Project Description

1. Introduction

Scientific problem.
The coexistence of superconductivity (S) and ferromagnetism (F) in low-dimensional heterostructures is a fundamental challenge in condensed matter physics. These two ordered states are antagonistic: a superconductor expels magnetic field (Meissner effect), while a ferromagnet exhibits spontaneous magnetization. However, when ultrathin S and F layers are brought into contact, a proximity effect arises, leading to unusual phenomena such as oscillatory superconducting order parameter, induced magnetism, and triplet superconducting correlations. Understanding these effects is crucial for next-generation spin-electronics, cryogenic memory, and quantum computing.

Current research.
Intensive studies are performed worldwide on S/F multilayers, Josephson junctions with ferromagnetic barriers, and superconductor/ferromagnet hybrids. Key experimental techniques include polarized neutron reflectometry (PNR). Theoretical models (e.g., Buzdin, 2005; Khaydukov et al., 2019) predict rich phase diagrams depending on layer thickness, temperature, and magnetic field.

Applied tasks.
Results of this research can be used to develop:

- Superconducting spintronic devices with low energy dissipation.
- Controllable magnetic memories based on the S/F proximity effect.
- Sensitive magnetic field sensors exploiting the superconducting screening.

2. Main part: what the student will learn and what skills will be acquired

During the project, the student will:

1. Understand the physical principles of polarized neutron reflectometry (PNR) and its application to magnetic heterostructures.
2. Learn the specifics of the REMUR neutron reflectometer at the IBR-2 reactor (JINR, Dubna).
3. Acquire hands-on experience in processing raw neutron reflectivity data using the *Spectra_Viewer* software.
4. Master data fitting with a physical model (magnetic depth profile) using *Matlab* scripts.
5. Learn how to extract quantitative magnetic information: magnitude and direction of magnetic moments, thickness of layers, interface roughness, and domain sizes.
6. Interpret the results in terms of the S/F proximity effect and compare with theoretical predictions.
7. Prepare a scientific report and present the obtained results.

3. Description of work on the project

3.1. Experimental setup

The project uses the **REMUR** polarized neutron reflectometer at the IBR-2 pulsed reactor (Frank Laboratory of Neutron Physics, JINR).

https://flnp.jinr.int/en-us/main/facilities/ibr-2/remur
Figure 1 shows the classical scheme of a polarized neutron reflectometer (as in the original application).

Scheme:

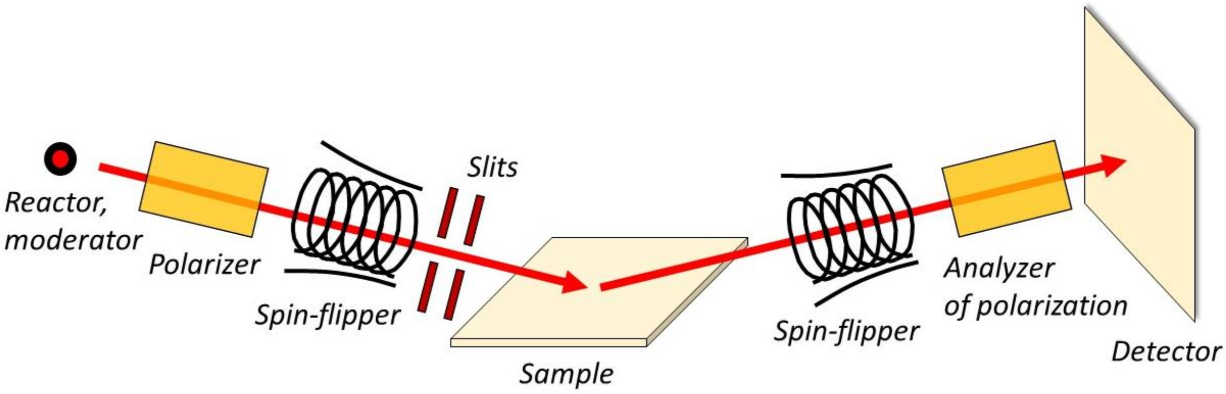

Fig.1. Layout of a polarized neutron reflectometer

3.2. Measurement procedure (what the student must do)

Because the project lasts only 3 weeks, the student will **not perform real experiments** at the beamline. Instead, he/she will work with previously measured raw reflectivity spectra from real S/F samples. The procedure includes:

1. **Loading raw data** into *Spectra_Viewer* – two spectra corresponding to neutron spin parallel (R+) and antiparallel (R-) to the applied magnetic field.
2. **Normalisation and background subtraction** – convert raw counts to reflectivity versus momentum transfer (Q).
3. **Model building** – construct a multilayer model (thickness, scattering length density, magnetic moment per layer) in *Matlab*.
4. **Fitting** – adjust model parameters to simultaneously fit R+ and R- curves using least-squares minimization.
5. **Analysis** – extract magnetic depth profile and discuss the proximity effect.

3.3. Form of presentation of results

The student must deliver:

- A **short written report** (3-5 pages) containing:
  - Description of the sample and measurement conditions.
  - Processed reflectivity curves (R+ and R-) with fitted models.
  - Reconstructed magnetic moment profile (magnetization vs. depth).
  - Conclusions regarding the S/F proximity effect.
- A **5-minute oral presentation** (or a set of slides) summarising the work.

4. Requirements to the student's preparation level

The student is expected to have:

- Basic knowledge of **solid state physics** (magnetism, superconductivity).
- Understanding of **neutron scattering** (at the level of introductory lectures).
- Elementary **computer skills** (file handling, working with Matlab scripts).
- Ability to read and understand scientific papers in English.

5. Recommended literature (in English)

1. A.I. Buzdin, "Proximity effects in superconductor-ferromagnet heterostructures", *Reviews of Modern Physics*, Vol. 77, No. 3, p. 935 (2005).

2. Yu.N. Khaydukov et al., “Magnetic and superconducting proximity effects in a Fe/Nb/Fe trilayer”, *Physical Review B*, Vol. 99, No. 14, p. 140503 (2019).

3. V.L. Aksenov et al., “REMUR – polarized neutron reflectometer at the IBR-2 reactor”, *JINR Communications* D13-2004-47 (2004).

4. J. Daillant & A. Gibaud, *X-ray and Neutron Reflectivity: Principles and Applications*, Springer (2009).

6. Number of project participants

The project is designed for **2 students simultaneously**.
They can work **individually** (each on his/her own data set) or as a **team** (dividing tasks: data processing vs. fitting). Both options are acceptable.

7. Project supervisor from JINR

Full name: Dr. Vladimir D. Zhaketov

Position: Head of the group
Scientific degree: PhD
Laboratory: Frank Laboratory of Neutron Physics (FLNP)
Division: Sector for Neutron Optics

Scientific interests:

- Polarized neutron reflectometry
- Magnetic low-dimensional heterostructures
- Superconductivity/ferromagnetism proximity effects
- Hydrogen dynamics in thin films

Selected scientific results:

- Developed advanced data analysis methods for PNR on S/F multilayers.
- Discovered unconventional magnetic states in Nb/Gd/Nb trilayers and superlattices.
- Authored more than 40 peer-reviewed papers (see JINR publications).

Personal webpage:
https://scholar.google.com/citations?hl=en&user=M-IDS3UAAAAJ&view_op=list_works&sortby=pubdate