Thesis proposal

title of the thesis	
Quantum walks under classical stochastic resetting	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics	
supervisor	
name:	Przemysław Chełminiak
department:	Department of Theory of Condensed Matter
room:	D/116
personal webpage:	https://isik.amu.edu.pl/team/prof-przemyslaw-chelminiak/
email:	geronimo@amu.edu.pl

description

Stochastic resetting is a natural mechanism that has become a prominent topic across physics, chemistry, biology, ecology, engineering, and economics. Since the seminal work of Evans and Majumdar (Phys. Rev. Lett. 2011, 106, 160601), extensive research has explored its applications. These include first-passage and search theory, stochastic thermodynamics, optimization, and quantum mechanics. Further connections span animal foraging, protein-DNA interactions, coagulation-diffusion, chemical reactions, and stock-market or population dynamics involving resetting events.

Quantum walks are interesting for many reasons: (1) they are useful to build new quantum algorithms, (2) they can be directly implemented in laboratories without using a quantum computer, and (3) they can simulate many complex physical systems. A quantum walk takes place on a graph, whose vertices (nodes) are the places the walker may step and whose edges (links) tell the possible directions the walker can choose to move. Space is discrete but time can be discrete or continuous. In the discrete-time case, the motion consists in stepping from one vertex to the next over and over. Each step takes one time unit and it takes a long time to go far. The walker starts at some initial state and the dynamic in its simplest form is described by a unitary operator, i.e. the evolution operator dependent on the position and the number of steps. At the end, a measurement is performed to determine the walker’s position. In the continuous-time case, there is a transition rate controlling the jumping probability, which starts with a small value and increases continually so that the walker eventually steps on the next vertex.

The research will concern a few variants of quantum walk governed by different types of quantum coins: coined walks on infinite lattices, coined walks with cyclic boundary conditions and continuous-time quantum walks. The work is mainly focused on the properties of the mean squared displacements (standard deviation) and the probability density function of the quantum walks in the presence of stochastic resetting. In addition, a graduate student will explore the first-passage properties of quantum walks intermittent by resetting events in order to find analytical expressions for mean hitting time and determine the optimal resetting rate which minimizes the mean time needed for a walker to reach a pre-determined target.

literature

[1] Martin R. Evans, Satya N. Majumdar and Gr´egory Schehr, *Stochastic resetting and applications,* J. Phys. A: Math. Theor **53** 193001 (2020)
[2] Renato Portugal, *Quantum Walks and Search Algorithms*, Springer 2018.

Thesis proposal

title of the thesis

Non-linear diffusion under stochastic resetting in various confining potentials

stage of the study, field, specialty

II (master), physics, quantum information and spintronics

supervisor

name: Przemysław Chełminiak
department: Department of Theory of Condensed Matter
room: D/116
personal webpage: https://isik.amu.edu.pl/team/prof-przemyslaw-chelminiak/
email: geronimo@amu.edu.pl

description

A simple and natural concept, stochastic resetting has become a unifying theme across physics, chemistry, biology, ecology, engineering, and economics. Following the pioneering work of Evans and Majumdar (Phys. Rev. Lett. 2011, 106, 160601), extensive research has been dedicated to its applications.

This work spans different contexts starting from first-passage and search theory, stochastic thermodynamics, optimization theory, and all the way to quantum mechanics. To be more precise, resetting or restart, when applied to a stochastic process, usually brings its dynamics to a time-independent stationary state. In turn, the optimal resetting rate makes the mean time to reach a target to be finite and the shortest one. These and other intriguing problems have been intensively studied in the case of ordinary diffusive processes over the last decade. The purpose of this master thesis is to consider the effect of stochastic resetting on a diffusive motion modeled in terms of the non-linear differential equations in the presence of different external potentials. The reason for the non-linearity is the power-law dependence of the diffusion coefficient on the probability density function or, in another context, the concentration of particles. As the external potentials, we can mention here the wedge potential, the parabolic (harmonic) potential, the logarithmic potential, to name but a few typical examples.

The research will concern, inter alia, the properties of the mean squared displacements, the probability density functions and how they attain the steady-state profiles under the influence of stochastic resetting, In addition, a graduate student will explore the first-passage properties for non-linear diffusion intermittent by resetting events in order to find analytical expressions (the exact or approximation ones) for the mean first-passage time (mean hitting time) and determine the optimal resetting rate which minimizes the mean time needed for a diffusing particle to reach a pre-determined target. Finally, a test will be performed to confirm the universal property concerning the exponential resetting that the relative fluctuation in the mean first-passage time of optimally restarted non-linear diffusion in confining potentials is equal to unity.

literature

[1] Martin R. Evans, Satya N. Majumdar and Gr´egory Schehr, *Stochastic resetting and applications*, J. Phys. A: Math. Theor **53**, 193001 (2020)

[2] Saeed Ahmad, Indrani Nayak, Ajay Bansal, Amitabha Nandi and Dibyendu Das, *First passage of a particle in a potential under stochastic resetting: A vanishing transition of optimal resetting rate*, Phys. Rev. E **99**, 022130 (2019)

Thesis proposal

title of the thesis

Optimal finite-time non-linear diffusion in stochastic thermodynamics

stage of the study, field, specialty

II (master), physics, quantum information and spintronics

supervisor

name: Przemysław Chełminiak
department: Department of Theory of Condensed Matter
room: D/116
personal webpage: https://isik.amu.edu.pl/team/prof-przemyslaw-chelminiak/
email: geronimo@amu.edu.pl

description

Thermodynamic fluctuations, in particular thermal noise (white or color noise), play an important role for processes occurring at the nanoscale (mesoscale). They concern both objects from the world of inanimate matter, such as colloidal particles, and those that are a key element in the world of biological matter, namely proteins and nucleic acids. A key development in recent years of so-called stochastic thermodynamics is Jarzynski's relation and the fluctuation theorem, from which the fluctuation-dissipation theorem emerges, since it is valid only for states close to thermodynamic equilibrium. Interestingly, it is also possible to violate the second law of thermodynamics at the nanoscale. Subsequent versions of the fluctuation theorem also included elements of "information theory," which contributed to the explanation and experimental realization of the Maxwell-Szilard demon model.

For a small system like a colloidal particle or a single biomolecule embedded in a heat bath, the optimal protocol of an external control parameter minimizes the mean work required to drive the system from one given equilibrium state to another in a finite time. In general, this optimal protocol obeys an integrodifferential equation. Explicit solutions both for a moving laser trap and a time-dependent strength of such a trap show finite jumps of the optimal protocol to be typical both at the beginning and at the end of the process. The master thesis will consider the above problems in terms of diffusion dynamics described by the non-linear partial differential equation.

literature

[1] Naoto Shiraishi, *An Introduction to Stochastic Thermodynamics. From Basic to Advanced*, Springer 2023.

Thesis proposal

title of the thesis	
Spin waves in time varyin media	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics	
supervisor	
name:	Paweł Gruszecki
department:	Department of Physics of Nanostructures
room:	G276
personal webpage:	https://isik.amu.edu.pl/team/dr-pawel-gruszecki/
email:	gruszecki@amu.edu.pl

description

Goal: Demonstrate novel phenomena for spin waves that can be observed in media with time-varying parameters (e.g. effects as time-reflection, time-refraction, space-time magnonic crystals)

Motivation: Time-varying media offer an exciting frontier for wave propagation research, with unique phenomena that emerge when the properties of the medium change over time. These effects can lead to new, often surprising behaviors that don't occur in static systems. While much of the research on time-varying media has focused on electromagnetic waves (field of photonics) [1]. However, for spin waves[2], which are precessional perturbations of magnetization, this is still a new field of research which presents immense opportunities for discovery and holds significant potential for practical applications. Spin waves are emerging as a promising information carrier, offering exciting possibilities for next-generation technologies that go beyond CMOS[3,4], like hardware-implemented neural networks operating on spin waves[4].

Methods: theoretical studies using numerical simulations (e.g., mumax3, Comsol Multiphysics)

literature

[1] E. Galiffi, et al. *Photonics of time-varying media.* Advanced Photonics **4.1**, 014002 (2022).
[2] S. O. Demokritov et al. *Magnonics: From Fundamentals to Applications.* Physics Reports **538**, 1 (2014).
[3] A. Chumak et al. *Magnon-based information storage and processing: From classical to quantum.* Journal of Physics D: Applied Physics **48**, 203001 (2015).
[4] A. Chumak et al. *Advances in magnetics roadmap on spin-wave computing.* IEEE Transactions on Magnetics 58, 1-72 (2022).
[5] A. Papp et al. *Nanoscale neural network using non-linear spin-wave interference*. Nature Communications **12**, 6422 (2021).

Thesis proposal

title of the thesis	
Phase transitions in a quasi-two-dimensional superconductor model with an extremely short coherence length on a geometrically frustrated lattice	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics or general physics I (bachelor), physics, quantum computing, computer technologies	
supervisor	
name:	Konrad J. Kapcia
department:	Department of Theory of Condensed Matter
room:	D/108
personal webpage:	https://isik.amu.edu.pl/team/dr-konrad-kapcia/
email:	Konrad.Kapcia@amu.edu.pl

description

The topic of the diploma thesis concerns the theoretical description of unconventional superconductivity in low-dimensional systems. The research problem solved in the thesis will be related to finding a numerical solution of a certain model that describes a superconductor with an extremely short coherence length. The studied system is described by the extended Hubbard Hamiltonian in the atomic limit (i.e., zero integral of the single electron hopping), but with the included electron pair hopping interaction responsible for the superconductivity (and the standard Hubbard interaction at the node). Moreover, other competitive interactions as magnetic and density-density intersite interactions (of different range) might be included, effecting the superconducting properties of the system. The interesting aspect of the project is the fact that the lattice system considered exhibits geometrical frustration, what might introduce novel phases occurring in the system, which are present on the non-frustrated lattices. The extension to the systems containing two species of particles (e.g., being the mixture of wide band fermions and real space pairs or hard-core bosons) is possible. The results can be related to the experimental findings in the field of the ultra-cold atomic gases on optical lattices (which are an example of true quantum simulators).

Using the mean field approximation (site-dependent), equations for the order parameters and concentration on two-dimensional lattices (including in particular the triangular lattice) should be found. Then, by changing the model parameters and comparing the appropriate thermodynamic potentials, a phase diagram of the model as a function of the particle concentration is found. Phase transformations between different phases that can occur on the phase diagram of the model and states with phase separation will be analyzed. The solution of the sets of equation are found numerically and the processing data is performed with self-written programs (in Fortran, C++, Python programing language or Mathematica Wolfram software environment).

literature

[1] R.G. Sharma, *Superconductivity. Basics and Applications to Magnets*, Springer Series in Materials Science, **214**, 123-160 (2021)
[2] R. Micnas, J. Ranninger, S. Robaszkiewicz, *Superconductivity in narrow-band systems with local nonretarded attractive interactions*, Rev. Mod. Phys. **62**, 113 (1990)
[3] J.J. Binney, N.J. Dowrick, A.J. Fisher, M.E. Newman, *The theory of critical phenomena: an introduction to the renormalization group*. Oxford University Press (1992) [pl version available].
[4] I.M. Georgescu, S. Ashhab, F. Nori, Quantum simulation, Rev. Mod. Phys. **86**, 153 (2014)

Thesis proposal

title of the thesis	
Heralded generation of entangled states in optical setups	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics I (bachelor), physics, quantum informatics	
supervisor	
name:	Marcin Karczewski
department:	Department of Nonlinear Optics
room:	G/216
personal webpage:	https://isik.amu.edu.pl/team/dr-marcin-karczewski/
email:	marcin.karczewski@amu.edu.pl

description

Quantum computing is an active field of research that investigates how the principles of quantum mechanics can be harnessed for information processing. Among the various experimental platforms being explored in this context, optical systems have emerged as one of the most promising candidates [1,2].

A key challenge in using photons for quantum computing is the fact that it is hard to make them interact with each other. This makes it difficult to prepare them in entangled states—an essential resource for many information processing tasks. To address this issue, a technique known as heralding is often employed. It uses a signal, generated by an event in one part of a quantum system, to confirm the preparation of a desired quantum state in another part of the system [3,4].

Depending on the student's skills and interests, the thesis can focus on one of the following areas:

- **Theoretical Analysis:** Investigating the effects of experimental imperfections on the performance of schemes for heralded entanglement generation.
- **Algorithm Development:** Creating algorithms for the automated search of schemes for heralded entanglement generation.

literature

[1] Walmsley, N., Light in quantum computing and simulation: perspective, Opt. Quantum 1, 35-40 (2023)

[2] Maring, N., Fyrillas, A., Pont, M. et al., *A versatile single-photon-based quantum computing platform,* Nat. Photon **18**, 603–609 (2024)

[3] Chin, S., Kim, YS., Karczewski, *M. Shortcut to multipartite entanglement generation: A graph approach to boson subtractions*, npj Quantum Inf **10**, 67 (2024)

[4] Karczewski, M., Lee SY., Ryu J., et al., *Sculpting out quantum correlations with bosonic subtraction*, Phys. Rev. A **100**, 033828 (2019)

Thesis proposal

title of the thesis

Zeldovich effect for spin waves

stage of the study, field, specialty

II (master), physics, quantum information and spintronics or general physics
I (bachelor), physics, quantum computing, computer technologies

supervisor

name: Jarosław W. Kłos
department: Department of Physics of Nanostructures
room: G/294
personal webpage: https://isik.amu.edu.pl/team/prof-jaroslaw-w-klos
email: klos@amu.edu.pl

description

In 1969, Roger Penrose suggested that an advanced civilization might one day be able to extract energy from a rotating black hole. Yakov Zel'dovich translated this idea of rotational superradiance from a rotating black hole to that of a rotating absorber, such as a metallic cylinder, and showed that it would amplify incident electromagnetic waves. This phenomenon, named after Zeldovich, is a general wave effect and should be observed for any type of wave carrying orbital angular momentum and propagating in a rotating medium - the effect is a counterpart of the Doppler effect for rotational dynamics. The Zeldovich effect was demonstrated a few years ago for acoustic waves [1].

The aim of the master's thesis is to investigate the possibility of the existence of the Zeldovich effect for magnetization waves (so-called spin waves), which can also carry the orbital angular momentum [2], and for which a derived effect, i.e. the Doppler effect, has already been observed [3].

The work will include both theoretical studies and micromagnetic simulations [4].

literature

[1] M. Cromb, G. M. Gibson, E. Toninelli, et al. *Amplification of waves from a rotating body,* Nat. Phys. **16**, 1069–1073 (2020)
[2] C. Jia, D. Ma, A. F. Schäffer, et al. *Twisted magnon beams carrying orbital angular momentum,* Nat Commun **10**, 2077 (2019)
[3] Philippe, G., Moalic M., Kłos, J. W. *Unidirectional spin wave emission by traveling pair of magnetic field profiles*, J. Magn. Magn. Mater. **587**, 171359 (2023).
[4] Mumax3: https://mumax.github.io/ ; Boris: https://www.boris-spintronics.uk/ ; COMSOL: https://www.comsol.com/

Thesis proposal

title of the thesis
Edge states for spin waves in synthetic antiferromagnet

stage of the study, field, specialty

II (master), physics, quantum information and spintronics or general physics
I (bachelor), physics, quantum computing, computer technologies

supervisor

name:	Jarosław W. Kłos
department:	Department of Physics of Nanostructures
room:	G/294
personal webpage:	https://isik.amu.edu.pl/team/prof-jaroslaw-w-klos
email:	klos@amu.edu.pl

description

Magnetic nanoelements with so-called magnetic shape anisotropy (stripes, ellipsoids) can be coupled in a similar way as macroscopic magnets [1]. In a special case, the magnetization of nanoelements can be antiparallel, as in the case of magnetic atoms in antiferromagnets [2,3]. Such systems are called syntenic antiferromagnets [4].

The spectrum of spin waves in an infinite magnonic crystal composed of antiparallely magnetized strips is the same regardless of the direction of the external magnetic field. But this is not true in general for a finite sequence of such strips. There we can observe the magnonic states localized at the end of such sequence, called spin-wave edge modes. The spectrum of edge modes in synthetic antiferromagnet can change with the change of direction of external magnetic field.

The aim of this project is to study the spin-wave dynamics in finite chains of antiferromagnetically coupled strips using the macrospin model, where the magnetic shape anisotropy of the strips is included in the model. The results will be compared with numerical solutions based on the micromagnetic model.

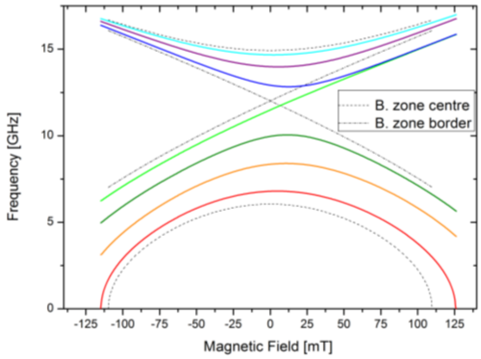

Fig.1. *The exemplary spin wave spectrum of synthetic antiferromaget composed of seven dipolary coupled stipes (colour lines). The bulk modes are grouped in two bands delimited by dashed lined – edges of bands for infinite magnonic crystal. In the gap between top and bottom band, we can see pair of the edge modes for positive fields.*

literature

[1] P. Schiffer, C. Nisoli, *Artificial spin ice: Paths forward*, Appl. Phys. Lett. **118**, 110501 (2021)
[2] K. Szulc, F. Lisiecki, A. Makarov, M. Zelent, et al., *Remagnetization in arrays of ferromagnetic nanostripes with periodic and quasiperiodic order*, Phys. Rev. B **99**, 064412 (2019)
[3] M. Krawczyk and D. Grundler, *Review and prospects of magnonic crystals and devices with reprogrammable band structure*, J. Phys.: Condens. Matter **26**, 123202 (2014)
[4] R. A. Duine, K.-J. Lee, S. S. P. Parkin and M. D. Stiles, *Synthetic antiferromagnetic spintronics*, Nature Physics **14**, 217 (2018)

Thesis proposal

title of the thesis	
Nonlinear dynamics with chiral resonators	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics or general physics I (bachelor), physics, quantum computing, computer technologies	
supervisor	
name:	Maciej Krawczyk
department:	Department of Physics of Nanostructures
room:	G/277
personal webpage:	https://isik.amu.edu.pl/team/prof-maciej-krawczyk/
email:	krawczyk@amu.edu.pl

description

Recently, there has been a great interest in the hardware realisation of artificial neural networks (ANN), including those operating on spin waves [1-2]. One of the main properties required for the realisation of computations with ANN is a nonlinear response. The topic of the proposed Master's or Bachelor's thesis is the study of the nonlinear magnetisation dynamics of a nanoresonator coupled to the waves (in this case spin waves) propagating in a thin ferromagnetic film placed just below the nanoresonator [3]. The novelty of the proposed work is to probe the non-linear magnetisation dynamics induced by the spin waves in assistance of the global microwave radiation. The energy delivered to the system by the microwaves will bring it close to the threshold required to enter the nonlinear dynamics, which will be passed by the spin waves passing under the resonator.

The study will be based on numerical simulations using the open source code MuMAx3, Boris or Comsol Multiphysics [4], or on analytical modelling based on the nonlinear Schrödinger equation, depending on the candidate's preference. Basic knowledge of magnetism and programming in Python, if the numerical approach is chosen, will be helpful but not necessary.

The level of difficulty of the research to be carried out will be agreed with the candidate and adapted to their time availability and level of training. The research will be carried out in collaboration with other team members.

literature

[1] Dan A. Allwood, et al., *A perspective on physical reservoir computing with nanomagnetic devices*, Appl. Phys. Lett. **122**, 040501 (2023)
[2] Wataru Namiki, et al., *Experimental Demonstration of High-Performance Physical Reservoir Computing with Nonlinear Interfered Spin Wave Multidetection*, Adv. Intell. Syst., **5**, 2300228 (2023)
[3] V. V. Kruglyak, *Chiral magnonic resonators: Rediscovering the basic magnetic chirality in magnonics*, Appl. Phys. Lett. **119**, 200502 (2021)
[4] Mumax3: https://mumax.github.io/ ; Boris: https://www.boris-spintronics.uk/; COMSOL: https://www.comsol.com/

Thesis proposal

title of the thesis	
Study of spin wave hybridization in magnonic structures	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics	
supervisor	
name:	Sławomir Mamica
department:	Department of Physics of Nanostructures
room:	G/186
personal webpage:	https://isik.amu.edu.pl/team/prof-slawomir-mamica/
email:	mamica@amu.edu.pl

description

Magnonics [1] is a field of science focused on the study and application of spin waves (magnons), which are collective excitations of magnetization. Due to their unique properties, spin waves offer new possibilities in the areas of information storage and processing. The significant increase in interest in this field observed in recent years is primarily due to the development of several key magnonic devices aimed at enabling computations directly on spin waves, such as diodes, circulators, and delay lines [2]. All these systems rely on the coupling between different types of spin-wave modes and the accompanying hybridization. The phenomenon of hybridization is therefore particularly important from the perspective of applications, as it allows manipulation of the propagation of spin waves using physical quantities such as magnetic fields, electric fields, or temperature. One of the more important structures that are the subject of interest in magnonics are two-dimensional magnonic crystals (2D MCs). As periodic composites, they are the magnetic counterpart of structures such as photonic or phononic crystals. In such systems, the hybridization of spin waves has been observed both theoretically [3] and experimentally [4].

The aim of this master thesis is to theoretically investigate the hybridization of spin waves in two-dimensional magnonic crystals (2D MCs). The theoretical method chosen to carry out this analysis is the Plane Wave Method (PWM), which has been successfully applied to study spin waves in MCs. We are interested in how the structure of MCs and other physical conditions (such as external magnetic fields) affect hybridization, as well as the consequences of hybridization itself, meaning its impact on the behavior of spin waves. Of course, this topic is very broad, so after obtaining preliminary results, the final shape of this master thesis will be specified.

literature

[1] B. Flebus *et al.*, *The 2024 magnonics roadmap*, J. Phys.: Condens. Matter. **36**, 363501 (2024).
[2] K. G. Fripp, Y. Au, A. V. Shytov, and V. V. Kruglyak, *Nonlinear chiral magnonic resonators: toward magnonic neurons*, Appl. Phys. Lett. **122**, (2023).
[3] S. Mamica, *Spin-wave mode coupling in the presence of the demagnetizing field in cobalt-permalloy magnonic crystals*, Sci Rep **14**, 22966 (2024).
[4] S. Tacchi, G. Gubbiotti, M. Madami, and G. Carlotti, *Brillouin light scattering studies of 2D magnonic crystals*, J. Phys.: Condens. Matter. **29**, 073001 (2017).
[5] S. Mamica and M. Krawczyk, *Reversible tuning of omnidirectional band gaps in two-dimensional magnonic crystals by magnetic field and in-plane squeezing*, Phys. Rev. B **100**, 214410 (2019)

Thesis proposal

title of the thesis	
Imaginary time crystals in condensed matter physics	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics	
supervisor	
name:	Tomasz Polak
department:	Condensed Matter Theory Division
room:	D/106
personal webpage:	https://isik.amu.edu.pl/team/dr-tomasz-polak/
email:	tppolak@amu.edu.pl
description	
Temperature is a fundamental thermodynamic variable for matter. Physical observables are often found to either increase or decrease with it, or show a non-monotonic dependence with peaks signaling underlying phase transitions or anomalies. Statistical field theory has established connection between temperature and time: a quantum ensemble with inverse temperature β is formally equivalent to a dynamic system evolving along an imaginary time from 0 to iβ in the space one dimension higher. The idea of the imaginary time crystals (iTime cystals) is related to the question if dominant contributions to the partition function come from trajectories evolving periodically in the imaginary time with the same period? In other words if, for example, density-density correlation functions of a system can reveal periodic behavior versus the imaginary time. It should be stressed that such periodic paths in the imaginary time cannot be directly measured. However, signatures of their existence should be visible in oscillatory behavior of observables of a system versus the inverse temperature β= 1/T. Using path integral analysis of the dissipative systems we show the natural way to form imaginary time crystals which is generated by the imaginary time correlations.	
literature	
[1] Krzysztof Sacha, *Time Crystals*, 2020, Springer, https://doi.org/10.1007/978-3-030-52523-1	

Thesis proposal

title of the thesis	
Magnon-magnon coupling in magnetic tunnel junction	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics or general physics I (bachelor), physics	
supervisor	
name:	Bivas Rana
department:	Department of Physics of Nanostructures
room:	G/184
personal webpage:	https://isik.amu.edu.pl/team/dr-bivas-rana/
email:	bivran@amu.edu.pl

description

In magnetic tunnel junctions (MTJs) two thin magnetic layers are separated by a oxide layer. It is well known that the junction resistance depends upon relative orientation of the magnetic moments in two magnetic layers. In a MTJ, magnetic layers are coupled by magnetostatic dipolar interaction. Therefore, it can be expected that the magnons in one magnetic layer may be coupled to the magnons in other magnetic layer under certain conditions [1,2].

This proposal aims to investigate the magnon-magnon coupling in MTJs. In particular we would like to investigate the role of interfacial magnetic anisotropy and relative orientation of magnetization on the coupling strength. The aim will be to find out optimum condition for achieving strong coupling. The proposal includes both micromagnetic simulation and experimental study. The magnons will be characterized by vector network analyzer – ferromagnetic resonance (VNA-FMR) and Brillouin light scattering (BLS) spectroscopy technique. Of course the scope of the work is very broad. The master thesis is expected to set up a preliminary understanding of the magnon-magnon coupling phenomena in MTJs and in similar structures.

literature

[1] K. Szulc, P. Graczyk, M. Mruczkiewicz, G. Gubbiotti, and M. Krawczyk, *Spin-wave diode and circulator based on unidirectional coupling*, Phys. Rev. Applied **14,** 034063 (2020).

[2] C. Dai and F. Ma, *Strong magnon–magnon coupling in synthetic antiferromagnets*, Appl. Phys. Lett. **118,** 112405 (2021).

Thesis proposal

title of the thesis

The impact of perpendicular magnetic anisotropy (PMA) on the propagation of spin waves (both bulk and surface) in multilayer systems

stage of the study, field, specialty

II (master) physics, quantum information and spintronics
I (bachelor) physics

supervisor

name: Aleksandra Trzaskowska
department: Department of Physics of Nanostructures
room: G/180
personal webpage: https://isik.amu.edu.pl/team/prof-aleksandra-trzaskowska/
email: olatrzas@amu.edu.pl

description

Spin waves (SW), the collective precessions of localized magnetic spins, are crucial for developing energy-efficient technologies. Their ability to propagate without electric charge flow makes them ideal for low-energy applications such as data processing, signal transmission, and quantum computing. The practical realization of spin-wave-based devices depends on effective methods for their generation, guidance, manipulation, and detection.

This research focuses on the dispersion relations of spin waves in materials with perpendicular magnetic anisotropy (PMA), a property that significantly influences spin-wave dynamics. PMA introduces unique boundary conditions and enhances specific wave modes, stabilizing spin structures at nanometer scales, which is vital for low-energy technologies.

The experimental work will utilize Brillouin light scattering (BLS) spectroscopy to measure the dynamic properties of spin waves in multilayer systems. BLS enables precise characterization of parameters such as dispersion relations, damping mechanisms, group velocities, and spatial profiles. Experimental results will be integrated with theoretical and computational models to gain a comprehensive understanding of spin-wave behavior in PMA materials.

Key research tasks include:

- Performing BLS measurements to analyze spin-wave dispersion in multilayer systems (Bachelor’s and Master’s level in physics, spatiality: General Physics, PAMEB, IKS).
- Conducting data analysis, comparing experimental results with theoretical models. (Master’s level in physics, spatiality: General Physics, IKS).

The study will examine the role of interlayer coupling, the impact of material interfaces, and the effect of external fields on spin-wave propagation and stability. Insights gained will contribute to controlling spin waves in nanoscale devices, supporting the development of advanced technologies based on phonons and magnons.

Outcomes of this research could lead to innovations in magnonics, spintronics, and nanostructure physics, enabling energy-efficient information and communication systems. These findings will expand our understanding of the interplay between magnetism, spin dynamics, and wave phenomena, fostering advancements in cutting-edge technological applications.

literature

[1] S. Janardhanan, A. Trzaskowska, et al., Scientific Reports, **13**, 22494 (2023)
[2] S. Janardhanan, M. Krawczyk, A. Trzaskowska, *Nanomagnets and dynamical systems*, Springer (2024), ISSN 1571-5744

Thesis proposal

title of the thesis	
Effect of correlations on the properties of minimal Kitaev chains	
stage of the study, field, specialty	
II (master), physics, quantum information and spintronics	
supervisor	
name:	Ireneusz Weymann
department:	Department of Mesoscopic Physics
room:	J/203
personal webpage:	https://isik.amu.edu.pl/team/prof-ireneusz-weymann/
email:	weymann@amu.edu.pl

description

Topological states of matter are in the forefront of investigations in modern physics. An important example of such states are Majorana zero-modes that can be realized at the ends of topological superconducting nanowires [1]. Predicted by Ettore Majorana particles that are their own anti-particles, which in solid-state systems can be realized as quasiparticle excitations, are considered for applications in topological quantum computing. Despite various efforts to demonstrate the existence of Majorana modes experimentally [2], their presence has so far not been uniquely confirmed. Therefore, recent approach has focused on a bottom-up construction of consecutive sites of the topological chain, the so-called Kitaev chain, that could host Majorana modes at its ends [3]. It was shown that such chain can be built from quantum dots connected through superconducting elements. Theoretical investigations for such nanostructures have so far mostly focused on noninteracting systems. However, the effects of correlations can drastically change the physics and, thus, their inclusion is crucial to properly predict the properties of the system. This project aims at theoretical exploration of the correlation effects on the properties of minimal Kitaev chains built from quantum dots coupled through superconducting leads. The considerations will be performed with the state-of-the-art numerical methods, such as numerical renormalization group methods, that allow for taking into account all correlations effects in a fully nonperturbative manner [4]. The obtained high-quality results should be therefore of importance to the nanoscale-physics and quantum-information communities. The results will be published in a high-rank international scientific journal. The student will also be able to present the obtained results at international conferences

literature

[1] V. Mourik, et al., *Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices*, Science **336**, 1003 (2012).
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[3] T. Dvir et al., *Realization of a minimal Kitaev chain in coupled quantum dots*, Nature **614**, 7948 (2023); F. Zatelli et al., *Robust poor man's Majorana zero modes using Yu-Shiba-Rusinov states*, Nat. Commun. **15**, 7933 (2024); A. Bordin et al., *Signatures of Majorana Protection in a Three-Site Kitaev Chain*, arXiv:2402.19382 (2024).
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