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

Symposium on Spintronics and Quantum Information 2022

Book of Abstracts

Institute of Spintronics and Quantum Information

Poznań, Poland, December 08–09, 2022

Symposium Venue

The Symposium will be held in a stationary form.

The event will take place at the Faculty of Physics Adam Mickiewicz University, ul. Uniwersytetu Poznańskiego 2, Poznań, Poland. The lectures will be held in Auditorium Maximum named after prof. Franciszek Kaczmarek.

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– Krzysztof Grygiel (ZON),
– Jarosław W. Kłos (ZFN),
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About the Institute

Establishment of the Institute

The Institute of Spintronics and Quantum Information (ISQI) has been appointed on January 1, 2021 by Prof. Bogumiła Kaniewska, the Rector of Adam Mickiewicz University in Poznań. The Institute has been established on the initiative of three departments of the Faculty of Physics: the Department of Mesoscopic Physics, the Department of Nanostructures Physics and the Department of Nonlinear Optics. In September 2021 the Department of Theory of Condensed Matter joined the Institute.

Main focus of ISQI

The main scientific interests of the Institute encompass the most fundamental aspects of condensed matter physics including spintronics, magnonics, phononics, photonics, quantum matter physics, as well as quantum optics, quantum information and cavity- and circuit-electrodynamics. The conducted research is important for designing the nanodevices processing, transmitting and storing classical and quantum information. Our scientific investigations are focused on theory and numerical simulations, however, experimental studies on magnonic and phononic nanostructures are also carried out.

Webpage: http://isik.amu.edu.pl

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Abstracts

FROM SPIN WAVES TO MAGNETIZATION PATTERN AND TIME CRYSTALS

Maciej Krawczyk[1], Paweł Gruszecki[1]

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Spontaneous pattern formation is an intriguing process that can start from linear dynamics and ends in spontaneously broken translational symmetry after a phase transition. Such effect was observed in hydrodynamic systems, such as thermal convection or parametric-wave instabilities, in nonlinear optics, chemical reactions, as well as in biological systems [1]. In ferromagnetic materials, a magnetization pattern usually appears as a result of a change of the bias magnetic field. From the opposite side, the regular magnetization pattern forms a periodic potential for the formation of the spin-wave band structure and thus can be treated as a natural magnonic crystal [2].

We realized spontaneous translational symmetry breaking by strong homogeneous microwave pumping of a micron-sized permalloy stripe with the resulting transition directly imaged by scanning transmission x-ray microscopy [3]. For an understanding of the experimental findings, the micromagnetic simulations are adapted. Beyond the formation of discrete translational symmetry in space, we also observed regular oscillations in time, indicating the generation of the magnonic space-time crystals. Periodicity allows for observing the formation of a magnonic band structure, which clearly demonstrates interaction of spin waves with the periodic in space and oscillating magnetization pattern, and results in the generation of ultrashort spin waves down to 100-nm wavelengths.

The research leading to these results has received funding from the Polish National Science Centre project UMO-2020/37/B/ST3/03936.

References:

[1] M. C. Cross and P.C. Hohenberg, *Pattern formation outside of equilibrium*, Rev. Mod. Phys. **65**, 851 (1993).

[2] C. Banerjee, et al., *Magnonic band structure in a Co/Pd stripe domain system investigated by Brillouin light scattering and micromagnetic simulations*, Phys. Rev. B **96**, 024421 (2017).

[3] N. Träger et al., *Real-space observation of magnon interaction with driven space-time crystals*, Phys. Rev. Lett. **126**, 057201 (2021).

INELASTIC SCATTERING OF SPIN WAVE BEAM AT EDGE LOCALIZED SPIN WAVES AND GOOS-HÄNCHEN EFFECT FOR INTELASTICALLY SCATTERED SPIN WAVES

Paweł Gruszecki[1], Krzysztof Sobucki[1], Konstantin Guslienko[2], Igor Lyubchanskii[3], and Maciej Krawczyka[1]

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Spin waves (SWs) are precessional magnetization disturbances propagating in magnetic systems in the form of waves at microwave frequencies[1] that are the most commonly used frequency range for wireless communication. SWs may be confined to certain areas of the thin layer, e.g., in a potential well created by inhomogeneity of the static demagnetizing field in the vicinity of the film's edge. Such localized modes are called edge SWs (E-SWs). Usually, the frequencies of E-SWs are downshifted with respect to bulk-type SWs (B-SWs, i.e., SWs propagating far from the edge where the effective static field is homogenous); see exemplary dispersion displayed in Fig. 1(b).

Here, we will theoretically study by means of micromagnetic simulations and analytical modeling the dynamics of the E-SWs localized at the edge of thin permalloy film and their interaction with B-SWs. The geometry of the investigated system is shown in Fig. 1(a). Firstly, we will focus on the utilization of the E-SWs to excite short B-SWs propagating in the form of plane waves [1]. Secondly, we study the inelastic non-linear scattering of SW beams at the E-SWs [2] and analyze its efficiency. We also observe the lateral shift along the interface between the incident and scattered beam spots, which proves the existence of the Goos-Hänchen effect for the inelastically scattered beams.

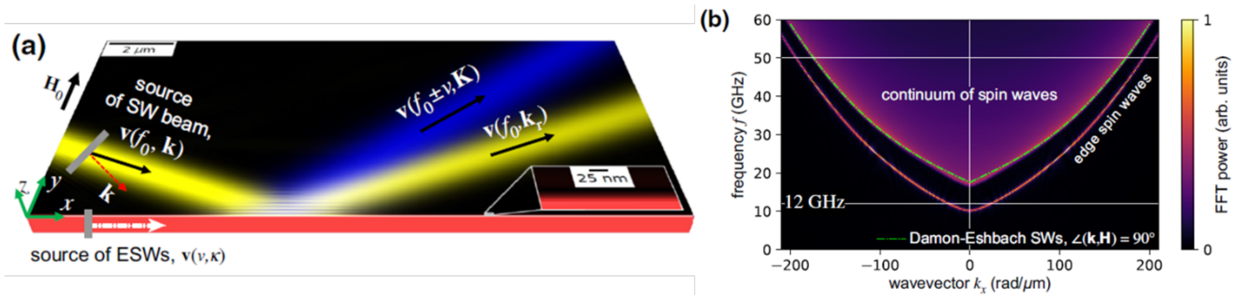

Fig. 1: (a) Schema of the system under investigation. The red (at the edge), yellow, and blue (beams) colors correspond to SWs at frequencies ν (E-SW), f (incident and reflected bulk SWs), and $f \pm \nu$ (inelastically scattered SWs), respectively. (b) Simulated dispersion relation with distinguished dispersion of edge spin waves.

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

References:

[1] Gruszecki et al. *Applied Physics Letters*, **118**, 062408 (2021).
[2] Gruszecki et al. *Physical Review Applied*, **17**, 044038 (2022).

MODELLING DYNAMICS OF SPINS AND CURRENTS WITHIN S-D MODEL APPROXIMATION

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I will present the principles of spin pumping and spin-transfer torque basing on the phenomenological model for spins and charges that we solve numerically. Then, I will show our recent results of simulations of direct and inverse charge-mediated magnetoelectric effects. It is shown, that ferromagnetic-dielectric interface is a source of a spin-polarized current when the system is subject to an ac electric field [1]. This is used to modulate the amplitude of propagating spin wave in a system which consists of two ultrathin ferromagnetic layers [2]. Secondly, with the support of DFT calculations we show that electronic resonant states are potentially the source of Stoner instabilities at Fe/MgO interface which lead to the generation of spin current pulses. Finally, I will show the preliminary results of generation of voltage from magnetization dynamics via inverse charge-mediated magnetoelectric effect.

This work was conducted under grant no. 2018/28/C/ST3/00052 from National Science Centre in Poland.

References:

[1] P. Graczyk and M. Krawczyk, *Phys. Rev. B*, vol. **100**, no. 19, p. 195415, 2019

[2] P. Graczyk and M. Krawczyk, *Sci. Rep.*, vol. **11**, 15692, 2021

HEUSLER ALLOY THIN FILMS ON GRAPHENE AND GRAPHENE-BASED MATERIALS – APPROACH TO GRAPHENE-BASED SPINTRONIC DEVICES

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Spin transport in lateral spin valve (LSV) devices depends on the state of LSVs building blocks: spin injectors/detectors (ferromagnetic electrodes) and a nonmagnetic spin transport channel. Since the basic operation in spintronic devices is switching bistable nanomagnets [1] – the ferromagnetic electrodes – deployed for injection or detection of a spin-polarized current, their spin polarization at the Fermi level is crucial. The ideal candidates for spin injection/detection are half-metallic ferromagnets which exhibit 100% spin polarization of conduction electrons. Examples of these are some Heusler alloys: NiMnSb, Co_2FeSi, and Co_2MnSi, among others [2]. The suitable spin transport channel should allow for a long spin lifetime and long-distance spin propagation. The experimental studies of spin transport measurements identified graphene as the most favorable material for spin transport channels in spin-logic devices [3].

The properties of CVD-grown graphene on the surface of magnetron sputtered $Co_2FeGe_{0.5}Ga_{0.5}(001)$ half-metallic Heusler alloy thin film was studied by Li et al. [4]. They suggest that the electronic properties of the Heusler alloy were preserved at the interface with graphene. Yamaguchi et al. demonstrated the dry transfer of a multilayer graphene flake on the Co_2FeSi spin valve electrodes [5]. The performance of their device – large nonlocal magnetoresistance signal – was significantly large compared with previously reported values. Recently, Li et al. reported epitaxial growth of Co_2MnSi film on Ge(111) substrate via a graphene interlayer [6].

Herein, we present the influence of the properties of a graphene substrate on the growth of Heusler alloy thin films. The sputter deposited thin films of Co_2MnSn and Co_2MnAl Heusler alloys on HOPG (highly oriented pyrolytic graphite – whose surface is similar to graphene) have a polycrystalline structure. However, Co_2FeSi films grown on the same substrate have (001) texture. In the case of MBE (molecular beam epitaxy) growth of Co_2FeSi thin films on the epitaxial graphene on SiC and transferred graphene on Si/SiO_2, the morphology of the film is an island-type with (022) texture.

This work is supported by the National Science Centre - Poland under the contract 2016/23/D/ST3/02121.

References:
[1] B. Behin-Aein, D. Datta, S. Salahuddin and S. Datta, *Nat. Nanotechnol.* **5** 266 (2010)
[2] C. Felser, G.H. Fecher, *Spintronics: From Materials to Devices,* Springer (2013)
[3] W. Han, R. K. Kawakami, M. Gmitra and J. Fabian, *Nat. Nanotechnol.* **9** 794 (2014)
[4] S. Li, et al., *Advanced Materials* **32** 1905734 (2020)
[5] T. Yamaguchi, et al., *Applied Physics Express* **9** 063006 (2016)
[6] G. Li, et al., *Applied Physics Letters* **120** 162403 (2022)

MODE SOFTENING IN THIN MAGNETIC FILM INFLUENCED BY PERPENDICULAR MAGNETOCRYSTALLINE ANISOTROPY, DZYALOSHINSKII-MORIYA INTERACTION, AND DAMPING

Nikodem Leśniewski[1] and Paweł Gruszecki[1]

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Basic magnetic parameters determining the internal structure and chirality of domain walls are perpendicular magnetocrystalline anisotropy (PMA), film's thickness, and Dzyaloshinskii–Moriya interaction (DMI)[1]. However, these parameters also significantly influence spin wave (SW) dynamics in uniformly in-plane magnetized thin films. For example, the presence of PMA may induce a minimum in the dispersion relation for a non- zero wave number ($k \neq 0$) in the so-called Damon-Eshbach geometry[2]. DMI, on the other hand, introduces the nonreciprocity to the dispersion relation (breaking of the mirror symmetry with respect to $k = 0$). It happens due to the different spatial chirality of the waves propagating in the opposite directions. Furthermore, the thicker film, the more pronounced the dipolar interactions, which also affects SWs. Here, we perform an extensive study of the effects of DMI, PMA, thickness, and damping values on the SW dispersion relation. Using the finite element method, we solve the linearized Landau-Lifsthitz-Gilbert equation in the frequency domain for the Damon-Eshbach geometry. In our study, we analyze and compare films of various thicknesses made of two different magnetic materials, i.e., CoFeB and Ga-doped yttrium iron garnet. We show that even for small values of PMA, the minimum for $k \neq 0$ may appear (see the example shown in Figure 1). Furthermore, as the field value decreases, the minimum deepens significantly. This is related to the softening of SWs. Interestingly, for the case shown in Figure 1(b) and the field 60.3 mT, the difference in frequencies for $\alpha = 0.03$ is up to 0.4 GHz lower than for $\alpha = 0.001$ whereas for 75 mT there is no difference. Finally, we analyze the impact of all the beforementioned parameters on mode profiles of SWs. Our results reveal unique properties of the softened SWs from the bottom of the dispersion relation.

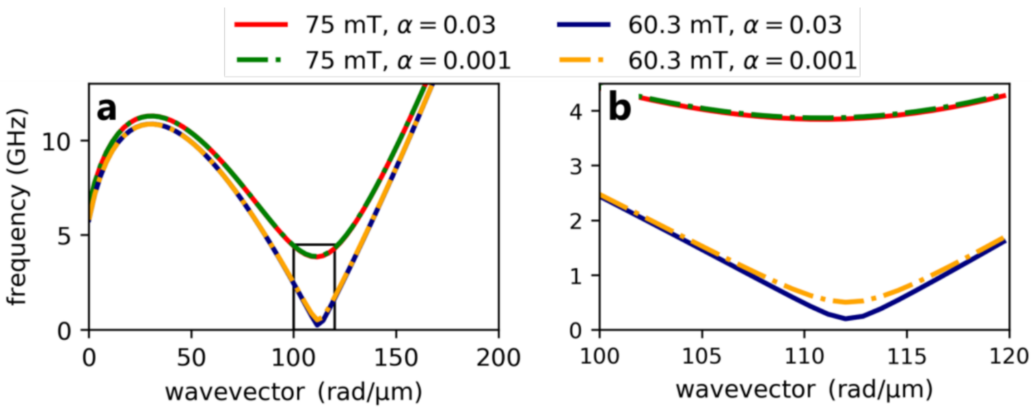

Fig. 1: Dispersion relations of SWs in a 15 nm thick uniformly in-plane magnetized CoFeB film with PMA (K_{PMA} = 690 kJ/m^3) and no DMI for the following combinations of the magnetic field and damping constant: 75 mT and $\alpha = 0.03$ (the solid red line); 75 mT and $\alpha = 0.001$ (the dash-dotted green line); 60.3 mT and $\alpha = 0.03$ (the solid navy blue line); and 60.3 mT and $\alpha = 0.001$ (the dash-dotted orange line). (b) shows a zoomed-in section of the dispersion relation from (a) marked by the black rectangle.

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

References:

[1] Kisielewski et al. *New J. Phys.* **21**, 093022 (2019).
[2] Banerjee et al. *Phys. Rev. B* **96**, 024421 (2017).

FERROMAGNETIC RESONANCE IN SINGLE AND BE-LAYERED CRESCENT-SHAPED NANOROD DEPENDING ON THE VALUE OF THE MAGNETIC FIELD

Uladzislau Makartsou[1], Hanna Reshetniak[1], Nikodem Leśniewski[1], Mateusz Gołębiewski[1], Mathieu Moalic[1], Paweł Gruszecki[1], Maciej Krawczyk[1]

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Spintronic devices operating on spin waves (SW) can be more efficient than oxide semiconductors due to their high frequencies and low energy cost. Therefore, SW based technology may prove to be more powerful than CMOS devices due to its intrinsic characteristics [1]. Magnetic field is the primary stimuli controlling magnetism and SW dynamics. Thus, the study of the influence of the magnetic field on ferromagnetic nanostructures with different geometries is critical for modern technologies, especially for the development of 3D-magnonic circuits, where the geometric constraints generate a strong relationship between the fields of demagnetization, exchange and bias.

Recently, it has been experimentally demonstrated that the 3D network formed from crescent-shape nanorods (CSN) is promising for development of 3D ferromagnetic systems for various applications [2]. As yet, CSN-s have not been investigated for their effect on SW spectra and manipulations in relation to magnitude. Unusual results make our analysis relevant for future investigations and applications. In particular, we show that there are edge/anti-edge localized modes, bulk SW mode and hybridized modes Fig.1. For strong magnetic fields with magnitude higher than 1000 mT, we observe a transition from hybrid modes Fig.1b and c to edge localized and anti-edge localized modes Fig.1d. When an additional magnetic layer is added to the CSN, the magnetostatic coupling between the elements leads to additional modes splitting, Fig. 2. For magnitudes over 1000 mT, we can also observe some anti-edge localized modes for the bottom layer and bulk modes for the top layer over 1000 mT. On the top layer, the CSN-s can support 3D magnonic circuits at nanoscale, which operate at a wide range of frequencies, offer multimode operation, and promise nonreciprocal effects.

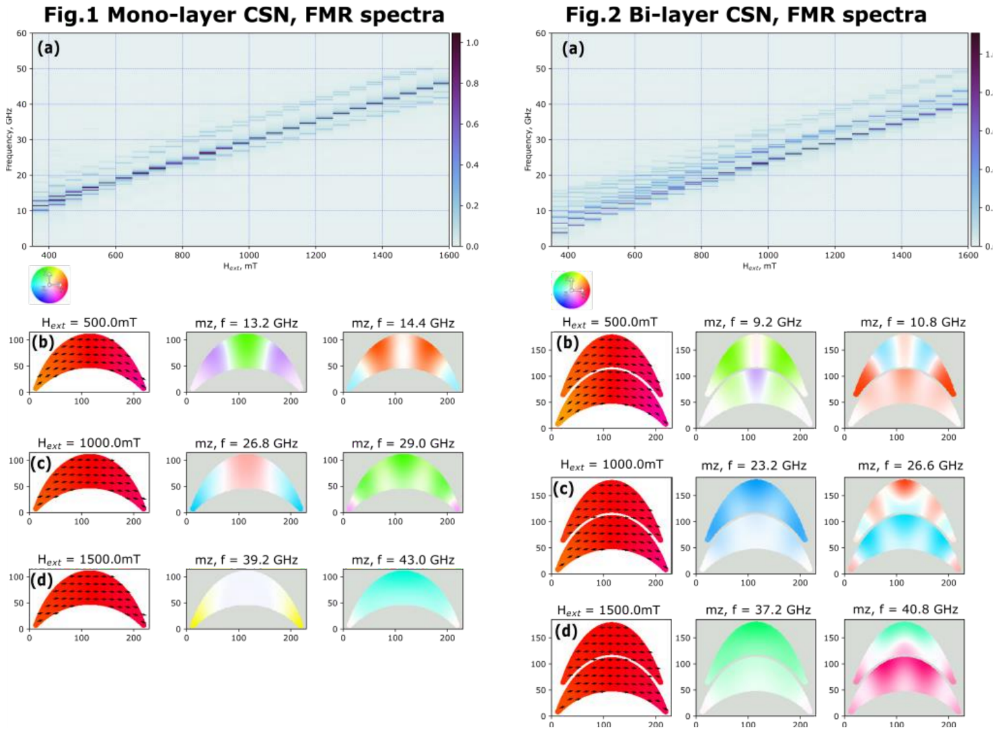

Fig. 1: (left): FMR spectra for monolayer CSN (a), magnetization and two-highest modes for difference magnitude of external magnetic field (b),(c),(d). (right): FMR spectra for belayer CSN (a), magnetization and two highest modes for difference magnitude of external magnetic field (b),(c),(d).)

The research has received founding from the NCN Poland, project no 2020/39/I/ST3/02413.

References:

[1] Q. Wang, et al., *A magnonic directional coupler for integrated magnonic half-adders*, Nat. Electron. **3**, 765, (2020).
[2] A. May, et al., *Realisation of a frustrated 3D magnetic nanowire lattice*, Commun. Phys. **2**, 13 (2019).

FAILURE OF THE MEAN-FIELD LIKE METHODS IN STRONGLY CORRELATED MANY BODY SYSTEMS

Tomasz Polak

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Bosonic lattice systems with extended interactions constitute a unique platform to study new phases of matter. This work presents an analysis of the Bose-Hubbard model with density-induced tunneling. The U(1) quantum rotor method in the path integral effective action formulation is used. This approach enables the discovery of a second kind of superfluidity in physical systems: pair superfluidity, thus adding to the phases of matter. It also sheds light on the properties of singleparticle Bose-Einstein condensation (BEC) in optical lattice systems with higher inter-particle correlations. The derived effective phase Hamiltonian includes the residue of many-body correlations, providing information about phase transitions between the normal state and single-particle and pair superfluids at finite temperatures. The thermodynamical properties of the system are investigated. The impact of density-induced tunneling on single-particle BEC is also analyzed. The density-induced term supports single-particle coherence at high densities and low temperatures, improving the single BEC critical temperature. It is also responsible for dissipative effects, which are independent of the system's thermal properties.

UNCONVENTIONAL PHOTON-PHONON BLOCKADE IN HYBRID QUANTUM SYSTEMS

Shilan Ismael Abo[1]

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Quantum technologies use light sources with a certain number of photons for several applications, including optical quantum information processing and quantum cryptography. During a photon (phonon) blockade, a driven nonlinear system can only emit one photon at a time. Statistics based on sub-Poissonian excitation-numbers can be used to describe this quantum phenomenon. In this talk, a novel kind of blockade in a hybrid mode that is produced by linear coupling of photonic and phononic modes will be discussed. The main focus of the explanation will be on how it can be produced and detected in a driven nonlinear optomechanical superconducting system. For photons, phonons, and hybrid bosons, we find such system parameters for which we observe eight types of different combinations of either blockade or tunneling effects (defined by sub- and super-Poissonian statistics, respectively). Specifically, we show that the hybrid photon-phonon blockade can be produced by combining photonic and phononic modes that do not exhibit blockade [1].

References:

[1] S. Abo, G. Chimczak, A. Kowalewska-Kudłaszyk, J. Peřina, R. Chhajlany, and A. Miranowicz, *Hybrid photon–phonon blockade*, Scientific Reports **12** (2022), 10.1038/s41598-022-21267-4

NONEQUILIBRIUM THERMOELECTRIC TRANSPORT THROUGH KONDO CORRELATED IMPURITIES

Anand Manaparambil, Andreas Weichselbaum, Jan von Delft and Ireneusz Weymann

Describing the nonequilibrium transport through Kondo correlated systems in the nonlinear regime of finite potential bias and temperature gradient had been an open challenge in the field of theoretical condensed matter physics. Tensor networks came into the field as a promising way to describe quantum many-body problems. Here, we use a hybrid Numerical Renormalization Group – time dependent Density Matrix Renormalization Group (NRG-tDMRG) method based on a matrix product state framework to describe the transport. Thus, we present the first quantitatively accurate theoretical description of the nonequilibrium transport through a quantum dot in the presence of a finite temperature gradient.

ROLE OF MAGNETIC SURFACE ANISOTROPY IN MAGNONIC CRYSTAL

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Magnonics is a rapidly developing field of science and technology. Using spin waves as information carriers allows operations in the GHz frequency range while keeping the size of the device in the nanometer range [1]. To tailor the spin wave propagation according to our needs, we can use various approaches. One possibility is the patterning of magnetic material, e.g. by forming so-called magnonic crystals, which are periodic magnetic nanostructures. However, changing the geometry or material composition may not be sufficient, so other factors are being sought to tailor the properties of the spin wave. One possibility inherent in the geometry is to change the boundary conditions, which were described by Rado and Weertmann [2] and later developed by K. Yu. Guslienko [3,4]. The boundary conditions were refined using the spin wave pinning parameter, which describes the contribution of shape and surface anisotropy. Due to the complexity of the issue, the effect of the spin wave pinning and the possible applications are still under consideration.

In my research, I focused on the role of surface anisotropy in the case of a planar two-dimensional magnonic crystal. The investigated system consists of square CoFeB dots, separated by a non-magnetic spacer. The surface anisotropy at the lateral edges of the dots modifies the spin wave pinning and thus dynamic surface magnetic charges. As a result, the spin wave profiles (inside magnetic dots) and the distribution of dynamic stray fields (in the spacer between them) are changing. These effects influence magnetization dynamics inside the dots and the dynamic coupling provided by the stray field which is reflected in the modification of the collective spin wave modes in the array of dots.

We considered co-called forward geometry, where the static magnetization is oriented out-of-plane. The implementation of surface anisotropy on selected edges of dots can break the four-fold symmetry of the structures and introduce the difference in spin wave propagation in two principal directions of the square lattice.

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References:

[1] Chumak, A. V., Serga, A. A., & Hillebrands, B., Magnonic crystals for data processing, *Journal of Physics D: Applied Physics* **50**, 244001 (2017).
[2] Rado, G. T., & Weertman, J. R., Spin-wave resonance in a ferromagnetic metal, *J. Phys. Chem. Solids* **11**, 315 (1959)
[3] Guslienko, K. Yu., & Slavin, A. N., Boundary conditions for magnetization in magnetic nanoelements. *Physical Review B* **72**, 014463 (2005)
[4] Guslienko, K. Yu., Demokritov, S. O., Hillebrands, B., & Slavin, A. N., Effective dipolar boundary conditions for dynamic magnetization in thin magnetic stripes. *Physical Review B*, **66** 132402 (2002)

INFLUENCE OF UNDERLAYER ON SURFACE ACOUSTIC WAVES VELOCITY IN CoFeB/MgO HETEROSTRUCTURE

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Surface acoustic waves (SAWs) are the sound waves that travel along the surface of an elastic material with amplitude decreasing in the depth of the material and the associated quasiparticle is known as phonons. Based on the propagation of atoms in the material, it can be categorized into Rayleigh waves, Sezawa waves and Love waves. The velocities of theses waves can be used to extract the elastic properties of the film. SAWs can be measured using Brillouin light scattering (BLS) spectroscopy, which is a non-contact and non-invasive technique to measure elastic properties of the material. Here, we have investigated SAWs (mainly Rayleigh waves) in CoFeB/MgO heterostructure which have shown potential for spintronics based applications like magnetic tunnel junction [1], race-track memory [2], read-head [3] etc. and also for magnon-phonon interaction-based application. The sample we studied is: Si/SiO_2/X/CoFeB(1.4)/MgO (2)/Al_2O_3 (10) where X = Ta(10), Pt(10), W(10) and Ta(5)/Ru(20)/Ta(5) and the numbers in parentheses are in nm. From the measured dispersion relations, we observed that the slope decreases with increasing density of the underlayer material (Ta $<$ W $<$ Pt), except for TRT one where overall thickness of the sample changes. We also performed COMSOL simulation based on finite element methods and observe the similar trend. The possible reason might be the change of effective elastic property of the film by changing the underlayer which leads to different Rayleigh wave velocities in the films. This study is our first step towards the study of magnon-phonon coupling phenomena in these set of samples.

References:

[1] Ikeda, S., Miura, K., Yamamoto, H. et al. *A perpendicular-anisotropy CoFeB–MgO magnetic tunnel junction*, *Nature Mater* **9**, 721–724 (2010)

[2] Y. Zhang, W. S. Zhao et al. *Journal of Applied Physics* **111**, 093925 (2012)

[3] K. Tsunekawa, D. D. Djayaprawira et al. *Appl. Phys. Lett.* **87**, 072503 (2005)

INVESTIGATION OF SPIN WAVE DYNAMICS IN Si/Ti/Au/CoFeB/Au MULTILAYERS WITH AND WITHOUT PMA

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KEY WORDS: Perpendicular Magnetic Anisotropy, Brillouin Light Scattering, Dzyaloshinskii-Moriya interaction, backscattering geometry, Focused Iron Beam

We investigated the interaction between spin waves based on ferromagnetic/heavy metal multilayers with Perpendicular Magnetic Anisotropy (PMA). Here we employed Brillouin Light Scattering method to quantify frequency of magnons in thin-film samples composed of magnetic and non-magnetic layers deposited on Si substrate. Measurements were taken in 180° backscattering geometry. We observed Dzyaloshinskii-Moriya Interaction (DMI) and characterize the strength of interfacial DMI in perpendicularly magnetized thin films. Field dependent study and spin wave dispersion relations were extracted and studied the nonlinear effect as well as system behavior. To further investigate synergy of complex magnetization textures we partially destroyed PMA by Ga together with introduced magnetic patterns by Focused Iron Beam (FIB) technique in samples with modified properties and also extracted the influence of anisotropy, DMI and other parameters.

MICROMAGNETIC AND EXPERIMENTAL STUDIES ON SPIN WAVE SCATTERING IN VARIOUS MAGNONIC SYSTEMS

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Spin waves are a form of disturbance of the ordered magnetization propagating in the material over macroscopic distances. They are more and more intensively studied and considered as a promising candidate for practical applications, especially as information carrier. If we are able to control the propagation of spin waves in the material – for example, influence their speed or amplitude – then we can code information in the spin-wave parameters. However, we cannot directly control individual spins – manipulation of spin-wave parameters must therefore be done by selecting the appropriate medium in which it is to propagate. One tool to control spin waves is elastic scattering at artificially created interfaces or artificial magnetic patterns. So, further progress in this field requires the creation of new systems to exploit the opportunities that lie ahead.

In our work, using micromagnetic simulations, we study at a zero magnetic field a hybrid system consisting of three layers: (i) a long permalloy waveguide; (ii) a thin circular nanodot hosting stable Néel type skyrmion made of material with the perpendicular magnetic anisotropy and Dzyaloshinskii-Moriya interactions; and (iii) a non-magnetic separation layer between the stripe and the nanodot. In our study, we (i) check the static coupling between the nanodot and the waveguide; (ii) verify whether it is possible to excite skyrmion dynamics using propagating spin waves; and (iii) investigate how the presence of a nanodot with skyrmion and its imprint affects spin-wave transmission through the waveguide[1].

As an alternative system, we also study the propagation of spin waves in a waveguide under the influence of an asymmetric defect located in the waveguide. We aim to answer how its presence in the waveguide interacts with propagating spin waves and influences their transmission.

Both studied systems show the scattering of the propagated spin waves in the waveguide due to presence of the defect or skyrmion in the system. We observe various types of conversions of the incident spin-wave mode into other types of modes.

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References:

[1] Kotus K. A. et al., *APL Materials* **10**, 091101 (2022)

SPIN-DEPENDENT LOCAL AND NON-LOCAL THERMOELECTRIC RESPONSE IN HYBRIDS QUANTUM DOT CONNECTED TO TWO FERROMAGNETIC AND A SUPERCONDUCTING LEAD

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Superconductors perfectly conduct electric current but are poor thermal conductors exhibiting small thermoelectric response. It is also known that at low temperature in a normal metal-superconductor bilayer the main contribution to the transport is due to Andreev states. However, these states reveal particle-hole symmetry and thus Andreev processes cannot alone generate any voltage when temperature gradient is applied to such a hybrid. Fortunately, this problem can be overcome by inserting quantum dot (QD) between normal metal and superconductor and making use of quasiparticle states [1]. As a result, the sign and magnitude of thermovoltage can be tuned by gate voltage applied to the dot.

Here, we consider a multi-terminal hybrid quantum dot-based system. Particularly, we investigate spin-dependent thermoelectric properties of a quantum dot coupled to one superconducting lead and two ferromagnetic metal electrodes. Such a configuration allows us to study both local and non-local spin-resolved thermoelectric response in a Cooper beam splitter device. To describe thermal properties of multi-terminal system we provide local and non-local transport coefficients like electrical and thermal conductances, thermoelectric powers and its spin counterparts. These quantities have been calculated with the help of non-equilibrium Green's function method within the Hubbard I approximation in respect to on-site dot's Coulomb repulsion. Moreover, we present the efficiency at maximum power written in terms of generalized figures of merit [2]. The main goal of the work is to show how an additional terminal changes/improves the hybrid QD-based device's performance and under which conditions non-local thermoelectric effects can be observed.

References:

[1] P. Trocha and J. Barnaś, *Phys. Rev. B* **95**, 165439 (2017).

[2] F. Mazza et al., *New J. Phys.* **16**, 085001 (2014).

FINITE-TEMPERATURE PAIRING MECHANISM IN THE BOSE-HUBBARD MODEL

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The Bose-Hubbard model is well-known within mean-field approximations, but its more complex properties have still not been fully described. The path integral regime is analytically exact, until any approximations are introduced by hand. The methods used and the order of operations determine what information can be obtained in a path integral study. The quantum rotor method states that the phases of the bosonic fields are where the system's dynamics can be easiest observed. The strategy then is to transform the many-body model into an effective phase model. In the usual quantum rotor approaches to the Bose-Hubbard model, the trace obtained by integrating over the bosonic amplitudes is approximated to first-order terms of its series expansion. Extending the approximation by second-order terms leads to a new term appearing in the effective action: a pairing term, which gives rise to an additional condensate phase of bosonic pairs. The pairing term also strengthens the single Bose-Einstein condensate by boosting the critical temperature of the BEC-to-normal phase transition.

MAJORANA-KONDO COMPETITION IN CORRELATED QUANTUM DOT SYSTEMS

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One of the most exciting topics in condensed matter research is the hunt for Majorana quasiparticles. The idea of the particle which is its antiparticle came up to Ettore Majorana almost 90 years ago. Originally, this hunt was focused on particle physics, however, the potential solution was proposed within solid-state physics over sixty years later. Nowadays, the recipe of mixing semiconducting one-dimensional nanowires with spin-orbit interaction, superconductivity, and magnetism is being exploited by leading experimental groups. On the other hand, quantum dots are well-explored nanoscale devices, which are commonly used in Majorana research. In this communication, I want to shortly introduce the concept of Majorana zero modes in condensed matter physics. Then, I would like to show how the presence of Majorana quasiparticles affects the electronic and thermoelectric transport properties of Kondo-correlated quantum dots, sharing the results obtained with the aid of the numerical renormalization group technique.

FROM ORDER TO CHAOS IN REDUCED QUANTUM DYNAMICS

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We consider a modified system of N interacting qubits that is commonly known as the kicked top. We introduce a dissipation to this model (described by the parameter $0 < r < 1$, where $r = 0$ corresponds to maximal dissipation and $r = 1$ to no dissipation) and focus on a reduced dynamics of a single qubit as N goes to infinity. We observe an order-to-chaos transition as the parameter r grows. The road to chaos leads via the universal period doubling behaviour that starts around $r = 0.3181$ and ends in the fully chaotic behaviour around $r = 0.578$. Interestingly, we observe windows of periodicity within the chaotic range, as well as some small scale chaotic dynamics around $r = 0.544$. The chaotic behaviour takes place on a strange attractor, that can be visualised using the Bloch sphere, and its fractal dimension is estimated to be $d = 1.84$.

References:

[1] W. Kłobus, P. Kurzyński, M. Kuś, W. Laskowski, R. Przybycień, and K. Życzkowski, *Phys. Rev. E* **105**, 034201 (2022)

QUANTUM LIOUVILLIAN EXCEPTIONAL AND DIABOLICAL POINTS FOR BOSONIC FIELDS WITH QUADRATIC HAMILTONIANS: THE HEISENBERG-LANGEVIN EQUATION APPROACH

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Equivalent approaches to determine eigenfrequencies of the Liouvillians of open quantum systems are discussed using the solution of the Heisenberg-Langevin equations and the corresponding equations for operator moments. A simple damped two-level atom is analyzed to demonstrate the equivalence of both approaches. The suggested method is used to reveal the structure as well as eigenfrequencies of the dynamics matrices of the corresponding equations of motion and their degeneracies for interacting bosonic modes described by general quadratic Hamiltonians. Quantum Liouvillian exceptional and diabolical points and their degeneracies are explicitly discussed for the case of two modes. Quantum hybrid diabolical exceptional points (inherited, genuine, and induced) and hidden exceptional points, which are not recognized directly in amplitude spectra, are observed. The presented approach via the Heisenberg-Langevin equations paves the general way to a detailed analysis of quantum exceptional and diabolical points in infinitely dimensional open quantum systems.

SYNERGIC QUANTUM GENERATIVE MACHINE LEARNING

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We introduce a new hyperparameter-free approach toward generative quantum machine learning and report on a proof-of-principle experiment demonstrating our approach. Our proposal depends on collaboration between the generators and discriminator, thus, we call it quantum synergic generative learning. We present numerical evidence that the synergic approach, in some cases, compares favorably to the recently proposed quantum generative adversarial learning. In addition to the results obtained with quantum simulators, we also present experimental results obtained with an actual programmable quantum computer. We investigate how a quantum computer implementing a generative learning algorithm could learn the concept of a Bell state. After completing the learning process, the network is able both to recognize and generate an entangled state. Our approach can be treated as one possible preliminary step to understanding how the concept of quantum entanglement can be learned and demonstrated by a quantum computer.

THE EFFECT OF PASSIVE PT SYMMETRY ON THE PERIODIC BEHAVIOR OF A QUANTUM SYSTEM

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We show how to perform quantum operations with very high fidelity in a three-level system in which one of the levels is an auxiliary level. It is possible to tune the system's eigenfrequencies in such a way that prevents the population of the auxiliary level from reducing fidelity. Unfortunately, this so-called fine-tuning technique is sensitive to damping, which is present in all open systems. Here we show that fine tuning works correctly even in the presence of damping if the quantum system is described by a passive symmetric PT Hamiltonian.

STOKES AND ANTI-STOKES CORRELATIONS AND IDEAL PHOTON-PAIR GENERATION IN RAMAN SCATTERING

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Raman scattering is known as a significant nonlinear process in the implementation of quantum technologies. More recently Raman process is also studied in context of photon-pair generation both theoretically and experimentally. We systematically analyze performance of the Stokes–anti-Stokes photon-pair generation in Raman scattering, analogous to the signal–idler photon-pair generated in the spontaneous parametric down conversion. The study results in the suitable conditions for photon pair-generation the Raman process. This photon-pair generation requires small (non-zero) phonon number and losses in the phonon mode. The Raman active materials with stronger anti-Stokes coupling with respect to the Stokes coupling strength can generate such photon-pairs for suitably calibrated pump power. The Stokes–anti-Stokes correlations are characterized using different nonclassicality witnesses and measures, such as sub-shot noise, Cauchy-Schwarz inequality, Gaussian entanglement and steering, Bell nonlocality. The results are reported in [1].

References:

[1] K. Thapliyal and J. Peřina Jr., *Ideal pairing of the Stokes and anti-Stokes photons in the Raman process, Phys. Rev. A* **103**, 033708 (2021).

ELECTRICAL CONTROL OF SINGLE SPIN DYNAMICS IN SINGLE ATOMS WITH SPIN-POLARIZED STM

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We develop theory of the spin-dependent electron transport and spin dynamics due to presence of noncollinear spin polarized magnetic electrodes or spin-polarized STM in quantum dot (QD) and single atoms (adatoms) on surface. In the such system we can observe the nonequilibrium accumulated spin on the QD (or atom), and virtual spin-dependent exchange processes between the QD and the ferromagnetic electrodes resulting in an effective exchange field [1, 2], that can be controlled by the gate and bias voltages. Using the real time diagrammatic technique and the Lindblad equation approach we define effective Lindblad jump operators for noncolinear systems and find a general Bloch equation [2, 3], which describes the complex spin dynamics in the presence of spin polarized current, and its solutions for various useful and important limits both in the sequential and the cotunneling regime. We derive effective relations describing the effect of the spin accumulation on the dc current flowing in the analyzed systems. We demonstrate that the dc current is related to distinct projections of the induced spin that 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 translate a spin information into a charge signal, while the readout direction can be controlled electrically. These findings allow us to explain the tunnel magnetoresistance characteristics from the recent experiment [4], 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 [5] related to recent breakthroughs in spin-polarized STM that make it possible to probe and control the spin dynamics of individual atoms.

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References:

[1] J. Martinek, Y. Utsumi, H. Imamura, J. Barnaś, S. Maekawa, J. Koning, and G. Schon, *Phys. Rev. Lett.* **91**, 127203 (2003).
[2] P. Busz, D. Tomaszewski, J. Martinek, *JMMM*, **546**, 168831, (2022).
[3] P. Busz, D. Tomaszewski, J. Martinek, *to be published*.
[4] A. D. Crisan, S. Datta, J. J Viennot, M. R. Delbecq, A. Cottet, and T. Kontos, *Nat. Commun.* **7**, 10451 (2016).
[5] S. Loth, K. Bergmann, M. Ternes, A. F. Otte, Ch. P. Lutz and A. J. Heinrich, *Nat. Phys.* **6**, 340 (2010).

STATIC AND DYNAMIC MAGNETIC PROPERTIES OF MONOLAYERS AND BILAYERS OF CHROMIUM TRIHALIDES

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Magnetic van der Waals crystals are currently of great attention due to their interesting magnetic and topological properties that may be useful for applications in new spintronics and electronics devices. One of the most important group of such structures are chromium trihalides CrX_3 (X = I, Cl, Br). In the first part of this talk we will provide a general theoretical and experimental background for these materials [1,2]. Then, we will present our numerical results on magnetic ordering as well as on magnetic excitations.

The numerical simulations have been performed within the Monte-Carlo and atomistic spin dynamic (ASD) methods, as implemented in Vampire code [3,4]. We will discuss the impact of the layer stacking and Dzyaloshinskii-Moriya interaction (DMI) on the hysteresis loops, magnon modes, and other magnetic properties of the monolayers and bilayers of CrI_3. Specifically, we will show that strong DMI, induced e.g. by an external electric field, can lead to the formation of various magnetic textures, including also topological excitations – skyrmions. In our simulations we have also identified the regions on hysteresis loops where the formation of skyrmions can take place spontaneously. In addition, from the ASD simulations we have determined dispersion relations of spin waves in both monolayers and bilayers of CrI_3.

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References:

[1] R. Jaeschke-Ubergo, E. S. Morell, A. S. Nunez, *Phys. Rev. B* **103**, 174410 (2021).
[2] M. Hossain, B. Qin, B. Li, X. Duan, *Nano Today* **42**, 101338 (2022).
[3] R. F. L. Evans, W. J. Fan, P. Chureemart, T. A. Ostler, M. O. A. Ellis and R. W. Chantrell, *J. Phys.: Condens. Matter* **26**, 103202 (2014).
[4] B. Skubic, J. Hellsvik, L. Nordström, O. Eriksson, *J. Phys.: Condens. Matter* **20**, 315203 (2008).

THERMAL GENERATION OF SPIN CURRENT IN A QUANTUM DOT-BASED HYBRID SYSTEM

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Generation of spin current by temperature gradient in a quantum dot hybrid system is investigated. In particular, we study thermoelectric properties of a quantum dot hybrid device consisting of a quantum dot coupled to a magnetic insulator and magnetic metallic electrode. Each electrode is kept at a different temperature. In the considered system spin current is generated by means of temperature gradient set between the electrodes. Furthermore, spin current of the magnonic (electric) type is converted to electric (magnonic) spin current. Here, we investigate an influence of magnonic energy-dependent density of states on thermally induced spin current. Moreover, we take into account many-body magnon interactions and analyze its influence on spin current. Furthermore, a spin Seebeck engine based on quantum dot is investigated. Particularly, we show its power and corresponding efficiency indicating the conditions under which maximum output spin power can be achieved. We also present the conditions under which the considered device works as thermal spin-diode.

ANOMALOUS, SPIN NAD VALLEY HALL EFFECTS IN GRAPHENE-BASED EX-SO-TIC VAN-DER-WAALS STRUCTURES

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Two-dimensional crystals and van-der-Waals structures focus enormous interest due to interesting electronic and magnetic properties controlled by external fields. The development of van-der-Waals structure engineering and advanced modeling of various proximity effects in multilayer hybrid structures lead to the prediction of hybrid materials where one can simply swap between an exchange (EX) and spin-orbit (SO) coupling by electric gate voltage. As a result of such property these structures are called EX-SO-TIC van-der-Waals structures. An example of such materials is bilayer graphene (GG) sandwiched between a 2D ferromagnet $Cr_2Ge_2Te_6$ (CGT) and a monolayer TMDC – WS_2. The efficient swapping between the presence of exchange and spin-orbit coupling in CGT/GG/WS_2 is possible due to the interplay of gate-dependent layer polarization in bilayer graphene and short-range spin-orbit and exchange proximity effects affecting the layers of graphene.

We will present a theoretical study of electronic and topological properties of CGT/GG/WS_2 based on an effective modeled Hamiltonian derived from symmetry considerations and DFT study [1]. Within Green's function formalism we have derived numerical and analytical characteristics describing intrinsic (topological) anomalous, valley and spin Hall effects. Among others, we will explain how the certain Hall effects characteristics reflect the changes of band structure (topological properties described by the Berry curvature) due to external gate voltage.

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References:

[1] K. Zollner, M. Gmitra, J. Fabian, *Phys. Rev. Lett.* **125**, 196402 (2020)

DYNAMIC INTERACTIONS BETWEEN EDGE AND BULK MODES IN AN ANTIDOT LATTICE WITH PERPENDICULAR MAGNETIC ANISOTROPY

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Patterned arrays in thin films have shown a lot of potential due to their abilities to manipulate magnetic microwave excitation, called spin waves (SWs). These types of periodic nanostructures, also called magnonic crystals, are seen as the magnetic variant of the photonic crystals with the added advantage that SWs can have a wavelength smaller than their optical counterpart, which can lead to the creation of magnonic devices with a very small footprint. In the case of antidot lattices, the inhomogeous material found around each antidot can bring forward an interesting range of complex, hybridized resonant SW modes. Thin films with out-of-plane magnetization are more interesting than those with in-plane magnetization due to the SWs dispersion relation being isotropic. The out-of-plane magnetization is achieved in ferromagnetic thin films with perpendicular magnetic anisotropy due to a multilayered approach using multiple layers of alternating ferromagnetic metals and heavy metals.

The film we study is made up of 8 repetitions of Co (0.75 nm) and Pd (0.9 nm) bilayers for a total of 13.2 nm [1]. Periodically throughout this thin-plane film, nanodots were etched out using a 10 nm wide focused ion beam creating a pattern of antidots. This process not only removed some material, but also damaged the area around each antidot, creating a 'ring' of low anisotropy in the film. This results in the configuration of the magnetization at the edges of the antidot being almost in-plane. For a circular antidot shape, the ground state of such a system has magnetization in the edge ring in a vortex-like configuration as seen in Fig. 1(left). Through micromagnetic simulations, we are analysing dynamical coupling between edge localised and bulk modes in the film. We modify many parameters in this system such as lattice constant, antidot shape, antidot size, ring width, external field direction, etc. Different types of modes are identified, such as the ferromagnetic resonant mode of the thin film around 9.5 GHz as well as higher frequency bulk modes resulting from the antidot lattice. A multitude of edge modes have also been identified in the low anisotropy rings at frequencies from 3 to 13 GHz with, for example, the one seen in Fig. 1(right). We show that the strong dynamical coupling between the rings can be obtained, which demonstrates collective behaviour on the lattice and promises usefulness for magnonic applications.

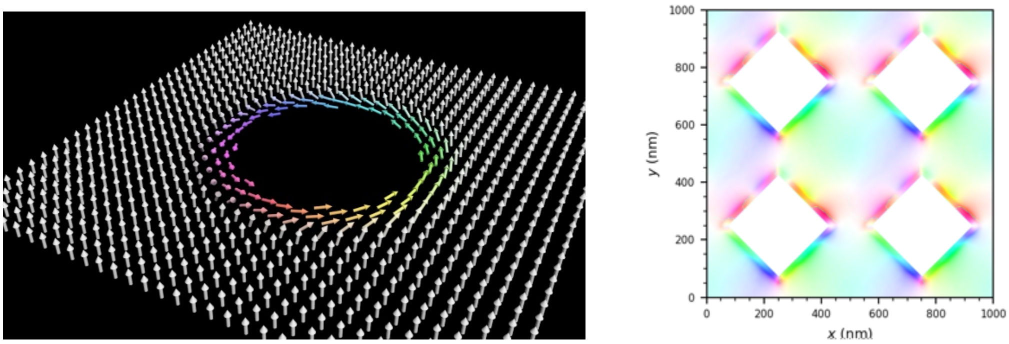

Fig. 2: (left) Magnetization for one cell of the antidot lattice. (right) Edge modes for a diamond antidot lattice for a lattice constant of 500 nm

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References:

[1] Pan, S., et al. *Physical Review B* **101**, 1 (2020): 014403.

MAGNETIC PROPERTIES OF MONOLAYER AND BILAYER OF VANADIUM-BASED TRANSITION METAL DICHALCOGENIDES VX_2 (X=S, Se, AND Te)

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The semi-metallic two-dimensional Vanadium based transition metal dichalcogenides are currently of great interest due to their electronic and magnetic properties, which make them very promising for possible application in spintronics [1,2,3]. We will present the results of first-principle studies of the electronic and magnetic properties of the monolayers and bilayers of VX_2 (X=S, Se, and Te). We have found that the Vanadium atoms within individual atomic layers are coupled ferromagnetically. In contrast, the exchange coupling between V atoms located on different layers is either ferromagnetic or antiferromagnetic, depending on the type of stacking and on the sort of X atoms. Apart from electronic structures and magnon spectra, we will discuss the magnetic properties of these materials, like the intra- and interlayer nearest and next-nearest-neighbors exchange interactions and the orbital-resolved magnetocrystalline anisotropy energy (MAE) of V atoms. We will also present the data on Curie temperatures, determined in the mean-field approximation (MFA), as well as on the spin dynamics obtained from the Landau-Lifshitz-Gilbert (LLG) equation. Additionally, we will also present results on transport properties (including thermoelectric characteristics) of the monolayer and bilayer VX_2 systems [4].

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References:

[1] Fuh, Huei-Ru, et al. *Newtype single-layer magnetic semiconductor in transition-metal dichalcogenides VX 2 (X= S, Se and Te).* Scientific reports **6.1** (2016): 1-11.
[2] Chen, Wei, et al. *Electronic structure and magnetism of MTe_2 (M= Ti, V, Cr, Mn, Fe, Co and Ni) monolayers.* Journal of Magnetism and Magnetic Materials **508** (2020): 166878.
[3] Wang, Chen, and Yukai An. *Effects of strain and stacking patterns on the electronic structure, valley polarization and magnetocrystalline anisotropy of layered VTe_2.* Applied Surface Science **538** (2021): 148098.
[4] Jafari, M. A., et al. *Spin valve effect in two-dimensional VSe_2 system.* Journal of Magnetism and Magnetic Materials **548** (2022): 168921.

MAGNONIC COUNTERPARTS TO PHENOMENA KNOWN IN OPTICS FOUND IN SPIN-WAVE REFLECTION FROM MAGNONIC GIRES-TOURNOIS INTERFEROMETER

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Wood's anomaly is a phenomenon discovered in 1902 [1], manifesting as a sudden decrease in the amplitude of reflected waves due to the excitation of surface mode that is still being investigated in photonics [2]. Another interesting effect observed in the reflection of obliquely incident light is the Goos-Hanchen effect (GHE) [3], which manifests as a spatial shift of the reflected waves and is caused by the phase shift at the interface. GHE was predicted numerically for spin-waves (SWs)[4] as well as observed experimentally[5]. One of the configurations suitable for observation of both phenomena is the Gires-Tournois interferometer (GTI) proposed in Ref. [6], built of a magnetic nanostripe placed above the edge of a magnetic layer. We use micromagnetic simulations to study the reflection of a SW beam cast obliquely on GTI. We found the resonance conditions required to excite SW modes in the GTI by the incident SW beam. The excitation of GTI modes causes the decrease of the reflected SW's amplitude what we explain as a magnonic counterpart to Wood's anomaly in our system. The amplitude of excited modes is only partially confined in GTI and remits SWs back to the layer; therefore, we classify these modes as 'leaky modes'. The reemission of SWs from leaky modes creates multiple spatially shifted SW beams in the layer parallel to one another. The new beams are laterally shifted; the shift spans several wavelengths compared to the system without excited leaky-mode, which is significant for magnonic systems. These spatial shifts of the reflected SW beams can be described as a magnonic counterpart to GHE. In Fig. 1a and 1b we show the distributions of SW intensity for the case with the resonant excitation of a leaky mode and without the excitation, respectively. In Fig. 1b, additional reflected SW beams are evident. Our findings contribute to understanding and utilizing the interaction of propagating SWs in thin films with localized leaky modes. The magnonic phenomena we described are a bridge between magnonics and optics that will be used for employing SWs in functional devices.

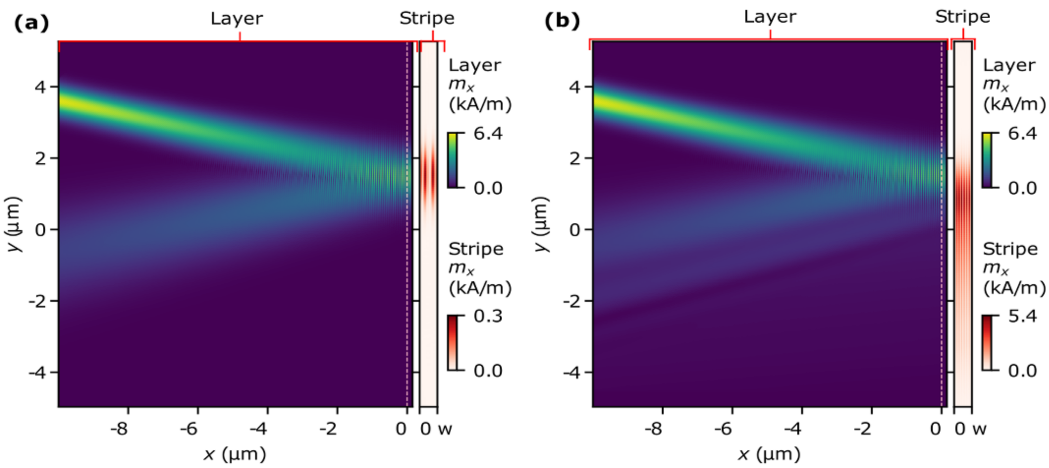

Fig. 2: The SW intensity distribution in the layer (left panels) and in the stripe (right panels) placed above the film in the systems, with stripes: (a) $M_S = 350$ kA/m and (b) $M_S = 550$ kA/m, without and with excited leaky-mode, respectively.

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References:

[1] RW. Wood, Lond. Edinb. *Dublin philos. mag. j. sci.* **4**, 396 (1902).
[2] E. Galiffi, YT. Wang, Z. Lim, *Phys. Rev. Lett.* **125**, 127403 (2020).
[3] F. Goos, H. Hänchen, Annalen der Physik 436, 333 (1947).
[4] P. Gruszecki, J. Romero-Vivas, Yu. S. Dadoenkova, *Appl. Phys. Lett.* **105**, 242406 (2014).
[5] J. Stigloher, T. Taniguchi, HS. Körner, *Phys. Rev. Lett.* **121**, 137201 (2018)
[6] K. Sobucki, W. Śmigaj, J. Rychły, *Sci. Rep.* **11**, 4428 (2021).

CONVERSION BETWEEN ELECTRONIC AND MAGNONIC SPIN CURRENTS DRIVEN WITH SPIN-THERMOELECTRIC EFFECT IN A QUANTUM DOT HYBRID SYSTEM

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Due to its advantageous transport properties, utilizing magnonic spin current seems to be a promising direction in the further enhancement of performance of the spintronic devices. For the time being spintronic circuits operating fully on magnons as carriers of information are lacking. On the other hand, number of devices working as converters between the magnonic and electronic spin current were proposed. Usually such a conversion is realized at the interface of magnetic insulator and heavy or normal metal. Moreover the spin current in the converter can be driven with temperature gradient which allows to utilize waste heat generated during the transport of electrons. Quantum dot is an ideal addition to the temperature driven converter, because, owing to its reduced dimensionality, it improves the efficiency of the conversion.

We investigate a hybrid system which utilizes a temperature gradient to drive spin current with conversion of magnonic spin current to electronic spin current and vice versa. The considered system consists of a quantum dot coupled to ferromagnetic insulator (reservoir of magnons) and metal (reservoir of electrons). Expanding spin and heat currents flowing through the system, up to linear order, we introduce basic spin thermoelectric coefficients including spin conductance, spin Seebeck and spin Peltier coefficients and heat conductance. We analyse the spin thermoelectric properties of the system in two cases: in the large ondot Coulomb repulsion limit and when these interactions are finite.

ROLE OF THE SURFACE ANISOTROPY ON THE SPIN-WAVE DISPERSION OF A THIN FERROMAGNETIC LAYER

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The spin-wave dynamics are described by the Landau-Lifshitz equation. To solve it in finite systems, one requires boundary conditions to be applied. The most basic case describes the condition coming only from the exchange interaction which states that the first derivative of the magnetization is zero on the boundary. This condition is known as free boundary condition as it results in a fact that a spin on the boundary is "free". In 1959, Rado and Weertman [1] proposed a way to describe the boundary conditions in the presence of anisotropy on the surface.

We present an in-depth study of the effect of the surface anisotropy on the spin-wave dynamics of a thin CoFeB layer in Damon-Eshbach geometry. We extended the model of the spin-wave dynamics in a dipole-exchange regime [2] to boundary conditions with surface anisotropy. This model is in full agreement with numerical simulations of Landau-Lifshitz equation and it allows to apply different surface anisotropy strength on both interfaces. The dispersion relation was calculated for the cases of the symmetrical and one-sided surface anisotropy for wide ranges of different parameters like surface anisotropy constant, external magnetic field, and layer thickness. We focused on the main effect on the dispersion relation – the hybridization between the surface mode with perpendicular standing modes and the mode profiles.

References:

[1] G. T. Rado and J. R. Weertman. *Spin-wave resonance in a ferromagnetic metal.* J. Phys. Chem. Solids **11**, 315-333 (1959).

[2] J. S. Harms and R. A. Duine. *Theory of the dipole-exchange spin wave spectrum in ferromagnetic films with in-plane magnetization revisited.* J. Magn. Magn. Mater. **557**, 169426 (2022).

NON-LINEAR HALL EFFECT INDUCED BY BERRY CURVATURE DIPOLE IN A TWO-DIMENSIONAL ELECTRON GAS WITH RASHBA SPIN-ORBIT INTERACTION

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The nonlinear Hall effect (NLHE) is an effect that appears beyond linear system response with respect to the external electric field and may be nonzero even in the presence of the time-reversal symmetry. One of the intrinsic contributions to NLHE has its origin in the Berry curvature dipole (BCD) and requires space-inversion symmetry breaking [1,2].

We have found that a two-dimensional electron gas (2DEG) with Rashba spin-orbit interaction in the presence of an in-plane external magnetic field exhibit the non-zero BCD that can be tuned by the in-plane external magnetic field. We analyze 2DEG with k-linear and k-cubed forms of Rashba spin-orbit interaction. It is well known that 2DEG at the interface of many semiconductor heterostructures reveals the k-linear Rashba SOI [3], whereas the cubic form of Rashba SOI dominates at the interfaces and surfaces of perovskite oxides such as $LaAlO_3/SrTiO_3$ (LAO/STO) that seem to be an excellent platform for the investigation of spin-orbit-driven phenomena [4,5].

Based on our theoretical modelling of BCD and NLHE under an in-plane magnetic field, we will show how the transport characteristics related to these phenomena can be tuned by the orientation of the in-plane magnetic field. Moreover, the comparison of theoretically obtained results for different Rashba models with experimental data enables the determination of the dominant component of Rashba SOI in the systems under consideration.

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References:

[1] Sodemann I., Fu L.. *Quantum Nonlinear Hall Effect Induced by Berry Curvature Dipole in Time-Reversal Invariant Materials.* Phys. Rev. Lett., **115**(21), 216806 (2015)

[2] Ma Q., et al., *Observation of the nonlinear Hall effect under time-reversal-symmetric conditions,* Nature, **565**(7739), 337–342 (2019)

[3] Winkler R., *Spin-Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems*, Springer, Berlin, Germany (2003)

[4] Liang, H. et al. *Nonmonotonically tunable Rashba spin-orbit coupling by multiple-band filling control in $SrTiO_3$-based interfacial d-electron gases. Phys. Rev. B* **92**, 075309 (2015); Zhong, Z., Tóth, A. and Held, K. *Theory of spin-orbit coupling at $LaAlO_3/SrTiO_3$ interfaces and $SrTiO_3$ surfaces.* Phys. Rev. B 87, 161102 (2013)

[5] Lesne E. et al., *Highly efficient and tunable spin-to-charge conversion through Rashba coupling at oxide interfaces.* Nat. Mater. 15, 1261 (2016); Narayanapillai K. et al., *Interfacial Rashba magnetoresistance of the two-dimensional electron gas at the $LaAlO_3/SrTiO_3$ Interface.* Phys. Rev. B 96, 064401 (2017)

A DIRECT METHOD FOR MEASURING QUANTUM ENTANGLEMENT AND BELL NONLOCALITY OF TWO-QUBIT STATES THROUGH HONG-OU-MANDEL INTERFEROMETR

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Quantum entanglement is one of the fundamental phenomena used in quantum engineering and processing. The measure of entanglement can be expressed as the negativity parameter [1], which describes the cost of positivity- preserving partial transpose (PPT) operations. The physical detection of entanglement is often a problematic issue. A frequently used method is the quantum tomography (QST), which results in full information about the given state. This approach turns out to be problematic because of the large number of the measured parameters (scaling with the square of the total dimension of the measured system). It is possible to determine negativity without using quantum tomography. A direct method for the experimental determination of the negativity of any two-qubit state can be based on singlet measurements performed on multiple copies of the two-qubit system [2,3]. This makes it possible to apply the Peres-Horodecki separability criterion to any two-qubit state.

In our study, we demonstrate the direct approach experimentally by measuring a set of Makhlin invariants [4] by singlet projections. The experiments were performed on the *IBMQ* quantum processor. We investigate that with this method we can perform a test of the Bell-Clauser-Horne-Shimony-Holt (Bell-CHSH) inequality violation. We compare described approach with the QST method.

This work was supported by the Polish National Science Centre (NCN) under the Maestro Grant No. DEC-2019/34/A/ST2/00081.

References:

[1] K. Życzkowski, P. Horodecki, A. Sanpera, and M. Lewenstein. *Volume of the set of separable states*. Phys. Rev. A, **58**:883–892, Aug 1998.

[2] K. Bartkiewicz, G. Chimczak, and K. Lemr. *Direct method for measuring and witnessing quantum entanglement of arbitrary two-qubit states through Hong-Ou-Mandel interference*. Phys. Rev. A, **95**:022331, Feb 2017.

[3] K. Bartkiewicz and G. Chimczak. *Two methods for measuring Bell nonlocality via local unitary invariants of two-qubit systems in Hong-Ou-Mandel interferometers.* Phys. Rev. A, **97**:012107, Jan 2018. [

[4] Y. Makhlin. *Nonlocal properties of two-qubit gates and mixed states, and the optimization of quantum computations.* Quantum Information Processing, **1**(4):243–252, Aug 2002.

NONLINEAR LONGITUDINAL AND TRANSVERSE DC CONDUCTIVITY IN TOPOLOGICAL INSULATORS: EFFECT OF SCATTERING ON SPIN-ORBITAL IMPURITIES AND NON-EQUILIBRIUM SPIN POLARIZATION

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Bilinear magnetoresistance (BMR) and nonlinear planar Hall effect (NPHE) appear in nonmagnetic materials as a consequence of strong spin-orbit interaction. These effects behave linearly with respect to both external electric and in-plane magnetic fields. As far, several microscopic mechanisms have been proposed [1], related to the inhomogeneities of spin-momentum locking and/or the hexagonal warping of the Dirac cones [2].

Using Green functions formalism, we have performed a consistent theoretical study of the nonlinear terms in diagonal and transverse conductivities, that are due to current-induced spin polarization and scattering on impurities inherently including spin-orbit coupling [3]. We will present detailed characteristics of BMR and NPHE, and compare our results with those obtained in other models. Our results provide additional contribution to understanding the origin of both these effects.

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References:

[1] W. Rao, Y.-L. Zhou, Y.-j. Wu et al., *Phys. Rev. B* **103**, 155415 (2021).

[2] A. Dyrdał, J. Barnaś, and A. Fert, *Phys. Rev. Lett.* **124**, 046802 (2020).

[3] K. Boboshko, A. Dyrdał, and J. Barnaś, *J. Magn. Magn. Mater.* **545**, 168698 (2022).

FIRST-PASSAGE TIME STATISTICS FOR NON-LINEAR DIFFUSION

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Evaluating the completion time of a random algorithm or a running stochastic process is a valuable tip not only from a purely theoretical, but also pragmatic point of view. In the formal sense, this kind of a task is specified in terms of the first-passage time statistics. Although first-passage properties of diffusive processes, usually modeled by different types of the linear differential equations, are permanently explored with unflagging intensity, there still exists noticeable niche in this subject concerning the study of the non-linear diffusive processes. Therefore, our objective is to fill this gap, at least to some extent. Here, we will consider the non-linear diffusion equation in which a diffusivity is power-law dependent on the concentration/probability density, and analyze its properties from the viewpoint of the first-passage time statistics. Depending on the value of the power-law exponent, we will demonstrate the exact and approximate expressions for the survival probability and the first-passage time distribution along with its asymptotic representation. These results refer to the freely and harmonically trapped diffusing particle. While in the former case the mean first-passage time is divergent, even though the first-passage time distribution is normalized to unity, it is finite in the latter. To support this result, we will demonstrate the exact formula for the mean first-passage time to the target prescribed in the minimum of the harmonic potential.

CONNECTION BETWEEN THE SEMICONDUCTOR–SUPERCONDUCTOR TRANSITION AND THE SPIN-POLARIZED SUPERCONDUCTING PHASE IN THE HONEYCOMB LATTICE

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The realization of the honeycomb lattice in graphene draws a lot of attention of the scientific community. The extraordinary properties of the honeycomb lattice are mainly associated with massless Dirac fermions, which are located in the corners of the Brillouin zone. As a consequence, fermions in this lattice manifest a semiconducting behavior below some critical value of the onsite attraction, U_c. However, above U_c, the superconducting phase can occur. This lattice exhibits also topological properties manifested by the existence of zero-energy edge states or in the quantum Hall effect, associated to the finite Berry curvature in these systems. The electronic properties of the honeycomb lattices has opened new avenues of research in which applications play a very important role, i.e., spintronics or valleytronics.

Here, we discuss an interplay between the semiconductor–superconductor transition and the possibility of realization of the spin-polarized superconductivity (the so-called Sarma phase) [1]. We show that the critical interaction can be tuned by the next-nearest-neighbor (NNN) hopping in the absence of the magnetic field. Moreover, a critical value of the NNN hopping exists, defining a range of parameters for which the semiconducting phase can emerge. In the weak coupling limit case, this quantum phase transition occurs for the absolute value of the NNN hopping equal to one third of the hopping between the nearest neighbors. Similarly, in the presence of the magnetic field, the Sarma phase can appear, but only in a range of parameters for which initially the semiconducting state is observed. Both of these aspects are attributed to the Lifshitz transition, which is induced by the NNN hopping as well as the external magnetic field.

References:

[1] A. Cichy, K. J. Kapcia, A. Ptok, **Phys. Rev. B 105**, 214510 (2022)

CORRELATIONS IN 1D OPTICAL LATTICES WITH AEL ATOMS

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We study ground-state properties and emerging many-body corrrelations peculiar to gaseous systems consisting of interacting fermionic ytterbium or strontium atoms in state-dependent optical lattices. Restricting ourselves to two orbital and two spin components, as well as quasi-one-dimensional lattice geometry, we construct Hubbard model with the experimentally relevant hierarchy of tunneling and interaction ampli- tudes. We employ exact diagonalization and matrix product states approaches to analyze correlation functions in density, spin, and orbital sectors as functions of vari- able densities of atoms in the ground and metastable excited states. We show that in certain ranges of densities each of the atomic systems demonstrates strong antiferromagnetic as well as antiferroorbital correlations.

THEORY OF THREE-WAVE SCATTERING OF BULK AND EDGE SPIN WAVES

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Multimagnon scattering processes play an important role in magnetization dynamics in magnetic nanostructures, constituting, in particular, an additional dissipation channel, as well as allowing for signal processing with a frequency change. Here we present a combined theoretical description supported by micromagnetic simulation results of inelastic scattering of bulk and edge spin waves (SWs) in the in-plane magnetized semi-infinite ferromagnetic film. Although this topic was considered in Ref. [1], the previous theoretical approach failed to explain obtained in the simulations significant difference between confluence and splitting efficiencies, because didn't take into account the influence of SW group velocity, a phase shift between an incident and reflected beams, the ellipticity of dynamical magnetization precession etc.

Using vector Hamiltonian formalism [2] for calculations of three magnon coefficients and Hamilton motion equations for describing magnetization dynamic, we have developed a strict, but a quite simple analytical model and derived efficiency of the 50 GHz SW beam scattering on edge SWs at frequency 12 GHz depending on the incident beam angle (we assumed external magnetic field applied perpendicularly to the film edge and angle counted from the edge normal). As seen in Fig. 1, the magnetization amplitude of the resulting wave for the stimulated splitting process is much larger than for confluence one, and both processes' efficiencies are increasing with the incident angle. The theoretical calculations are in perfect agreement with the simulations.

It should be noted, that three-magnon efficiency is determined by the range of factors (three-magnon coefficient, group velocity, incident angle, film thickness, edge mode depth length), which opens possibilities to control inelastic scattering efficiency and, consequently, is of great importance due to the various applications in magnonics.

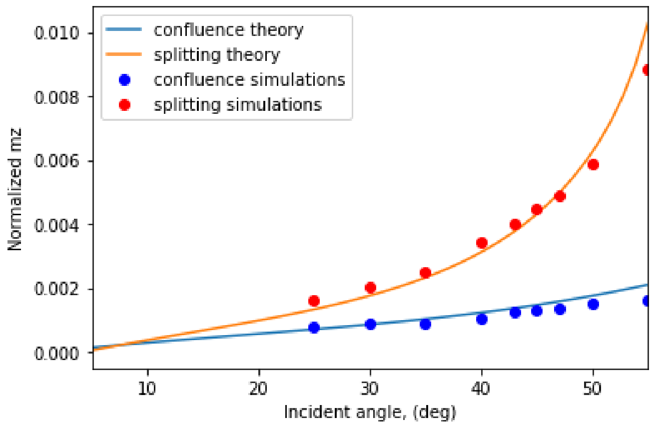

Fig. 2: Comparison between the results of micromagnetic simulations (empty circles) with theoretical calculation (solid lines) for the angular dependence of normalized magnetization z-component of inelastically scattered waves. Blue circles and line correspond to the confluence process, red circles and line correspond to the splitting process respectively.

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References:

[1] P. Gruszecki, K.Y. Guslienko, I.L. Lyubchanskii, M. Krawczyk, arXiv:2106.09954 [cond-mat.mes-hall] 18 Jun 2021.

[2] V. Tyberkevych, A. Slavin, P. Artemchuk, and G. Rowlands. Vector Hamiltonian Formalism for Nonlinear Magnetization Dynamics. arXiv:2011.13562 [cond-mat.mtrl-sci].

Presenting authors

Symposium on Spintronics and Quantum Information 2022
Poznań, 08 – 09.12.2022

	08.12.2022 Thursday	09.12.2022 Friday
09:30 – 10:00	Opening	
10:00 – 12:00	**Scientific Session 1.** chair: Jarosław W. Kłos	**Scientific Session 3.** chair: Wojciech Rudziński
12:00 – 13:00	Lunch	Lunch
13:00 – 15:15	**PhD Session 1.** chair: Maciej Krawczyk	**PhD Session 2.** chair: Anna Dyrdał
15:15 – 16:00	Coffee break	Coffee break
16:00 – 18:00	**Scientific Session 2.** chair: Krzysztof Grygiel	**Scientific Session 4.** chair: Tomasz Kostyrko
18:00 – ...	Dinner	Final remarks and closing

legend:
- PhD session
- scientific session
- lunch / coffee break