Institute of Spintronics and Quantum Information
Faculty of Physics
Adam Mickiewicz University, Poznań

Symposium on Spintronics and Quantum Information 2024

Book of Abstracts

The Będlewo Palace
Research and Conference Centre of the Polish Academy of Sciences
January 11-13, 2024

Symposium Venue

The Symposium on Spintronics and Quantum Information will take place in Będlewo Palace – Research and Conference Centre of the Polish Academy of Sciences (www.palacbedlewo.pl/en/).

About Symposium

The Symposium is organized by the Institute of Spintronics and Quantum Information (ISQI) of the Faculty of Physics of the Adam Mickiewicz University, Poznań. Since its establishment on January 1, 2021, ISQI has been organizing yearly symposia on broad aspects of condensed matter physics and quantum information. The first Symposium took place in 2021 at the Faculty of Physics of AMU, Poznań, and started with the official inauguration of the Institute. The second Symposium was also organized at the Faculty and took place at the end of 2022.

The aim of the Symposium is to provide an international platform for the presentation and discussion of novel scientific ideas at the intersection of the fields of broadly understood quantum information and condensed matter physics, including among others:

- Spintronics and molecular magnetism,
- Magnonics, spin waves and magnonic crystals,
- Quantum information and quantum physics,
- Quantum optics, cavity and circuit QED,
- Strongly correlated systems,
- Quantum simulators and quantum matter,
- Nonlinear dynamics,
- Quantum information and quantum physics,
- Topological states of matter,
- Quantum transport in low-dimensional systems,
- 2D materials and spin-orbit phenomena,
- Bound states in superconductors.

More information can be found on the conference webpage: https://symposium-isqi.amu.edu.pl/.

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Local Committee:

- Krzysztof Sobucki,
- Kacper Wrześniewski,
- Mateusz Zelent.

Invited speakers

Oleksandr Dobrovolskiy
University of Vienna, Vienna, Austria
Nonreciprocal Magnon Fluxonics

Tadeusz Domański
Maria Curie-Skłodowska University, Lublin, Poland
Josephson junctions: platform for exotic superconducting phases

Tobias Grass
Donostia International Physics Center, San Sebastián, Spain
Quantum simulation of non-standard Hubbard models

Maciej Maśka
Wrocław University of Science and Technology, Wrocław, Poland
Topological superconductivity in one-, quasi-one- and two-dimensional spin structures

Tomáš Novotný
Charles University, Prague, Czech Republic
Theoretical approaches to correlated quantum dots coupled to superconducting leads

Adam Sajna
Wrocław University of Science and Technology, Wrocław, Poland
Large velocity approximation to the digitized-counterdiabatic protocol in spin systems

Victor Tkachenko
DESY (Deutsches Elektronen-Synchrotron), Hamburg, Germany
Ultrafast X-ray induced magnetization dynamics in Co and Ni

Vojtěch Trávníček
Joint Laboratory of Optics of Palacký University
and Institute of Physics of Czech Academy of Sciences, Olomouc, Czech Republic
Sensitivity versus selectivity in entanglement detection via collective witnesses

Schedule

Symposium on Spintronics and Quantum Information 2024

	January 11, 2024	January 12, 2024	January 13, 2024
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9.00 - 9.35		**Adam Sajna**	**Maciej Maśka**
9.35 - 9.55		Przemysław Chełminiak	Clemens Schmid
9.55 - 10.15		Martin Žonda	Grzegorz Chimczak
10.15 - 10.30		Anand Manaparambil	Dominik Pavelka
10.30 - 10.45		Julia Kharlan	Jaganandha Panda
10.45 - 11.00		Krzysztof Wójcik	Jakub Holobrádek
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11.30 - 13.10		**Scientific session 4**	**Scientific session 8**
11.30 - 12.05		**Victor Tkachenko**	**Oleksandr Dobrovolsky**
12.05 - 12.25	**Registration & Reception**	Tomasz Polak	Karol Bartkiewicz
12.25 - 12.40		Katarzyna Kotus-Kozyra	Jan Klíma
12.40 - 12.55		Josef Kadlec	Ondřej Wojewoda
12.55 - 13.15		Jan Martinek	Bogdan Idzikowski
13.15 - 14.15		**Group photo** **Lunch**	**Symposium closing** **Lunch**
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15.25 - 15.45	Nicholas Sedlmayr	Piotr Kozłowski	
15.45 - 16.00	Ryszard Stagraczyński	Grzegorz Centała	
16.00 - 16.15	Paweł Gruszecki	Peter Zalom	
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17.35 - 17.55	Paweł Kurzyński	Jarosław Kłos	
17.55 - 18.10	Piotr Busz	Vladislav Pokorný	
18.10 - 18.25	Jan Wójcik	Piotr Trocha	
18.25 - 18.40	Krzysztof Szulc	Katerina Jirakova	
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Abstracts

QUANTUM SIMULATION OF NON-STANDARD HUBBARD MODELS

T. Grass[1]

[1] *ICFO Institute of Photonic Sciences, Barcelona, Spain*

The Hubbard model in all its variations plays a central role in the description of strongly correlated many-body systems. Despite its simple form, the solution of the model remains a challenge for analytical and numerical methods. Quantum simulation has been established as an alternative solution method in the last 20 years. My talk takes a comprehensive look at this development and introduces both atomic and electronic many-body systems suitable for quantum simulation of Hubbard models. Here, I will focus on the bosonic Hubbard model and study different extensions of the model, such as long-range interactions or lattices without dispersion.

EXCITATION OF HIGH-FREQUENCY SHORT-WAVELENGTH SPIN WAVES

N. Kumar[1], P. Gruszecki[2], M. Gołębiewski[2], J. W. Kłos[2] and M. Krawczyk[2]

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[2] *Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, Poznań, Poland*

To use spin waves as an information carrier, it is necessary to convert a signal from another commonly used carrier. Because of the frequency range of spin waves, from a few GHz to a few hundred GHz, and the corresponding short wavelength, from micrometres to a few nm, it would be beneficial to have an effective transducer to convert the signal encoded in microwaves to spin waves. Research in this direction has been going on for a long time, one could say since the beginning of magnetic resonance (FMR) research. However, this classical magnetic resonance experiment uses a uniform microwave magnetic field in a cavity, which induces only uniform magnetisation oscillations, i.e. spin waves with zero wave vector and the lowest frequency available in a given material. For modern applications, however, conversion methods are being sought that allow the excitation of very short spin waves (below 100 nm) and high frequencies, e.g. those used in the wireless and cellular transmission range (including future 6G technologies), i.e. from 1 GHz to 100 GHz. I will critically review the selected techniques for exciting spin waves using a microwave field that have been proposed in recent years. Finally, I will present some promising approaches recently developed in our group to excite high frequency and very short wavelength spin waves. There, we exploit nonlinear effects in the magnonic crystal under microwave magnetic field excitation to induce high-frequency harmonics of very short wavelength, i.e. reaching 100 GHz at wavelengths below 30 nm (Figure 1) [1].

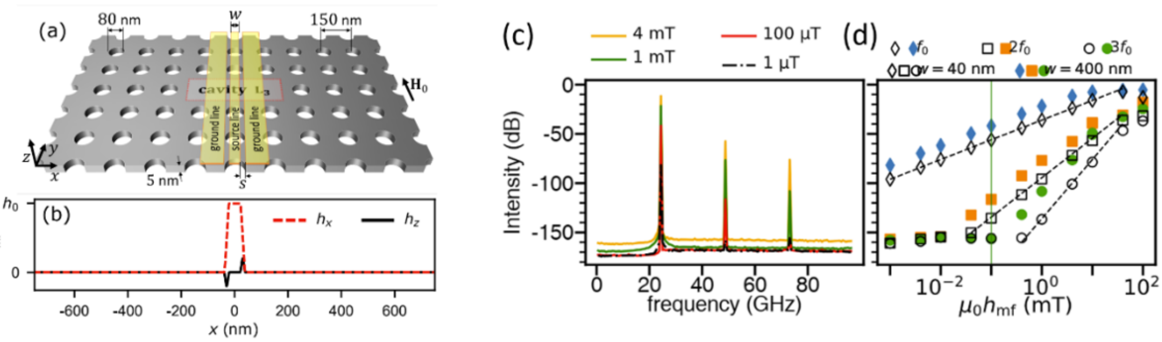

Fig. 1: (a) Schematic of the device – an antidot lattice with a three-hole defect cavity (L3). Magnonic crystal is made of a 5 nm thick Py-film with magnetization saturated by the magnetic field H0 directed along the y-axis, the diameter of the antidots is 80 nm and the lattice constant is 150 nm. A CPW antenna is placed just above the film. (b) The spin waves are excited by the magnetic field produced by CPW. (c) The spin wave spectra ($\propto$ m2z) in the L3 cavity excited with CPW at frequency 24.3 GHz of different amplitudes. (d) Intensity of the fundamental cavity mode (f0 = 24.3 GHz), and its second (f2 $\equiv$ 2f0 = 48.6 GHz), and third (f3 $\equiv$ 3f0 = 72.9 GHz) harmonics on the microwave excitation field strength.

Acknowledgements: *This work was supported in part by the National Science Center Poland project OPUS-LAP no 2020/39/I/ST3/02413. The simulations were partially performed in Poznan Supercomputing and Networking Center and at the National Institute of Technology Calicut, India.*

References:

1 Nikhil Kumar, Paweł Gruszecki, Mateusz Gołębiewski, Jarosław W. Kłos, and Maciej Krawczyk, *Exciting high-frequency short-wavelength spin waves using high harmonics of a magnonic cavity mode*, arXiv: 2311.14143v1 (2023).

HINGE STATES OF SECOND-ORDER TOPOLOGICAL INSULATORS AS A MACH-ZEHNDER INTERFEROMETER

A. Y. Chaou[1], P. W. Brouwer[1,2] and N. Sedlmayr[2]

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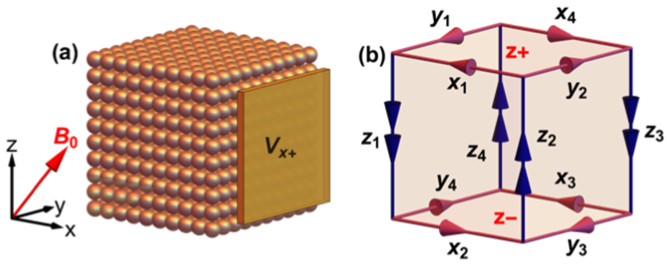
Three-dimensional higher-order topological insulators can have topologically protected chiral modes propagating on their hinges. Hinges with two copropagating chiral modes can serve as a “beam splitter” between hinges with only a single chiral mode. Here we show how such a crystal, with Ohmic contacts attached to its hinges, can be used to realize a Mach-Zehnder interferometer. We present concrete calculations for a lattice model of a first-order topological insulator in a magnetic field, which, for a suitable choice of parameters, is an extrinsic second-order topological insulator with the required configuration of chiral hinge modes.



Acknowledgements: *This work was supported by the Polish National Agency for Academic Exchange (NAWA) under the Grant No. PPN/BEK/2020/1/00338/DEC/2 and by the National Science Centre (NCN, Poland) by the Grant No. 2019/35/B/ST3/0362 (NS), and by the Deutsche Forschungsgemeinschaft Project No. 277101999—CRC TR 183 (Project A03) (A.Y.C. and P.W.B.).*

References:
[1] A. Yanis Chaou, P. W. Brouwer and N. Sedlmayr, Physical Review B, 107, 035430 (2023)

SHORT QUANTUM SPIN CHAINS IN QUANTUM INFORMATION PROCESSING

R. Stagraczyński[1] and T. Lulek[2]

[1] *Rzeszów University of Technology, Powstańców Warszawy 12, Rzeszów, Poland*

[2] *Adam Mickiewicz University Poznań, Uniwersytetu Poznańskiego 2, Poznań, Poland*

Spin chains are quantum integrable systems, that is, they dispose a complete set of basis states in the corresponding Hilbert space which are eigenstates of the Hamiltonian, the transfer matrix, or another operator characterizing a system. It provides a comfortable position for quantum engineers like Alice, Bob, etc., to perform several quantum operations on such systems. We aim to demonstrate it in the case of a magnetic hexagonal ring of N=6 qubits (i.e. dimH=26=64), where the so called basis of wavelets (the momentum Fourier transform) admits to store all necessary data within the set of some exact density matrices of the rank not larger than 4x4 [1].

References:

[1] T. Lulek, R. Stagraczyński, M. Łabuz, Separation of spherically and translationally covariant finite quntum spaces within the XXX model, Nuclear Physics B, 991, 116215(2023).

SOFTENING OF SPIN WAVES IN THIN MAGNETIC FILMS WITH PERPENDICULAR MAGNETIC ANISOTROPY

N. Leśniewski[1,2] and P. Gruszecki[1]

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The competition between long-range dipole interactions (which are anisotropic in nature) and short-range isotropic exchange interactions causes the dynamics of spin waves to be very complex compared to, for example, electromagnetic waves. Interactions that further enrich the propagation of spin waves are the perpendicular magnetic anisotropy (PMA) and the interfacial Dzyaloshinskii-Moriya interaction (iDMI). All of these interactions impact not only the propagation of spin waves, but also the magnetic configuration at low magnetic fields (below the critical bias field). An intriguing outcome of PMA's existence in uniformly magnetized thin ferromagnetic films is the emergence of a local minimum in the dispersion relation for a non-zero wave vector in the Damon-Eshbach configuration. The depth of this minimum increases as the bias magnetic field value decreases. This process is referred to as mode softening, and spin waves originating from this minimum in the dispersion relation are referred to as softened spin waves. Moreover, in films with PMA, there is a strong connection between softened spin waves and magnetization texture, since the wavelength of softened spin waves is equal to the period of the magnetic texture obtained after the phase transition between the uniformly magnetized film/stripe domain pattern (or spin spirals for films with large iDMI) [1].

Here we theoretically study the process of spin-wave mode softening and how it is affected by various parameters, in particular thickness, PMA, iDMI and damping. For example, we demonstrate and explain the physical mechanism of the reversal of the direction of precession of the magnetic moments on one of the surfaces of the film, which can occur for softened spin waves under certain conditions.

Acknowledgements: *We acknowledge the funding from the Polish National Science Centre project No. UMO-2019/33/B/ST5/02013.*

References:

[1] J. Kisielewski, P. Gruszecki, M. Krawczyk, V. Zablotskii, and A. Maziewski, Phys. Rev. B 107, 134416 (2023)

PURE DEPHASING OF LIGHT-MATTER SYSTEMS IN THE ULTRASTRONG AND DEEP-STRONG COUPLING REGIMES

S. I. Abo[1]

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The field of cavity quantum electrodynamics (CQED) holds great promise for studying strong inter- actions between light and matter. However, there is still a lot to be understood about pure dephasing in quantum systems, especially in the strong coupling regimes where new physical phenomena and quantum applications can arise.

In weak interaction scenarios, the difference in perturbation forms between the dipole gauge and the Coulomb gauge is often negligible. However, ignoring this difference can result in incorrect and unphysical outcomes in ultra-strong and deep-strong coupling regimes.

In this talk I will address this issue, focusing on calculating the pure dephasing rate in two different models: the quantum Rabi model and the Hopfield model. I will explain that the interaction in a light-matter system in ultra- strong and deep-strong coupling regimes can significantly impact the form of the stochastic perturbation that describes the dephasing of a subsystem, depending on the gauge that is adopted [1].

References:

[1] A. Mercurio, S. Abo, F. Mauceri, E. Russo, V. Macri, A. Miranowicz, S. Savasta, and O. Di Stefano, Pure Dephasing of Light-Matter Systems in the Ultrastrong and Deep-Strong Coupling Regimes, Phys. Rev. Lett. 130, 123601 (2023).

SENSITIVITY VERSUS SELECTIVITY IN ENTANGLEMENT DETECTION VIA COLLECTIVE WITNESSES

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We present a supervised learning technique that utilizes artificial neural networks to design new collective entanglement witnesses for two-qubit and qubit-qutrit systems. Deep-learned collective entanglement witnesses allow for continuous tuning of their sensitivity and selectivity. These witnesses are, thus, a conceptually novel instrument and allow us to study the sensitivity vs. selectivity trade-off in entanglement detection which is not accessible to previously deployed analytical witnesses. In particular we show that there exists experimentally relatively cheap (in the number of measurements) methods where the sensitivity can be significantly improved at a slight expense of selectivity of the entanglement detection. The chosen approach is also favored due to its high generality and potential for superior performance with regards to other types of entanglement witnesses. Our findings could pave the way for the development of more efficient and accurate entanglement detection methods in complex quantum systems, especially considering realistic experimental imperfections.

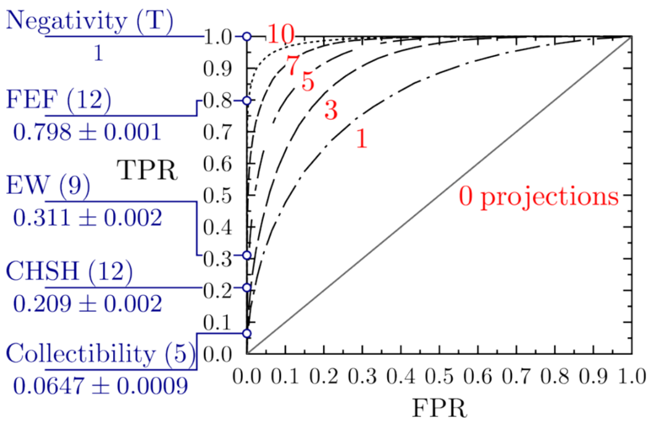

Fig. 1: Comparison of the ROC curves of CEW models for the two-qubit system. The vertical and horizontal axes of the graph represent the true positive rate (sensitivity) and false positive rate (fall-out), respectively. The number close to each curve indicates the length B of the feature vectors used during the training process. Note that for B = 0 the line is diagonal due to prevalence of 0.5. Additionally, we highlighted sensitivity values corresponding to prominent analytical entanglement measure (Negativity), Bell's inequality (CHSH) and witnesses (FEF, EW, Collectibility), where, the number in parentheses represent the number of measurement configurations required for calculation of a said quantity and the letter T represents a full quantum state tomography. It is worth noting that for the analytical entanglement measure, inequality and witnesses, the FPR = 0.

EXPOSING HYPERSENSITIVITY IN QUANTUM CHAOTIC DYNAMICS

A. Grudka[1], P. Kurzyński[1], A. S. Sajna[2], J. Wójcik[3] and A. Wójcik[1]

[1] *Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland*
[2] *2 Institute of Theoretical Physics, Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, 50-370 Wroclaw, Poland*
[3] *Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland*

We study hypersensitivity to initial state perturbation in unitary dynamics of a multi-qubit system [1]. We use quantum state-metric, introduced by Girolami and Anza in [2], which can be interpreted as a quantum Hamming distance. To provide a proof-of-principle, we take the multi-qubit implementation of the quantum kicked top, a paradigmatic system known to exhibit quantum chaotic behaviour. Our findings confirm that the observed hypersensitivity corresponds to commonly used signatures of quantum chaos. Furthermore, we demonstrate that the proposed metric can detect quantum chaos in the same regime and under analogous initial conditions as in the corresponding classical case.

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References:
[1] A. Grudka, P. Kurzyński, A. S. Sajna, J. Wójcik, A. Wójcik, arXiv:2307.14678 (2023)
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QUANTUM-COHERENT MANIPULATION AND DETECTION OF INDIVIDUAL ATOMIC SPINS WITH THE USE OF SPIN-POLARIZED STM

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Our objective is to formulate a theoretical description that enables to evaluate the conditions and results of modern experiments on electrical control of single spin dynamics in quantum dots (QD) in the presence of noncollinear magnetic electrodes or in spin-polarized STM of single atoms on a surface. Despite the fast-growing number of experimental works in this research area, the fundamental principles still remain unclear. In such setups one can observe a nonequilibrium spin accumulated on the quantum impurity (QD or atom on a surface), and also the effects due to virtual spin-dependent exchange processes between the impurity and ferromagnetic electrodes, which result in an effective exchange field [1-4] that can be controlled by the gate and bias voltages. We use the real-time diagrammatic technique and the Gorini-Kossakowski-Lindblad-Sudarshan (GKLS) equation approach, where we define effective jump operators for the system with noncollinearly magnetized electrodes. With these techniques we find a Bloch-like equation [2-4], which describe the complex spin dynamics in the presence of spin polarized current for various useful and important limits, both in the sequential and the cotunneling regimes. We demonstrate that the dc current is related to distinct projections of the induced spin, which allows for a single spin read-out locally by means of the electric transport measurements. Thus, the ferromagnetic electrodes can act effectively as spin detectors, that transform a spin information into a charge signal, while the readout direction can be controlled electrically by the gate voltage. These findings allow us to explain the tunnel magnetoresistance characteristics from the recent experiment [5], where the nonequilibrium spin transport in the canted quantum dot spin valve was studied and signatures of out of equilibrium spin precession, that are electrically tunable, were observed. We also predict a new type of the zero-bias anomaly that is related to both the switching of the spin detection direction at the zero bias and to the spin dynamics due to the exchange field. Moreover, using our model with a compact equations we can explain analytically experimental results [6-8] related to recent breakthroughs in spin-polarized STM that make it possible to probe and control the spin dynamics of individual atoms on a surface. We also suggest a series of transport experiments in such setups. For example, we show that the measurement of the Hanle effect can be used as a tool for determination of the local exchange field and the spin relaxation time from the dc current magnetoresistance measurements.

Acknowledgements: *Two of us (PB, DT) acknowledge support from National Science Centre, Poland, grant No. 2020/36/C/ST3/00539.*

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QUANTUM WALK WITH STOCHASTIC RESET

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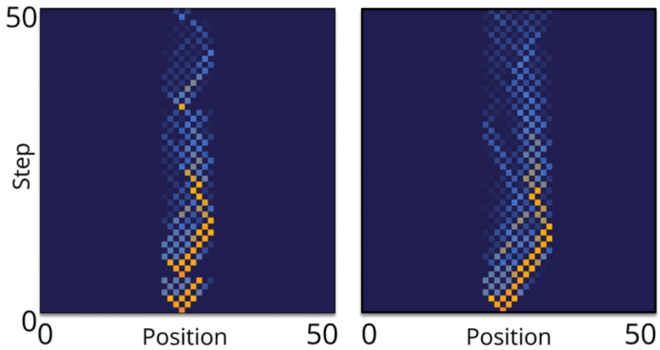
We focus our presentation on mean hitting time in the discrete-time quantum walks with stochastic reset. Quantum walks are periodically driven (Floquet) systems. Their discrete model due to its simplicity may be a very powerful tool while studying complex systems.

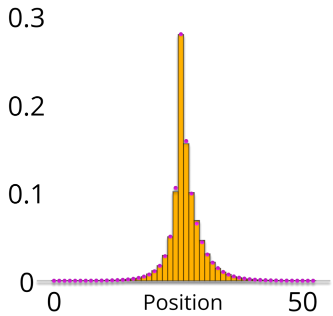
We investigate a model with an observer that constantly measures whether the particle is at one or two chosen positions. The mean hitting time in such a model is defined as the average time at which the observer will measure the particle.

We study now how the concept of stochastic reset can influence the mean hitting time. In the case of only one measured position, it is easy to show how the stochastic reset can boost the mean hitting time. However, in the case of two measured positions, the result is surprising.

Here we present the evolution of quantum walk with and without stochastic reset.



Lastly, we show the analytical solution for the probability distribution of a quantum walk with stochastic reset at the long time limit.



HAVING FUN WITH SIMULATIONS: ON NUMERICAL MODELLING OF CHARGE POPULATION DECAY IN PEROVSKITE SOLAR CELLS

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Charge population decay in perovskite solar cells in the timescales from single picoseconds to single nanoseconds is described with different processes as charge injection to transporting materials, charge diffusion, and first-, second-, and third-order charge recombination. The complexity of the charge population evolution makes the problem to be not fully solvable analytically.

The answer to this problem is numerical modelling. We prepared a numerical model in COMSOL Multiphysics to solve the differential equation for charge population decay in thin-film perovskite solar cells [1]. The results of simulations were used to fit the experimental data from broadband transient absorption measurements. Moreover, an in-depth analysis of the material parameters effect on the charge population decay rate was performed. We also propose a step-by-step method combining numerical modelling and experimental measurements which allows the determination of investigated material parameters.

Acknowledgements: *K.S. acknowledges the financial support from the Foundation for Polish Science (FNP).*

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LARGE VELOCITY APPROXIMATION TO THE DIGITIZED-COUNTERDIABATIC PROTOCOL IN SPIN SYSTEMS

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Precise and fast control of quantum systems before they decohere is an important task for current quantum technologies. The challenge of ensuring such control becomes especially difficult as quantum systems grow more complex. Efficient ground state preparation of many-body systems is one such challenge. By using the large velocity approximation to the standard digitized counterdiabatic protocol, we demonstrate that one can significantly reduce the circuit depth of the accelerated adiabatic protocol. As an application example, we achieve an almost twofold increase in the fidelity of the ground state preparation of the XXZ model on the IBM quantum computer. The present work highlights the importance of the large velocity limit of the counterdiabatic protocol family for noisy intermediate-scale quantum devices.

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NON-LINEAR SUBDIFFUSION DEFEATS ORDINARY DIFFUSION IN SHORTENING THE MEAN TIME OF REACHING A TARGET BY HARMONICALLY TRAPPED PARTICLE

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During the talk we present an unexpected paradox in the behavior of a harmonically trapped particle. This contradiction emerges from a comparison of the mean times downhill the harmonic potential for the ordinarily and nonlinearly diffusing particles. On the one hand it can be shown the non-linear (sub)diffusion occurring in the harmonic potential is slower than the normal (linear) diffusion in the same potential. This observation results from a comparison of the time courses of the mean square displacements for both processes. On the other hand, we demonstrate that the mean time to the minimum of the harmonic potential is shorter for the non-linear diffusion compared to the linear diffusion.

SPIN DYNAMICS IN MAGNETIC NANOJUNCTIONS —HYBRID QUANTUM-CLASSICAL APPROACH

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We will present our theoretical investigation of nonequilibrium phenomena within magnetic nanojunctions via a computational approach that combines classical spin dynamics with the hierarchical equations of motion technique for quantum dynamics of the conduction electrons [1]. Our focus will be on spin dynamics, particularly the charge driven spin damping. We will discuss a non-monotonic trend in spin relaxation rates relative to the coupling strength between localized spins and conduction electrons. Here a distinctive maximum at intermediate coupling strength is observed, which we attribute to a competition between the increasing influence of the coupling and the impact of diminishing local electronic density of states at the Fermi level.

In the context of a magnetic junction, i.e., nanodevice coupled to leads, subjected to an external DC voltage; we observe resonant features in the spin relaxation, reflecting the electronic spectrum of the nanodevice. The precession of classical spin gives rise to additional side energies in the electronic spectrum, which in turn, leads to a broadened range of enhanced damping in the voltage

We will further demonstrate that the spin dynamics of a large open system can be faithfully simulated using a short chain connected to simple semi-infinite metallic leads. We will show that the hybrid method with large spin approximates well the full quantum-mechanical solution and will briefly discuss its application to a more complex system, namely a spin valve with noncollinear magnetization [2].

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UNDERSCREENED KONDO CLOUD IN AN S-WAVE SUPERCONDUCTOR

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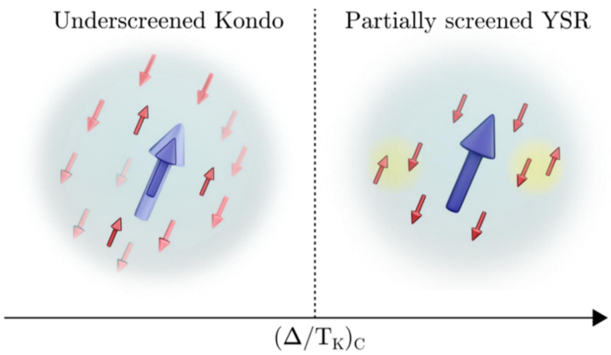
Magnetic impurities coupled to a band of conduction electrons generate a many-body correlated state known as the Kondo state. The correlations in the Kondo state extends to large length scales compared to the size of the impurity. In general, the quantum dots/magnetic impurities in such systems are usually of nanometers in size, where as the Kondo cloud has been predicted to extend up to micrometers and recent experiments have confirmed the presence of such large screening clouds. In the presence of superconducting correlations, such screening clouds have been shown to exist even outside the Kondo phase[1]



In this work, we study a large spin Kondo model coupled to an s-wave superconductor. We show that there exist an underscreened Kondo doublet to unscreened triplet phase transition according to the dominant energy scale, I.e, the Kondo energy scale or the superconducting band gap. We observe different behaviors of the screening in both of the phases predicted analytically by the renormalized perturbation theory(RPT) and confirmed numerically using the Numerical Renormalization Group(NRG) methods. The spatial extension of the correlations estimated from the equal-time spin-spin correlation function calculated using Density Matrix Renormalization Group (DMRG) corroborate the presence of screening clouds in both the phases. Moreover, the influence of the unscreened half-spin in the underscreened Kondo phase have also been unveiled in this work.

Acknowledgements: *This work has been supported by the Polish National Science Center through the grant No: 2021/41/N/ST3/02098*

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SPIN WAVE LOCALIZATION INDUCED BY SUPERCONDUCTING STRIP

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Eddy currents in a superconductor (SC) shield the magnetic field in its interior and are responsible for the formation of a magnetic stray field outside of the SC structure. The stray field can be controlled by the external magnetic field and affect the magnetization dynamics in the magnetic system within its range. In our work, we investigate theoretically and numerically the spin-wave (SW) confinement induced in a uniform magnetic layer by the stray field of a SC strip.

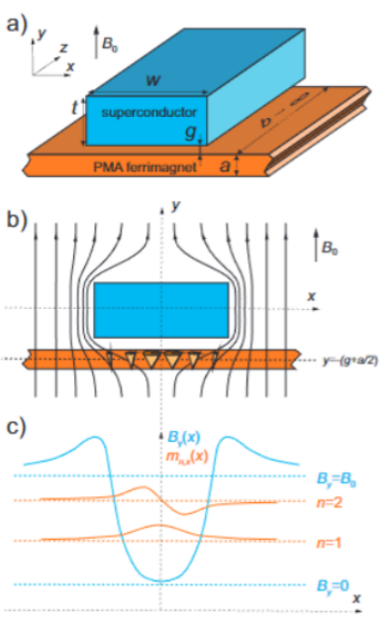

Fig.1. (a) A thin FM film (a = 20 nm) is exposed to the stray field of a rectangular SC strip (w = 400/800 nm, t = 100 nm). The FM and the SC are separated by a small gap (g = 10 nm). (b) The static internal magnetic field is lowered in the region of the FM underneath the SC strip. This leads to the confinement of SW modes, (c) which are quantized in the quasi-parabolic well of the internal field.

The considered hybrid system consists of Ga:YIG ferrimagnetic (FM) thin film and Nb SC stripe. (Fig. 1). According to the Meissner effect, a SC strip expels a magnetic field from its volume by means of eddy currents. These currents create a non-uniform distribution of the magnetic field in the FM film. The system is placed in an external magnetic field perpendicular to the FM layer. In Ga:YIG, the shape anisotropy is overcome by the out-of-plane anisotropy, leading to the magnetization being directed out of plane. Then, the stray field of SC induces the well of static effective field in the FM layer, which can confine the SWs of the frequencies lower than the FMR frequency of FM layer in the absence of SC stripe. Although, the stray field of SC strip results in the presence of weak magnetization texture induced in FM layer close to SC strip edges, stray field produced by such texture is small and can be neglected. Therefore, there is no need to take into account the mutual interaction between the FM layer and the SC stripe.

According to these assumptions, our studies were carried out in two stages. We first calculated the static stray field generated by the SC strip. It was determined from the distribution of SC currents, which was found by semi-analytical solution of the London equation [1]. The static field generated by SC stripe was then included as a correction to the effective field to Landau-Lifshitz (LL) equation, which was used to find the confined SW modes. The solutions of LL equation were found both semi-analytically [2] and numerically. We have shown that the applied field can tune the depth of the stray field well, and thus we can control the number and frequencies of the SW modes confined in the well (Fig.2).

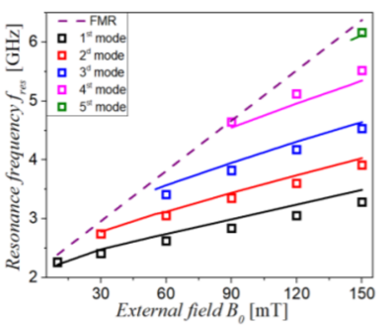

Fig.2 The dependence of the localized SW modes on the external magnetic field. The solid lines and square dots correspond to the semi-analytical theory and micromagnetic simulations respectively. Dashed lines show FMR frequency of homogeneous film.

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SIGNATURES OF KONDO-MAJORANA INTERPLAY IN AC RESPONSE

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In this contribution [1] we present the results concerning dynamical transport properties of a hybrid nanostructure, comprising a correlated quantum dot embedded between the source and drain electrodes, which are subject to an ac voltage, focusing on signatures imprinted on the charge transport by the side-attached Majorana zero-energy mode. The considerations are based on the Kubo formula, for which the relevant correlation functions are determined by using the numerical renormalization group approach, which allows us to consider the correlation effects due to the Coulomb repulsion and their interplay with the Majorana mode in a nonperturbative manner. We point out universal features of the dynamical conductance, showing up in the Kondo-Majorana regime, and differentiate them against the conventional Kondo and Majorana systems. In particular, we predict that the Majorana quasiparticles give rise to universal fractional values of the ac conductance in the welldefined frequency range below the peak at the Kondo scale. We also show this Kondo scale to actually increase with strengthening the coupling to the topological superconducting wire.

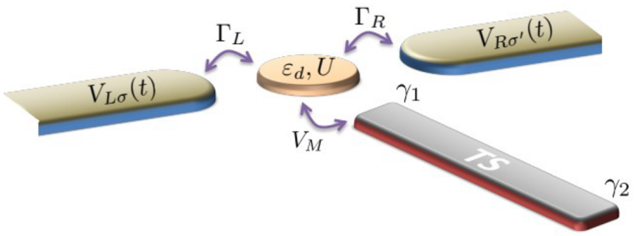

Fig. 1: Schematic illustration of the considered system.

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ULTRAFAST X-RAY INDUCED MAGNETIZATION DYNAMICS IN Co AND Ni

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We investigated the role of electronic excitation, relaxation and transport processes in X-ray induced ultrafast demagnetization of magnetic single- and multilayer systems. In what follows, we report on the results obtained with the newly developed modeling tool, XSPIN, which enables nanoscopic description of electronic processes occurring in X-ray irradiated ferromagnetic materials [1,2]. With this tool, we have studied the specific response of cobalt/platinum (Co/Pt) multilayer system irradiated by an ultrafast XUV pulse at the M-edge of Co (photon energy around 60 eV) and the response of cobalt/palladium (Co/Pd) multilayer system at the L-edge of Co (photon energy around 778 eV) [1,2]. Those were previously studied experimentally at the FERMI and LCLS free-electron facilities respectively [3,4]. The XSPIN simulations show that the magnetic scattering signal from cobalt decreases on the femtosecond timescales considered due to electronic excitation, relaxation and transport processes both in the cobalt and in the non-magnetic layers. The signal decrease scales with the increasing fluence of incoming radiation, following the trend observed in the experimental data. Confirmation of the predominant role of electronic processes for X-ray induced demagnetization in the regime below the structural damage threshold, achieved with our theoretical study, is a step towards quantitative control and manipulation of X-ray induced magnetic processes on femtosecond timescales.

Additionally, we describe with XSPIN simulations the demagnetization observed in a single layer of nickel (Ni) [5], and present a more comprehensive extension of the XSPIN code, XSPIN+, which takes into account atomic movement and changing band structure predicted with density functional tight binding (DFTB) formalism.

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IMAGINARY TIME DYNAMICS IMPACT ON STRONGLY CORRELATED BOSON SYSTEMS

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Open many body quantum systems play a paramount role in various branches of physics, such as quantum information, non-linear optics or condensed matter. The dissipative character of open systems has gained a lot of interest especially within the fields of quantum optics, due to unprecedented stabilization of quantum coherence, and quantum information, with its desire to control environmental degrees of freedom. We look beyond the typical mechanism of dissipation associated with an external source and show that strongly interacting many particle systems can create quantum decoherence within themselves. We study a quantum bosonic two-dimensional many body system with extended interactions between particles. Analytical calculations show that the system can be driven out of its coherent state, which is prevalent among commonly used setups. However, we also observe a revival of the superfluid phase within the same framework for sufficiently large interaction strength. The breakdown of quantum coherence is inevitable, but can be misinterpreted if one assumes improper coupling between the constituents of the many particle system. We show an adequate path to retrieve physically relevant results and consider its limitations. The system displays a natural cutoff that enforces the breakdown of superfluidity.

DEFECT-INDUCED CHANGES IN THE PROPAGATION OF SPIN WAVES IN FERROMAGNETIC WAVEGUIDE

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A significant amount of research has been conducted on magnetization dynamics within nanostructures in recent decades in the field of nanomagnetism. This has resulted in the discovery of new effects, the development of various applications, and the identification of promising new directions such as magnonics, which focuses on studying the dynamics of spin waves and their potential applications.

As a part of our study, we conducted micromagnetic simulations of a waveguide-defect system to investigate how the size and placement of circular defects affect propagating spin waves and their transmission. Simulations were performed on a 768 nm wide Py waveguide with a defect diameter between 50 and 400 nm and a vertical displacement from the center of the waveguide every 50 nm towards the edge. To excite all frequencies, a broadband source was used.

It has been found that displacement and size changes have different effects on the transmission of spin waves in waveguides. Using the transmission spectrum for the waveguide with varying sizes and displacements of the antidot defect, we distinguished three main areas. (i) In the low-frequency range up to 5 GHz, corresponding to the FMR frequency, we observe a change in the maximum frequency of the transmitted wave with a change in the diameter of the antidot defect. As the defect moves toward the edge, the transmittance of spin waves at low frequencies increases. These relationships can be used as a spin wave filtering at low frequency part of the spectra. (ii) In the range from 5 to 12 GHz, the resonance effects with multiple transmission maximums and minimums are observed which can be controlled by the defect placement. This interesting relationship shows the ability of using the system for controlling transmission channels. (iii) As the size and displacement from the center of the defect increase, the transmission amplitude decreases monotonously in high-frequency ranges above 12 GHz.

Our findings suggest that creating a defect in a waveguide is a viable method of controlling spin wave propagation, making it a promising technique for various applications, as a filters or demultiplexers.

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EXPERIMENTAL HIERARCHY OF THE NONCLASSICALITY OF SINGLE-QUBIT STATES VIA POTENTIALS OF ENTANGLEMENT, STEERING, AND BELL NONLOCALITY

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Entanglement potentials are a promising way to quantify the nonclassicality of single-mode states. They are defined by the amount of entanglement (expressed by, e.g., the Wooters concurrence) obtained after mixing the examined single-mode state with a purely classical state; such as the vacuum or a coherent state. We generalize the idea of entanglement potentials to other quantum correlations: the EPR steering and Bell nonlocality, thus enabling us to study mutual hierarchies of these nonclassicality potentials [1]. We test this concept on the platform of linear optics by combining our multi-purpose single qubit decoherence channel [2] with a tubable two-qubit interaction gate. This experimental setup allows to observe a wide variety of effects in accordance with theoretical predictions [3]. Instead of the usual vacuum and one-photon superposition states, we experimentally test this concept using specially tailored polarization-encoded single-photon states. One polarization encodes a given non-classical single-mode state, while the other serves as the vacuum place-holder. This technique proves to be experimentally more convenient in comparison to the vacuum and a one-photon superposition as it does not require the vacuum detection.

Acknowledgements: *J.K. gratefully acknowledges the support from the project IGA_PrF_2023_005 of Palacky Universit*

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SPIN CROSS-CORRELATION MEASUREMENTS OF ENTANGLED ELECTRONS IN QUANTUM DOT COOPER PAIR SPLITTERS

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More than a decade has passed since the first implementation of Cooper pair splitting (CPS) consisting of a superconducting electrode tunnel-coupled with a double quantum dot system [1-3]. However, it had still not been possible to experimentally confirm that the electrons from the Cooper pair separated in this way retain their quantum entangled state. We proposed a theoretical model of a relatively simple experiment that would allow this to be clearly stated [4,5]. The theoretical proposals so far were based in particular on measurements of current correlations (current noise), which is difficult to achieve for today's hybrid systems. We explored a general model of the CPS coupled to two spin-polarized or ferromagnetic detectors converting spin information into charge information. We demonstrated that it is also possible to determine spin correlation by dc current measurements in this system, which is much simple than current correlation measurements. In series of recent experimental works [6-8] for the first time the direct measurement of the spin cross-correlations between the electron currents of CPS has been reported using the dc current measurements as suggested in previous theoretical papers [5,9]. In one of experiments authors use ferromagnetic split-gates [6], compatible with nearby superconducting structures, to individually spin polarize the transmissions of the quantum dots in the two electronic paths, which act as tunable spin filters. In another experiments, single and triplet pairing between spin-polarized quantum dots is measured, where this pairing is proximity-induced from an s-wave superconductor into a semiconducting nanowire [7] or a semiconductor two-dimensional electron gas (2DEG) [8] both with strong spin–orbit interaction. In these experiments [7,8] the presence of a magnetic field turns the dots into effective spin-filters that allows to obtain information about the spin of the electrons forming the Cooper pair also from the direct current measurements. Using these possibility of spin correlation measurements we in turn propose some next steps: an entanglement test based on the Bell inequalities [4,5] and the entanglement witness approach [4,8].

Acknowledgements: *Two of us (PB, DT) acknowledge support from National Science Centre, Poland, grant No. 2020/36/C/ST3/00539.*

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THEORETICAL APPROACHES TO CORRELATED QUANTUM DOTS COUPLED TO SUPERCONDUCTING LEADS

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I will present a brief overview of relatively simple theoretical approaches developed in our Prague group in past several years and applied to the problem of description of correlated quantum dots attached to the BCS superconducting leads. As a thorough Quantum Monte Carlo analysis [1] of the experimental data [2] showed realistic experimental setups can be even quantitatively captured by the Single Impurity Anderson Model (SIAM) with superconducting leads. Pioneering semi-analytical approaches have not matched the so far employed heavy numerical tools such as Numerical Renormalization Group (NRG) and/or Quantum Monte Carlo (QMC) in the ability of quantitatively predicting the properties of this model. However, we have shown recently that self-consistent perturbation expansion up to the second order in the interaction strength [3,4] yields at zero temperature and for a wide range of other parameters excellent results for the position of the 0 - π impurity quantum phase transition boundary and the Josephson current as well as the energy of Andreev bound states in the 0-phase. This method can be also extended to the three-terminal situation with an extra normal lead corresponding to the experimentally interesting STM setup [5], where it allows to study phase-dependent Kondo physics. Furthermore, we have discovered exact identities connecting symmetric and asymmetric coupling situations which significantly reduce computational requirements in experimentally generic asymmetric setups [6] and provided simple approximate analytical formulas for the fitting of the phase boundaries from finite-temperature experimental data [7]. I will also briefly mention an exact mapping of a half-filled superconducting SIAM onto a normal SIAM with a structured semiconducting lead which simplifies some technical aspects of its NRG solution significantly [8,9] and a simple way of determination of the quantum critical point from finite-temperature QMC statistics [10]. Finally, the most recent extensions of those methods to more quantum dots [11] or superconducting leads [12] will be mentioned.

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BLOCKADES IN OPTICAL AND OPTO-MECHANICAL SYSTEMS

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Photon blockades are the bosonic analogues of well known Coulomb blockades for electrons. Systems in which photon blockades appear may be used for example as perfect single (or two) photon sources due to the fact that generation of one (or two) photons blocks generation of more photons in the same system. For succesful blockades a presence of nonlinearity is necessary.

We will show that one of the possible sources of nonlinearity may come from the interaction with squeezed reservoir. Nonlinearity is also responsible for generation blockades and other effect related to quantum correlations in hybrid modes of opto-mechanical system. Possible improvement of two-photon blockade via quantum interference within a cavity with many emitters will also be mentioned.

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PROXIMITY INDUCED ELECTRON TRANSFER IN HYBRID MOLECULAR MAGNETS

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Molecular magnets have been synthesized in the last decades in the hope of finding practical application in quantum computing or molecular electronics and to investigate quantum effects in nanoscale. Their properties are determined by the type of magnetic ions and the molecular structure in which they are incorporated. Hybrid molecular magnets comprise at least two different types of magnetic molecules coupled with each other, which should lead to new interesting properties and applications.

In this contribution we present magnetic and electronic properties of a family of hybrids $(PcLn)_n$-$V_{12}O_{32}$ (n=1,2) consisting of a vanadium core $V_{12}O_{32}$ coupled covalently to a phtalocyaniato lanthanide moiety (LnPc). By using combined experimental (EPR, DC and AC SQUID) and theoretical (DFT, MD and model Hamiltonian approach) methods it is demonstrated that the proximity of the molecules in solid state and in concentrated solutions induces partial reduction of V^{5+} centers due to the electron transfer from Pc to $V_{12}O_{32}$. The intramolecular (through Ln) and intermolecular (through counter cations) electron transfers can coexist in different proportions dependent on Ln. As a result an unpaired electron can be found delocalized over $V_{12}O_{32}$ and/or at Pc. The research is carried out for Ln=Sm^{3+} - Er^{3+} and diamagnetic Lu^{3+} and Y^{3+}, but we focus mainly on molecules with n = 1 and Ln=Lu^{3+} or Ln=Dy^{3+} for which all the effects can be clearly demonstrated. The Dy^{3+} based hybrid appears to be also a field induced single molecule magnet with a slow relaxation time of order 10^{-3} s. It has been also proven that there is an interaction between a radical electron and Dy^{3+}.

Our results open the way to further investigation of such hybrids, e.g. in electric field, which can pave the way to their application in molecular electronics or spintronics.

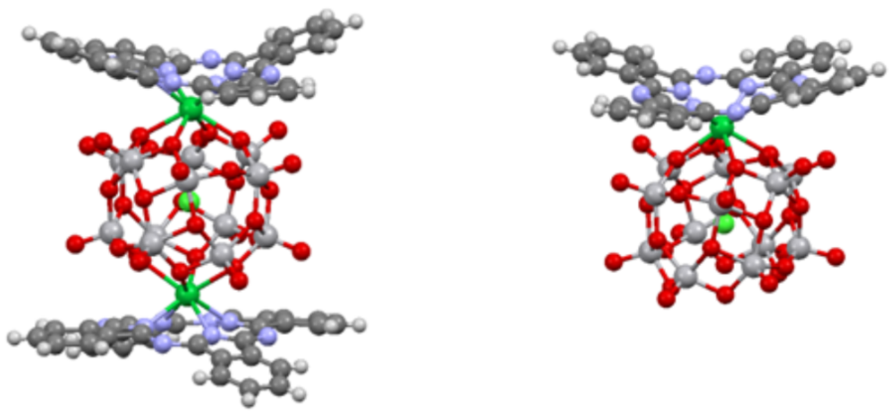

Fig. 1: Hybrid molecular magnets $(PcLn)_n$-$\{V_{12}O_{32}\}$ consisting of vanadium core and one (n=1) or two (n=2) PcLn moieties.

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MULTIMODAL WAVEGUIDE FOR SPIN WAVES BASED ON A MAGNONIC BRAGG MIRRORS

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Information can be transmitted through either charge transport or wave phenomena. Wave-based technologies offer an alternative to power-consuming but easy-to-build electrical devices. Magnonics is a wave technology that utilizes spin-wave propagation and is considered promising due to its capability to reduce Joule heating and enable the reconfigurability of magnonic devices [1]. A core element, essential to the construction of magnonic devices and circuits, is the waveguide.

In this study, we focused on developing a multimodal waveguide that enables the propagation of spin wave modes. Bragg mirrors, operating in frequency gaps, are widely used in optical waveguides [2]. Here, we propose the magnonic equivalent of this type of waveguide. We utilized a CoFeB layer as a conductor for spin waves. The surface anisotropy was applied periodically on the top and bottom faces of the layer, creating a pair of Bragg mirrors that confine the spin waves in a channel (waveguide) between them. The width of the frequency gaps relies strictly on the strength of the surface anisotropy and the film thickness. However, using too thin layer to create such a device is not possible, since the value of the group velocity decreases as the layer becomes thinner. The interplay of these parameters allows for the design of a waveguide that supports strongly confined modes that propagate with high group velocity. The proposed design is simple (requiring only the periodization of non-magnetic materials) and resolves the issue of unwanted edge modes induced by demagnetizing effects.

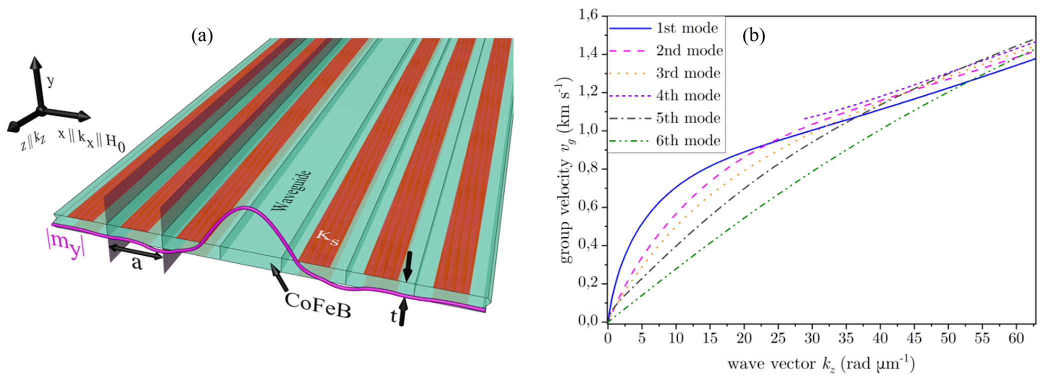

Fig. 1: (a) On the top and bottom face of the CoFeB layer (of the thickness $t = 6$ nm), we applied the surface anisotropy (K_S=1.05 mJ/m^2) in the periodically repeated (a = 100 nm) areas (red stripes of width 50 nm). These periodic patterns form the pair of Bragg mirrors which confine the spin wave modes (magenta profile) in the waveguide. (b) The group velocity (v_g) of the spin wave modes propagating along the waveguide, is shown as a function of the wave vector (k_z). The 4th mode is plotted for k_z>28 mm^{-1}, since for smaller values of k_z, the mode is not confined by Bragg mirrors.

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MULTI-TERMINAL INTERACTING-QUANTUM-DOT-BASED DEVICES

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Recent breakthroughs in experimental physics pave the way for the creation of intricate nanoscale devices featuring three or more superconducting electrodes. Such multi-terminal systems differ markedly from conventional two-lead Josephson junctions due to the supercurrent distribution into the constituent terminals. Exerting full phase-control leads then to a multitude of practical applications.

In this talk, we explore the potential for using nanowires or carbon nanotubes in the central scattering region to enhance the existing functionalities via the underlying quantum phase transitions. Our findings, as elucidated in [1], lay the foundation for purely phase-controlled superconducting transistor and diode effects in three-terminal systems even in the absence of inter-lead couplings. Proceeding with more complex architectures requires, however, development of new Numerical Renormalization Group (NRG) methods to accommodate arbitrary gapped tunneling densities of states. This critical development, recently detailed in Ref. [2], significantly expands our theoretical understanding, particularly in devices incorporating topological effects.

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SPIN-WAVE BEAM INELASTIC SCATTERING ON LOCALIZED MODES FOR SPIN-WAVE BEAM FREQUENCY AND TRAJECTORY CONTROL

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A spin wave (SW) is a fascinating research object and a potential information carrier. One of the properties of SWs is that their dynamics allows for easy access to nonlinear phenomena, e.g., confluence and stimulated splitting processes. Here, we examine the interaction between an incident SW beam and SW modes localized in the vicinity of the ferromagnetic film's edge. During nonlinear interactions between the incident SW beam and the localized modes, new beams with shifted frequencies appear due to confluence and stimulated splitting processes, see Fig 1. Here, we use two different approaches to obtain localized SWs, i.e., (i) using the demagnetizing field about the film's edge [1] and (ii) placing a ferromagnetic strip directly over the edge of the film. In the second approach, we employ a magnonic Gires-Tournois interferometer [2,3], which influences the localized mode properties depending on the interferometer's geometry and, thereby, allows access the modes that differ in quantization by the strip's width. The result is two additional primary beams whose frequencies are lowered and raised relative to the incident beam by the frequency of the localized mode resulting from the stimulated splitting and confluence processes, respectively. In our investigation, we compare the efficiency of the inelastic scattering processes for both types of mode's localization and investigate the lateral displacement of inelastically scattered SW beams' along the interface, see the inset in Fig 1. This phenomenon is an SW analog to the Goos-Hänchen effect for inelastically scattered beams [4]. In both cases of mode localization, we show that the stimulated splitting process has higher efficiency than the confluence process. Moreover, we demonstrate that the lateral shift of the inelastically scattered beams depends on the edge mode frequency. Our research provides a better understanding of nonlinear processes involving SW and may open new avenues for the development of magnonic systems using nonlinear SW dynamics.

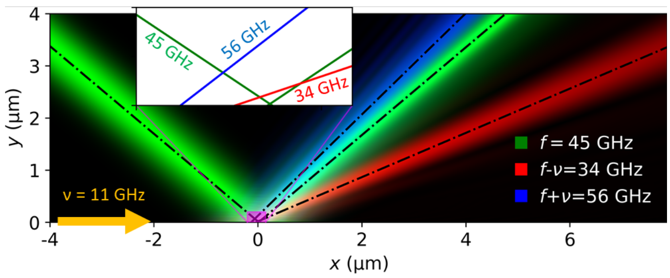

Fig. 1: Example of the inelastic scattering of a SW beam (frequency 45 GHz, green color) on an edge mode (frequency 11 GHz, orange color). The inelastic scattering results in creation of two new SW beams with new frequencies, 32 GHz (stimulated splitting process, red color) and 56 GHz (confluence process, blue color). The new beams are also shifted spatially at the interface as shown in the inset.

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JOSEPHSON JUNCTIONS: PLATFORM FOR EXOTIC SUPERCONDUCTING PHASES

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We consider various heterostructures with conventional superconductors interconnected through nanoscopic samples where, by the proximity effect, on can induce exotic forms of electron pairing. In particular, the setup comprising metallic strip embedded into planar Josephson junction allows for realization of the topological superconductivity. We investigate its spectroscopic properties manifested by the zero-energy boundary modes, propose feasible means for their detection by the spin-selective Andreev spectroscopy and consider the localization effects driven by inhomogeneities or defects[1]. Topological phase is also self-sustained when classical magnets are brought in contact with superconducting substrates [2,3]. Other promising platforms are related with the superconducting diode discovered in van der Waals heterostructures, where the superflow of Cooper pairs is restricted solely to one direction [4], novel devices based on phase engineering of the anomalous Josephson effect from Andreev molecules [5] and superconducting nanostructures out of equilibrium.

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EDGE AND INTERFACE MODES IN 1D ARTIFICIAL CRYSTALS

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The adiabatic change of the wave vector in the momentum space leads to the acquisition of a geometrical phase. This phase, calculated on a closed loop, is a topological parameter. In a 1D system, a loop for the geometric phase can be realized by sweeping the wave number over the 1st Brillouin zone. To close the loop, we take advantage of the properties the Bloch function in reciprocal space. Such phase is called Zak phase [1]. It characterizes each band of a 1D crystal and allows to relate the topology of the band structure to the existence of surface/interface modes. The concept of the Zak phase, originally introduced for electronic states, can be actually used for any kind of system where the stationary wave excitations are the solutions of a linear differential equation with periodic coefficients, i.e. expressed as Bloch functions. Therefore, the bulk edge correspondence can be studied for 1D artificial crystals based on different physical platforms, e.g. for photonic, phononic, plasmonic crystals, etc.

In this work, we discuss two separate problems concerning the edge/interface modes in 1D microwave systems with centrosymmetric unit cell, where the Zak phase takes only the values 0 or π:

1) the topological criteria for the existence of interface modes at the junction of two planar magnonic crystals (joined at the symmetry point) [2],

2) the non-existence of edge modes in a 1D microwave photonic crystal realized as a microstrip of modulated width (terminated at symmetry points).

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LOW-ENERGY MODEL FOR SUPERCONDUCTING IMPURITY SYSTEMS

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We present a method to extract the Andreev bound state (or Yu-Shiba-Rusinov state) energies of a magnetic impurity coupled to superconducting leads from imaginary-time results of the hybridization-expansion quantum Monte-Carlo method without the use of any ill-defined analytic continuation technique like the maximum entropy method. We describe the system using the superconducting impurity Anderson model and show that for low energies it maps on an atomic-like model. The relation between the parameters of the original and the low-energy model model can be determined from the low-frequency behavior of the self-energy calculated using the quantum Monte Carlo. We compare the results to zero-temperature numerical renormalization group data to show the limits of usability of the presented low-energy model [1]. This method can be also trivially extended to multi-level systems.

Acknowledgements: *This work was supported by Grant No. 23-05263K of the Czech Science Foundation.*

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GENERATION OF CURRENT IN A QUANTUM DOT HYBRID SYSTEM COUPLED TO TOPOLOGICAL SUPERCONDUCTOR

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We investigate theoretically the out-of-equilibrium transport properties of a single-level quantum dot coupled to a normal metal electrode and attached to a topological superconductor. Both voltage and thermal bias responses of the system in the nonequilibrium regime are studied. To obtain transport characteristics we used the nonequilibrium Green's function approach. Particularly, we calculated current and the corresponding differential conductance in two distinct cases. In the former situation, the charge current is induced by applying a bias voltage, whereas in the latter case it is generated by setting temperature difference between the leads with no bias voltage.

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ENHANCING COLLECTIVE ENTANGLEMENT WITNESSES THROUGH CORRELATION WITH STATE PURITY

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Collective quantum measurements [1], which are measurements performed simultaneously on multiple copies of the investigated state, are an invaluable tool in quantum state analysis and were instrumental in practical implementation of several entanglement witnesses [2] and in inferring quantum state purity or fidelity [3]. The key advantage of these measurements lies in the projection of subsystems from different copies of the examined state onto a common entangled state (see nonlocal projection in the conceptual diagram in Figure 1). Thanks to these nonlocal projections, collective measurements outperform ordinary single-copy measurements in terms of sensitivity (e.g., the volume of detected entangled states [4]) or in the efficiency in achieving set tasks with fewer measurements [5].

We analyse [6] the adverse impact of white noise on collective quantum measurements and argue that such noise poses a significant obstacle to the otherwise straightforward deployment of collective measurements in quantum communications. This effect was documented on the example of collectibility loosing the capability to detect entangled Werner states when noise level exceeds 13%. We then suggest addressing this issue by correlating the outcomes of these measurements with quantum state purity. To test the concept, a support vector machine is employed to boost the performance of several collective entanglement witnesses by incorporating state purity into the classification task of distinguishing entangled states from separable ones. Our findings indicate that the range of detected entangled states can be expanded by a significant percentage at a minimal cost in sensitivity. Furthermore, targeting several sensitivity values and identifying the corresponding selectivity (or true positive rate) allows us to reconstruct the entire receiver operating characteristic (ROC) curve, evaluating the method's effectiveness in terms of the area under this curve (AUC).

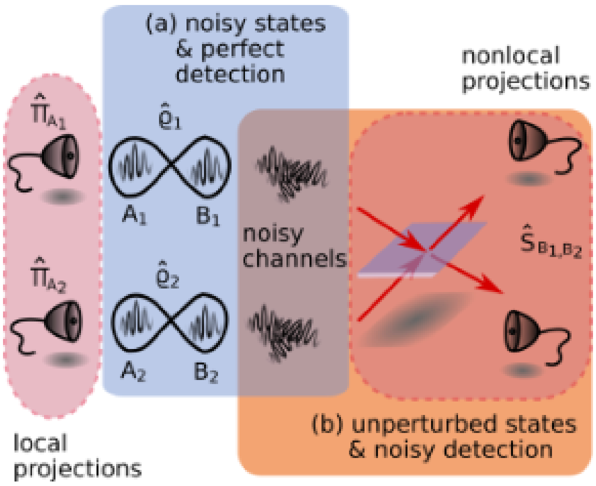

Fig. 1: Conceptual scheme of collective measurement with 1 nonlocal projection. Imperfections in the setup can be modelled by insertion of two noisy channels. The effect of these channels can be described by two equivalent strategies: (a) the two states become noisy while the nonlocal measurement remains perfect or (b) perfect unperturbed states are subject to imperfect nonlocal projection.

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TOPOLOGICAL SUPERCONDUCTIVITY IN ONE-, QUASI-ONE- AND TWO-DIMENSIONAL SPIN STRUCTURES

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We study the temperature-dependent self-organization of magnetic moments coupled to itinerant electrons in finite-size low-dimensional nanostructures proximitized to a superconducting reservoir. In a one-dimensional system, an effective Ruderman-Kittel-Kasuya-Yosida-type interaction between localized magnetic moments mediated by itinerant electrons leads, at low temperatures, to their helical ordering. This ordering, in turn, affects the itinerant electrons, inducing a topologically nontrivial superconducting phase that hosts Majorana end mods. The same mechanism can induce topological superconductivity also in a ladder and in finite-width systems, though in these cases self-organized spin structures can be much richer than a simple helix.

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NONLINEAR CONDUCTIVITY AND VORTEX DYNAMICS IN SUPERCONDUCTOR MgB_2 FILMS

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Knowing the maximal vortex velocities is essential for assessing the energy relaxation mechanisms in superconductors and their applications in superconducting single-photon detectors (SSPDs) [1]. These devices offer some of the best properties among all available single photon detectors [2]. The dynamics of vortices at a few km/s velocities is furthermore interesting of itself, because of the question regarding the ultimate speed limits for magnetic flux transport in superconductors and generation of sound and spin waves in heterostructures [3]. Here, we investigate the current-voltage curves of single crystal MgB2 thin films which have a comparably high critical temperature of around 30 K [4] and are interesting as potential materials for SSPDs. In the regime of nonlinear conductivity, we investigate the escape of non-equilibrium electrons from the vortex cores and compare the associated relaxation time of quasiparticles for MgB_2 films of different structural quality and capped with a good-conductor (Au) layer. The deduced parameters are discussed in the context of crossover from global to local instability models and the application of MgB_2 films in SSPDs [5].

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BREAKING THE EQUIVALENCE BETWEEN LEP AND HEP IN A SEMICLASSICAL SYSTEM

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Exceptional points (EPs) are points in a parameter space, for which at least two eigenvectors of a matrix coalesce. There are many novel phenomena in vicinity of EP, because eigenvalues of the matrix coincide in EP in a non-linear way. EP can appear only in a non-Hermitian matrix, and therefore, quantum systems described by non-Hermitian Hamiltonians have recently attracted growing attention. EP calculated from a non-Hermitian Hamiltonian is called Hamiltonian exceptional point (HEP). It has recently been pointed out [1] that a Liouvillian superoperator, which describes evolution of an open quantum system taking into account also quantum jumps, can also be represented as a non-Hermitian matrix, and therefore, it is possible to calculate EP also from Liouvillian (LEP). It has been shown that LEP is placed in the same point as HEP for semiclassical systems. Such a semiclassical system is, for example, two linearly coupled dissipative quantum oscillators [1]. Here, we show that the position of HEP is moved away from the position of LEP if the semiclassical system is placed in a thermal environment [2].

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DETECTION OF PARAMETRICALLY PUMPED SPIN WAVES BY MIE-ENHANCED BRILLOUIN LIGHT SCATTERING

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Spin waves have the potential to play a key role in the future of information technology as they can carry information with minimal energy losses. When it comes to integrated logic devices, it is generally most desirable to shrink them down to the nanoscale. This enables more devices to be put on a single chip, resulting in increased computational power. For optimal performance in nanoscale devices, the information-carrying wave must have a short wavelength. However, finding an efficient source of such spin waves is still challenging. Parametric pumping seems to be a promising method of selective excitation and amplification of short-wavelength spin waves [1, 2]. The advantage of this approach is that the accessible wavevectors of excited spin waves is not determined by the antenna geometry but instead by a threshold excitation power coming through it. This allows for a selective excitation of spin waves across a wide spectrum of wavevectors.

We investigate the excitation of short wavelength spin waves by parametric pumping using an induction antenna and subsequent dynamics in a thin ferromagnetic layer. To analyse the spin waves, we utilize a Mie-enhanced micro-BLS, which allows us to increase the detection limits [3, 4]. We observed parametrically pumped spin waves and explored their frequency dependence of threshold power. The Mie-enhanced measurements also revealed a broader spin wave spectrum, which could be possibly caused by nonlinear effects (see Figure 1). These exciting observations stimulate new subjects of interest for upcoming research.

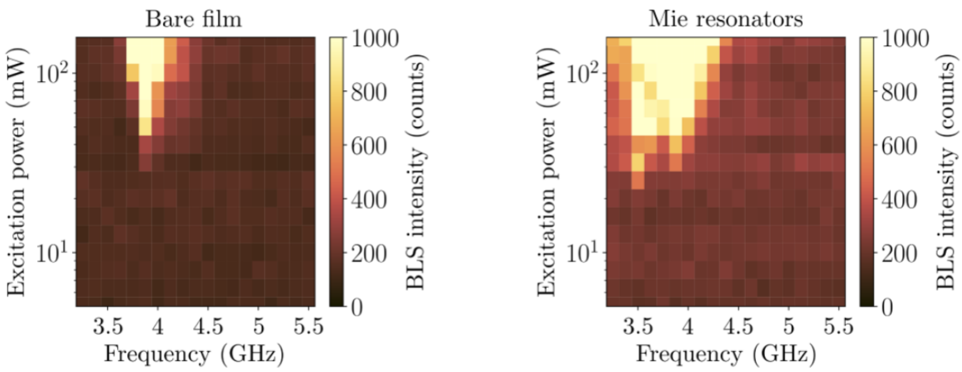

Fig. 1: Micro-BLS measurements where an intensity of parametrically pumped spin waves with certain frequency was measured for different excitation powers. We compare measurements done on a bare thin ferromagnetic film (on the left) and on a dielectric Mie resonators (on the right). One can see that the spin waves are excited only from a certain threshold value of the excitation power which is frequency dependent. Also, a broadening of the detection spectrum when utilizing the Mie resonators is clearly visible.

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EFFICIENT SPIN TRANSPORT IN COMMERCIAL CHEMICAL VAPOR DEPOSITED GRAPHENE

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Over the past two decades, utilizing spin currents that are streams of spin-polarized up or down electrons has revolutionized computer memory storage. This advancement, driven by the giant and tunnel magnetoresistance effects, has propelled the information technology era forward significantly. Graphene, a remarkable two-dimensional crystal, stands out as an exceptional platform for transporting spin-polarized electrons, enabling spin communication across impressive distances, even exceeding tens of microns at room temperature [1]. In this presentation, I aim to delve into spin transport in graphene on alternative substrates. Specifically, I will explore how the exceptional resilience of graphene can be utilized to create flexible spin circuits, showcasing the potential for highly effective spin transport over bendable substrates for the first time [2]. Moreover, our research has uncovered an extraordinary spin communication span of 45 μm and achieved the longest recorded spin diffusion length of 13.6 μm in graphene on SiO_2/Si at room temperature [3]. This comprehensive demonstration of high-performance spin transport not only underlines the significance of commercial polycrystalline CVD graphene for spintronics but also opens doors for exploring novel functions of spin currents and developing large-scale spin-computing circuits in practical research and development.

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UNIDIRECTIONAL PROPAGATION OF ZERO-MOMENTUM MAGNONS IN SYNTHETIC ANTIFERROMAGNETS

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Synthetic antiferromagnets (SAFs) recently attracted a lot of attention in the magnonics community, as they can provide additional degrees of freedom for spin wave dispersion engineering compared to conventional ferromagnetic systems [1],[2]. One of the most prominent features of dispersion relation in SAFs is non-reciprocity caused by the dipolar field interaction between the layers [3]. Spin wave non-reciprocity and symmetry breaking in material systems are of fundamental interest and can also be exploited in practical magnonic applications, such as diodes or circulators. We report on experimental observation of unidirectional propagation of zero-momentum magnons in synthetic antiferromagnet consisting of strained CoFeB/Ru/CoFeB trilayer [4]. Inherent nonreciprocity of spin waves in synthetic antiferromagnets with uniaxial anisotropy results in smooth and monotonous dispersion relation around Gamma point (see Figure 1b), where the direction of the phase velocity is reversed, while the group velocity direction is conserved. The experimental observation of this phenomenon by intensity-, phase- (see Figure 1c,d), and time-resolved Brillouin light scattering microscopy is corroborated by analytical models and micromagnetic simulations. The unusual dispersion relation offers many possibilities for further investigations of e.g., propagation of wavepackets with bidirectional phase velocities, or spin wave accumulation on domain boundaries. In practical applications such unidirectional system can pave the way towards designing new non-reciprocal elements for signal processing and unconventional spin-wave computing.

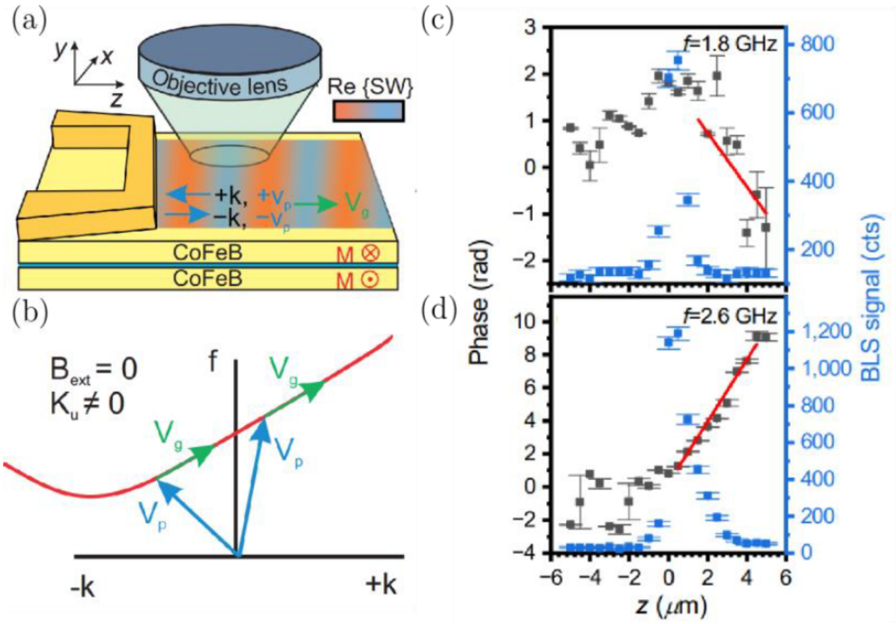

Fig. 1: (a) Schematics of the experiment and unidirectional excitation of spin waves with positive and negative wavevectors. (b) Due to the linear dispersion, the group velocity direction is not changed upon the reversal of wavevector direction. (c,d) Phase velocity reversal upon Γ point crossing. Spin-wave intensity (blue squares) and spin-wave phase (black squares) at 1.8 GHz and 2.6 GHz.

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NONRECIPROCAL FLUXON MAGNONICS

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One of the primary advantages offered by spin waves for operations on data is a rich palette of nonreciprocal phenomena, implying that spin-wave propagation in opposite directions has different properties. The current great interest in quantum magnonics [1] stimulates the exploration of spin waves at cryogenic conditions and in environments of superconductors [2], see the phase diagram in Fig. 1(a). In this regard, the combination of magnonic materials with superconductors allows for use of structures with vanishingly small electrical resistance for spin-wave control. In such heterostructures, nonreciprocal spin-wave generation and scattering in ferromagnet (F) can be induced by Meissner screening currents and nonreciprocal motion of the Abrikosov vortex lattice in superconductor (S).

In this talk, a selection of nonreciprocal phenomena in S/F heterostructures will be discussed. First, the propagation of spin waves in a ferromagnet/superconductor Py/Nb heterostructure is non-reciprocial because of the Bragg scattering of spin waves on a moving vortex lattice, which is accompanied by the Doppler effect [1]. Second, the introduction of a periodic array of asymmetric vortex pinning sites breaks symmetry in their motion under transport current polarity reversal, thus resulting in further non-reciprocal features (so-called "ratchet" or diode effect) in the magnon frequency spectra [4]. Finally, in the regime of vortex dynamics at a few km/s, nonreciprocity stems from the unidirectional excitation of spin waves by dc-driven fluxons via a Cherenkov-type mechanism [5], see Fig. 1(b). Overall, the selection of findings emphasizes the functionalities of cryogenic magnonics which go far beyond those at room temperature.

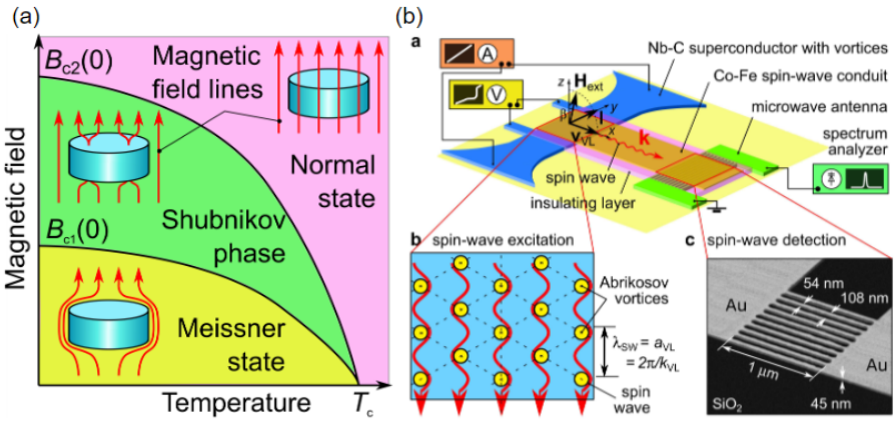

Fig. 10

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LIOUVILLIAN EXCEPTIONAL POINTS OF NON-HERMITIAN SYSTEMS VIA QUANTUM PROCESS TOMOGRAPHY

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Hamiltonian exceptional points (HEPs) are degeneracies of non-Hermitian Hamiltonians for classical and semiclassical systems, which usually exhibit both dissipation and amplification. However, this definition ignores the effect of quantum jumps on the evolution of quantum systems. Quantum Liouvillian exceptional points (LEPs), defined as degeneracies of quantum Liouvillians, are natural generalizations of the standard semiclassical HEPs by including the effect of quantum jumps [Minganti et al., Phys. Rev. A 100, 062131 (2019)]. Here we explicitly describe how standard quantum process tomography, which is a popular method to reveal the dynamics of a quantum system (a black box), can be readily applied for revealing and characterizing LEPs of non-Hermitian systems. We analyze a prototype model of a single qubit decaying through three competing channels to show how to tune their system parameters to observe LEPs, although the model does not exhibit HEPs. Specifically, we tomographically reconstructed the corresponding experimental Liouvillian and its LEPs by applying single- and two-qubit operations on an IBM quantum processor.

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ZERO-FIELD SPIN-WAVE STEERING IN CORRUGATED WAVEGUIDES

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In recent years, magnon-based computing has been intensely investigated as a promising candidate to complement and surpass CMOS-based technologies [1]. Many of the basic logic devices have already been demonstrated experimentally [2, 3]. But so far, no complex magnonic circuit has been experimentally realized, because the steering of spin waves, which is essential for two-dimensional chip design, is a major challenge [4]. If an external magnetic field is used to stabilize magnetization in the plane of a thin magnetic waveguide, even a basic circuit element such as a spin-wave turn shows a large dispersion mismatch for regions before and after the turn, and thus exhibits huge energy losses. We tackled these challenges by locally controlled effective field, which stabilizes the magnetization of different parts of the magnonic circuit in the desired direction and enables us to excite spin waves in arbitrary modes. Usually-used Damon-Eshbach mode exhibits significant overturning [Fig. 1(a)], while the caustic direction allows us to match both, spin-wave group velocity and frequency and prevents dispersion mismatch and reflections from boundaries [5], see Fig. 1(b). In the presented experiments we use corrugated magnetic thin films and waveguides to locally control the effective field [Fig. 1(c, d)]. The surface curvature in the films locally modifies the contributions of dipolar and exchange energies and can be described as an effective uniaxial anisotropy term that is perpendicular to the corrugation direction [6]. The direction of the anisotropy axis can be spatially controlled, and arbitrary magnetization landscapes can be created on demand. Using this approach, one can design non-trivial magnonic circuits functioning without the need for an external magnetic field and pave the way towards complex magnonic circuits and all-magnon data processing.

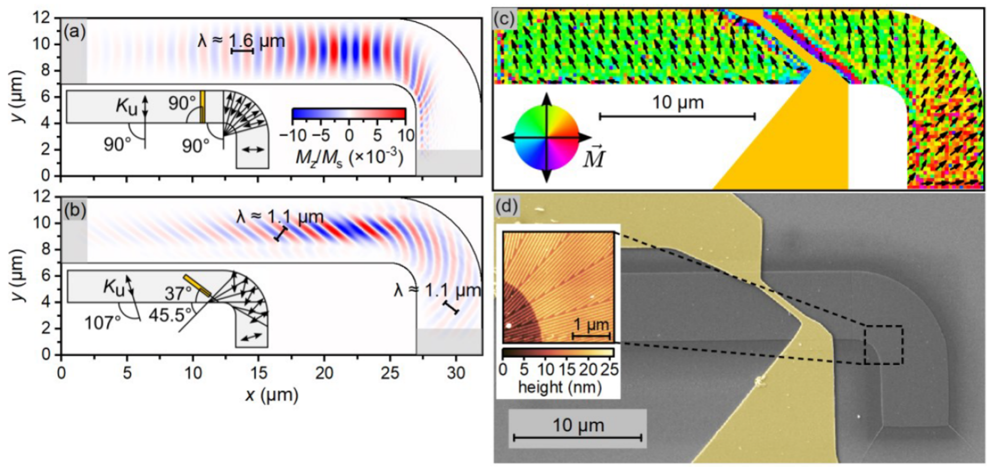

Fig. 1: Spin waves propagating through bend waveguides in (a) DE geometry, (b) caustic direction. (c) Magnetization landscape in zero external field. (d) Scanning electron microscope image of a corrugated waveguide and its topography acquired by atomic force microscopy (inset).

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MODELLING OF THE MICRO-FOCUSED BRILLOUIN LIGHT SCATTERING SIGNAL AND ENHANCEMENT OF THE MAXIMAL DETECTABLE WAVE-VECTOR

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Advances in Brillouin light scattering (BLS) spectroscopy allowed to study and develop first generation of magnon devices and is one of the main reasons why magnonics became one of the most promising candidates for "beyond CMOS" technology. However, further development and especially miniaturization is needed to bring spin-wave devices to real application. Here, BLS is limited momentum conservation in probing short wavelength magnons. This can be described by the condition: $k_{\mathrm{i}}=k_{\mathrm{r}}+k_{\mathrm{m}}$, where k_{i} (k_{r}) is wavevector of the incident (reflected) light and k_{m} is wavevector of the magnon [1]. Thus, in the back-scattering geometry, the maximal wavenumber of spin waves, which can be detected, equals twice the incident light wavenumber. In micro-focused BLS situation is even more complicated and require precise modelling. To tackle standard BLS limitation, we propose a novel way of detecting short-wavelength spin waves beyond the fundamental limitation of the BLS [Fig. 1 (a), (b)]. We employ Mie resonance-based dielectric nano-resonators to localize and amplify the incident electric wave [2,3]. We were able to increase the maximal detectable wavevector approx. three times [Fig. 1 (c), (d)]. We have also demonstrated phase-resolved experiments, were we reconstructed dispersion relation up to 30 rad/μm.

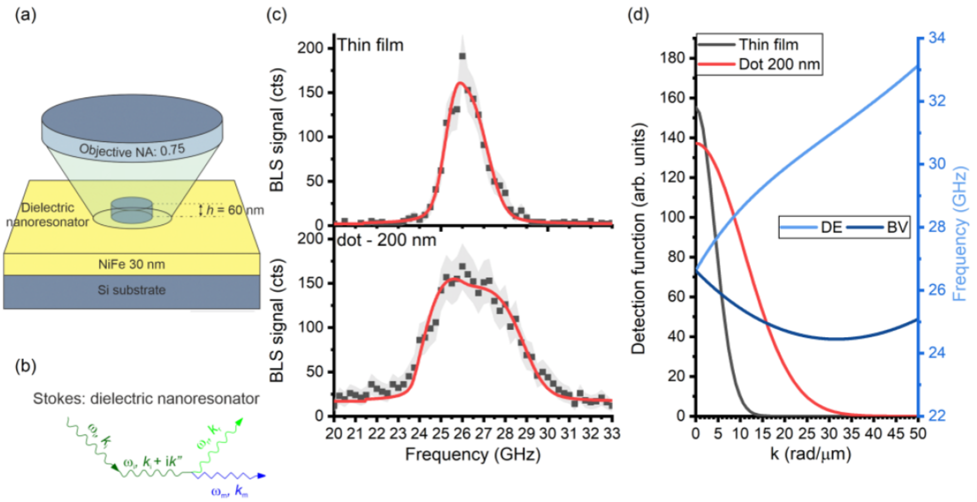

Fig. 1: (a) Schematics of the nano-resonator enhanced BLS. (b) Schematics of the Stokes processes during the BLS mediated by the localized resonances. (c) BLS experimental data for bare film (top panel) and dielectric nanoresonator (bottom panel) fitted by the model based on the gaussian detection function of BLS. (d) Left axis: fitted detection function of conventional BLS (black) and nano-resonator enhanced BLS (red). Right axis: calculated dispersion relation of a Permalloy thin film of Damon-Eshbach (DE) and backward volume (BV) modes.

Acknowledgements: *CzechNanoLab project LM2023051 funded by MEYS CR is gratefully acknowledged for the financial support of the measurements/sample fabrication at CEITEC Nano Research Infrastructure.*

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NEW DIRECTIONS IN THE SEARCH AND DESIGN OF SELECTED MATERIALS FOR SUSTAINABLE INDUSTRIAL DEVELOPMENT

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Sustainability in an industry dependent on the synthesis of metallic materials requires reliable access to affordable raw materials and improvement of energy efficiency of final products. For instance, development and reduction of synthesis cost of permanent magnets, which are widely used in many areas, are of the highest importance nowadays. The best known ones characterized by the highest energy product are based on rare earth elements, such as Sm or Nd, with well-known representatives in $Nd_2Fe_{14}B$, Sm_2Co_{17} or $Sm_2Fe_{17}N_3$. The range of new compositions (e.g. $Hf_2Co_{11}B$, MnBi, $Mn_{50}Bi_{49}Pd$) and possible applications is broad and still growing. With the development of new phases and the improvement of intrinsic and extrinsic properties [1, 2], permanent magnets are still implemented in a rather trivial way, as a replacement of electromagnets, in loudspeakers and actuators, but also find more sophisticated applications in magnetic resonance imaging, in information storage devices, magnetic levitation, as bearings, or as miniaturized magnetic field sensors.

Current research driven by a strong demand for magnetic cooling as an environmentally friendly and efficient technology, focuses on such systems as amorphous and nanostructured bulk materials, as well as thin films, multilayers, and quantum dots. The solutions based on these systems are also realizations of the idea of energy harvesting associated with the search for new methods for efficient energy production and cooling or heating processes. There has been great interest in new high performance magnetocaloric materials characterized by high magnetic entropy and adiabatic temperature changes. Usually, the refrigeration capacity of soft magnetic amorphous materials is much higher than that of their crystalline counterparts. Although the values of entropy changes at the transition temperature for amorphous materials are lower than those of crystalline systems, a higher refrigeration capacity and excellent mechanical properties still make them attractive candidates for further studies as candidates for magnetic refrigeration systems [3].

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Poster Session

QUANTUM GENERATIVE MACHINE LEARNING

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We present a new approach to generative quantum machine learning and describe a proof-of-principle experiment demonstrating our approach. We call our proposed approach quantum synergic generative learning [1] because the learning process is based on the cooperation between the generators and the discriminator. The goal of the learning is for the quantum computer implementing the generative learning algorithm to learn a concept of a Bell state. After the learning process, the network is able to recognize as well as generate the entangled state. We compare our approach with the recently proposed quantum generative adversarial learning (QGAN) [2]. We present numerical proofs, obtained using quantum simulators, for single qubits as well as more qubits, and we also present experimental results obtained on a real programmable quantum computer [3].

We propose a different type for quantum GAN machine learning, simplifying the training process compared to the conventional QGAN method. Leveraging the reversibility of the discriminator, we use properties like relative entropy and time reversal in unitary transformations. Throughout the learning phase, our objective is to minimize the cost function while ensuring the correct functioning of the discriminator.

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MANY-BODY PHASES IN OPTICAL-LATTICE SYSTEMS WITH ALKALINE-EARTH-LIKE ATOMS. DYNAMICAL MEAN-FIELD APPROACH

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We study finite-temperature properties of ultracold mixtures of alkaline-earth-like atoms in state-dependent quasi-two-dimensional optical lattices that can be effectively described by the two-band Hubbard model. We use the Dynamical Mean Field approach (DMFT) with Local Density Approximation (LDA) to include the effects of a (harmonic) trap, which is inevitably present in all experiments with ultracold gases on the lattices, and to obtain the real-space distributions of the density of particles, local order parameters and other local physical observables relevant for the experiments.

In certain ranges of densities, we investigate the stability of different possible strongly correlated phases of the atomic system. We estimate the critical temperature below which these phases occur. In order to account for the proximity effects that are usually present at the boundaries between phases in strongly-correlated systems, we extend our analysis using the real-space generalization of DMFT.

NONRECIPROCITY OF SPIN WAVES IN FERROMAGNETIC NANOWIRES WITH CURVED CROSS-SECTIONS

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The nonreciprocity effect in the propagation of spin waves (SW) is a phenomenon that enables the development of devices such as diodes or circulators [1], which are essential components in signal processing applications. Several theoretical and experimental studies have already demonstrated the nonreciprocity effect in the propagation of SW in thin layers [2, 3]. Typically, this effect is achieved by creating an interface between a ferromagnet and either an oxide or a heavy metal which introduce the interfacial interaction called Dzyaloshinskii-Moriya interaction (DMI) [2]. In all cases, it is achieved by creating an asymmetry in magnetization between the lower and upper layers of the ferromagnetic film, which are oriented parallel to the external magnetic field. The wavevector is perpendicular to the inplane magnetization, a configuration known as the Damon-Eshbach Configuration (DEC). Previously, this asymmetry was primarily achieved using the DMI or by creating a gradient in magnetization saturation [3]. In my research we focus is on achieving and enhance of SW non-reciprocity by employing a curved geometry, what's we already showed in ours previews study about SW dynamics in crescent-shaped ferromagnetic nanorods (CSN) [4]. Asymmetry in magnetization was introduced by giving to the ferromagnetic waveguide crossection shape with curvature, where the asymmetry axis which is parallel to the orientation of the external magnetic field. The curvature nanorod geometry have interesting properties for the applications according recent development of new fabrication techniques, which allow the fabrication complex structures with curvature at the nanometer scale. CSN exhibits nonreciprocity at high external magnetic fields, up to 3 Tesla, because to its inherent shape anisotropy, maintaining nonlinear magnetization. This phenomenon allows us to achieve high resonant frequencies (up to tens of GHz), and non-reciprocity based not only on frequency differences between negative and positive wavevectors but also based on intensity, what has not been present for ferromagnetic nanotubes (NT).

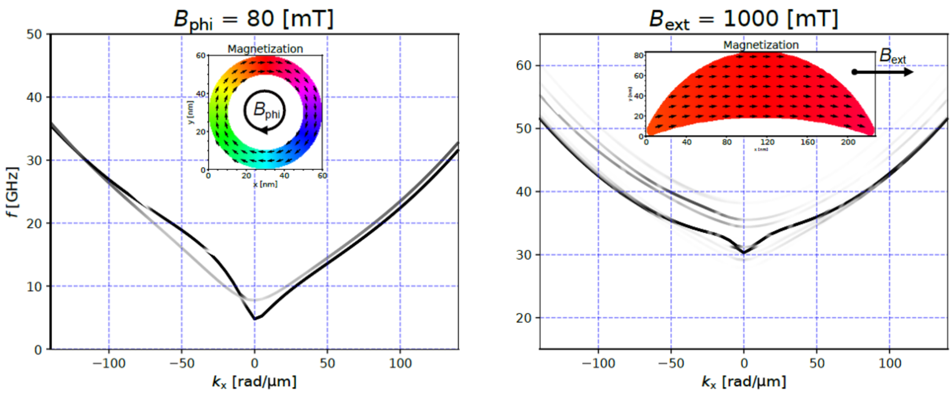

Fig. 1: The left panel displays the dispersion for NT with azimuthal orientation of the external magnetic field. The right panel shows the case for CSN in the presence of a high-magnitude external magnetic field.

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INFLUENCE OF CoFeB LAYER THICKNESS ON ELASTIC PARAMETERS IN CoFeB/MgO HETEROSTRUCTURES

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Surface acoustic waves (SAWs), i.e., phonons (quasiparticles of SAWs) are acoustic waves propagating along the surface of an elastic material with decreasing amplitude with the depth of the material [1]. SAW-based devices have become an integral part of our daily lives [2]. They may also have potential applications in future spintronic devices if coupled with other waves (e.g., spin waves (SWs)) and/or quasiparticles. So, it is quite important to understand the coupling of phonons with other quasiparticles to enhance the coupling efficiency, especially in magnetic thin film heterostructures such as CoFeB/MgO, one of the most promising materials for future spintronics applications [3,4]. As a first step it is important to understand how elastic parameters of magnetic heterostructures and properties of acoustic phonons evolve with the CoFeB layer thickness.

Here, we have investigated SAWs in CoFeB/MgO multilayers by probing thermally generated acoustic phonons by Brillouin light scattering (BLS) spectroscopy to find out effective elastic parameters of the multilayers with varying CoFeB thickness. The multilayer structures: Ta(10)/$Co_{20}Fe_{60}B_{20}$(t=1 to 20)/MgO(2)/Al_2O_3(10) are deposited on Si[001]/SiO_2(700) substrates (the numbers in parentheses are the nominal thicknesses of layers in nm). We observe that the group velocity of Rayleigh type SAWs decreases with increasing CoFeB layer thickness and the phase velocity of Rayleigh waves is lower in studied multilayers as compared to Si/SiO_2 substrate. The experimental results are supported with Finite element method (FEM) based simulations, which helped us to estimate the elastic parameter of the CoFeB layer. Additionally, we estimate the effective elastic parameters (elastic tensors, Young's modulus, Poisson's ratio) of the whole stacks for varying CoFeB thickness. Interestingly, the simulated dispersion characters of SAWs with both types of parameters show very good agreement with the experimental results. These estimated elastic parameters will be quite useful to investigate magnon-phonon interaction in CoFeB/MgO heterostructures.

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UNCONVENTIONAL SUPERCONDUCTOR'S IMPACT ON TRANSPORT PROPERTIES OF MULTI-TERMINAL QUANTUM DOT BASED HYBRID

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The well known BCS theory of superconductivity presents the Cooper pair of electrons having a net zero spin (S=0). On the other hand, the unconventional superconductors[1] can exhibit electron pair with non zero angular momentum, triplet spin pairing and anisotropy in the superconducting gap parameter. As the electron-phonon interaction is responsible for conventional BCS (s-wave) superconductors, the phenomenological reason for triplet superconductors is not uniquely defined. The production, tunability and interaction with magnetic order of such finite spin supercurrent is crucial to the spintronics devices[2].

In this work, we evaluate the spin dependent charge/heat transport in a hybrid structure of quantum dot coupled to triplet superconductor of chosen phase(s) and ferromagnetic electrodes. Our approach is theoretical and computational in nature. The analytical method of non-equilibrium Green's function is employed to calculate the observables. Since this is a three terminal device, both local and non-local transport coefficients[3] such as electrical conductance, thermopower, thermal conductance are presented. In the system driven out-of-equilibrium and in non linear response regime, we investigate the prospects of this device to function as a particle exchange heat engine and present the obtainable power and efficiency. It is possible that the triplet superconductor breaks time reversal and point group symmetry and thus we evaluate how this affects the transport properties in the system.

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SUPERCONDUCTOR-INDUCED EFFECTS ON NAGAOKA FERROMAGNETISM IN A QUNATUM DOT ARRAY

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Nagaoka ferromagnetism is a type of ferromagnetic ordering predicted theoretically in a near half-filled band [1]. Although predicted more than half a century ago, its occurrence has never been confirmed experimentally in any material and has only recently been found in a quadruple quantum dot system [2]. This observation has stimulated further research on signatures and robustness of Nagaoka ferromagnetic states in quantum dot nanostructures [3, 4]. To deepen our understanding, we study this type of ferromagnetism in the context of the proximity effect of s-wave superconductor that is coupled to a quadruple quantum dot array. For energies much smaller that the superconducting energy gap, the tunnelling in the considered system occurs via Andreev bound states in the processes of direct and crossed Andreev reflections. Since the Cooper pair consists of two electrons of opposite spins, Andreev reflections compete with Nagaoka ferromagnetic order leading to complex behaviour of the magnetic ground state of the system. In the presentation, we show the relevant phase diagrams of the system's ground state, considering on-dot Coulomb interactions and Cooper pair tunneling rate, examining direct and crossed Andreev reflections, and exploring scenarios involving both mechanisms. We show that the the system's phase strongly depends on the ratio of Coulomb correlations and strength of direct and crossed Andreev reflections.

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SUPREMACY OF QUANTUM BATTERIES

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The phenomenon of quantum entanglement has been shown to benefit computation, secure communication, and metrology. These potential benefits have recently gained some attention in the area of batteries [1]. Entangling operations, according to Alicki and Fannes [2], led to higher work extraction from an energy storage device, which they named a "quantum battery" (QB). QBs are formally described as d-dimensional quantum systems with non-degenerate energy levels from which work may be reversibly extracted - and energy can be reversibly deposited - using cyclic unitary operations [3].

We will present the advantages of quantum batteries over classical batteries and how energy dissipation affects the performance of quantum batteries.

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LIOUVILLIAN EXCEPTIONAL POINTS: AN EXPERIMENTAL APPROACH USING LINEAR OPTICS

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In the field of non-Hermitian quantum mechanics, Liouvillians and their exceptional points (EPs) represent an intriguing area of exploration, particularly in the context of an open quantum systems. Inspired by theoretical frameworks from recent literature, our research focuses on the experimental investigation of Liouvillians with the use of a platform of linear optics. The goal is to observe and analyse EPs and their immediate surroundings, contributing to a deeper understanding of their role and potential in quantum information theory.

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BEHAVIOR OF EDGE AND BULK MODES IN AN ANTIDOT LATTICE EXHIBITING PERPENDICULAR MAGNETIC ANISOTROPY

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Magnonic crystals (MCs) demonstrate remarkable capabilities for controlling the transmission of spin waves (SWs). Their ability to create and steer SWs offers the potential for the development of magnonic devices that outperform optical devices in spatial efficiency and surpass current electronic devices in energy efficiency. Our research specifically concentrates on examining a unique MC structure in a thin film, composed of eight layers of alternating Co (0.75nm) and Pd (0.9nm) bilayers, culminating in a cumulative thickness of 13.2 nm [1]. This specific arrangement, comprising a ferromagnetic and a heavy metal layer, establishes a strong perpendicular magnetic anisotropy (PMA). This PMA is notably significant for its contribution in making SW dispersion isotropic. During the manufacturing of this thin film, a pattern of antidots was meticulously created at uniform intervals by precisely etching out nanodots using a 10nm wide focused ion beam. This process not only involved the removal of material but also brought about modifications in the nearby areas of each antidot, resulting in the formation of a 'rim.' These changes notably influenced the magnetic characteristics, especially the PMA, causing the magnetization near the antidot edges to align nearly in-plane. As shown in Fig. 1, the foundational state of a circular antidot displays magnetization around its edge ring, forming a vortex-like structure.To thoroughly examine the interplay between localized and bulk modes within the film, we conduct micromagnetic simulations. Our initial investigation focuses on stationary SWs, where we adjust the excitation field and the strength of the externally applied static magnetic field, which is oriented perpendicularly. This adjustment enables us to explore the SW modes in both the rim and bulk areas. We then explore the dynamic interactions between the rim and bulk areas, uncovering collective dynamics within the lattice, as depicted in Fig. 2. These insights are highly promising for future advancements in magnonic technologies.

(a) (b)

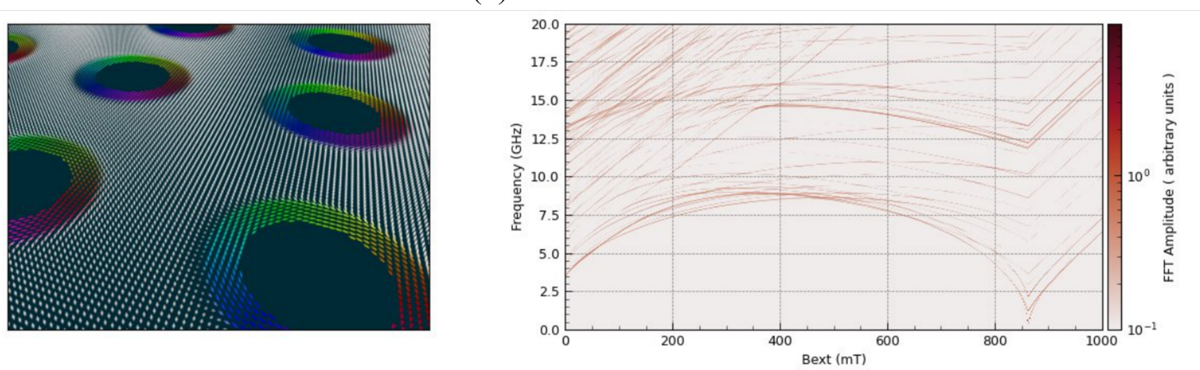

Fig. 1: (a) Magnetization in the magnonic crystal. (b) Resonance spectra of spin waves depending on the saturating field.

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NUMERICAL MODELLING OF NONRECIPROCAL SPIN WAVE PROPAGATION IN Co/Pt MULTILAYERS

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The phenomenon of nonreciprocity in wave dynamics refers to a scenario where the dispersive properties of waves are influenced by the direction of wave propagation. This results in waves traveling in opposite directions exhibiting different wavelengths at the same frequency. This unique behavior has been detected in multilayers combining heavy metals and ferromagnets, and induced by interfacial Dzyaloshinskii-Moriya interactions (IDMI) [1]. It is also evident in dipolarly coupled magnetic bilayers [2]. Beyond traditional applications of spin waves, the introduction of nonreciprocity opens new possibilities in areas like communication technology and logical operations, offering additional functionalities. Creating a multi-layered structure from alternating films of ferromagnet (Co) and heavy metal (Pt), with 22 repetition, allows for introducing IDMI and perpendicular magnetocrystalline anisotropy (PMA) in the system, which also modify the magnetization dynamics [3]. This research focuses on explaining surpassingly strong nonreciprocity measured experimentally by means of Brillouin light spectroscopy (BLS) with the use of micromagnetic simulations. The propagation of spin waves in a sample magnetized with magnetic fields of different amplitudes has been studied experimentally. Accordingly, the dispersion of spin waves propagating in both uniformly magnetized and magnetized in an aligned stripe domain pattern were measured, with propagation along and across the direction of periodicity measured for the second scenario. The dispersion relation extracted from the BLS measurements show a strong nonreciprocity in the system. The results are counter-intuitive because the nonreciprocity caused by the IDMI is expected when there are two different materials are present on the top and bottom surfaces of the ferromagnetic layers, in our case we have a nominally symmetrical multilayer composition. Moreover, the spin wave propagation in the stripe domain pattern also has some interesting features like bias exchange interaction. We explain these results numerically, using mumax3 simulations and propose a model of a structure that displays the same characteristics as the measured sample. In the proposed model the dipolar interactions are the cause of significant nonreciprocity in the system. Moreover the first dispersion band displaying the biggest nonreciprocity corresponds to two different bands contributed by the spin waves propagating in two different directions.

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THE ROLE OF MATERIAL PARAMETERS, EXTERNAL FIELD AND GEOMETRY ON THE ARRANGEMENT OF VORTICES IN SUPERCONDUCTING STRUCTURES

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The Ginzburg-Landau (GL) theory provides a phenomenological description of type II superconductors. It allows to describe the processes of nucleation and ordering of magnetic field vortices in the mixed state. In confined geometries, the induction of vortices and their arrangement depend not only on the material parameters of the superconductor (e.g. the correlation length, which determines the size of the vortices) and the external field (which determines the distances between the vortices), but also on its shape and dimensions.

In this study, we simulate the mixed state in a superconducting wire of infinite length, with the external field applied along its axis. We study how the shape of the wire cross section and its size affect the arrangement of the vortices for different values of correlation length and external field. We also study how these geometric factors affect the nucleation of vortices and how they impact the first critical filed.

We solved the time-dependent GL equations numerically using the finite element method. We implemented the GL equations in Comsol Multiphysics using a 2D model. Our studies were supplemented by 3D calculations of the wires of finite length. For both the 2D and 3D models, we studied a two-domain system where the superconducting domain of compact shape is embedded in a large non-magnetic and non-conducting surrounding. The presence of this surrounding is of particular importance for the proper description of the stray field produced by the superconductor, which, in turn, is crucial for the formation and ordering of the magnetic vortices.

Our future research aims to expand our exploration to ferromagnetic-superconductor heterostructures, investigating how vortices affect magnetization dynamics and magnetic domain behavior in the ferromagnetic layer. The presence of vortices can cause significant alterations in local magnetic fields and interactions, potentially reshaping ferromagnetic properties, spin textures, and magnetic ordering at the ferromagnetic material.

This investigation aims to enhance our understanding of vortex behavior, with the promise of improving superconducting materials for a wide range of technological applications. Insights from this research facilitate the development of improved superconducting devices, advanced energy transmission technologies, and potential breakthroughs in manipulating magnetic interactions at the nanoscale.

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HIGHER ORDER SPIN INTERACTIONS MEDIATED BY THE SUBSTRATE

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The effective exchange interaction between magnetic impurities, mediated by the conduction electrons of the underlying lattice (Ruderman-Kittel-Kasuya-Yosida interaction [1]) has been studied in a multitude of systems and scenarios. In bipartite lattices (as e.g. square or honeycomb lattices) this interaction is (anti) ferromagnetic if the impurities reside on the (opposite) same sublattice [2]. It is interesting to see if the substrate can also mediate interactions between four adsorbates, such as those appearing as higher order terms in the Hubbard expansion [3]. Using perturbation theory for the thermodynamic potential, we show how the so called ring exchange can be induced between four impurities coupled to a square lattice substrate.

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SIMULATION OF UNIDIRECTIONAL SPIN-WAVES GENERATED BY THE CHERENKOV EFFECT IN A FERROMAGNET/SUPERCONDUCTOR HYBRID

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A magnetic profile propagating in space can be a source of spin waves in magnetic materials [1]. Using type II superconductors, in which the magnetic vortices can be moved by a flowing current, we can practically realize this idea. In a ferromagnet/superconductor (F/S) hybrid system composed of the ferromagnetic layer and the type II S layer (placed near F), the magnetic field of the moving vortices generates the spin waves [2]. While the velocity of the moving vortices is comparable or even higher than the phase velocity of the spin waves, the Cherenkov effect of the spin waves can be observed [3].

The aim of this work is to perform the numerical simulation of spin-wave propagation (and spin-wave Cherenkov) in the F/S hybrid system. We assumed a specific shape of the field generated by the vortex [4] and observed the induced spin waves for a given value of the vortex velocity. We performed micromagnetic simulations using MuMax3 solver and the output data were post-processed using Phyton codes.

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SPIN WAVE DYNAMICS IN CoFeB LAYERS

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The field of magnonics is dedicated to the study of spin wave dynamics and their practical applications. Perpendicular Magnetic Anisotropy (PMA) is a phenomenon observed in various magnetic materials, generating considerable interest for its potential applications in the development of advanced magnetic recording devices. Thin CoFeB layers represent one such material where the PMA effect is particularly notable, especially in the context of their reduced thickness. This study presents experimental investigations into the PMA effect in thin CoFeB layers, emphasizing the presence of a nuanced magnonic band structure. The magnetic properties of thin layers are highly contingent on their thickness, with an escalation in thickness resulting in the diminishing of the PMA effect. The findings, employing Brillouin Light Scattering (BLS), provide a quantitative assessment of magnon energy in thin magnetic layers (CoFeB) deposited on a Si substrate. Extracted dispersion relations of spin waves, along with an exploration of nonlinear effects, offer insights into the system's behavior relative to the thickness of the magnetic layer, revealing anomalous dispersion characteristics.

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NONMONOTONIC BUILDUP OF SPIN-SINGLET CORRELATIONS IN DOUBLE QUANTUM DOT

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Dynamical buildup of spin-singlet correlations between the two quantum dots is investigated by means of the time-dependent numerical renormalization group method. By calculating the time evolution of the spin-spin expectation value upon a quench in the hopping between the quantum dots, we predict a nonmonotonic buildup of spin-singlet state. In particular, we find that in short timescales the effective exchange interaction between the quantum dots is of ferromagnetic type, favouring spin-triplet correlations, as opposed to the long-time limit, when strong antiferromagnetic correlations develop and eventually an entangled spin-singlet state is formed between the dots. We also numerically determine the relevant timescales and show that the physics is generally governed by the interplay between the Kondo correlations on each dot and exchange interaction between the spins of both quantum dots. Finally, we qualitatively compare our findings with results predicted for single quantum dot system.

Acknowledgements: *This work was supported by the Polish National Science Centre from funds awarded through the decision No. 2022/45/B/ST3/02826.*

References:

[1] K. Wrześniewski, T. Ślusarski, I. Weymann Nonmonotonic buildup of spin-singlet correlations in a double quantum dot Phys. Rev. B 108, 144307 (2023)
[2] K. Wrześniewski, I. Weymann Quench dynamics of spin in quantum dots coupled to spin-polarized leads Phys. Rev. B 100, 035404 (2019)

STABILISATION OF SKYRMIONS AT REMANENCE IN RE/CO/PT EPITAXIAL HETEROSTRUCTURES

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Magnetic skyrmions, topologically protected nanoparticles, are stabilized by the interfacial Dzyaloshinskii–Moriya interaction (iDMI). This interaction occurs in heterostructures composed of magnetic materials coupled with heavy metals, which exhibit high spin-orbit coupling. We have observed a zero-field (remanence state) magnetic skyrmion lattice that can be immobilized by applying an inclined saturation magnetic field to the sample using different protocols. The stabilization of skyrmions at remanence was noted when the field was tilted at an angle ($\Theta < 45^\circ$) for samples with (Q > 1), and $\Theta > 45^\circ$) for (Q<1), where (Q) is defined as the ratio of uniaxial anisotropy to demagnetization energy, and (Θ) is the angle between the normal to the sample surface and the applied external field. The maximum number of skyrmions observed at remanence was equal to ($\frac{470}{25\mu\mathrm{m}^2}$) for the [Re(1nm)/Co(0.8nm)/Pt(1nm)]20 sample. To reproduce the experimental results, we developed a new micromagnetic simulation approach, specifically a new stabilisation algorithm. This allows us to more precisely simulate the complex remagnetization process. This approach yielded a high degree of correlation with the experimental data. Specifically, it accurately modelled the remagnetization process of the samples and provided a quantitative analysis of skyrmion nucleation as a function of both the angle and intensity of the magnetic field. In this study, we demonstrated a new way to stabilise skyrmions in the presence iDMI in the wide thickness of Co with non-zero iDMI and stabilisation of skyrmion lattices can be useful for fundamental study of future spintronics and skyrmion technology in data storage medium.

RESONANT 2-PARTICLE STATES IN THE EMPTY LATTICE LIMIT

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BCS theory goes over to a problem of two electrons in an empty lattice in the extremely low-density limit. The two electrons form a bound state in the models with attractive interaction under certain conditions. The problem can be solved exactly via lattice Green's functions. A pedagogical review describing the properties of these states appeared recently [1]. If such states enter the band, their lifetime becomes finite, and the states become resonant. They are much less examined. In the present work, the T-matrix is calculated for the resonant pairs of different symmetries in the extended Hubbard model. The relative robustness of the pairs in the d-wave symmetry channel is shown respectively to other symmetry channels. The results may have implications for superconductivity, particularly within the resonant Boson-Fermion model [2].

Acknowledgements:

References:

[1] P.E. Kornilovitch, Annals of Physics 460 (2024) 169574; arXiv:2305.02548

[2] R. Micnas, Philosophical Magazine, 95:5-6, 622-632, (2015); arXiv:1912.04094

MAGNONIC PROPERTIES OF GYROIDAL FERROMAGNETIC NETWORKS

M. Gołębiewski[1] and M. Krawczyk[1]

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The exploration of three-dimensional networks in magnonics opens new avenues for spin wave manipulation and control, offering major advances in the field. Among these structures, gyroids – characterized by their chiral triple bonds and periodicities in all spatial directions (Fig. 1) – stand out as particularly promising yet underexplored in magnetism research. In our study, we have successfully fabricated nickel gyroid nanostructures through a meticulous process involving thermal annealing of a block copolymer template, selective dissolution, and electrodeposition. The orientation of these gyroid networks relative to the static magnetic field axis proved to be critical, as evidenced by broadband ferromagnetic resonance measurements, which revealed a significant influence of crystallography on spectral signals and their linewidth. To complement these findings, we used a finite element solver [1], tetmag, to perform micromagnetic simulations of the gyroid systems. These simulations provided deeper insights into the experimental results and revealed that the gyroid networks have significant metamaterial-like effects on the magnetic properties, such as tunable effective values of Ms and g-factor, and influence on the Gilbert damping parameter [2]. To further research, I have performed new micromagnetic simulations using Comsol Multiphysics software. These simulations focus on the analysis of spin-wave propagation and dispersion relations in gyroid structures over different thicknesses and filling factors. This approach allows us to delve into the intricate dynamics of spin waves within these complex 3D nanostructures, providing a more comprehensive understanding of their behavior and potential applications.

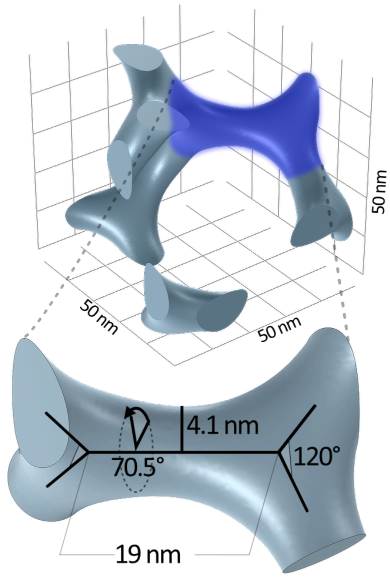

Fig. 1: A geometric model of the gyroid unit cell.

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[1] R. Hertel, S. Christophersen, and S. Börm, J. Magn. Magn. Mater. 477, 118-123 (2019)
[2] M. Gołębiewski, R. Hertel, M. d'Aquino, V. Vasyuchka, M. Weiler, P. Pirro, M. Krawczyk, S. Fukami, H. Ohno, and J. Llandro, [Manuscript submitted for publication] (2024)

Presenting authors

Symposium on Spintronics and Quantum Information

January 11-13, 2024, Będlewo, Poland

Symposium is organized by the Institute of Spintronics and Quantum Information (ISQI) of the Faculty of Physics of the Adam Mickiewicz University, Poznań. Since its establishment on January 1, 2021, ISQI has been organizing yearly symposia on broad aspects of condensed matter physics and quantum information.

Invited Speakers:

Oleksandr Dobrovolskiy, Tadeusz Domański, Tobias Grass, Maciej Maśka, Tomáš Novotný, Adam Sajna, Victor Tkachenko, Vojtěch Trávníček

Thursday, January 11	
12:00-14:15	**REGISTRATION & RECEPTION**
14:15-14:30	**OPENING**
14:30-16:30	**SCIENTIFIC SESSION 1**
14:30-15:05	Tobias Grass
15:05-15:25	Maciej Krawczyk
15:25-15:45	Nicholas Sedlmayr
15:45-16:00	Ryszard Stagraczyński
16:00-16:15	Paweł Gruszecki
16:15-16:30	Shilan Abo
16:30-17:00	**COFFEE BREAK**
17:00-18:40	**SCIENTIFIC SESSION 2**
17:00-17:35	Vojtěch Trávníček
17:35-17:55	Paweł Kurzyński
17:55-18:10	Piotr Busz
18:10-18:25	Jan Wójcik
18:25-18:40	Krzysztof Szulc
since 19:00	**CONFERENCE BANQUET**

Friday, January 12	
08:00-09:00	**BREAKFAST**
09:00-11:00	**SCIENTIFIC SESSION 3**
09:00-09:35	Adam Sajna
09:35-09:55	Przemysław Chełminiak
09:55-10:15	Martin Žonda
10:15-10:30	Anand Manaparambil

Friday, January 12	
09:00-11:00	**SCIENTIFIC SESSION 3**
10:30-10:45	Julia Kharlan
10:45-11:00	Krzysztof Wójcik
11:00-11:30	**COFFEE BREAK**
11:30-12:55	**SCIENTIFIC SESSION 4**
11:30-12:05	Victor Tkachenko
12:05-12:25	Tomasz Polak
12:25-12:40	Katarzyna Kotus-Kozyra
12:40-12:55	Josef Kadlec
12.55-13.15	Jan Martinek
13:15-14:30	**LUNCH**
14:30-16:30	**SCIENTIFIC SESSION 5**
14:30-15:05	Tomáš Novotný
15:05-15:25	Anna Kowalewska-Kudłaszyk
15:25-15:45	Piotr Kozłowski
15:45-16:00	Grzegorz Centała
16:00-16:15	Peter Zalom
16:15-16:30	Krzysztof Sobucki
16:30-17:00	**COFFEE BREAK**
17:00-18:40	**SCIENTIFIC SESSION 6**
17:00-17:35	Tadeusz Domański
17:35-17:55	Jarosław W. Kłos
17:55-18:10	Vladislav Pokorný
18:10-18:25	Piotr Trocha
18:25-18:40	Katerina Jirakova
19:00-20:00	**DINNER**
since 20:00	**POSTER SESSION**

Saturday, January 13	
08:00-09:00	**BREAKFAST**
09:00-11:00	**SCIENTIFIC SESSION 7**
09:00-09:35	Maciej Maśka
09:35-09:55	Clemens Schmid
09:55-10:15	Grzegorz Chimczak
10:15-10:30	Dominik Pavelka
10:30-10:45	Jaganandha Panda
10:45-11:00	Jakub Holobrádek
11:00-11:30	**COFFEE BREAK**
11:30-12:55	**SCIENTIFIC SESSION 8**
11:30-12:05	Oleksandr Dobrovolskiy
12:05-12:25	Karol Bartkiewicz
12:25-12:40	Jan Klíma
12:40-12:55	Ondrej Wojewoda
12.55-13.15	Bogdan Idzikowski
13:15-13:30	**SYMPOSIUM CLOSING**
13:30-14:30	**LUNCH**
since 14:30	**TRANSFER TO POZNAŃ**

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