JOINT INSTITUTE FOR NUCLEAR RESEARCH

Frank Laboratory of Neutron Physics

Investigation of superconductivity and magnetism in layered nanostructures by PNR with secondary radiation registration

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OUTLINE

1. *Superconducting technologies in nanoelectronics*

2. *Polarized neutron reflectometry with registration of secondary radiation*

3. *Rare-earth elements for spintronics*

4. *Further perspective – rare earth metals dysprosium and holmium*

SUPERCONDUCTING TECHNOLOGIES IN NANOELECTRONICS

Advantage of superconducting technologies:

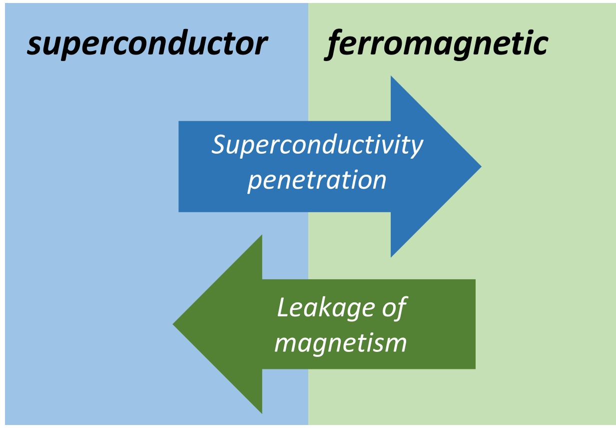
1. No electrical resistance
2. Superconducting electrons are ‘quantum fluid’
3. Rich physics due to proximity effects
4. Ability to control the magnetic properties of the system

Main analogues

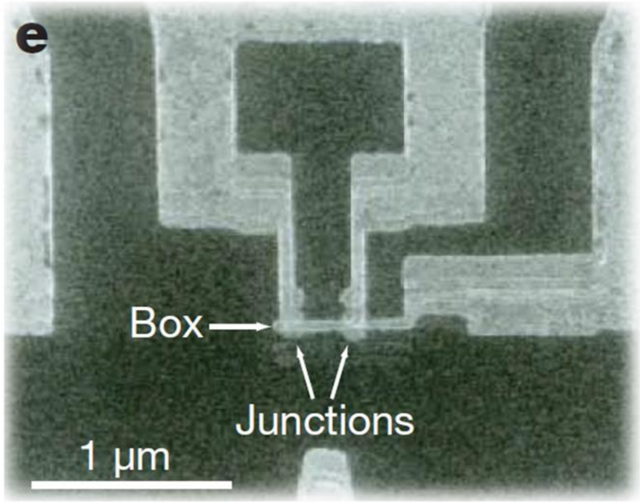
quantum non-superconducting technologies:

entangled quantum states of atoms or photons, quantum dots, etc.

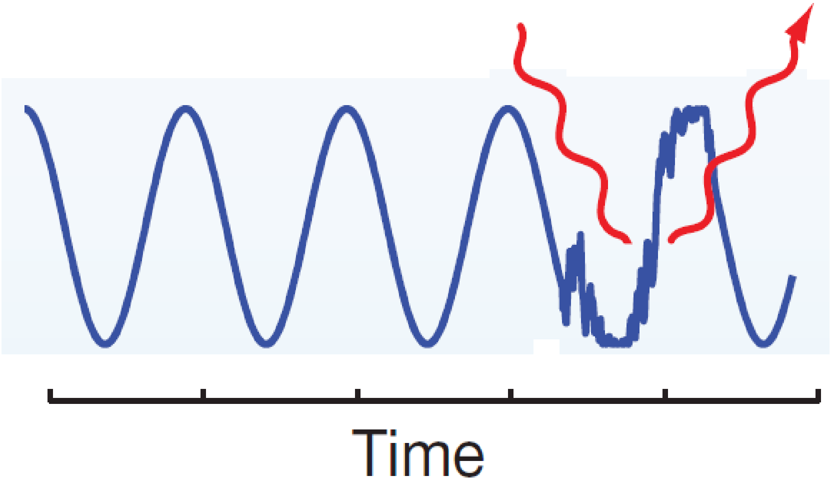
Proximity effect



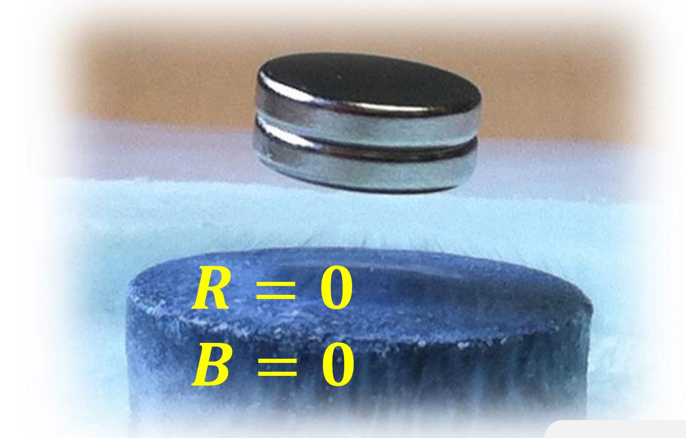
Josephson qubit



Decoherence of a quantum system with time

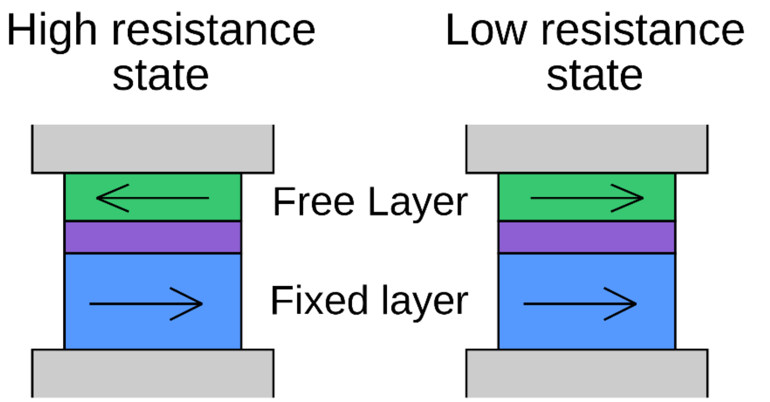


Meissner effect

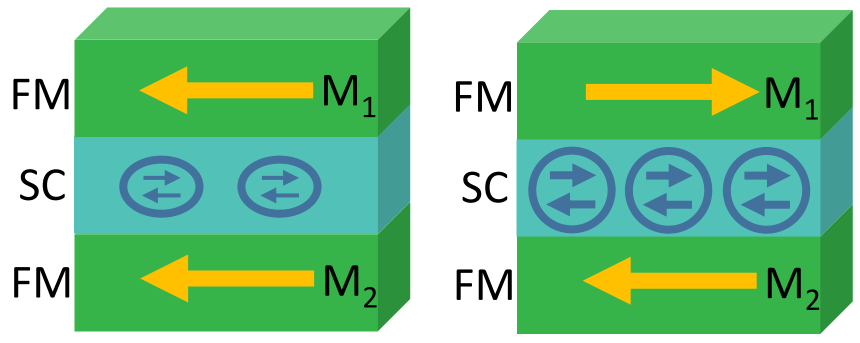


SUPERCONDUCTING SPIN VALVES

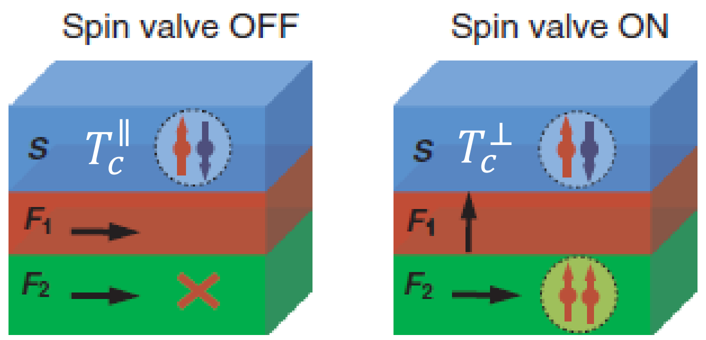
1. Scheme of classical spin valve



3. Controlling magnetism

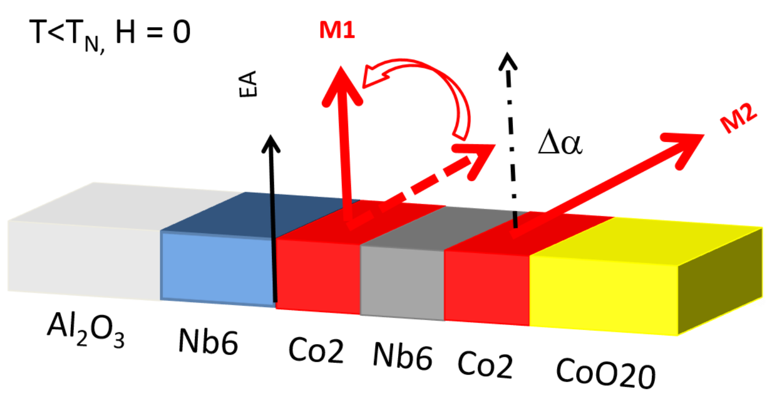


2. Superconducting spin valve



$$T_c^{\parallel} < T_c^{\perp}$$

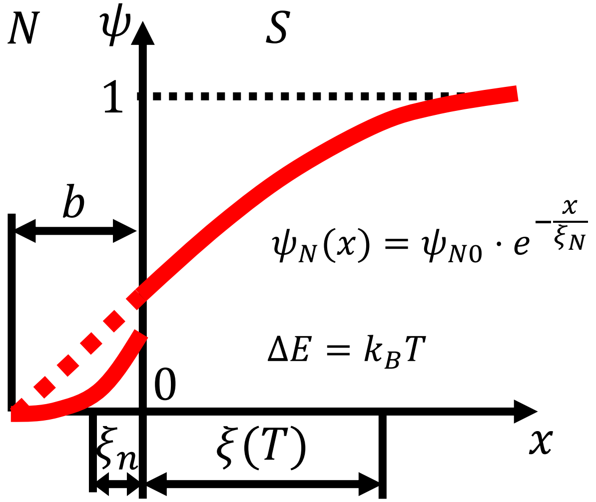
4. Non-collinear spin valves



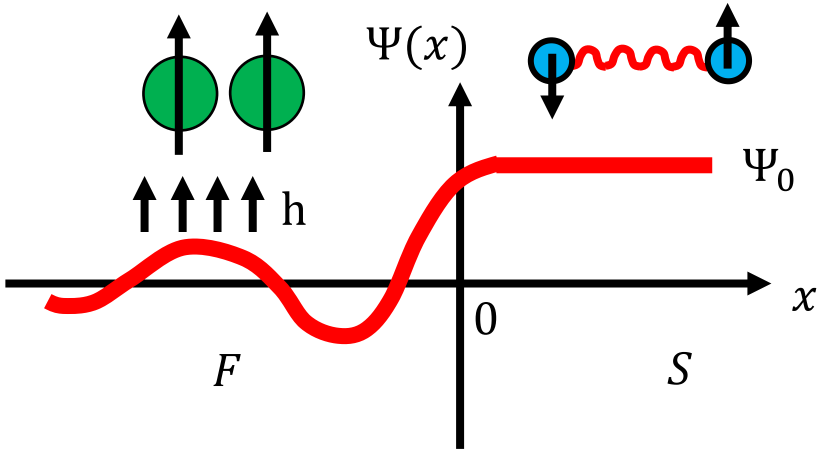
A. Singh et al. // Physical review X 5, 021019 (2015)
A. Golubov, M. Kupriyanov // Nature Materials, Vol. 16, Feb. 2017
Yury Khaydukov et al. // EU Patent application 21153254.4-1212

PROXIMITY EFFECTS IN THE PHYSICS OF SUPERCONDUCTIVITY

Normal metal / superconductor

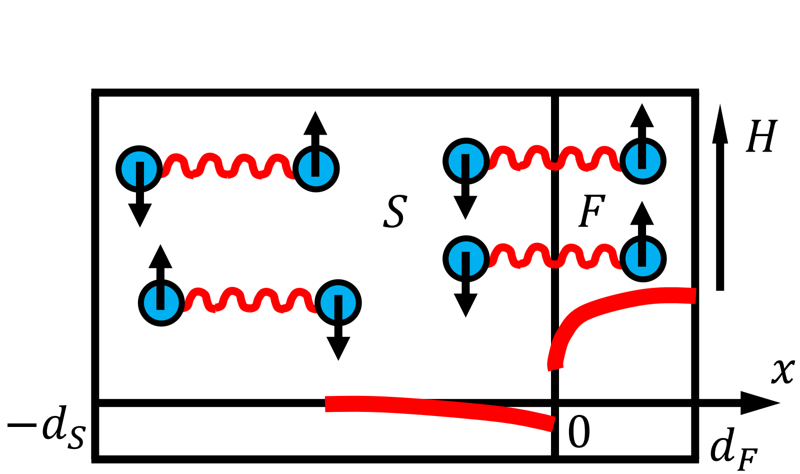


Ferromagnet / superconductor



$\psi_F(x) = \psi_{F0} \cdot e^{-\frac{x}{\xi_{F1}}} \cdot e^{-i\frac{x}{\xi_{F2}}}$ $E_{ex} \gg k_B T$

Inverse proximity effect



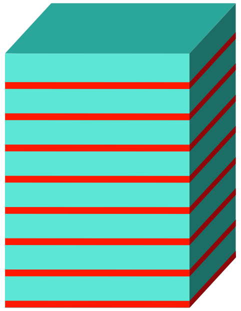
Magnetic states of S-FM systems under the influence of proximity effects

Low-dimensional systems $d \sim \xi$

Influence of magnetism on the superconducting properties of the system $\frac{I_F}{I_S} \sim 10^2$ $I \sim T_c$

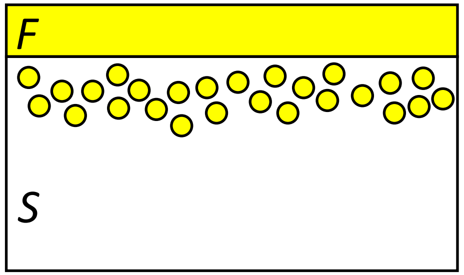
Influence of superconductivity on the magnetic properties of the system $d_F \sim \xi_F$ $d_F \ll d_S$

Inhomogeneous structures? $d_{cl} > \xi_F$



S-FM structure

$d \sim 1 \div 10^3\ nm$



Inhomogeneous S-FM structure

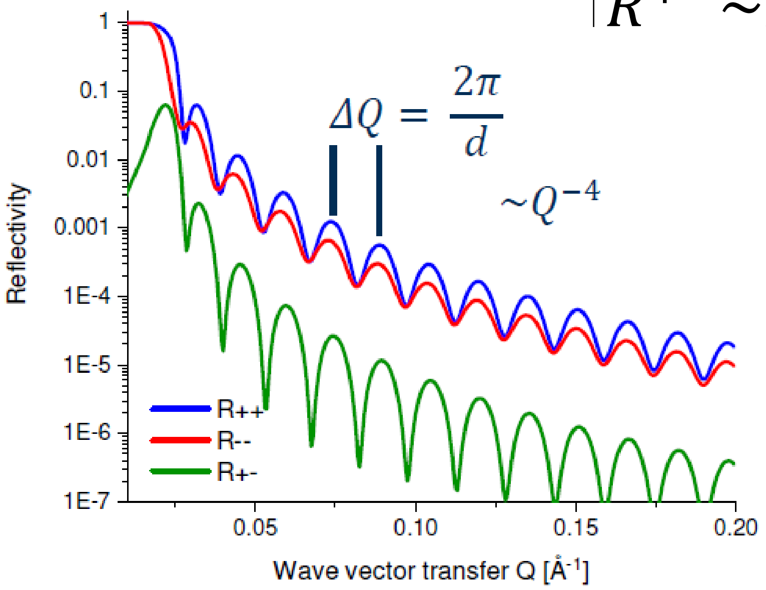
POLARIZED NEUTRON REFLECTOMETRY

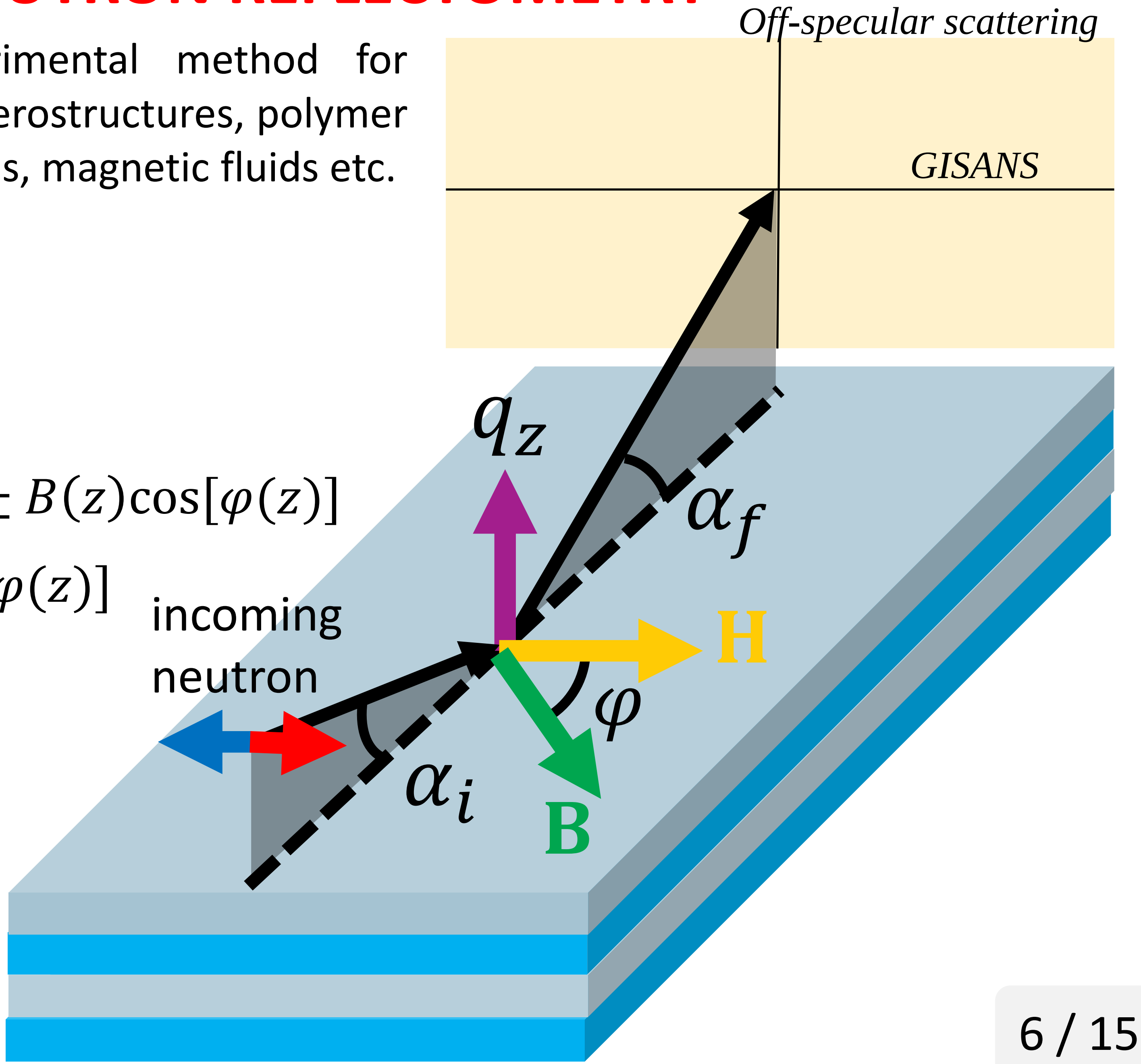
Polarized neutron reflectometry – experimental method for investigation of metallic low-dimensional heterostructures, polymer films, biological systems, free surface of liquids, magnetic fluids etc.

$$U = U_{nuc} + U_{mag}$$

$$U_{mag} = -\boldsymbol{\mu B} = |\mu_n|\boldsymbol{\sigma B}$$

$$r = \begin{pmatrix} r_{++} & r_{+-} \\ r_{-+} & r_{--} \end{pmatrix} \Rightarrow \left| \begin{array}{l} R^{\pm\pm} \sim SLD(z) \pm B(z)\cos[\varphi(z)] \\ R^{+-} \sim B(z)\sin[\varphi(z)] \end{array} \right.$$



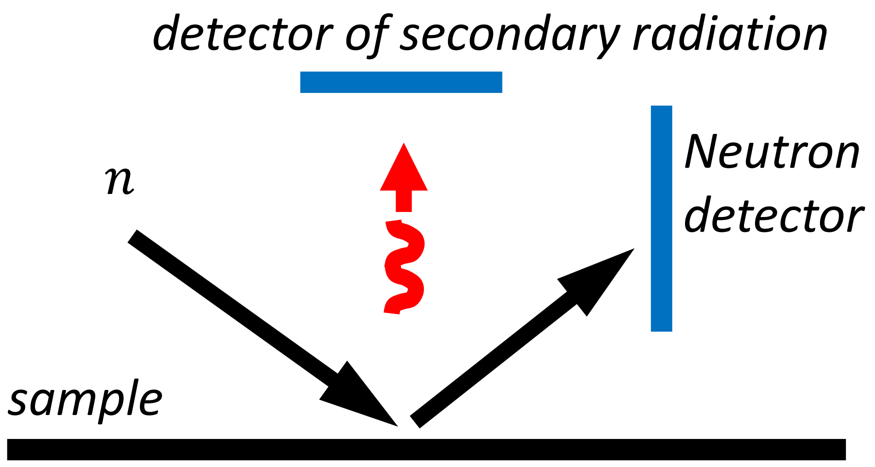


REGISTRATION OF SECONDARY RADIATION

$$W = \sum W_{ij} \propto \sum N_i \sigma_{ij}$$

i – isotope, j – type of secondary radiation

- *Charged particles (n, α); (n, t); (n, p)*
- *Gamma-quanta (n, γ)*
- *Fission fragments (n, f)*
- *Spin-flip neutrons*
- *Noncoherent scattered neutrons by nuclei*
- *Inelastically scattered neutrons*
- *Diffusely scattered neutrons on medium inhomogeneities*

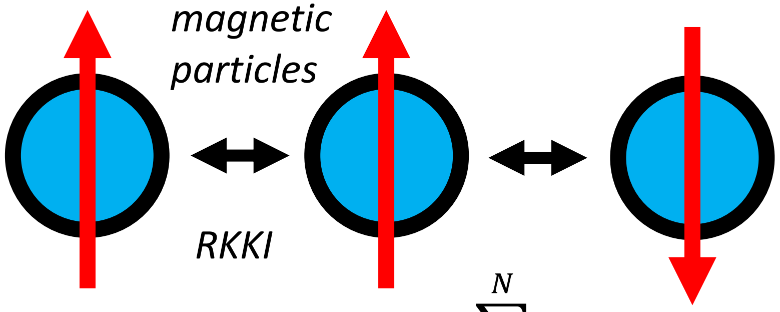


$$I_{i,j}(k_{z0}) \sim \int \frac{|\psi(z,k_{z0})|^2 \cdot Im(u)}{|\psi_0(k_{z0})|^2 \cdot k_0} N_i(z) dz$$

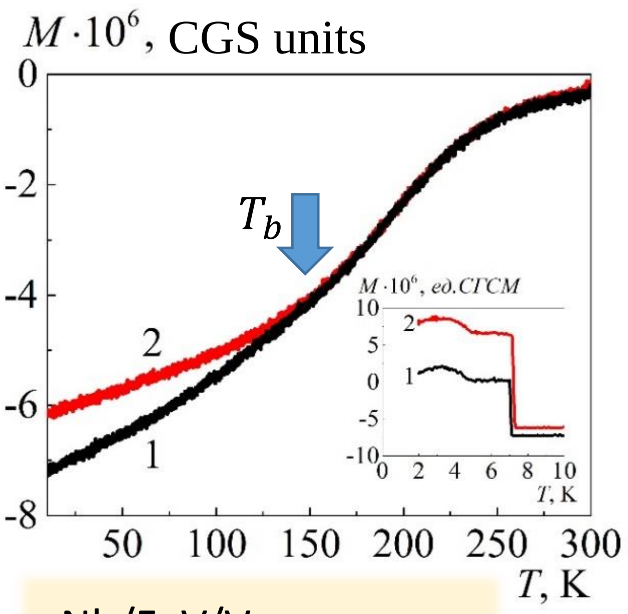
Zhaketov V.D. et al. // Journal of Surface Investigations, vol. 15, no. 3, pp. 549-562 (2021)
Zhaketov V.D. et al. // Journal of Surface Investigations, vol. 13, no. 3, pp. 478-487 (2019)

RARE-EARTH ELEMENTS (GADOLINIUM) FOR SPINTRONICS

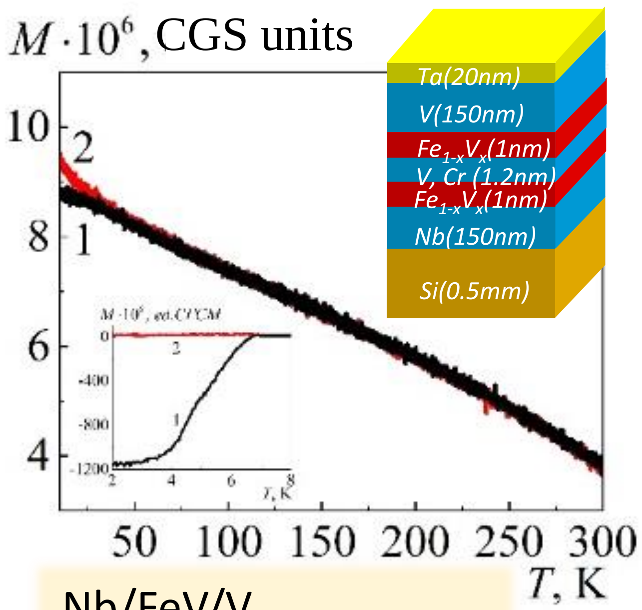
1. Gadolinium is a localized ferromagnet with a rather low (compared to Fe, Co, and Ni) bulk Curie temperature of T_m = 293 K. Strong localization of the magnetic moment stabilizes ferromagnetism even in ultrathin Gd layers.
2. Gd has ability to couple with other ferromagnets, forming nontrivial magnetic ordering patterns which can be used for the creation of superconducting spin valves.
3. Niobium and gadolinium components are not mutually soluble in either the solid or liquid phase.
4. Gadolinium has record cross-section of (n,γ)-reaction. $\sigma(^{157}Gd) = 253\ kbarn$



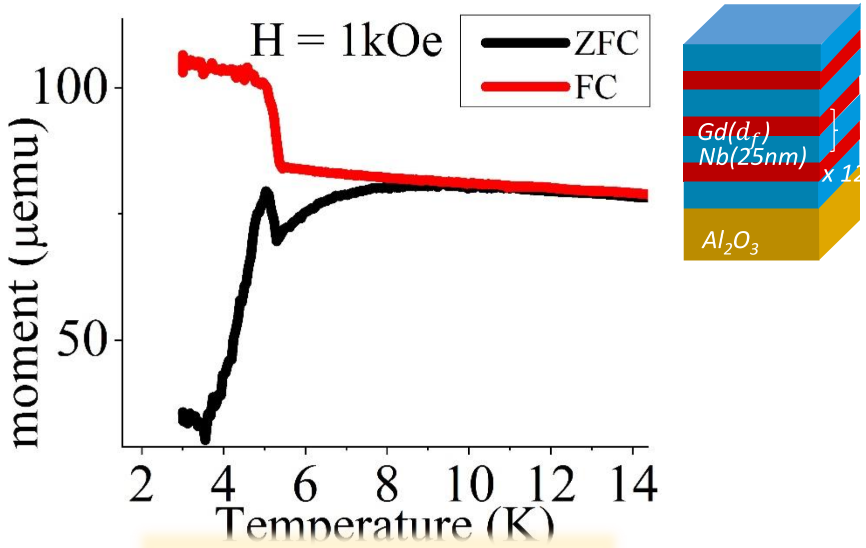
$$H = -\sum_{i \neq j}^{N} J_{ij}\sigma_i\sigma_j$$



Nb/FeV/V
H=20 Oe - T_b≈150 K



Nb/FeV/V
H=1000 Oe - T_b≈50 K

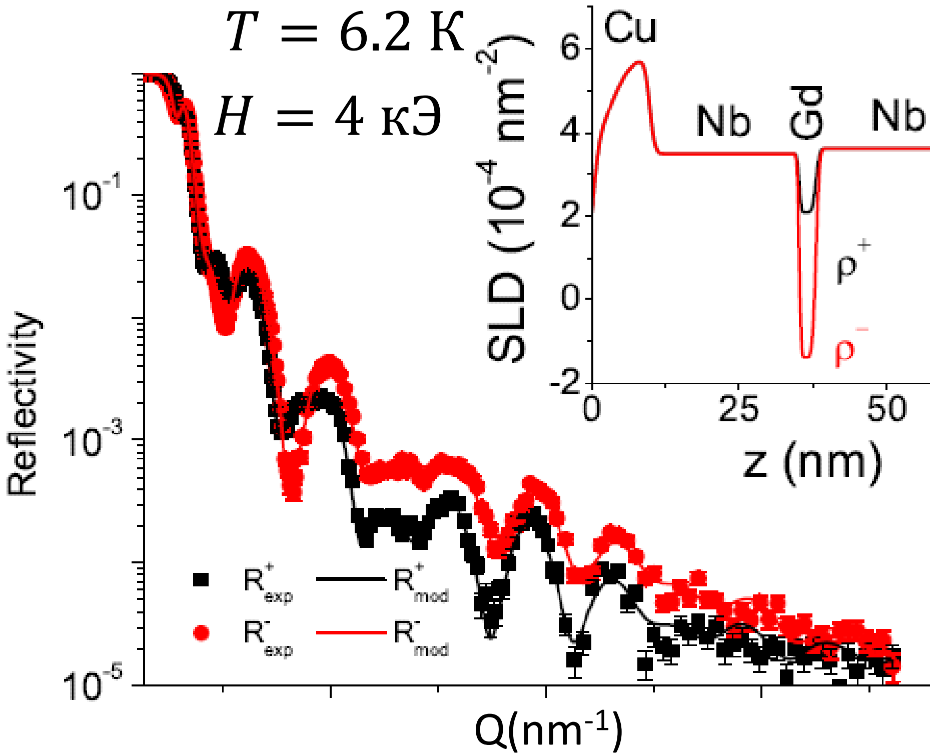


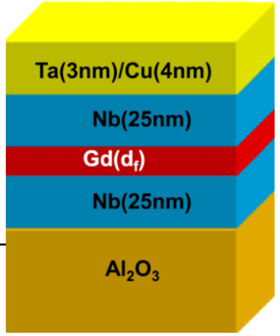
[Nb/Gd]x12
H=1000 Oe - T_b≈8 K

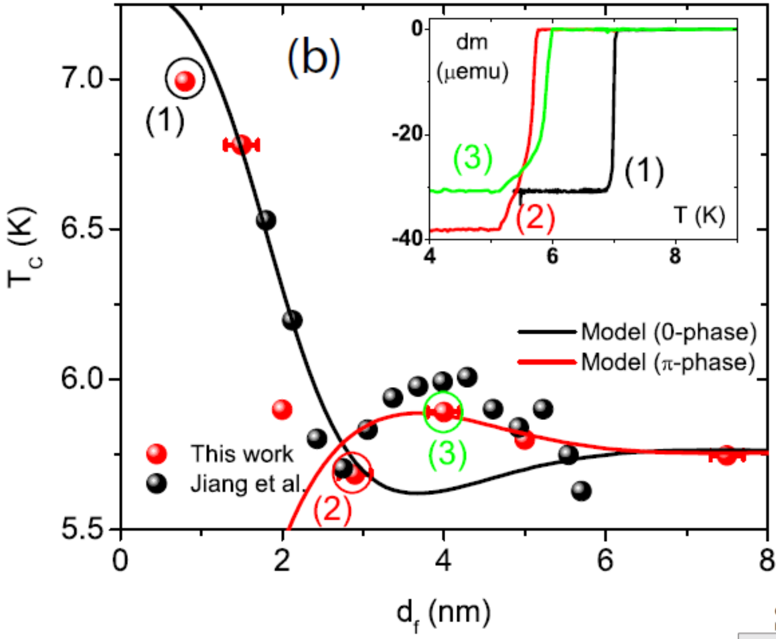
Zhaketov V.D. et al. // JETP, vol. 129, No.2, pp. 258-276 (2019)
Khaydukov Yu.N. et al. // Phys. Rev. B, 97, 144511 (2018)

EFFECT OF MAGNETISM ON SUPERCONDUCTIVITY IN NB/GD/NB TRILAYERS

- Structures Nb(25nm)/Gd(d_f)/Nb(25nm) were investigated
- Observed reducing of T_c with increasing of magnetic moment $T_c \sim M_F^{-1}$ $M_F = d_F \cdot B_F$
- Superconducting coherent length in gadolinium $\xi_F = 4$ nm



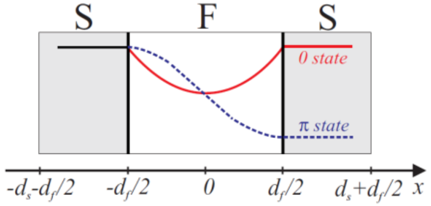




Dependance $T_c = f(d_f)$

$\xi_F = 4\ nm$

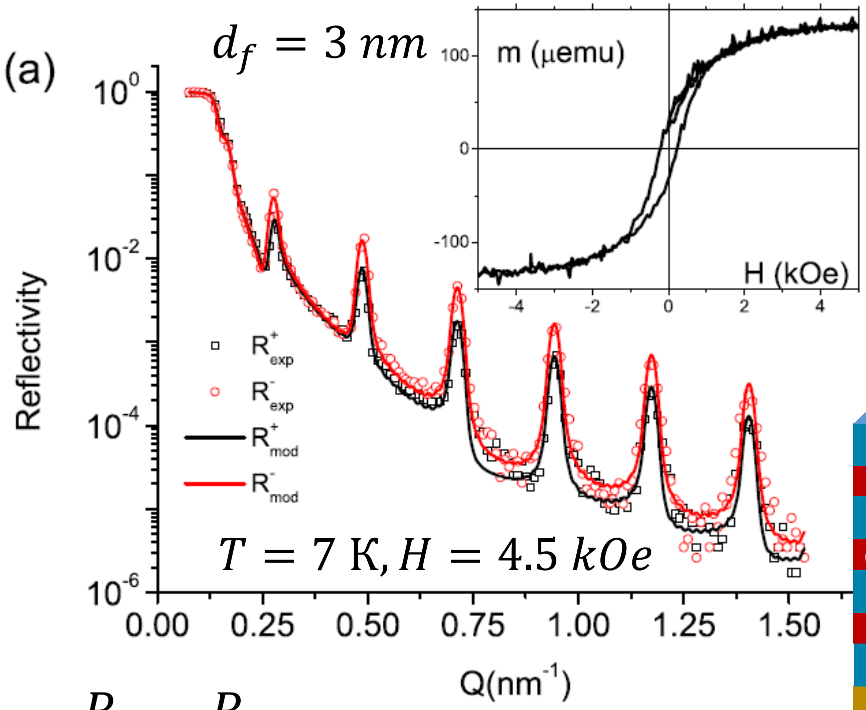
$d_F < \xi_F$

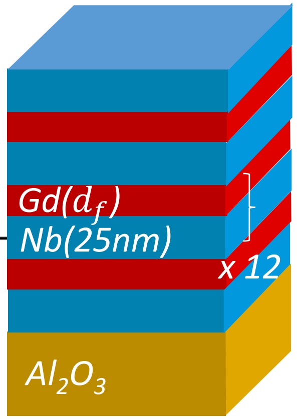


Khaydukov Yu.N. et al. // Phys. Rev. B, 97, 144511 (2018)

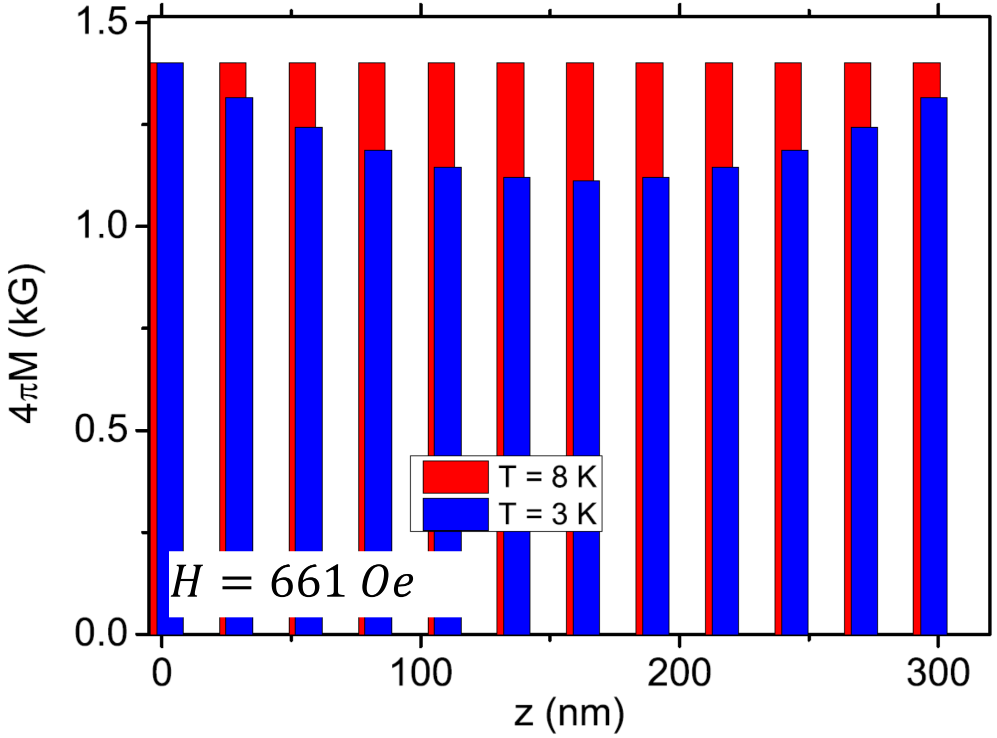
DIAMAGNETISM OF PERIODIC FERROMAGNETIC-SUPERCONDUCTING STRUCTURE

- Reducing the magnetic moment of structures *[Nb(25 nm)/Gd(x=1.2, 3, 5 nm)]x12* below T_c
- Transition of a ferromagnetic structure to superconducting state
- The superconductor displaces the magnetic field $H = H_{ext} \cdot ch(z/\lambda) \cdot ch(D_s/2\,\lambda)^{-1}$
- The penetration depth was $\lambda = 180 \pm 10$ nm > $\lambda(Nb) = 120$ nm





$$S = \frac{R_+ - R_-}{R_+ + R_-} \sim M$$



Results of experimental data fitting

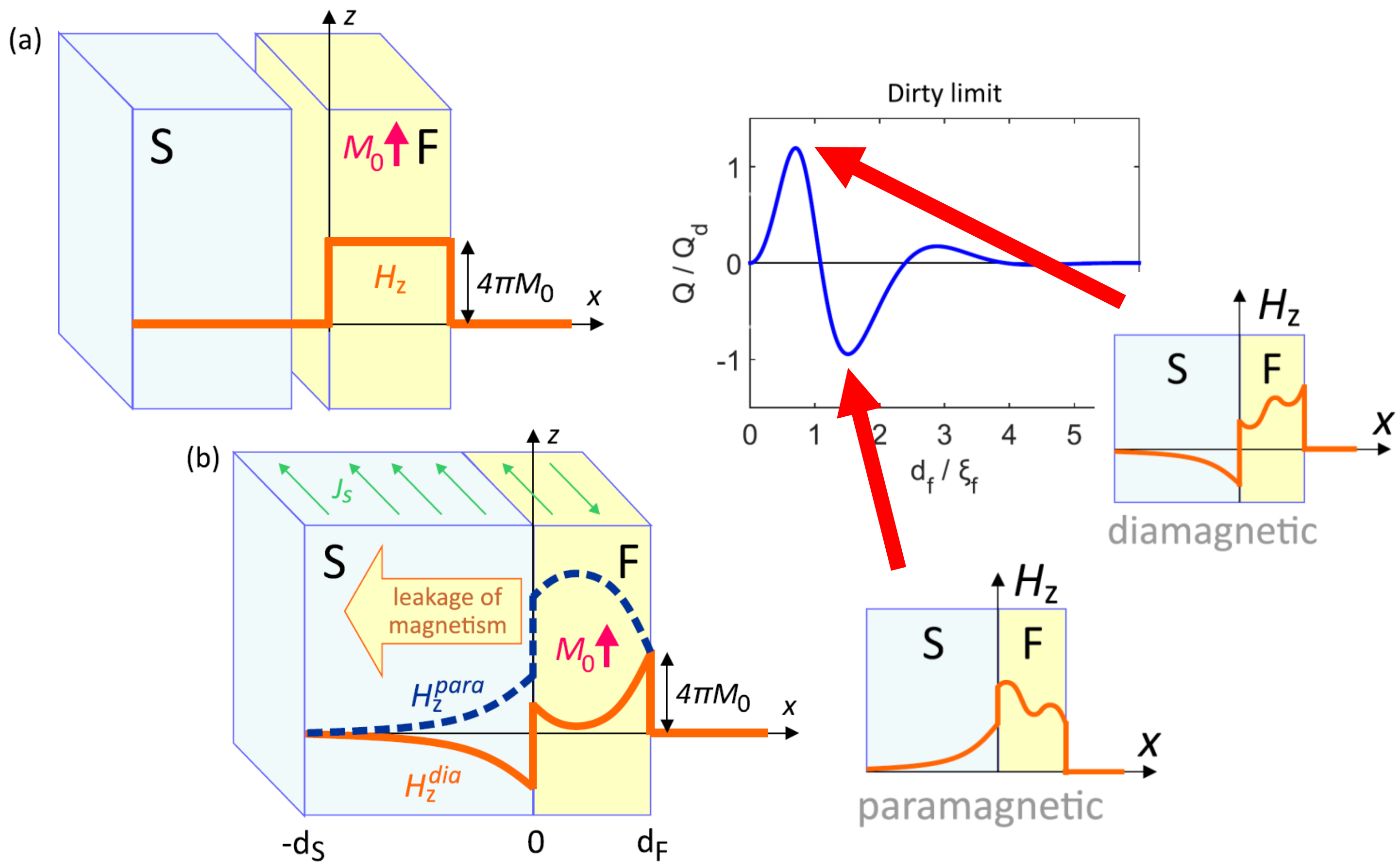
Khaydukov Yu.N. et al. // Phys. Rev. B, 99, 140503 (2019)

ELECTROMAGNETIC 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.

Electromagnetic proximity effect in planar superconductor-ferromagnet structures

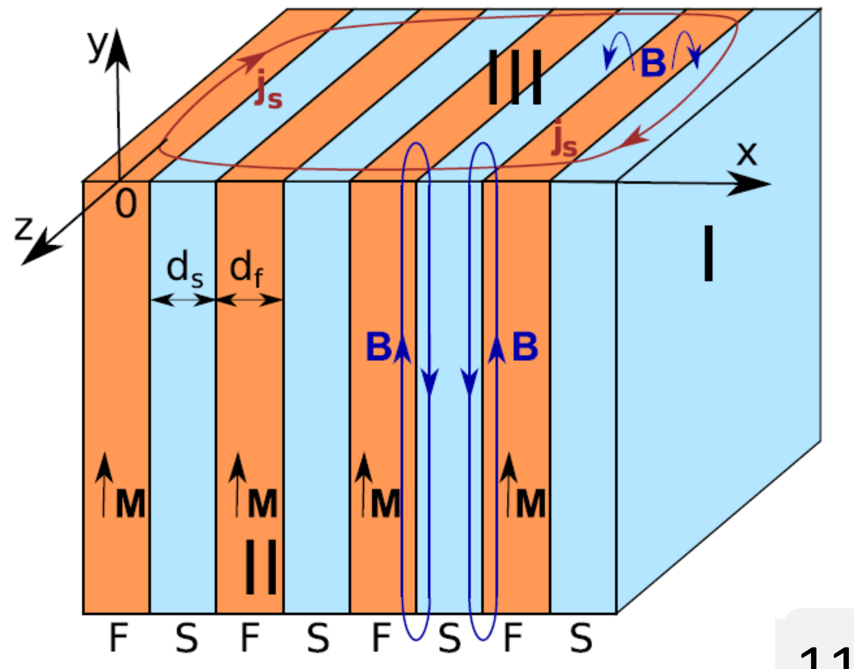
S. Mironov,[1] A. S. Mel'nikov,[1,2] and A. Buzdin[3,4,5] *2018*



Giant electromagnetic proximity effect in superconductor/ferromagnet superlattices

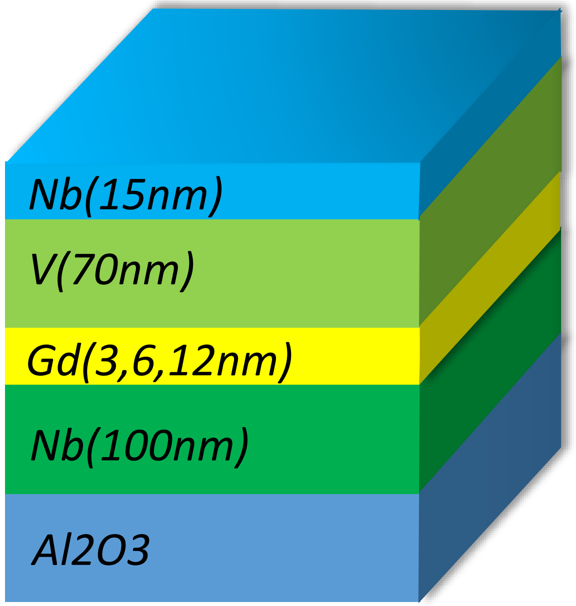
A.V. Putilov, S.V. Mironov, A.S. Mel'nikov, A.I. Buzdin

2022



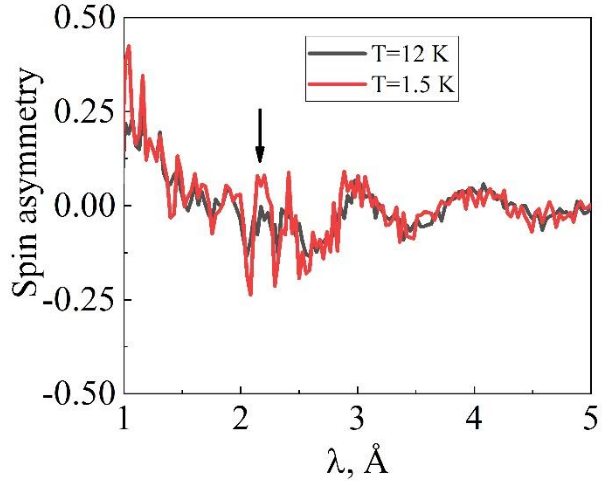
ELECTROMAGNETIC PROXIMITY EFFECT. EXPERIMENTAL RESULTS

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.



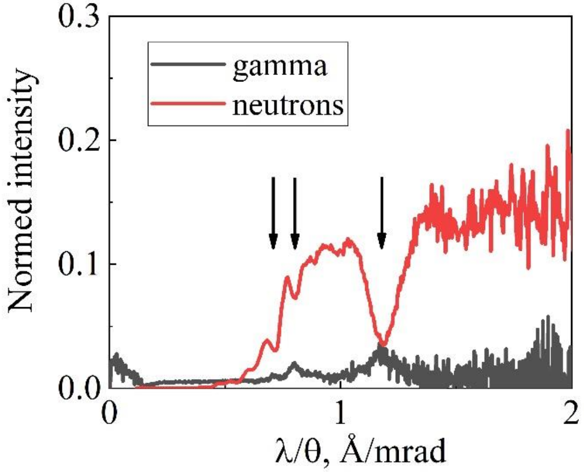
Polarized neutrons

determination of the magnetic profile of the Gd layer and superconducting layers; nuclear profile for sum of elements

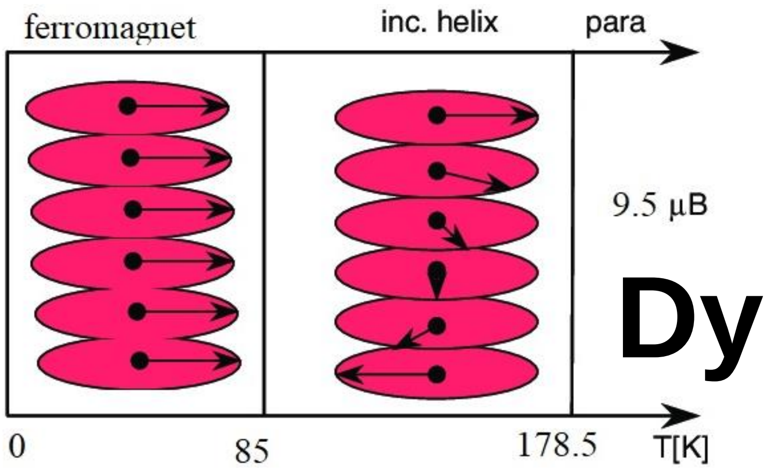


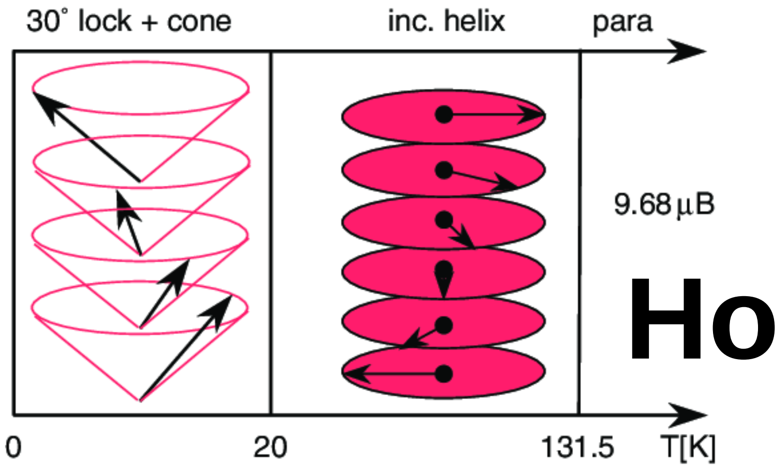
Secondary radiation channel (gamma-quanta)

Determination of the nuclear profile of the Gd layer



FURTHER PERSPECTIVE – RARE EARTH METALS DYSPROSIUM AND HOLMIUM



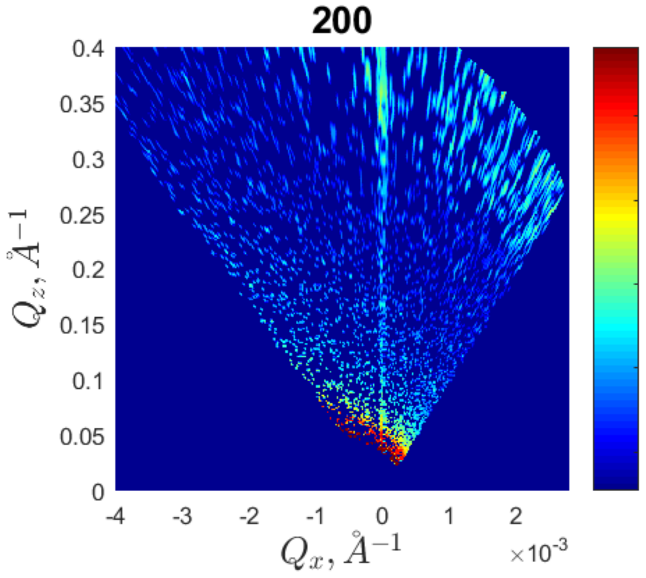


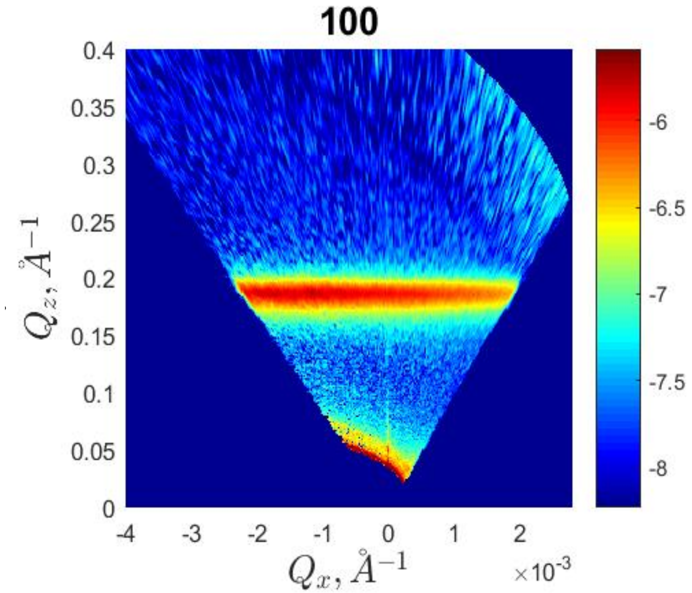
Investigated structures:

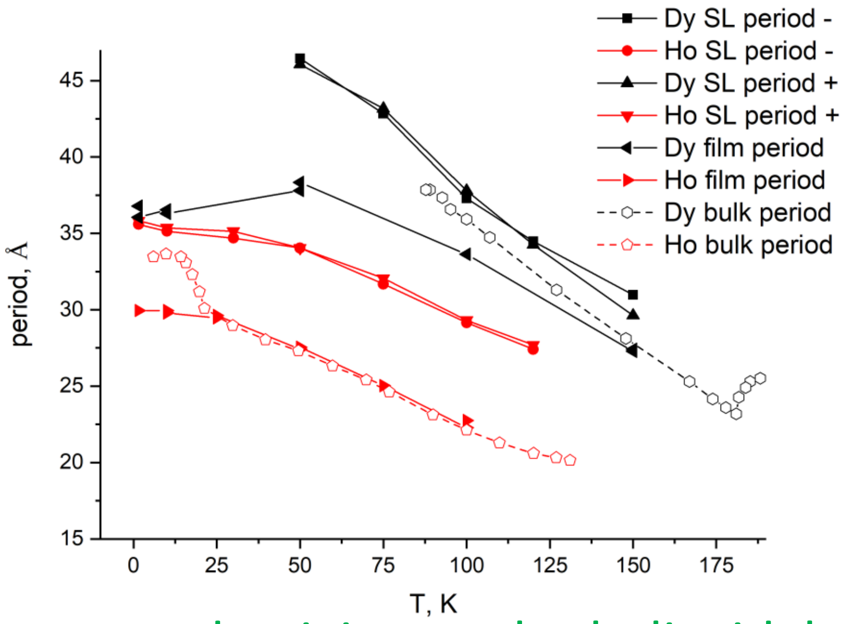
1) Dy (2000 Å)

2) Ho (2000 Å)

3) [Dy (60 Å)/Ho (60 Å)]×34







Further prospects are connected with the study of the effect of superconductivity on the helicoidal magnetic ordering in the Nb/Dy, Nb/Ho superlattice.

Devyaterikov D.I. et al. // Journal of Surface Investigations, Vol. 16, No. 5, pp. 839-842 (2022)

Devyaterikov D.I. et al. // Physics of Metals and Metallography, Vol. 122, No. 5, pp. 465-471 (2021)

Conclusion

1. Superconducting technologies are good candidate to replace classical semiconductor technologies. The creation of superconducting spin valves is one of the promising applications.
2. One of the effective methods for studying magnetism of heterostructures is polarized neutron reflectometry, which makes it possible to obtain chemical and magnetic depth profiles with nanometer resolution. Registration of secondary radiation make possible to determine distribution of separate elements.
3. Gadolinium is perspective element for creation of devices for spintronics. Detailed investigation of such systems demonstrate electromagnetic proximity effects at such systems.
4. Further prospects are connected with the study of the dysprosium and holmium as helimagnet elements with non-trivial magnetic order for creation of spintronics devices.

Thank you for your attention!