Investigation of superconductivity and magnetism in layered nanostructures by polarized neutron reflectometry with secondary radiation registration

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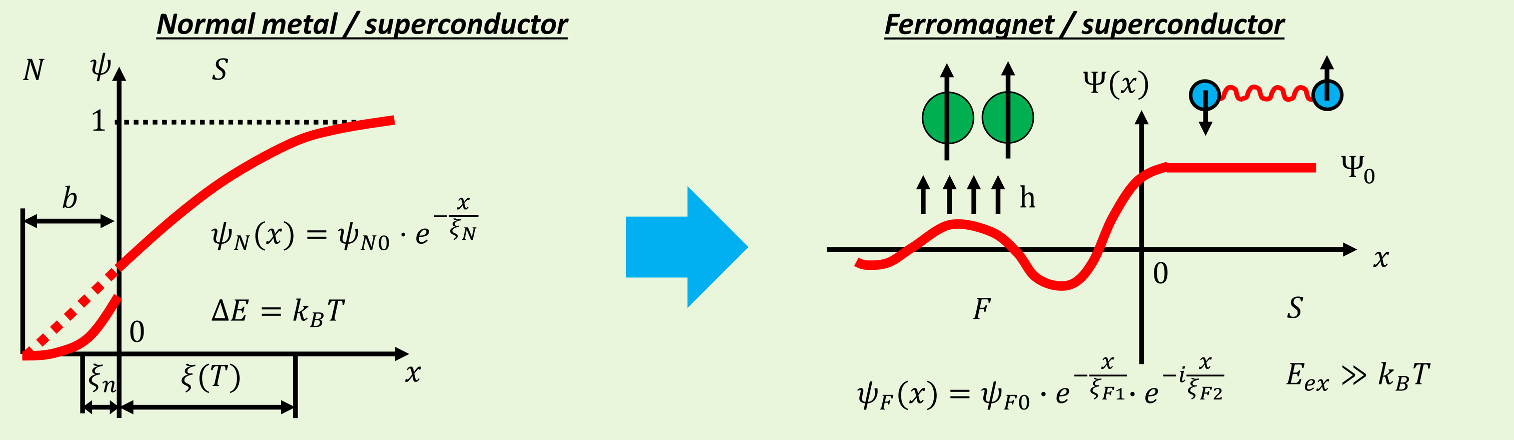
Nowadays studying of proximity effects at the interface between two media are in focus of view [1-5]. In particular it relates to the interface between superconductor and ferromagnet. Due to the mutual influence of ferromagnetism and superconductivity, because of the finite values of the coherence lengths, a significant modification of the magnetic and superconducting properties occurs. It appears, in particular, as changing of magnetization's spatial distribution. It is important to establish the correspondence of the magnetic spatial profile (spatial dependence of magnetization) to the nuclear spatial profiles of the elements of the contacting media. To determine the spatial magnetic profile, the standard method of reflectometry of polarized neutrons is used, which makes it possible to determine the energy of the potential interaction of a neutron with a medium. At the interface between two media, the interaction potential is the sum of the interaction potentials of elements penetrating each other. Standard neutron reflectometry does not make it possible to establish which elements are associated with changes in the interaction potential and, in particular, in the magnetic profile. To determine the profile of the interaction potential of a neutron with individual elements, it is necessary to register the secondary radiation of the elements. At the moment, channels for recording charged particles [6], gamma quanta and spin-flip neutrons [7] have been implemented at the REMUR spectrometer of the IBR-2 reactor in Dubna. Several tens of isotopes and magnetic elements are available for measurements.

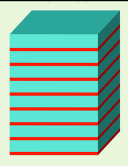
Magnetic and superconducting heterostructures

At the physics of superconductivity proximity effects are known. Classical proximity effects appear as penetration of superconducting correlations to normal metal. The same is possible in case of contact of superconductor (S) with ferromagnetic (F). Good candidates for investigation of proximity effects - low-dimensional heterostuctures. Because of development of spintronics, it is required creation of systems with the ability to control magnetic properties by superconductivity.



Magnetic states of S-F systems under influence of proximity effects

- *Low-dimensional heterostructures* $d \sim \xi$
  - *Influence of magnetism on superconducting properties of the system* $\frac{I_F}{I_S} \sim 10^2$ $\quad I \sim T_c$
    - *Influence of superconductivity on magnetic properties of the system* $d_F \sim \xi_F$ $\quad d_F \ll d_S$

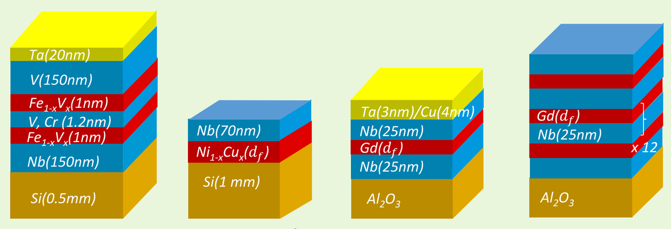


S-F structure $d \sim 1 \div 10^3\ nm$

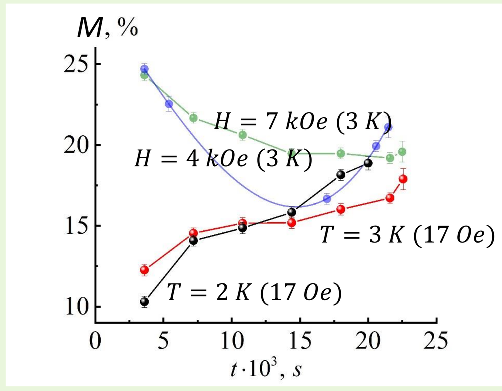
Proximity effects at S-F structures. Results

Structures of different type were investigated. They can be grouped by different ferromagnetic layers: alloys FeV and CuNi, and nature Gd. Nonequilibrium magnetic state was found at structures with FeV and CuNi layers, due to the presence of clusters. Relaxation of magnetic state at these structures were observed. Superconductivity changed magnetic state. Structures with Gd-layers were more homogeneous, and magnetic field displacement because of Meissner effect was observed.

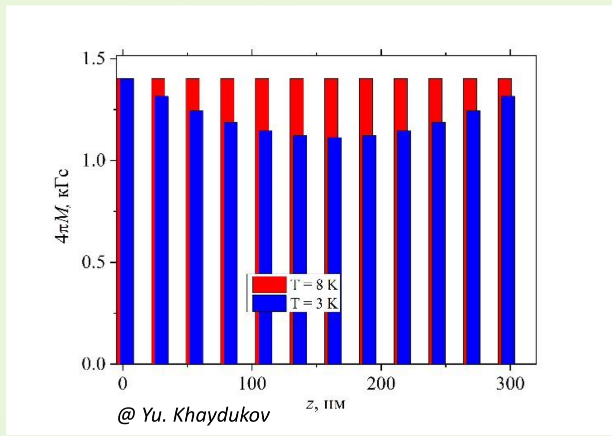
- $d_F \sim \xi_F$
- $d_F/d_S = 10^{-3} \div 10^{-2}$
- *Alloys: FeV, CuNi*
- *Systems S/Fe/S - type*
- *Different metalls (V, Nb, Fe, Ni, Gd)*



Nominal structures



Magnetic moment relaxation of the structure with ferromagnet FeV



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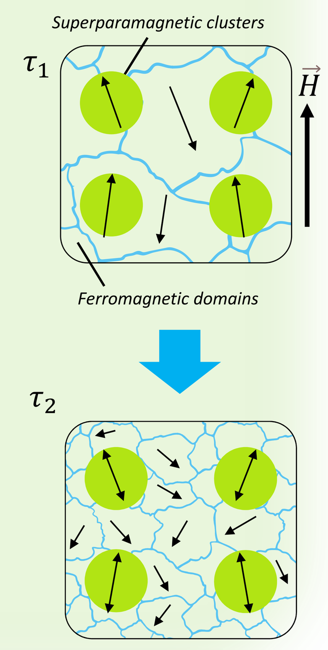
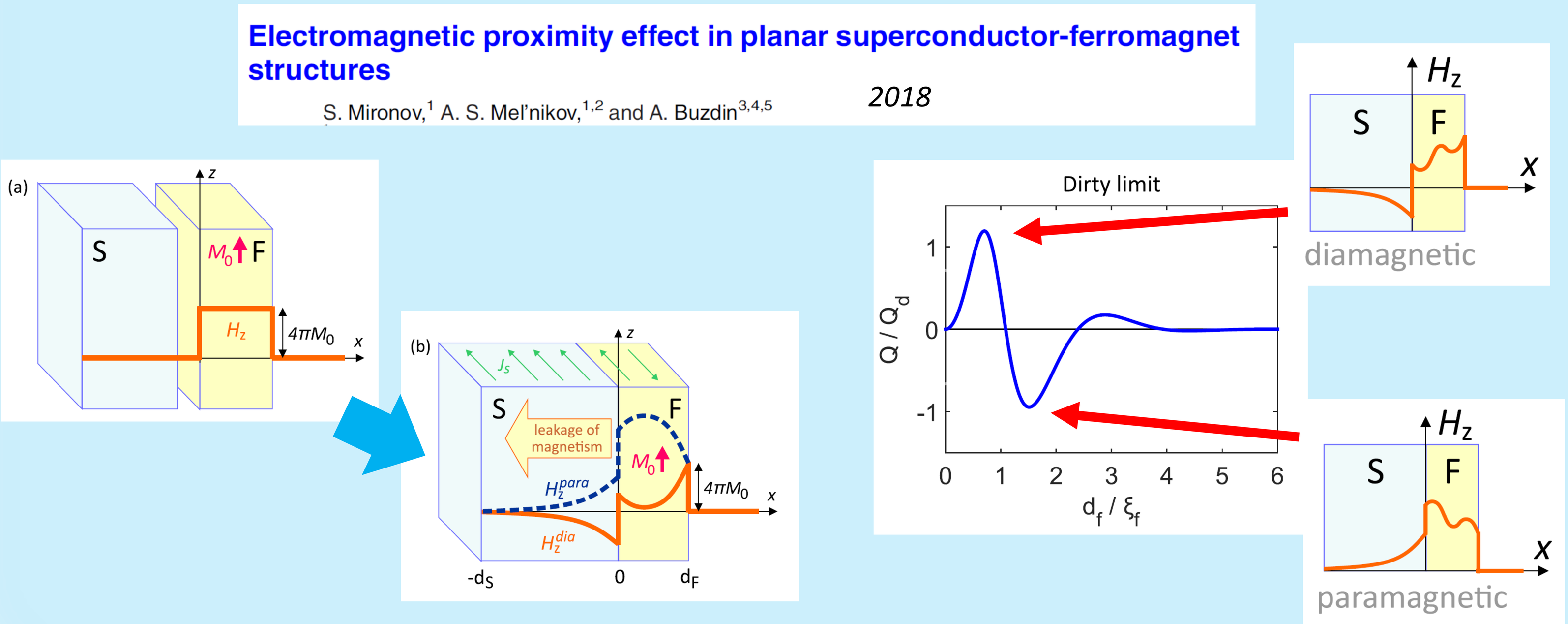
Magnetic field displacement by Nb/Gd superlattice



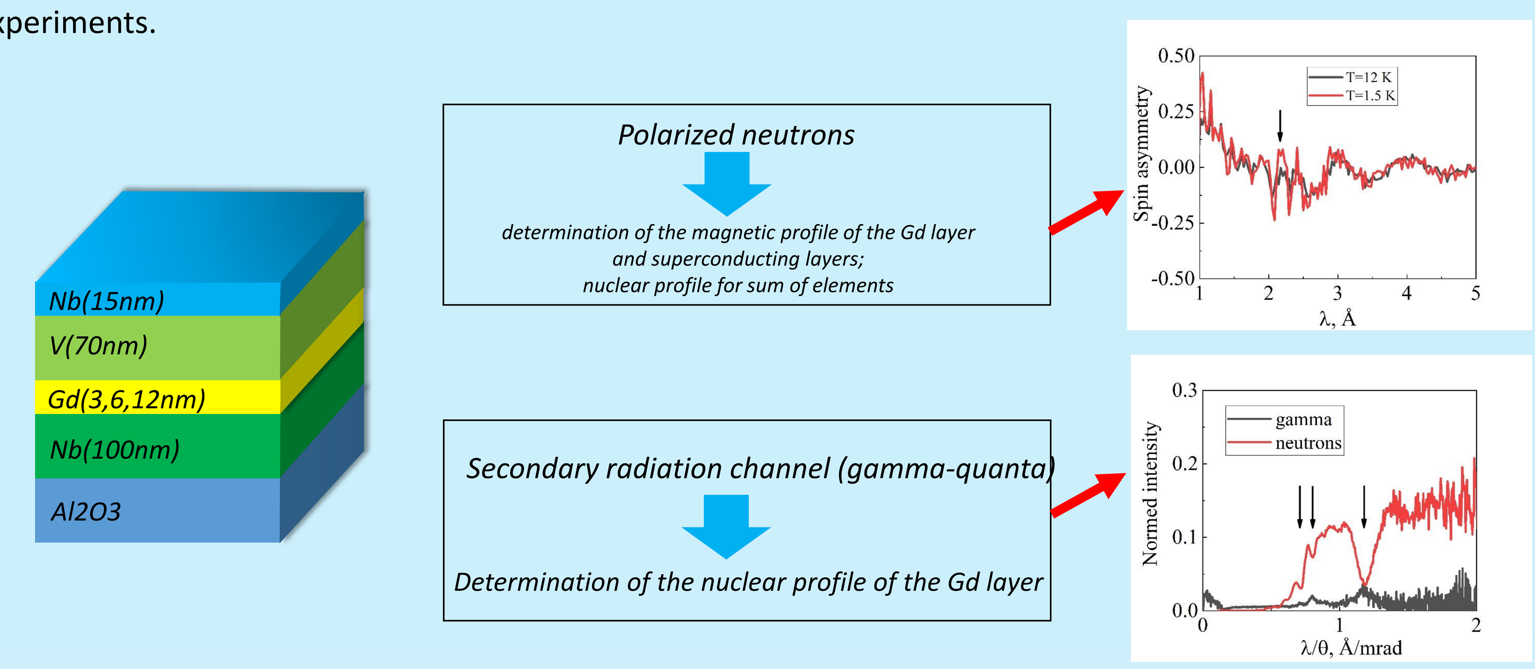
Inverse proximity effect

Recently, a new proximity effect has been described in ferromagnetic-superconducting layered nanostructures, which is characterized by a large scale (10 nm) of the interaction of superconductivity and magnetism, and which takes place for any ferromagnets.



Inverse proximity effect. Results and plans.

At present, the Al2O3//Nb(100nm)/Gd(3nm)/V(70nm)/Nb(15nm) structure, where Gd is a ferromagnet and Nb and V are superconductors, has been studied. A change in the magnetization in superconducting layers (at area 10 nm close to F-layer) under the influence of superconductivity at a level of 4-10% was found, which corresponds to the implementation of the inverse proximity effect. Further plans are in detailed processing of experimental data and new experiments.



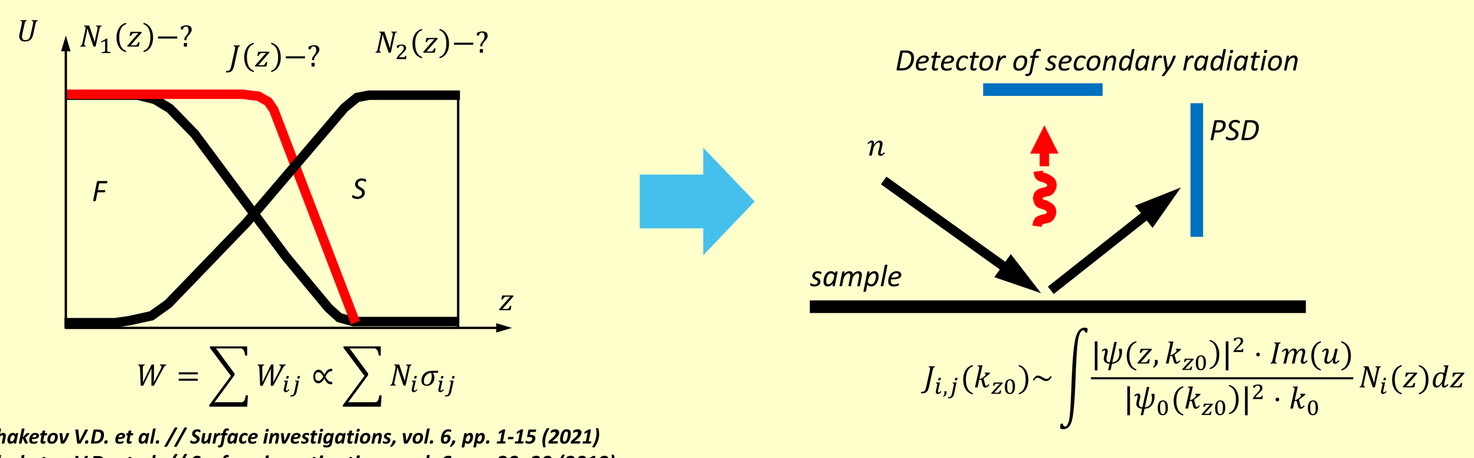
Secondary radiation registration

At the interface between two media, the interaction potential is the sum of the interaction potentials of elements penetrating each other. Standard neutron reflectometry does not make it possible to establish which elements are associated with changes in the interaction potential and, in particular, in the magnetic profile. To determine the profile of the interaction potential of a neutron with individual elements, it is necessary to register the secondary radiation of the elements.

Channel of secondary radiation registration at REMUR-spectrometer:

- *charged particles:* $\sigma_{min} = 0.025\ barn$ *(~ 22 isotopes)*
- *gamma-quanta:* $\sigma_{min} = 0.3\ barn$ *(> 100 isotopes)*
- *spin-flip neutrons:* $B_{min} = 1\ Gs$ *(9 elements: Fe, Co, Ni, Gd, Dy, Tb, Ho, Er, Tm)*

Data for layer with thickness 5 nm



Zhaketov V.D. et al. // Surface investigations, vol. 6, pp. 1-15 (2021)
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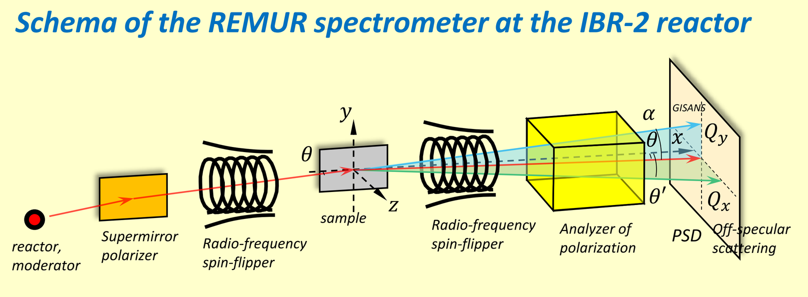
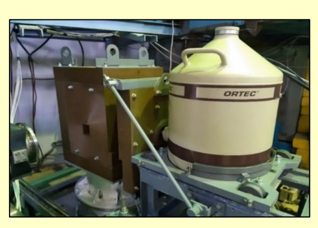
Secondary radiation registration at REMUR

At the moment, channels for recording charged particles [6], gamma quanta and spin-flip neutrons [7] have been implemented at the REMUR spectrometer of the IBR-2 reactor in Dubna. Several tens of isotopes and magnetic elements are available for measurements.

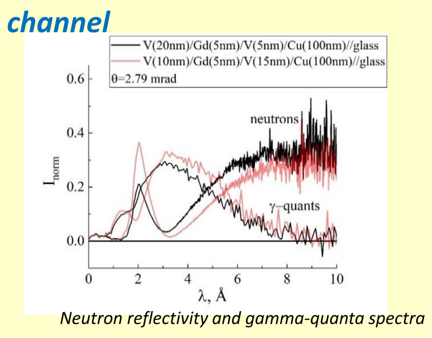
Schema of the REMUR spectrometer at the IBR-2 reactor



Gamma-quanta registration channel

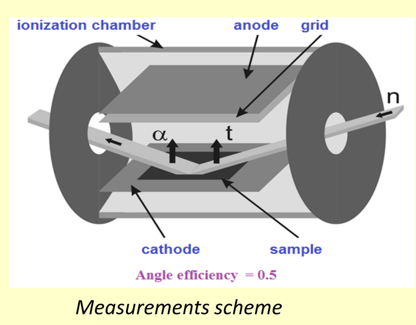


Gamma-quanta registration channel and position of the sample



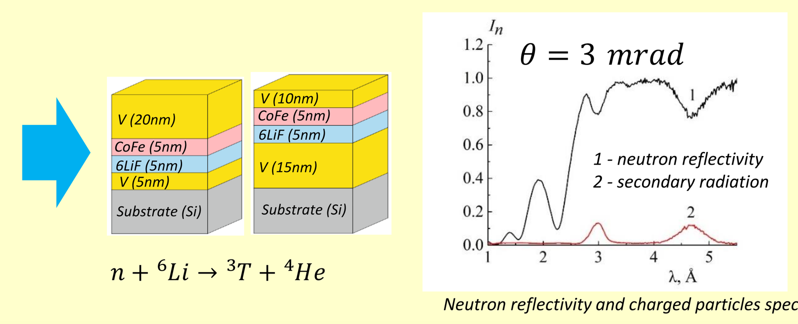
Neutron reflectivity and gamma-quanta spectra

Charged particles and polarized neutrons registration channels

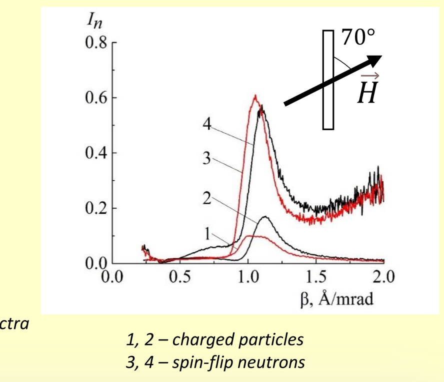


Measurements scheme

$n + {}^6Li \rightarrow {}^3T + {}^4He$



Neutron reflectivity and charged particles spectra



1, 2 – charged particles
3, 4 – spin-flip neutrons

Conclusion

1. Proximity effects in superconducting-ferromagnetic structures were studied. A nonequilibrium magnetic state in the structures with ferromagnets of the transition group of metals, such as FeV and NiCu, has been discovered and investigated.
2. At the structure Al2O3//Nb(100nm)/Gd(3nm)/V(70nm)/Nb(15nm) change in the magnetization in superconducting layers (at area 10 nm close to F-layer) under the influence of superconductivity at a level of 4-10% was found, which corresponds to the implementation of the inverse proximity effect.
3. At the REMUR reflectometer realized mode for detecting secondary radiation: charged particles, gamma quanta, and neutrons with spin flip, what makes it possible to determine the spatial profile of individual isotopes.

References

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