tried systems have excellent sensitivities in the range of 100pT/√Hz, but are intrinsically complex, requiring non-miniaturizable parts and electronics (fluxgate), or cryogenics and lasers (optically pumped atomic gas). We propose a new approach for a self-calibrating solid-state vector magnetometer, relying on spin-carrying quantum centers in silicon carbide semiconductor devices. We show a proof-of-concept miniature magnetometer leveraging off-the-shelf devices, reaching a sensitivity on the order of 100nT/√Hz. We discuss the potential increase of sensitivity by leveraging home-grown devices made by NASA Glenn Research Center, with fresh-from-the-lab news boasting a 100% increase of sensitivity with the first tested devices. We also discuss defect-engineering by irradiation, in collaboration with JPL's radiation facilities and the Japanese national quantum and radiation research institute QST, also showing some first tentative results. Finally, we take a look at the whole instruments, looking at the state and necessary steps to flight-ready a tech demo, also discussing potential advantages of this miniaturized approach in CubeSat/SmallSat or miniature rover missions.

Sensing the environment with two NV centers

Damian Kwiatkowski[1] **and Łukasz Cywiński**[1]

[1]*Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, PL 02-668 Warsaw, Poland*

The main source of decoherence of this qubit is its interaction with the bath of ^{13}C nuclei. We present an extension of calculation of spin echo decay due to the nuclear bath (using the state-of-the-art Cluster-Correlation Expansion method [1-2]) to the case of two qubits.

For two qubits in Bell states and when the bath is approximated as a source of Gaussian noise, we expect that common bath affects Ψ and Φ states in opposite ways, enhancing coherence of one while suppressing for the other. Such description naturally breaks down with growing number of strongly coupled nuclei. We find that, when sensors are up to 3 nm apart, such very strong non-Gaussian features are observed [3].

We also investigate how does the mere presence of another qubit modify the single qubit decoherence. Its presence affects the dephasing of the first qubit. The effect is observable, for natural concentration of ^{13}C nuclei, until the distance between the qubits is smaller than 1.5 nm.

This research is supported by funds of Polish National Science Center (NCN), grant no. DEC-2015/19/B/ST3/03152.

[1] W. Yang and R.-B. Liu, Phys. Rev. B **78**, 085315 (2008); Phys. Rev. B **79**, 115320 (2009).
[2] N. Zhao, S.-W. Ho, and R.-B. Liu, Phys. Rev. B **85**, 115303 (2012).
[3] D. Kwiatkowski and Ł. Cywiński, Phys. Rev. B **98**, 155202 (2018).

Fast unshielded optical magnetometers for magnetic nanoparticle metrology

V. Lebedev[1], S. Hartwig[1], T. Middelmann[1], and L. Trahms[2]

[1] *Physikalisch-Technische Bundesanstalt, Berlin, Germany*

Practical magnetometry often calls for sensors operating in magnetically unshielded environment, with μT-strong and kHz-fast magnetic perturbations yet delivering pT-to-fT sensitivity levels. We present optically pumped atomic magnetometer, based driven resonance at earth field via fast feedback loop. It reaches one-digit pT/√Hz sensitivity within the bandwidth of up to 50 kHz, and is capable to track ten μT large field changes. The sensor is optimal for studies of the magnetic nanoparticles' (MNP) dynamics, observed magnetically under mT-strong quickly oscillating or switching driving field ([1]). We demonstrate the sensor performance in broadband magnetorelaxometry under fringing fields of several μT.

References

[1] S. Colombo *et al*, IJMPI **3(1)**, 1703006 (2017)

Measurement of human weak magnetic field by high sensitivity multi-channel quantum magnetometer

Qiang Lin, Guiying Zhang, Xiang He, Shengran Su, Yuxiang Huang, and Wenqiang Zheng

Zhejiang University of Technology, Hangzhou, China

The weak magnetic fields produced by human body, such as cardiac and brain magnetic fields, contain a wealth of physiological and pathological information. Over the past several decades, superconducting quantum interference device (SQUID) magnetometers have become the dominant technique in the field of biomagnetic measurements. However, some technical limitations of SQUID magnetometers hinder the widespread use. With the rapid advances in atomic physics and laser techniques, optically pumped atomic magnetometers have emerged as a most promising non-cryogenic alternative to the SQUID magnetometers. Without the requirement for cryogenic cooling, the ongoing maintenance costs are significantly reduced. More importantly, without the liquid-helium-cooled dewar, the head of the subject is free and allowed to move naturally during the experiment.

In light of this, our group develop two typical kinds of optically pumped atomic magnetometers to detect the cardiac and brain magnetic fields. One is operating in the free induction decay (FID) configuration for magnetocardiography (MCG) measurements [1]. The FID magnetometer utilizes the separated pump and probe beam. The magnetic field is obtained by monitoring the free Larmor precession. Four such magnetometers, located with spacing 2 cm, record the four real time MCG signals from a healthy volunteer. Another type of magnetometer is the optically pumped atomic magnetometer based on spin exchange relaxation free (SERF) regime. The SERF magnetometer with high enough sensitivity and small enough size is the only type of optically pumped atomic magnetometer that can be used to observe the magnetoencephalography (MEG) signals. This high sensitivity is obtained by operating the magnetometer near a zero magnetic field and high atomic density. In the SERF regime, the spin exchange relaxation, which limits the sensitivity of atomic magnetometer, is eliminated. To measure the MEG signals, we develop two kinds of multi-channel SERF magnetometers based on a single large vapor cell [2,3]. By using the four-channel magnetometers, auditory evoked response MEG recordings are achieved.

References

[1] Pei-Xian Miao, Wen-Qiang Zheng, Shi-Yu Yang, Bin Wu, Bing Cheng, Jian-Hui Tu, Hong-Liang Ke, Wei Yang, Ji Wang, Jing-Zhong Cui, and Qiang Lin, JOSA B **36**, 819-828 (2019)

[2] Guiying Zhang, Shengjie Huang, Feixiang Xu, Zhenghui Hu and Qiang Lin, Optics Express **27**, 597-607 (2019)

[3] Guiying Zhang, Shengjie Huang, Qiang Lin, AIP Advances **8**, 125028 (2018)

Frequency shifts in noble-gas comagnetometers

J. Meinel*,[1], W. Terrano†,[1], N. Sachdeva[2], T.E. Chupp[2], S. Degenkolb[3], P. Fierlinger[1], F. Kuchler[4] and J.T. Singh[5]

[1]*Physikdepartment, Technische Universität München Germany*
[2]*Department of Physics, University of Michigan, Ann Arbor, USA*
[3]*Institut Laue-Langevin, Grenoble, France*
[4]*TRIUMF, Vancouver, Canada*
[5]*National Superconducting Cyclotron Laboratory and Department of Physics & Astronomy, Michigan State University*

Polarized nuclei are a powerful tool in nuclear spin studies and in searches for beyond-the-standard model physics[1]. Noble-gas comagnetometer systems, which compare two nuclear species, have thus far been limited by anomalous frequency variations of unknown origin[2,3]. We studied the self-interactions in a 3He-129Xe system by independently addressing, controlling and measuring the influence of each component of the nuclear spin polarization[4]. The comagnetometer allows us to separate interactions from magnetic field background. Our results directly rule out prior explanations of the shifts, and demonstrate experimentally that they can be explained by species dependent self-interactions. We also report the first gas phase frequency shift induced by 129Xe on 3He.

References

[1] Sachdeva, Natasha, Jonas Meinel, et al. "A new measurement of the permanent electric dipole moment of ^{129}Xe using ^{3}He comagnetometry and SQUID detection." arXiv preprint arXiv:1902.02864 (2019).

[2] Allmendinger, Fabian, et al. "New Limit on Lorentz-Invariance-and C P T-Violating Neutron Spin Interactions Using a Free-Spin-Precession ^{3}He - ^{129}Xe Comagnetometer." Physical review letters 112.11 (2014): 110801.

[3] Romalis, Michael V., et al. "Comment on "New Limit on Lorentz-Invariance-and C P T-Violating Neutron Spin Interactions Using a Free-Spin-Precession ^{3}He – ^{129}Xe Comagnetometer"." Physical review letters 113.18 (2014): 188901.

[4] Terrano, William A., Jonas Meinel, et al. "Frequency shifts in noble-gas magnetometers." arXiv preprint arXiv:1807.11119 (2018).

*current address: 3. Physikalisches Institut, University of Stuttgart, Germany

†current address: Department of Physics, Princeton University, USA

Stress MCG during exercise with Optically Pumped Magnetometers

T. Middelmann[1], S. Hartwig[1], T. Sander[1] and L. Trahms[1]

[1] *Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany*

Miniaturized optically pumped magnetometers (OPMs) with a sensitivity in the order of 20 fT/rtHz in the 1-100 Hz-band enable a new level of biomagnetic investigations. The associated flexibility enables to adapt the sensor arrangement to the individual shape of the body and to attach sensors to the body on top of the clothes. This reduces relative position changes of sensors versus subject and is of great benefit for paradigms in which the subject is moving. We present Magnetocardiography (MCG) recorded in PTB's magnetically shielded room BMSR-2. MCG was registered before, during and after exercise stress with 2 arrays of 8 OPMs (Quspin, QZFM, gen 1) attached to chest and back of the subject. The SNR of up to 300, allows for distinguishing details already without averaging. Remaining artifacts due to the OPM's motion in the residual magnetic gradient, can be strongly reduced by averaging without motional blurring, since relative positions between sensors and subject are fixed.

Magnetic Gradiometer for the Detection of Zero- to Ultralow-Field Nuclear Magnetic Resonance

M. Jiang[1], R. P. Frutos[2], T. Wu[2,3], J. W. Blanchard[3],
X. H. Peng[1], D. Budker[2,3]

[1]CAS Key Laboratory of Microscale Magnetic Resonance and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China
[2]Johannes Gutenberg-University Mainz, 55128 Mainz, Germany
[3]Helmholtz-Institut Mainz, 55099 Mainz, Germany

Magnetic sensors are important for detecting nuclear magnetization signals in nuclear magnetic resonance (NMR). As a complementary analysis tool to conventional high-field NMR, zero- to ultralow-field (ZULF) NMR detects nuclear magnetization signals in the submicrotesla regime. Current ZULF NMR systems are always equipped with high-quality magnetic shields to ensure that ambient magnetic-field noise does not dwarf the magnetization signal. An alternative approach is to separate the magnetization signal from the noise based on their differing spatial profiles, as can be achieved using a magnetic gradiometer. Here, we present a gradiometric ZULF NMR spectrometer with a magnetic-field-gradient noise of 17 fT/cm $Hz^{1/2}$ in the frequency ranging from 100 to 400 Hz, based on a single vapor cell ($0.7 \times 0.7 \times 1.0$ cm^3). With applied white magnetic-field noise, we show that the gradiometric spectrometer achieves 13-fold enhancement in the signal-to-noise ratio (SNR) compared to the single-channel configuration. By reducing the influence of the common-mode magnetic-field noise, this work enables the use of compact and low-cost magnetic shields. Gradiometric detection also proves to be beneficial for eliminating systematic errors in ZULF-NMR experiments searching for exotic spin-dependent interactions and molecular parity violation.

References

[1] M. Jiang, R. P. Frutos, T. Wu, J. W. Blanchard, X. H. Peng, and D. Budker, Phys. Rev. Applied **11**, 024005 (2019).

Open Quantum Systems description of spin-noise in single and multi-species alkali vapors

K. Mouloudakis[1] and I.K. Kominis[1,2]

[1]Department of Physics, University of Crete, 70013 Heraklion, Greece
[2] Institute for Theoretical and Computational Physics, University of Crete, 70013 Heraklion, Greece

Spontaneous spin-noise measurements provide useful spectroscopic information without in any way perturbing the physical system under consideration. Here we focus on spin-noise correlations that spontaneously build-up due to spin-exchange collisions in a dual-species atomic vapor [1]. Currently, there are two reported measurements of such correlations. In [1], we observe positive spin-noise correlation leading to a magnetic field dependence of the total spin-noise power while a similar measurement [2], reported both positive and negative correlation, such that the total cross-correlation noise power is zero. We present a first-principle calculation of spin-noise based on the tools of open quantum systems and quantum measurement theory, that directly applies to the spin-exchange process. Our model reproduces all the known characteristics of spin-exchange interactions and reveals the nature of spin-noise correlations in a binary mixture.

References

[1] A.T. Dellis, M. Loulakis and I.K. Kominis, Spin-noise correlations and spin-noise exchange driven by low-field spin-exchange collisions, Physical Review A, **90**, 032705 (2014).

[2] D. Roy, L. Yang, S.A. Crooker and N.A. Sinitsyn, Cross-correlation spin noise spectroscopy of heterogeneous interacting spin systems, Scientific Reports **5**, 9573 (2015).

Room-temperature photo-current detected coherent spin motion of V_{Si} in 4H-SiC

M. Niethammer[1], M. Widmann[1], T. Rendler[1], N. Morioka[1], Y-C. Chen[1], R. Stöhr[1], J. Hassan[2], S. Onoda[3], T. Ohshima[3], S-Y. Lee[4], A. Mukherjee[1], J. Isoya[5], N-T. Son[2], J. Wrachtrup[1,6]

[1] *3rd Institute of Physics and Center for Applied Quantum Technologies, University of Stuttgart, 70569 Stuttgart, Germany*

[2] *Semiconductor Materials, IFM, Linköping University, SE-58183 Linköping, Sweden*

[3] *National Institutes for Quantum and Radiological Science and Technology, Takasaki 370-1292, Japan*

[4] *Center for Quantum Information, Korea Institute of Science and Technology, Seoul 02792, Republic of Korea*

[5] *Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, 305-8573, Japan*

[6] *Max Planck Institute for Solid State Research, 70569 Stuttgart, Germany*

Color centers in wide bandgap solid state systems have been shown to form excellent quantum systems for metrology applications, as they combine room-temperature operation with excellent coherence times. Recently silicon carbide (SiC) as a host material has been investigated and proven to be a good host for such defects systems even for single defects [1,2].Thermometry and magnetometry applications have been demonstrated using ensemble by multiple groups [3,4,5]. However, usual readout methods detect fluorescence light, which for the V_{Si} defects in 4H-SiC only shows low contrast and photon-numbers, limiting the signal-to-noise ratio. Next to good quantum properties of e.g. the V_{Si} defects, 4H-SiC has matured fabrication on the wafer-scale and is in use by the high-power electronics industries for years. In the presented work, we demonstrate that photo-electrical readout is feasible also with V_{Si} in 4H-SiC. This even allows coherent manipulation and readout of a V_{Si} ensemble at room-temperature and low magnetic fields. For the future this technique holds promise for better signal-to-noise of SiC-based sensor systems and allows for industry-scale fabrication and integration of quantum devices.

References

[1] D. J. Christle, *et al.*, Nat. Mater **14**,160-163 (2015)
[2] M. Widmann, *et al.*, Nat. Mater **14**,164-168 (2015)
[3] M. Niethammer, *et al.*, PRAppl **6**, 034001 (2016)
[4] Y. Zhou, *et al.*, PRAppl **8**, 044015 (2017)
[5] D. Simin, *et al.*, Phys. Rev. X **6**, 031014 (2016)

Noise suppression techniques in atomic magnetometry for portable sensors

Carolyn O'Dwyer[1], Stuart J. Ingleby[1], Iain Chalmers[1], Aidan Arnold[1], Erling Riis[1], Paul F. Griffin[1]

Department of Physics, University of Strathclyde, 107 Rottenrow East, Glasgow, UK
E-mail: carolyn.odwyer@strath.ac.uk

Unshielded atomic magnetometry is well suited for portable, compact sensors. Operating in an unshielded environment brings specific challenges - periodic magnetic noise in particular can limit sensitivity. A variety of noise suppression and compensation techniques have been demonstrated [1,2]. We are developing techniques for noise suppression for use in small sensors with simple geometry and micro-fabricated components.

The dominant magnetic noise source in many unshielded environments is the 50 Hz mains current. In our double-resonance magnetometers, this large amplitude periodic noise slews the Larmor frequency outside the linear regime of the resonant response to the RF field. We have developed a measurement scheme which dynamically follows the ambient noise using a feed-forward technique, achieving 50 Hz noise suppression of 20 dB and a reduced total white noise floor. Our efforts to produce unshielded devices insensitive to periodic noise will be discussed here, including feed-forward and gradiometric schemes.

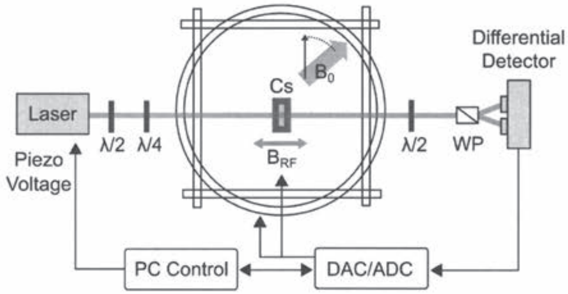


Figure 1: Schematic of the double resonance magnetometer. WP: Wollaston Prism

[1] C. Deans et al. Sub-picotesla widely tunable atomic magnetometer operating at room-temperature in unshielded environments, Rev. Sci. Instr., **89**, 083111 (2018).

[2] G. Bevilacqua et al.Self-adaptive loop for external-disturbance reduction in a differential measurement setup, Phys. Rev. Applied **11**, 014029 (2019).

Optically pumped magnetometer for ultrasensitive measurements of Earth's magnetic field

G. Oelsner[1], R. IJsselsteijn[2], V. Schultze[1], and R. Stolz[1]

1 Leibniz Institute of Photonic Technology, P.O. Box 100239, D-07702 Jena, Germany
2 Supracon AG, An der Lehmgrube 11, D-07751 Jena, Germany

The light-shift dispersed Mz (LSD-Mz) operational mode [1] for optically pumped magnetometers (OPMs) promises high magnetic field resolution for measurements outside of a designed lab environment. In measurements on the other hand, during which the sensor is moved in Earth's magnetic field, OPMs are known to suffer from directional dependences of sensitivity and falsifications of measurement data summarized under the term "heading error". Therefore, we carried out a performance analysis for the LSD-Mz mode investigating both, the error expected in the absolute field measurement [2] and the reduction of shot-noise limited sensitivity if the magnetometer is rotated within a controlled field (Fig. 1). We analyze our experimental findings theoretically in describing the light shift as well as the rates of population transfer as function of the magnetometer's orientation in the magnetic field. Based on the results of in these investigations, we will conclude on the usability of such types of OPMs for magnetic measurements.

In a next step and exploiting the LSD-Mz mode, a fully integrated, moveable measurement apparatus was set up containing the LSD-Mz Sensor combined with the corresponding electronics. We will report on this system and its performance in a first set of field measurements.

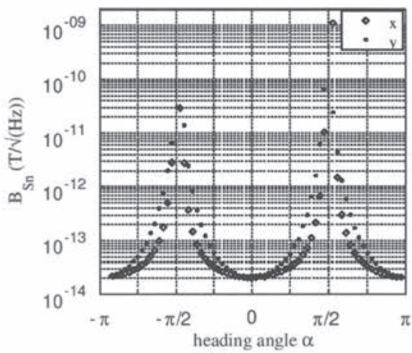


Figure 1 Measured shot noise limited sensitivity of a LSD-Mz magnetometer as a function of the angle between laser light direction and magnetic field B_0. The diamonds and dots correspond to B1-coil orientations perpendicular and parallel to the rotation axis, respectively.

References

[1] Schultze et al. Sensors **17**, 561 (2017)
[2] Oelsner et al. Phys. Rev. A **99**, 013420 (2019)

Helium-4 optically pumped magnetometers for medical imaging

W. Fourcault, F. Beato, G. Lieb, G. Le Gal, R. Garcés Malonda, E. Labyt, M. Le Prado and A. Palacios-Laloy[1]

[1] *CEA LETI, MINATEC Campus, F-38054 Grenoble, France*
Univ. Grenoble Alpes, F-38000 Grenoble, France

Our team develops optically pumped magnetometers (OPM) based on metastable helium-4 atoms. This sensitive species works at any temperature, needing no cooling nor heating, unlike SQUID or alkali OPM based on the SERF effect. This allows setting the sensors in contact with the surface of the body, as close as possible to signals to be observed in medical imaging.

These last years we have made proof-of-concept recordings of both magneto-cardiography (MCG) [1] and magneto-encephalography (MEG) [2] with ^{4}He magnetometers based on parametric resonance.

A full rework of the sensors has allowed us to obtain sensors with compact footprints of 2x2 cm. In contrast with other OPM we pump the atoms with linearly polarized light. This configuration allows measuring the component of the field radial to the head using light that propagates radially [3], which allows closer packing and a simpler optical setup. Our sensors currently have 2 kHz bandwidth, a dynamic range of several hundredths of nanotesla and resolutions better than 50 $fT/Hz^{1/2}$.

We are currently progressing towards a closed-loop magnetometer array with automatic correction of the cross-talks between the sensors. We are also exploring how the coupling of our OPMs with appropriate optical structures could allow reaching the Standard Quantum Limit of intrinsic noise.

References

[1] S. Morales et al., Phys. Med. Biol. **62** (2017)
[2] E. Labyt et al., IEEE Trans. Med. Imaging **38** (2019)
[3] F. Beato et al., Phys. Rev. A **98** (2018)

High-bandwidth optical magnetometry

C. Perrella[1], N. Wilson[1], R. Li[1], R. Anderson[1],
P. Light[1] and A. Luiten[1]

[1]*Institute for Photonics and Advanced Sensing, School of Physical Sciences, University of Adelaide, Adelaide, SA 5005 Australia*

Using two techniques that exploit phase-sensitive detection, we demonstrate broadband, high-bandwidth magnetic field measurements from DC up to 100kHz for magnetometers based on nonlinear magneto-optical rotation (NMOR). The first technique measures the instantaneous phase evolution of the optical polarisation rotation in the temporal domain which enabled quantitative measurements of modulated magnetic fields above 100kHz for a Larmor frequency of 15kHz, corresponding to a bias field of 2µT. This technique was used to measure arbitrarily-complicated modulation waveforms, see Fig. 1 (left). The second method employs phase sensitive detection and active feedback techniques to track magnetic field fluctuations up to 100kHz, nearly 4-orders of magnitude larger than the passive bandwidth, see Fig. 1 (right). This technique achieved a slew rate of 91.4nT/µs, and a sensitivity of 200fT/√Hz around 8Hz and 1nT/√Hz at 100kHz, for a bias field of 50µT. Both techniques are photon shot-noise limited above 100Hz. Our investigation shows that NMOR magnetometers are able to offer a high-bandwidth, broadband, and high-slew-rate field measurement for oscillating fields up to frequencies of 100kHz.

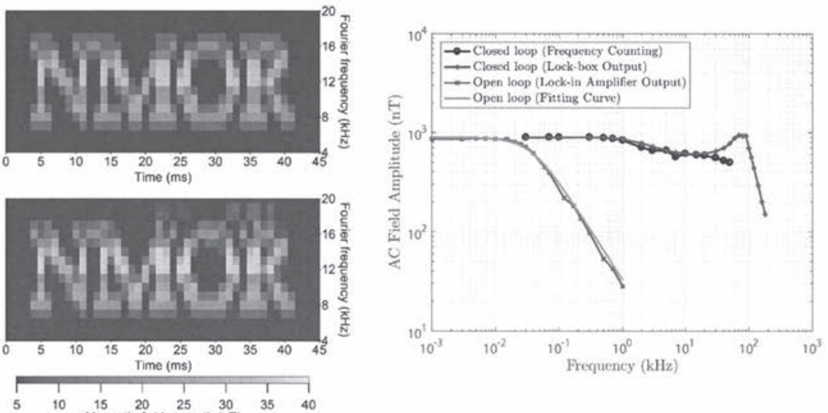


Figure 1: Left: Expected (top) and measured (bottom) spectrograms of the magnetometers response to magnetic-fields measured using the instantaneous phase extraction technique. Right: The amplitude response to AC fields when using phase sensitive detection and active feedback techniques.

NanoSQUIDs based on Nb nanobridges

R. Rodrigo[1,2], M. Faley[1] and R. E. Dunin-Borkowski[1,3]

[1] Peter Grünberg Institute 5, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
[2] RWTH Aachen University, 52062 Aachen, Germany
[3] Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

We have developed nanoSQUIDs with Josephson junctions in the form of Nb nanobridges, whose thickness, width and length are in the order of the superconducting coherence length in Nb thin films, which is approximately 15 nm at 4.2 K. 30-nm-thick Nb films with a critical current density of 30 MA/cm^2 at 4.2 K were deposited using magnetron sputtering. A 40-nm-thick mask of PMMA resist was formed by electron beam lithography using a dose of 25 mC/cm^2, at which PMMA operates as a high resolution negative resist. Compared to the previously used HSQ resist, PMMA has much better availability, lower health risk, a longer shelf life and a simpler development procedure, while maintaining sufficient resolution. Both Nb nanobridges with widths down to 10 nm and nanoSQUIDs with the incorporated nanobridges were fabricated using reactive ion etching with pure SF_6 gas. The I(V) curve of a 20-nm-wide Dayem bridge has shown a non-hysteretic behavior at 4.2 K. This makes the according nanoSQUIDs with a loop diameter of 900 nm suitable for the application in a high resolution Scanning SQUID Microscope. The detailed properties of the nanobridges and nanoSQUIDs will be presented.

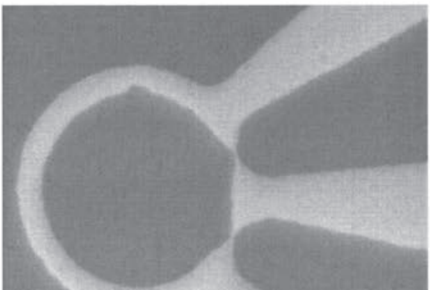


Fig. 1: SEM image of a nanoSQUID structured using negPMMA with a junction width of 20 nm.

Fig. 2: Non-hysteretic I-V-characteristics of an individual 20-nm-wide Josephson junction at 4.2 K.

A new measurement of the permanent electric dipole moment of ^{129}Xe using ^{3}He comagnetometry and SQUID detection

N. Sachdeva,[1] I. Fan,[2] E. Babcock,[3] M. Burghoff,[2] T. E. Chupp,[1] S. Degenkolb,[1,4] P. Fierlinger,[5] E. Kraegeloh,[51] W. Kilian,[2] S. Knappe-Grüneberg,[2] F. Kuchler,[5,6] T. Liu,[2] M. Marino,[5] J. Meinel,[5] Z. Salhi,[3] A. Schnabel,[2] J. T. Singh,[7] S. Stuiber,[5] W. A. Terrano,[5] L. Trahms,[2] and J. Voigt[2]

[1]*Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA*

[2]*Physikalisch-Technische Bundesanstalt (PTB) Berlin, 10587 Berlin, Germany*

[3]*Jülich Center for Neutron Science, 85748 Garching, Germany*

[4]*Institut Laue-Langevin, 38042 Grenoble, France*

[5]*Excellence Cluster Universe and Technische Universität München, 85748 Garching, Germany*

[6]*TRIUMF, Vancouver, British Columbia V6T 2A3, Canada*

[7]*National Superconducting Cyclotron Laboratory and Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

We describe a new technique to measure the EDM of 129Xe with 3He comagnetometry. Both species are polarized using spin-exchange optical pumping, transferred to a measurement cell, and transported into a magnetically shielded room, where SQUID magnetometers detect free precession in applied electric and magnetic fields. The result of a one week run combined with detailed study of systematic effects is $d_A(^{129}\text{Xe}) = (0.26 \pm 2.33_{stat} \pm 0.72_{syst}) \times 10^{-27}$ e cm. This corresponds to an upper limit of $|d_A(^{129}\text{Xe})| < 4.81 \times 10^{-27}$ e cm (95% CL), a factor of 1.4 more sensitive than the previous limit.

Atomic magnetometer research at Los Alamos

I. Savukov[1], Y. J. Kim[1], and P.-H. Chu[1]

[1]*Los Alamos National Laboratory, Los Alamos, New Mexico, USA*

High-sensitivity atomic magnetometers enable a variety of novel applications. Such applications developed at Los Alamos will be described: Detection of anatomical MRI [1]; Micro-imaging [2]; Search for dark matter particles [3,4]; (4) Multi-channel biomedical imaging [5]. Specifically, we demonstrated the first brain MRI using an atomic magnetometer operating at 120 kHz. We enhanced the resolution of an atomic magnetometer and reduced stand-off distance using flux guides for micro-biological imaging and micro-particle detection. We have conducted several experiments setting new limits on exotic spin- and velocity-dependent interactions. Finally, we have designed a multi-channel atomic magnetometer and applied it to magneto-cardiography.

References

[1] I. Savukov, T. Karaulanov, *Appl. Phys. Lett.* **103**, 043703 (2013).
[2] Y. J. Kim, I. Savukov, *Sci. Rep.* **6**, 24773 (2016).
[3] Y. J. Kim, P.-H. Chu, I. Savukov, *Phys. Rev. Lett.* **121**,091802 (2018).
[4] Y. J. Kim, P.-H. Chu, I. Savukov, S. Newman, *Nat. Commun.* **10**, 2245 (2019)
[5] Y. J. Kim, I. Savukov, S. Newman, *Appl. Phys. Lett.* **114**, 143702 (2019).

Towards integrated diamond sensors for biomedical application

P. Siyushev[1], **M. Nesladek**[2], **and F. Jelezko**[1]

[1] *Institute for Quantum Optics, Ulm University, Germany*
[2] *Institute for Materials Research, Hasselt University, Belgium*

Nitrogen-vacancy (NV) centre in diamond has become a prominent candidate for magnetic field sensing, nanoscale NMR, and quantum information processing. However, readout of measured signals is done optically. This requires bulky systems for detection and counting photons. Implementation of realistic devices would require miniaturization of the system and preferably its integration into a single chip for simple compatibility with existing electronics.

Here I will describe a novel approach for addressing NV centres, which does not require optical detection [1]. This method is based on direct photocurrent measurement originated from the colour centres. The photocurrent is spin dependent, which enables photoelectrical detection of magnetic resonance as well as readout of coherently prepared NV's spin state. This technique brings the realization of the compact all-diamond magnetometers to the new technological level and enables realistic biomedical application.

References

[1] P. Siyushev et al., Science **363**, 728-731 (2019)

Current Monitoring System based on Cesium Magnetometry

P. A. Koss[1], G. Bison[2], R. T. Dinani[1], V. Bonder[2, 3], L. Bienstman[1] and N. Severijns[1]

[1]Katholieke Universiteit, Leuven, Belgium
[2] Paul Scherrer Institute, villigen, Switzerland
[3] ETH, Zurich, Switzerland

We have developed a robust current monitoring system based on atomic magnetic resonance [1]. The system containing an array of four Cesium scalar magnetometers installed inside a dedicated confining magnetic field coil [2]. The magnetometers can operate in all-optical or RF-pulsed modes of operation and monitor drifts in current via drifts in magnetic field of the coil. The system is designed to discriminate the drifts in current from external magnetic perturbations. Ultimately, it would be used in an active current stabilization of a current source and is expected to be implemented in n2EDM experiment [3] at Paul Scherrer Institute to search for electric dipole moment of the neutron.

References

[1] V. Y. Shifrin, Rev. Sci. Instrum. **67**, 833 (1996)
[2] P. A. Koss, IEEE Magn. Lett. **8**, 1 (2017)
[3] C. Abel et al., arXiv:1811.02340 (2018)

Ultralow-field NMR of liquids confined in ferromagnetic and paramagnetic materials

M.C.D. Tayler[1,2], J. Ward-Williams[2] and L.F. Gladden[2]

[1]Institute of Photonic Sciences, Barcelona, Spain
[2] Department of Chemical Engineering and Biotechnology, Cambridge University, Cambridge, UK

Nuclear magnetic resonance (NMR) techniques provide unique physical and chemical insights into the behavior of fluids, including detail on composition, dynamics and reactivity. Furthermore, such insights are permitted even when the fluid is enclosed in a structure that is opaque to visible radiation, in particular in vivo and in porous nanomaterials. However, enclosures that are electrically conductive and/or have a high magnetic susceptibility remain a technical challenge. The spatial and spectroscopic resolution of NMR near metals can be obstructed by induced gradients in the static magnetic field, caused by sharp magnetic susceptibility changes at the material boundary. In addition, eddy currents limit the penetration of radiofrequency NMR signals through conductive materials. It is becoming established, however, that these problems can be mitigated by detecting NMR at a sufficiently low magnetic field strength, using optically pumped atomic magnetometers as efficient detectors of the nuclear precession signals[1,2].

This presentation reports on ultralow-field NMR of liquids enclosed in sample vessels or nanoscale confinement that are weakly ferromagnetic (i.e.\ have a magnetic moment even at zero applied field) and/or paramagnetic (i.e.\ have a magnetic moment proportional to the applied field) detected with a spin-exchange-relaxation-free (SERF) ^{87}Rb magnetometer. Both types of magnetism may contribute to the net field experienced by the nuclear spins and may consequently broaden or shift the center frequency of the NMR spectral line. Ultralow-field NMR is an advantageous method to detect and distinguish each contribution[3]. Simple experiments show application potential using closed containers of aluminum alloy 6082-T6 and nano-dispersed cobalt oxide supported on the surface of a porous silica matrix.

References

[1] M.C.D. Tayler et al. *J. Magn. Reson.* **297**, 1 (2018)
[2] S. Xu et al. Proc. *Natl. Acad. Sci. USA* **103**, 12668 (2008)
[3] M.C.D. Tayler et al. *Appl. Phys. Lett.*, submitted (2019)

Squeezed light enhanced magnetometer with high density alkali vapor

Charikleia Troullinou[1], Ricardo Jiménez-Martínez[1] , Jia Kong[1] and Morgan W. Mitchell[1,2]

1. ICFO, Castelldefels, Spain

2. ICREA, Barcelona, Spain

Quantum-non-demolition (QND) measurements to generate spin squeezing and squeezed light techniques, have both enabled magnetic sensitivities beyond their respective standard quantum limits. In theory these techniques are synergistic, although they are yet to be combined in a single instrument.

Squeezed-light-enhanced vapor-cell magnetometers reached nT/√(Hz) sensitivity in 2010 [1] and 2 pT/√(Hz) in 2011 [2]. Here we report a high-density Bell Bloom magnetometer with sensitivity below 100 fT/√(Hz), simultaneously limited by optical shot noise and spin projection noise. Using the same setup for spin noise spectroscopy our group achieved squeezing of 3.2dB in unpolarized Rb vapor [3]. This makes the instrument an attractive candidate, not just for the highest-sensitivity quantum-enhanced magnetometer, but also as a test bed for combining optical and atomic squeezing.

References

[1] Wolfgramm et al, Phys. Rev. Lett. **105**, 053601, (2010)

[2] Horrom et al, Phys. Rev. A **86**, 023803, (2012)

[3] Lucivero et al, Phys. Rev. A **95**, 041803(R) (2017).

Bright and dark coherent resonances in potassium

S. Gozzini[1], L. Marmugi[1], S. Tsvetkov[2], S. Gateva[2], S. Cartaleva[2]

[1]*Istituto Nazionale di Ottica CNR – UOS Pisa, Via Moruzzi 1, 56124 Pisa, Italy*
[2]*Institute of Electronics, BAS, 72 Tzarigradsko Chaussee blvd., 1784 Sofia, Bulgaria*

The phenomenon of electromagnetically induced transparency (EIT) has many applications in laser physics, precision laser spectroscopy, quantum information, all-optical magnetometers, miniaturized atomic clocks, precision measurements of fundamental symmetry, etc. One of the most significant and useful features of the EIT dark resonance is its width, which can be much smaller than the natural line width.

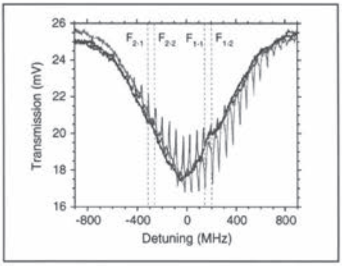


Figure 1. EIT (upward peaks) conversion to EIA (downward peaks). Dashed vertical lines mark the hyperfine optical transitions $F_g \rightarrow F_e$. T = 50.0°C.

We demonstrate high-contrast electromagnetically induced absorption (EIA) bright resonances on the D1 line of ^{39}K with characteristics comparable to those of the EIT resonances observed in the same conditions. We have obtained an order of magnitude increase of the EIA's contrast with respect to previous similar experiments, performed with other alkalis, without compromising its linewidth. Furthermore, we show that the magneto-optic resonances can be continuously tuned from EIT to EIA by the polarizations of pump and probe beams, or depending on whether they co- or counter-propagate. This opens new perspectives in the use of EIA in a broad range of physical domains and in a large wealth of potential applications in optics and photonics.

References

[1] S. Gozzini et al, "Tunable and polarization-controlled high-contrast bright and dark coherent resonances in potassium", Opt. Lett. **42**, 2930-2933 (2017)

[2] A. Krasteva et al, Proc. of SPIE **10226**, 102260L (2017)

Status of the heavily magnetic shielded Room BMSR-2.1 including an active stabilized B0-field

J.Voigt[1], L. Rupp[2], A. Schnabel[1], L. Trahms[1]

[1] Physikalisch-Technische Bundesanstalt, Berlin, Germany
[2] Technische Universität Berlin, Berlin, Germany

Very low and stable magnetic fields and field gradients are essential for the characterization of magnetic measurement devices such as SQUIDs, OPMs, and NV-Sensors, as well as for many applications, such as biomagnetic measurements and high-resolution experiments in fundamental physics where the nuclear precession of noble gases is observed. For this kind of research, the Berlin magnetically shielded Room 2 (BMSR-2) was developed some twenty years ago. Recently, an upgrade of the temperature control system and of the magnetic shield was performed. We will present the current status of the BMSR-2.1 in terms of the magnetic field and temperature stability.

For spin precession experiments in ultra-low fields, an additional field is generated inside the shielded room by a set of coils. The accuracy of such measurements is heavily influenced by the magnetic field characteristics, i.e., in particular, by its temporal stability. To overcome magnetic field drifts, we developed a feedback system consisting of a superconducting quantum interference device, an additional coil, programmable low noise current source and a software feedback control. By using this setup, the overall drift is about 0.1pT/h, corresponding to a drift of 30μHz within 7 hours at a 3He Larmor frequency of 85 Hz.

Silicon Vacancies in Silicon Carbide for Quantum Sensing

Matthias Widmann[1*], Matthias Niethammer[1], Dmitry Yu. Fedyanin[2], Igor A. Khramtsov[2], Ian D. Booker[3], Jawad Ul Hassan[3], Torsten Rendler[1], Naoya Morioka[1], Roland Nagy[1], Ivan G. Ivanov[3], Nguyen Tien Son[3], Takeshi Ohshima[4], Michel Bockstedte[5,6], Adam Gali[7], Cristian Bonato[8], Sang-Yun Lee[9†] & Jörg Wrachtrup[1]

[1]3. Physikalisches Institute and Research Center SCOPE and Integrated Quantum Science and Technology (IQST), University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

[2]Laboratory of Nanooptics and Plasmonics, Moscow Institute of Physics and Technology, 9 Institutsky Lane, 141700 Dolgoprudny, Russian Federation

[3]Department of Physics, Chemistry and Biology, Linköping University, SE-58183 Linköping, Sweden

[4]National Institutes for Quantum and Radiological Science and Technology, Takasaki, Gunma 370-1292, Japan

[5]Department Chemistry and Physics of Materials, University of Salzburg, Jakob-Haringer-Str. 2a, 5020 Salzburg, Austria

[6]Solid State Theory, University of Erlangen-Nuremberg, Staudstr. 7B2, 91058 Erlangen, Germany

[7]Hungarian Academy of Sciences, Wigner Research Centre for Physics, Budapest, Hungary

[8]Institute of Photonics and Quantum Sciences, SUPA, Heriot-Watt University, Edinburgh EH14 4AS, UK

[9]Center for Quantum Information, Korea Institute of Science and Technology, Seoul, 02792, Republic of Korea

Atomic scale defects in solids have attracted a great amount of interest over the last decades, because their spins show a promising potential for sensitive quantum sensors. Leading systems are colour centres in diamond, e.g. the NV centre, and impurities in silicon. However, the large band gap and exceptional hardness of diamond hinder the development of quantum devices. This problem can be overcome by switching to another host material, namely silicon carbide (SiC). SiC can combine the advantages of both diamond and silicon, offering single spins accessible optically at room temperature embedded in a CMOS compatible material. In this presentation, we introduce the silicon vacancy spin qubits [1] and their application for magnetometry [2], and recent efforts towards understanding of the charge state and electrical manipulation of colour centres in SiC quantum devices [3,4]. We also reveal the underlying mechanism for the observed charge state conversion, which is a complex interplay between the quasi-Fermi level tuning and optical excitation of nearby defects, and how this can be used to sense Fermi levels.

[1] M. Widmann, *et al.*, Nat Mater. **14**,164 (2015)

[2] M. Niethammer, *et al.*, Phys. Rev. Applied **6**, 034001 (2015)

[3] M. Widmann, *et al.*, Appl. Phys. Lett. **112**, 231103 (2018).

[4] M. Widmann, *et al.*, to be submitted

Challenges of fabricating fully integrated alkali vapour cells

Florian Wittkämper[1], Christian B. Schmidt[1], Gregor Oelsner[1], Rob IJsselsteijn[2], Volkmar Schultze[1], and Ronny Stolz[1]

[1] Leibniz Institute of Photonic Technology, Albert-Einstein Straße 9, 07745 Jena, Germany

[2] Supracon AG, An der Lehmgrube 11, 07751 Jena, Germany

The aim of our work is to fabricate fully integrated alkali vapour cells for optically pumped magnetometers, which will be used as sensors for biological and geological applications. These cells require specific properties, which can be adjusted by the design, functionalized surfaces, and buffer-gas pressure. Glass-silicon-glass anodic bonded cells offer the possibility also to control other cell characteristics such as temperature distributions, optical properties of surfaces, and heat radiation. To control the parameters of these cells, different methods are deployed including transparent electrical heaters, anti-reflection coatings as well as optical and heat mirrors. Some of these require low-temperature bonding of glass plates as cell windows for encapsulation at room temperature [1], a passivation of the cell inner surfaces or coatings exposed to the alkali vapor for increasing their lifetime [2]. Those features will be presented on the example of different alkali vapour cells for optically pumped magnetometers. Those include the application of a cell for a magnetic field camera, and another one for fetal magnetoencephalography.

[1] S. Woetzel, Journal of Micromechanics and Microengineering **24**, 095001 (2014)
[2] S. Woetzel, Surface and Coatings Technology **221**, 158 (2013)

Rb vapor cell quantum memory for SPDC photons

Janik Wolters[1,2], Gianni Buser[1], Roberto Mottola[1], Chris Müller[3], Tim Kroh[3], Richard Warburton[1], Oliver Benson[3], and Philipp Treutlein[1]

1) *University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
2) *Present address: DLR Inst. of Optical Sensor Systems, Rutherfordstr. 2, 12489 Berlin, Germany*
3) *Humboldt-Universität zu Berlin, Newtonstraße 15, D-12489 Berlin, Germany*

Quantum memories are an essential ingredient for quantum repeaters [1] and an enabler for advanced optical quantum simulators [2].

We implemented a broadband optical quantum memory with on-demand storage and retrieval in hot Rb vapor [3]. Operating at the Rb D2 line, the versatile memory is suited for storing single photons emitted by an GaAs droplet quantum dots [4,5] or single photons from spontaneous parametric downconversion (SPDC) sources [6].

We report on our recent achievements: reducing the readout noise far below the single input photon equivalent ($\mu_1 \ll 1$) while keeping the end-to-end efficiency at about 4 %; increasing the memory lifetime to several μs; storage of true single photons with a bandwidth of ~ 250 MHz, generated by a cavity enhanced SPDC source with 50 % heralding efficiency. After readout, the photons preserve their non-classical character with significance of about tree standard deviations.

With the present performance, we can already significantly increase the multi-photon rate for higher order interference experiments, e.g. for linear optical quantum simulation and computation.

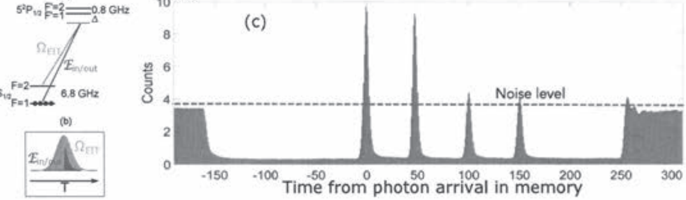


FIG. 1. (a) Energy level diagram showing the Rb D1 level scheme and transitions involved in the memory experiments. All atoms are initially prepared in F = 1 groundstate. The signal to be stored and read out ($\mathcal{E}_{in/out}$) is detuned by Δ from the F = 1 → F' = 1 transition, while the horizontally polarized control laser (Ω_{EIT}) is detuned by Δ from the F =2 → F' =1 transition. (b) Experimental sequency for storage or retrieval. (c) Arrival time histogram for heralded SPDC photons detected in a memory experiment with storage time of 50 ns. First peak at t=0 corresponds to leakage during read in, second peak is the read out signal, the two subsequent peaks are correspond to the noise level in read-out. The measured noise corrected end-to-end efficiency of the memory setup including the filtering system is typically 1 %, while the signal to noise level is SNR ~ 2.

References

[1] N. Sangouard et al., "Quantum repeaters based on atomic ensembles and linear optics." *Rev. Mod. Phys.* **83**, 33 (2011)

[2] J. Nunn et al., "Enhancing Multiphoton Rates with Quantum Memories." *Phys. Rev. Lett.* **110**, 133601 (2013)

[3] J. Wolters, et al., "Simple Atomic Quantum Memory Suitable for Semiconductor Quantum Dot Single Photons." *Phys. Rev. Lett.* **119**, 060502 (2017)

[4] J.-P. Jahn, et al., "An artificial Rb atom in a semiconductor with lifetime-limited linewidth." *Phys. Rev. B* **92**, 245439 (2015).

[5] L. Béguin, et al., "On-demand semiconductor source of 780-nm single photons with controlled temporal wave packets." *Phys. Rev. B* **97** 205304 (2018)

[6] A. Ahlrichs et al., "Bright source of indistinguishable photons based on cavity-enhanced parametric down-conversion utilizing the cluster effect." *Appl. Phys. Lett.* **108**, 021111 (2016)

Experimental Benchmarking of Quantum Control in Zero-Field Nuclear Magnetic Resonance

M. Jiang,[1] T. Wu,[2,3] J. W. Blanchard,[3] G. R. Feng,[4] X. H. Peng,[1] D. Budker[2,3]

[1]*CAS Key Laboratory of Microscale Magnetic Resonance and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

[2]*Johannes Gutenberg-University Mainz, 55128 Mainz, Germany*

[3]*Helmholtz-Institut Mainz, 55099 Mainz, Germany*

[4]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*

Experimental characterization of the controllability and quality of the level of coherent control in a specific quantum architecture is a central problem in contemporary experimental physics and an important ingredient to improving performance. As a complementary analysis tool to high-field nuclear magnetic resonance (NMR), this kind of benchmarking experiments has not been demonstrated in zero-field NMR[1]. Here we realize a composite-pulse technique for both arbitrary one-spin rotations (Fig. 1**a**) and a two-spin controlled-not (CNOT) gate in a heteronuclear two-spin system at zero field[2,3], which experimentally demonstrates universal quantum control in such a system. Moreover, using quantum-information-inspired randomized benchmarking and partial quantum process tomography, we evaluate the quality of the control, achieving for single-spin control for ^{13}C with an average fidelity of 0.9960(2) (Fig. 1**b**) and two-spin control via a CNOT gate with a fidelity of 0.9877(2) (Fig. 1**c**). Our method can also be extended to more general multi-spin heteronuclear systems at zero field. The realization of universal quantum control in zero-field NMR is important for quantum state/coherence preparation, pulse-sequence design, and is an essential step towards applications to materials science, chemical analysis, and fundamental physics[4].

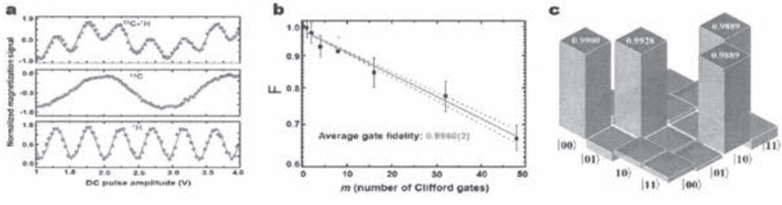


Fig.1*(a)Top: zero-field NMR signal amplitude of the formic acid with different DC pulse amplitude, which is fitted with two cosine functions as both ^{13}C and H are rotated. Middle: ^{13}C is selectively rotated. Bottom: H is selectively rotated. (b) Pulse fidelity estimation with randomized benchmarking testing protocol. Each experiment data point is an average over 32 random sequences of m Clifford gates. The error bars indicate the standard error of the mean.(c) Experimental result of CNOT gate.*

References

[1] J. W. Blanchard, and D. Budker, Zero-to ultralow-field NMR, eMagRes 5(3): 1395-1410 (2016).

[2] J. Bian, et al. Universal quantum control in zero-field nuclear magnetic resonance. Phys. Rev. A 95, 052342 (2017).

[3] M. Jiang, et al. Experimental Benchmarking of Quantum Control in Zero-Field Nuclear Magnetic Resonance. Science Advances 4, eaar6327 (2018).

[4] A. Garcon, et al. The Cosmic Axion Spin Precession Experiment (CASPEr): a dark-matter search with nuclear magnetic resonance. Quantum Science and Technology (2017).

Coil design framework for atomic sensors

Rasmus Zetter[1], **Joonas Iivanainen**[1], **Antti Mäkinen**[1] **and Lauri Parkkonen**[1]

[1]Aalto University, Espoo, Finland

Sensitive measurement devices, such as SERF magnetometers or atomic clocks, may require strict control of the ambient magnetic field to achieve high performance. Often, simple Helmholtz coils are used to control the homogeneous field components within a target volume. However, constraints on mechanical dimensions or stray magnetic field may not be met by such coils due to their comparatively large size (relative to the volume of generated homogeneous field) and slow field falloff outside the coils.

We have developed a coil design framework based on a stream function boundary element method (BEM) previously used for designing MRI gradient coils [1,2,3]. This approach yields *optimal* coils in the sense that they achieve e.g. minimum field energy or minimum power while keeping the magnetic field within the target volume as specified. The specified field shape within the target volume is not required to be homogeneous, but can be of arbitrary shape. Thus e.g. gradient coils, or coils with multiple homogeneous volumes can be designed. Additional linear constraints can also be applied, e.g. to keep certain spacing between the coil windings. The BEM framework is very flexible, and it can be applied for coil surfaces of arbitrary shape.

This work is part of ongoing development of a software package for magnetic field modelling. We intend to make the software package publicly available.

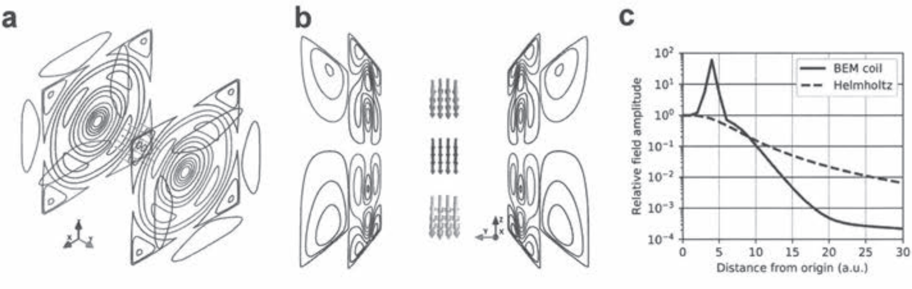


Figure 1: Self-shielded biplanar coil geometries designed to create **a)** a homogeneous Y-field and **b)** three homogeneous volumes with different Z-field amplitudes, while minimizing total field energy and stray field. **c)** Field falloff on the y-axis of the BEM coil in **a)** and a Helmholtz coil with similar mechanical constraints.

References

[1] S. Pissanetzky. Measurement Science and Technology, **3(7)**, 667–673 (1992)
[2] G. N. Peeren. Journal of Computational Physics, **191(1)**, 305–321 (2003)
[3] M. Poole, PhD Thesis, University of Nottingham (2007)

Participants

Seyed Khalil Alavi
Universität Bonn & Universität zu Köln
Institute of physical chemistry
Köln, Germany
alavi@iap.uni-bonn.de

Guzhi Bao
East China Normal University
Department of Physics
Shanghai, China
guzhi_bao@126.com

Patrick Bevington
The National Physical Laboratory
Time and Frequency
Teddington, UK
patrick.bevington@npl.co.uk

Georg Bison
Paul Scherrer Institute
Labor für Teilchenphysik
Villigen PSI, Switzerland
georg.bison@psi.ch

Andreas Blug
Fraunhofer IPM
Production Control
Freiburg, Germany
Andreas.Blug@ipm.fraunhofer.de

Sven Bodenstedt
ICFO – The Institute of Photonic Sciences
Atomic Quantum Optics
Castelldefels, Spain
sven.bodenstedt@icfo.eu

Elena Boto
University of Nottingham
Sir Peter Mansfield Imaging Centre
Nottingham, UK
elena.boto@nottingham.ac.uk

Dmitry Budker
Universität Mainz
Helmholtz-Institut
Mainz, Germany
dbudker@gmail.com

Timothy Chupp
University of Michigan
Department of Physics
Ann Arbor, MI, USA
chupp@umich.edu

Participants

Ruth Corkill
University of Stuttgart
3rd Physics Institute
Stuttgart, Germany
ruthcorkill@hotmail.com

Anna Ermakova
Max Planck Institute for Polymer Research
AK Weil
Mainz, Germany
anna.ermakova@mpip-mainz.mpg.de

Anne Fabricant
University of Mainz
Helmholtz Institute
Mainz, Germany
afabrica@uni-mainz.de

Michael Faley
Forschungszentrum Jülich GmbH
Peter Grünberg Institute 5
Jülich, Germany
m.faley@fz-juelich.de

Tino Fremberg
Leibniz Institute of Photonic Technology
Magnetometry
Jena, Germany
tino.fremberg@leibniz-ipht.de

Ilja Gerhardt
Max-Planck-Institut für Festkörperforschung
Stuttgart, Germany
ilja@quantumlah.org

Paul Griffin
University of Strathclyde
Department of Physics
Glasgow, UK
paul.griffin@strath.ac.uk

Zoran Grujić
University of Belgrade, Serbia
Institute of Physics
Belgrade, Serbia
zoran.grujic@ipb.ac.rs

Liam Hall
The University of Melbourne
School of Physics
Melbourne, Australia
UM-cqc2tadmin@unimelb.edu.au

Stefan Hartwig
Physikalisch Technische Bundesanstalt
Biosignale
Berlin, Germany
stefan.hartwig@ptb.de

Participants

Sophia Haude
Physikalisch-Technische Bundesanstalt
Abteilung 8 - Medizinphysik und metrologische Informationstechnik
Berlin, Germany
sophia.haude@ptb.de

Niall Holmes
University of Nottingham
Sir Peter Mansfield Imaging Centre
Nottingham, UK
niall.holmes@nottingham.ac.uk

Dominic Hunter
ICFO
Atomic Quantum Optics
Casteldefels, Spain
dhunter@icfo.net

Joonas Iivanainen
Aalto University
Department of Neuroscience and Biomedical Engineering
Espoo, Finland
joonas.iivanainen@aalto.fi

Stuart Ingleby
University of Strathclyde
Physics
Glasgow, UK
stuart.ingleby@strath.ac.uk

Andrey Jarmola
UC Berkeley
Physics
Berkeley, CA, USA
jarmola@berkeley.edu

Aaron Jaufenthaler
UMIT - Private University for Health Sciences, Medical Informatics and Technology
Institute of Electrical and Biomedical Engineering
Hall in Tirol, Austria
aaron.jaufenthaler@umit.at

Fedor Jelezko
Universität Ulm
Ulm, Germany
fedor.jelezko@uni-ulm.de

Kasper Jensen
University of Nottingham
School of Physics and Astronomy
Nottingham, UK
Kasper.Jensen@nottingham.ac.uk

Participants

Sylvain Karlen
CSEM SA
Time and Frequency
Neuchâtel, Switzerland
sylvain.karlen@csem.ch

Patrick Kaspar
University of Stuttgart
5th Institute of Physics
Stuttgart, Germany
p.kaspar@physik.uni-stuttgart.de

Vinaya Kavatamane
Max Planck Institute for Biophysical Chemistry
MPRG-Nanoscale Spin Imaging
Goettingen, Germany
vinay1786@gmail.com

Christopher Kiehl
JILA, National Institute of Standards and Technology and University of Colorado
Department of Physics
Boulder, CO, USA
christopher.kiehl@colorado.edu

Wolfgang Kilian
Physikalisch Technische Bundesanstalt
Fb 8.2
Berlin, Germany
wolfgang.kilian@ptb.de

Kiwoong Kim
Korea Research Institute of Standards and Science
Ultra-low Magnetic Field Team
Daejeon, South Korea
kiwoong@gmail.com

Svenja Knappe
University of Colorado
Department of Mechanical Engineering
Boulder, CO, USA
svenja.knappe@colorado.edu

Jia Kong
ICFO - The Institute of Photonic Sciences
Castelldefels, Spain
jia.kong@icfo.eu

Rainer Körber
Physikalisch-Technische Bundesanstalt
Biosignals
Berlin, Germany
rainer.koerber@ptb.de

Participants

Tom Kornack
Twinleaf LLC
Magnetometry
Plainsboro, NJ, USA
kornack@twinleaf.com

Peter Koss
Fraunhofer IPM
Freiburg, Germany
peter.koss@ipm.fraunhofer.de

Hannes Kraus
Jet Propulsion Laboratory / California Institute of Technology
Microdevices and Sensor Systems 389R
Pasadena, CA, USA
hannes.kraus@jpl.nasa.gov

Frank Kühnemann
Fraunhofer IPM
Gas and Process Technology
Freiburg, Germany
frank.kuehnemann@ipm.fraunhofer.de

Damian Kwiatkowski
Polish Academy of Sciences
Institute of Physics
Warsaw, Poland
kwiatkowski@ifpan.edu.pl

Sami Lähteenmäki
MEGIN Oy
R&D
Helsinki, Finland
sami.lahteenmaki@megin.fi

Roland Lammegger
Graz University of Technology
Institute of Experimental Physics
Graz, Austria
roland.lammegger@tugraz.at

Victor Lebedev
Physikalisch Technische Bundesanstalt
AG 8.21 Magnetooptische Metrologie
Berlin, Germany
victor.lebedev@ptb.de

Qiang Lin
Zhejiang University of Technology
College of Science
Hangzhou, China
qlin@zjut.edu.cn

Participants

Jonas Meinel
Universität Stuttgart
3. Physikalisches Institut
Stuttgart, Germany
johnny_meinel@web.de

Thomas Middelmann
Physikalisch Technische Bundesanstalt
Biosignale
Berlin, Germany
thomas.middelmann@ptb.de

Jiang Min
University of Science and Technology of China
Department of modern physics
Hefei, China
dxjm@mail.ustc.edu.cn

Morgan Mitchell
ICFO - The Institute of Photonic Sciences
Quantum Optics
Casteldefels, Spain
morgan.mitchell@icfo.es

Kostas Mouloudakis
University of Crete
Physics Department
Heraklion-Crete, Greece
kmoul@physics.uoc.gr

Matthias Niethammer
University of Stuttgart
3rd Institute of Physics and Center for Applied Quantum Technologies
Stuttgart, Germany
m.niethammer@pi3.uni-stuttgart.de

Carolyn O'Dwyer
University of Strathclyde
Physics
Glasgow, UK
carolyn.odwyer@strath.ac.uk

Gregor Oelsner
Leibniz Institute of Photonic Technology
Magnetometry
Jena, Germany
gregor.oelsner@leibniz-ipht.de

Agustin Palacios-Laloy
CEA
LETI
Grenoble, France
agustin.palacioslaloy@cea.fr

Participants

Chris Perrella
The University of Adelaide
Institute for Photonics and Advanced Sensing (IPAS)
Adelaide, Australia
chris.perrella@adelaide.edu.au

Szymon Pustelny
Jagiellonian University
Physics
Krakow, Poland
pustelny@uj.edu.pl

Erling Riis
Strathclyde University
Department of Physics
Glasgow, UK
e.riis@strath.ac.uk

Rebecca Rodrigo
Forschungszentrum Jülich GmbH
Peter Grünberg Institut 5
Jülich, Germany
r.rodrigo@fz-juelich.de

Michael Romalis
Princton University
Department of Physics
Princton, USA
romalis@princeton.edu

Yossi Rosenzweig
Israel Aerospace Industries
R&D Ramta division
Beer Sheva, Israel
yrozenzweig@iai.co.il

Natasha Sachdeva
University of Michigan
Physics
Ann Arbor, MI, USA
sachd@umich.edu

Igor Savukov
Los Alamos National Laboratory
Physics division, group P-21
Los Alamos, NM, USA
isavukov@lanl.gov

Andreas Schell
LUH Hannover
Quantentechnologie
Hannover, Germany
aws.kyoto@gmail.com

Participants

Piet Schmidt
PTB & LUH
QUEST Institute
Braunschweig, Germany
piet.schmidt@quantummetrology.de

Justin Schneiderman
University of Gothenburg
MedTech West and the Institute of
Neuroscience and Physiology
Gothenburg, Sweden
justin.schneiderman@neuro.gu.se

Peter Schwindt
Sandia National Laboratories
Atom-Optical Sensing
Albuquerque, NM, USA
pschwin@sandia.gov

Yongqi Shi
University of Basel
Department of Physics
Basel, Switzerland
yongqi.shi@unibas.ch

Petr Siyushev
Ulm University
Institute for Quantum Optics
Ulm, Germany
petr.siyushev@uni-ulm.de

Ronny Stolz
Leibniz-Institute of Photonic Technology
Research group Magnetometry
Jena, Germany
ronny.stolz@leibniz-ipht.de

Alex Sushkov
Boston University
Department of Physics
Boston, MA, USA
asu@bu.edu

Reza Tavakoli Dinani
Katholieke Universiteit Leuven
Institute for Nuclear and Radiation Physics
Celestijnenlaan
Leuven, Belgium
reza.tavakolidinani@kuleuven.be

Michael Tayler
ICFO - The Institute of Photonic Sciences
Castelldefels, Spain
michael.tayler@icfo.eu

Participants

Lutz Trahms
Physikalisch Technische Bundesanstalt
Berlin, Germany
lutz.trahms@ptb.de

Charikleia Troullinou
ICFO
Casteldefels, Spain
charikleia.troullinou@icfo.es

Stoyan Tsvetkov
Bulgarian Academy of Sciences
Institute of Electronics
Sofia, Bulgaria
stocvet@ie.bas.bg

Jens Voigt
Physikalisch Technische Bundesanstalt
Biosignals
Berlin, Germany
jens.voigt@ptb.de

Junmin Wang
Shanxi University
Institute of Opto-Electronics
Tai Yuan, China
wwjjmm@sxu.edu.cn

Yanhua Wang
Shanxi University
School of physics and electronic engineering
Tai Yuan, China
wangyanhua@sxu.edu.cn

Arne Wickenbrock
Universität Mainz
Helmholtz-Institut
Mainz, Germany
wickenbr@uni-mainz.de

Matthias Widmann
Universität Stuttgart
3. Physikalisches Insitut
Stuttgart, Germany
m.widmann@pi3.uni-stuttgart.de

Florian Wittkämper
Leibniz Institute of Photonic Technology
Magnetometry
Jena, Germany
florian.wittkaemper@leibniz-ipht.de

Janik Wolters
DLR e.v.
Institute of Optical Sensor Systems
Berlin, Germany
janik@physik.hu-berlin.de

Participants

Jörg Wrachtrup
Universtität Stuttgart
Physikalisches Institut
Stuttgart, Germany
j.wrachtrup@physik.uni-stuttgart.de

Christof Wunderlich
Universität Siegen
Department of Physics
Siegen, Germany
Christof.Wunderlich@uni-siegen.de

Peng Xinhua
University of Science and Technology of China
Department of Modern Physics
Hefei, China
dxjmmainz@gmail.com

Rasmus Zetter
Aalto University
Depatrment of Neuroscience and Biomedical Engineering
Espoo, Finland
rasmus.zetter@aalto.fi

Sunday	Monday, August 12th	Tuesday, August 13th	Wednesday, August 14th
	8:20 **Opening: Lutz Trahms** PTB Berlin, DE	8:45 **Mike Romalis** Princeton University, US	8:45 **Morgan Mitchell** ICFO Castelldefells, CU
	8:30 **Dmitry Budker** Helmholtz Institute Mainz, DE	9:30 **Kiwoong Kim** KSIT, Seoul, KR	9:30 **Piet Schmidt** PTB Braunschweig, DE
	9:15 **Tim Chupp** University of Michigan, US	10:00 **Arne Wickenbrock** Helmholtz Institute Mainz, DE	
	10:00 Coffee Break	10:30 Coffee Break	10:15 Coffee Break
Arrival	10:30 **Jörg Wrachtrup** University of Stuttgart, DE	11:00 **Ronny Stolz** IPHT, Jena, DE	10:45 **Rainer Körber** PTB Berlin, DE
↓	11:15 **Liam Hall** Melbourne University, AU	11:45 **Roland Lammegger** TU Graz, AT	11:30 **Justin Schneidermann** Chalmers University, SE
	12:00 **Christoph Wunderlich** University of Siegen, DE	12:35 Lunch	12:15 **Elena Boto** University of Nottingham, UK
	12:45 Lunch	13:45 **Georg Bison** Paul Sherrer Institute, CH	12:45 Poster Prize Closing Remarks
	14:00 **Svenja Knappe** Colorado Univesity, US	14:30 **Szymon Pustelny** Jagiellonian University, Krakow, PL	
	14:45 **Erling Riis** Strathclyde, Glasgow, UK	15:00 **Alexander Sushkov** Boston University, US	13:00 Lunch
	15:30 **Kasper Jensen** Nottingham Univesity, UK	15:30 Coffee Break	14:30 Departure to WOPM-2019 Mainz
17:00-21:00 Registration	16:00 Coffee Break 16:30 The WEH-Foundation & Poster Flash	16:00 **Contributed talks:** Patrick Bevington Sylvain Karlen Anne Fabricant Yongqi Shi Peter Schwindt	
18:00 Dinner	18:00 Heraeus-Dinner 19:30 Poster session	18:00 Dinner 19:30 Poster session	