



Joint Institute for Nuclear Research

Laboratory of Nuclear Problem

Final Report on the INTEREST Program

Coexistence of superconductivity and ferromagnetism at low-dimensional heterostructures

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Abstract

The coexistence of superconductivity and ferromagnetism in low-dimensional heterostructures creates a complex physical challenge because Cooper pairing and magnetic ordering compete with each other. This internship, part of the JINR INTEREST program, focused on analysing and modelling superconducting/ferromagnetic (S/F) layered systems. The primary method used was polarized neutron reflectometry (PNR).

The work involved creating a structured process for interpreting neutron reflectometry data. It started with understanding how neutrons interact with magnetic multilayers and extended to modelling spin-dependent reflectivity profiles. We analysed and used MATLAB tools (LEMUR framework) to compute neutron reflectivity curves for multilayer structures like Nb/Gd/V systems. The computational model included nuclear and magnetic scattering length densities for each layer, thickness changes, and contributions from external magnetic fields to generate polarization-dependent reflectivity spectra.

We also studied techniques for interpreting spectral data using tools like Spectra Viewer. We focused on extracting important parameters such as layer thickness, interface roughness, and profiles of magnetization depth. We systematically explored how parametric variations affect reflectivity curves. This included examining the impacts of magnetic moment orientation, layer periodicity, and neutron wavelength dependence.

The analysis shows that even small changes in magnetic configuration or layer thickness can significantly affect spin-dependent reflectivity. This highlights the sensitivity of PNR in resolving nanoscale magnetic structures. The study confirms the role of electromagnetic proximity effects in redistributing magnetic fields throughout superconducting layers, which aligns with recent theoretical predictions.

Overall, this work establishes a clear theoretical and computational framework for analysing S/F heterostructures using neutron reflectometry. It also provides insights into designing and interpreting experiments related to superconducting spintronics and nanoscale magnetic systems.

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1. Introduction

The interaction between superconductivity and ferromagnetism in hybrid structures has emerged as a significant topic in condensed matter physics due to its implications for both fundamental science and advanced technological applications. Superconductivity is characterized by the formation of Cooper pairs with opposite spins, resulting in zero electrical resistance and expulsion of magnetic fields (Meissner effect). In contrast, ferromagnetism arises from parallel alignment of spins due to exchange interactions, inherently opposing superconducting order.

When these two phases are combined in layered heterostructures, such as superconductor/ferromagnet (S/F) systems, a range of non-trivial phenomena emerges due to mutual proximity effects. These include oscillatory superconducting order parameters, suppression or modulation of magnetization, generation of spin-triplet pairing states, and redistribution of magnetic fields across interfaces. Understanding these effects is critical for the development of superconducting spintronics and nanoscale quantum devices.

Recent theoretical and experimental studies have demonstrated that, beyond conventional proximity effects, additional mechanisms such as the electromagnetic proximity effect can induce long-range magnetic field penetration into superconducting layers, extending over the London penetration depth. These effects significantly influence the behaviour of multilayer systems such as Nb/Gd and Nb/V structures, which are commonly investigated in neutron scattering experiments.

To probe such complex systems, polarized neutron reflectometry (PNR) has become a powerful experimental technique. By measuring the reflection of spin-polarized neutrons from layered materials, PNR enables the determination of depth-resolved structural and magnetic profiles with nanometer-scale resolution. The reflectivity depends strongly on the nuclear and magnetic scattering length densities, allowing detailed characterization of multilayer systems.

The present internship focuses on developing a theoretical and computational understanding of S/F heterostructures using PNR-based analysis. The work integrates fundamental physics, numerical modelling, and data interpretation techniques to simulate and analyse neutron reflectivity behaviour in magnetic multilayer systems.

2. Experimental Setup and Method

The study of superconducting/ferromagnetic (S/F) heterostructures in this internship was carried out through a combination of theoretical understanding, computational modelling, and data interpretation techniques centred around polarized neutron reflectometry (PNR). The methodology followed a structured workflow that mimics real experimental analysis pipelines used in neutron scattering facilities.

Polarized neutron reflectometry is based on the interaction of spin-polarized neutrons with layered materials, where the reflection coefficient depends on both nuclear and magnetic scattering length densities. The REMUR reflectometer at JINR, a time-of-flight instrument, operates by directing a pulsed beam of polarized neutrons onto a sample and measuring the reflected intensity as a function of neutron wavelength and incident angle. This allows extraction of depth-dependent structural and magnetic information with nanometer resolution. The system includes key components such as neutron choppers for time resolution, supermirror polarizers for spin selection, spin flippers for polarization control, and a position-sensitive detector for recording reflected intensity.

The reflectivity of a multilayer system is governed by interference effects arising from neutron wave propagation through layers with different scattering potentials. In magnetic systems, the reflectivity becomes spin-dependent, resulting in four possible reflection channels corresponding to spin-flip and non-spin-flip processes. This enables the determination of both magnitude and orientation of magnetization within the structure.

To simulate and analyse such systems, a computational modelling framework was studied and implemented using MATLAB-based scripts provided during the internship. The core simulation (LEMUR framework) models neutron reflectivity using a matrix formalism, where each layer is represented by its thickness, nuclear scattering potential, and magnetic field components. The total reflectivity is obtained by recursively calculating reflection and transmission coefficients across interfaces.

The primary input parameters for the model include:

- I. Layer thickness (d)
- II. Nuclear scattering potential (u)
- III. Magnetic field components (M_x, M_y, M_z)

- IV. External magnetic field (H)
- V. Neutron wavelength range

The MATLAB implementation computes spin-dependent wave vectors and constructs transfer matrices for each layer, enabling calculation of reflection amplitudes. For example, the code defines Pauli spin matrices and incorporates magnetic contributions to neutron interaction, allowing simulation of spin-polarized reflectivity channels.

Further extensions of the model include computation of secondary radiation and depth-dependent scattering contributions using advanced functions, where recursive matrix propagation is used to evaluate internal field distributions and scattering amplitudes across multilayer stacks.

In addition to modelling, data interpretation techniques were studied using tools such as Spectra Viewer, which allows visualization and preprocessing of experimental reflectivity spectra. The workflow includes normalization of raw data, background subtraction, and identification of key features such as critical edge, Kiessig fringes, and Bragg peaks, which correspond to structural and magnetic periodicities in the sample.

The overall methodological pipeline developed during this internship can be summarized as:

- I. Understanding neutron interaction physics in layered magnetic systems
- II. Modelling reflectivity using matrix-based computational methods
- III. Analysing spectral features to extract physical parameters
- IV. Studying parameter sensitivity to relate model outputs with physical structure

This approach enables a comprehensive understanding of how experimental reflectometry data is interpreted and modelled in real research environments.

3. Experimental Work

The primary focus of the internship work was to develop a conceptual and computational understanding of polarized neutron reflectometry applied to superconducting/ferromagnetic heterostructures. The work was structured as a progressive workflow involving theoretical study, computational modelling, and interpretation of simulated reflectivity data.

3.1. Understanding of S/F Heterostructure Physics

The initial phase of the work involved studying the fundamental physics governing S/F systems, with emphasis on proximity effects and magnetic interactions at interfaces. Literature on Nb/Gd and Nb/V multilayer systems was analysed to understand experimentally observed phenomena such as suppression of ferromagnetism below the superconducting transition temperature and oscillatory behaviour of superconducting properties.

Special attention was given to electromagnetic proximity effects, where magnetic fields penetrate superconducting layers over distances comparable to the London penetration depth. This understanding provided the physical basis for interpreting reflectometry data and modelling magnetic depth profiles.

3.2. Study of Polarized Neutron Reflectometry

A detailed study of polarized neutron reflectometry techniques was carried out, focusing on:

- I. Spin-dependent neutron scattering
- II. Reflectivity channels (R_{++} , R_{--} , R_{+-} , R_{-+})
- III. Sensitivity to magnetic and structural parameters

The working principle of the REMUR reflectometer was analysed, including beam polarization, spin manipulation, and detection mechanisms. It was understood that variations in reflectivity profiles directly correspond to changes in layer thickness, interface quality, and magnetic configuration.

3.3. Computational Modelling using MATLAB (LEMUR Framework)

A major part of the internship involved studying and working with MATLAB-based simulation codes for neutron reflectivity modelling.

The provided scripts were analysed in detail to understand:

- I. Representation of multilayer structures as discrete layers
- II. Incorporation of magnetic and nuclear scattering potentials
- III. Use of matrix formalism to compute reflectivity

The simulation workflow involved defining material-specific parameters such as:

- I. Superconducting layers (Nb, V)
- II. Ferromagnetic layers (Gd)
- III. Substrate materials

The model computes spin-dependent reflectivity by solving wave propagation across interfaces, considering both nuclear and magnetic interactions. Recursive calculations of reflection and transmission matrices were used to determine total reflectivity.

3.4. Parametric Analysis of Reflectivity Profiles

To understand the sensitivity of neutron reflectometry, various parameters were systematically studied:

- I. Layer Thickness Variation: Changes in thickness resulted in shifts in interference fringes (Kiessig fringes), indicating strong dependence of reflectivity on structural periodicity.
- II. Magnetization Strength and Orientation: Variation in magnetic moment components significantly altered spin-dependent reflectivity channels, demonstrating how PNR can resolve magnetic depth profiles.
- III. Neutron Wavelength Dependence: Reflectivity curves were analysed over a range of wavelengths, showing how resolution and penetration depth affect measured signals.
- IV. Multilayer Periodicity: Periodic structures such as Nb/Gd superlattices showed characteristic Bragg peaks, confirming the relationship between reflectivity features and structural repetition.

3.5. Interpretation of Reflectivity Features

Simulated reflectivity curves were analysed to identify key features:

- I. Critical edge corresponding to total reflection
- II. Oscillatory patterns due to layer interference
- III. Spin asymmetry indicating magnetic contributions

These features were correlated with physical properties of the system, enabling extraction of parameters such as layer thickness and magnetization distribution.

3.6. Integration of Theory and Modelling

The final stage of the work involved integrating theoretical concepts with computational results. Observations from simulations were compared with trends reported in literature, particularly regarding:

- I. Suppression of magnetic order in superconducting state
- II. Long-range magnetic field penetration
- III. Sensitivity of neutron reflectometry to nanoscale magnetic variations

This integration provided a complete understanding of how neutron reflectometry is used to study S/F heterostructures in real research environments.

4. Results

The computational modelling and theoretical analysis performed during this internship offered important insights into the behaviour of superconducting and ferromagnetic multilayer structures observed through polarized neutron reflectometry. The simulated reflectivity profiles showed strong sensitivity to both structural and magnetic parameters, confirming that PNR is an effective depth-resolved characterization technique.

One key observation from the modelling was the strong dependence of reflectivity oscillations on layer thickness. Changes in the thickness of individual layers led to noticeable shifts in the interference patterns, known as Kiessig fringes. These oscillations occur because of constructive and destructive interference of neutron waves reflected at different interfaces. As the thickness increased, the fringe spacing decreased, showing a direct inverse relationship between layer thickness and oscillation periodicity. This behaviour matches theoretical expectations and is commonly used in experimental practice to determine film thickness with high precision.

Beyond structural sensitivity, the simulations showed clear differences between spin-up and spin-down reflectivity channels in the presence of magnetic layers. Adding magnetization components to the model created asymmetry in the reflectivity curves, reflecting how neutron spin interacts with internal magnetic fields. This spin-dependent behaviour highlights how polarized neutron reflectometry can probe magnetic depth profiles, including the strength and direction of magnetization within individual layers. Even small changes in magnetic moment produced measurable variations in reflectivity, emphasizing the technique's high sensitivity.

Another important finding related to multilayer periodicity. When modelling periodic structures like Nb/Gd superlattices, distinct Bragg peaks appeared in the reflectivity curves. These peaks correspond to the periodic repetition of layers and provide direct information about the superlattice spacing. The presence and sharpness of these peaks rely heavily on interface quality and structural uniformity, suggesting that reflectometry can also assess fabrication quality in real samples.

The effect of neutron wavelength on reflectivity was examined as well. It was noted that longer wavelengths improve sensitivity to larger-scale structures, while shorter wavelengths offer better resolution for fine structural details. This trade-off is crucial in experimental design, especially when studying nanoscale heterostructures, where both resolution and penetration depth matter.

From a magnetic viewpoint, the simulations backed theoretical predictions regarding proximity effects in S/F systems. Specifically, the redistribution of magnetic fields across interfaces, often associated with electromagnetic proximity effects, was found to influence reflectivity profiles beyond the immediate interface. This suggests that neutron reflectometry can capture not just localized magnetic behaviour but also long-range magnetic interactions within the structure.

In summary, the results show that combining computational modelling and theoretical analysis leads to a deeper understanding of neutron reflectometry in complex multilayer systems. The observed trends align well with established physical principles and findings reported in literature, reinforcing the reliability of the modelling approach used in this work.

5. Conclusion and Future Prospects

This internship provided a solid understanding of how superconductivity and ferromagnetism coexist in low-dimensional heterostructures, especially through the use of polarized neutron reflectometry. By combining theoretical study, computational modelling, and data interpretation, I developed a clear framework for analysing the magnetic and structural properties of multilayer systems.

I built a strong conceptual foundation in neutron scattering physics. I learned how spin-polarized neutrons interact with magnetic materials. The study of reflectometry techniques and their use in computational models showed how to analyse complex physical systems

without direct experimental measurements. Using MATLAB for modelling allowed me to simulate reflectivity profiles and gain insights into how structural and magnetic factors affect measurable values.

One key outcome of this work is the insight that neutron reflectometry is very sensitive to nanoscale variations in both structure and magnetization. Its ability to resolve depth-dependent magnetic profiles makes it a powerful tool for studying S/F heterostructures, which are increasingly important in superconducting spintronics and quantum device applications. The effects of layer thickness, magnetic configuration, and periodicity on reflectivity emphasize the need for precise control in material design and fabrication.

Besides gaining technical knowledge, this internship also exposed me to research methods used in condensed matter physics. These methods include literature analysis, computational modelling, and interpretation of simulated data. These skills are essential for further research in advanced material systems and experimental physics.

Looking ahead, there are several opportunities to build on this work. One direction is to incorporate real experimental data to fit and validate the computational models. This would create a stronger link between theory and practice. Improvements can also be made by refining the modelling to include interface roughness, non-collinear magnetization, and temperature-dependent effects. Expanding the analysis to other material systems, such as Heusler alloys or complex oxide heterostructures, could lead to deeper insights into emerging magnetic and superconducting phenomena.

Overall, this internship has set a strong foundation for future work in condensed matter physics, especially regarding the study of nanoscale magnetic systems and their interactions with superconductivity.

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