JOINT INSTITUTE FOR NUCLEAR RESEARCH
Frank Laboratory of Neutron Physics

INVESTIGATION OF SUPERCONDUCTIVITY AND MAGNETISM IN LAYERED NANOSTRUCTURES BY POLARIZED NEUTRON REFLECTOMETRY WITH SECONDARY RADIATION REGISTRATION

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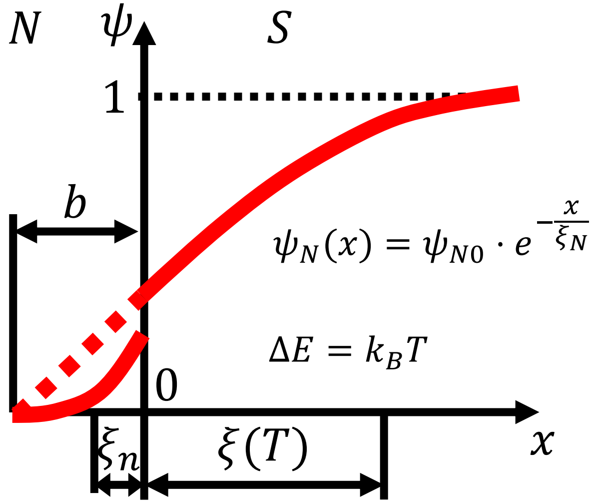
Talk plan

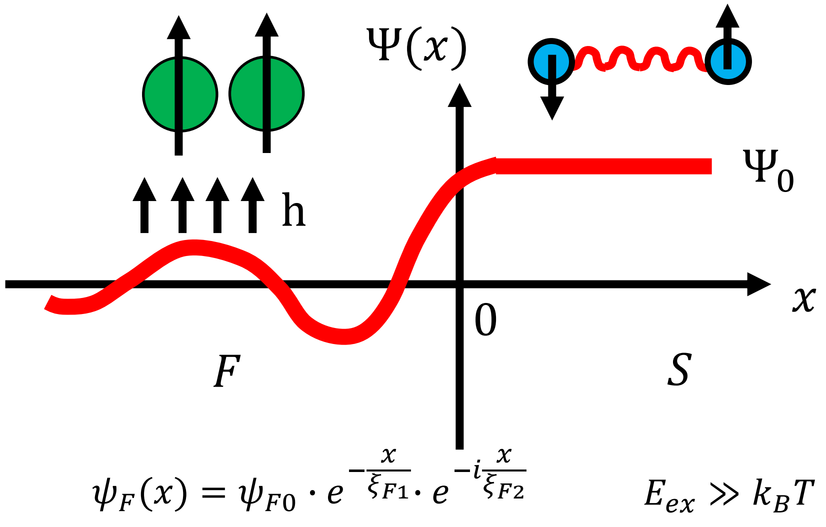
1. *Ferromagnetic(F)-superconducting(S) heterostructures*
2. *Electromagnetic proximity effect in SF structures*
3. *Neutron reflectometry with registration of secondary radiation*

Magnetic and superconducting heterostructures

Normal metal / superconductor



Ferromagnet / superconductor

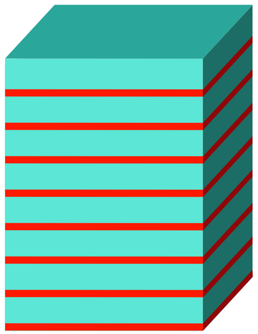


Magnetic states of S-F systems under influence of proximity effects

Low-dimensional heterostructures $d \sim \xi$

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

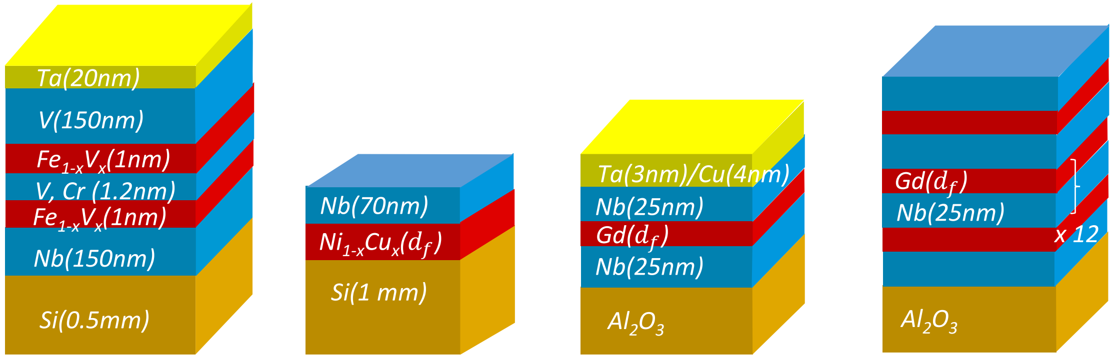
Influence of superconductivity on magnetic properties of the system $d_F \sim \xi_F$ $d_F \ll d_S$



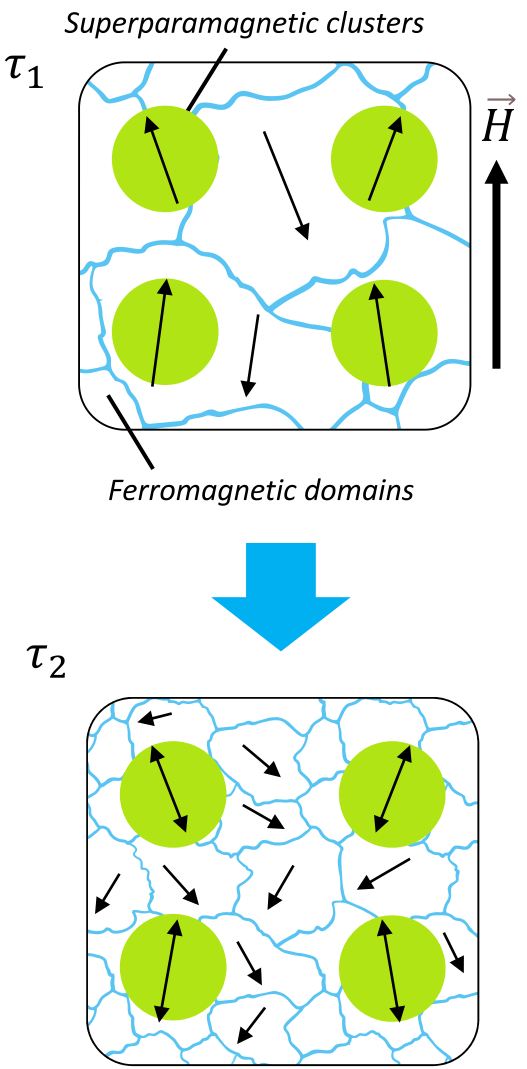
S-F structure
$d \sim 1 \div 10^3\ nm$

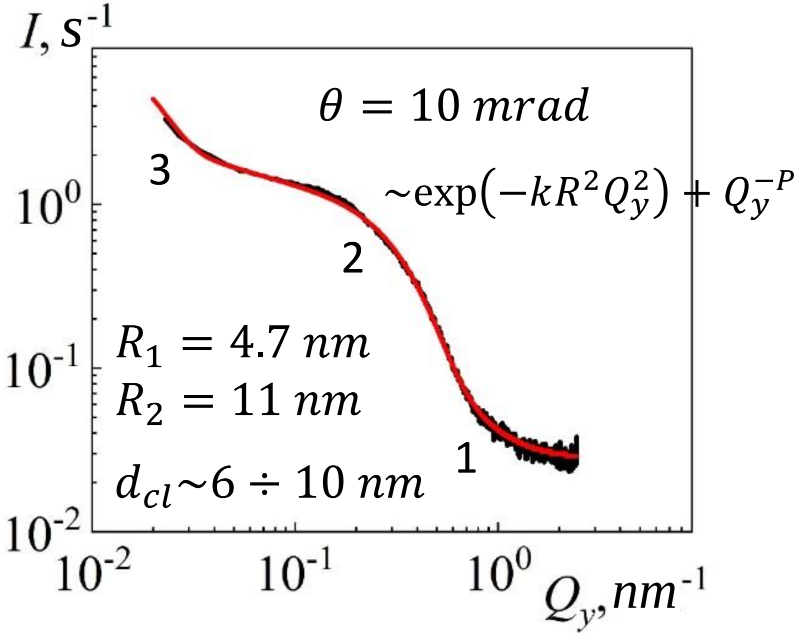
Proximity effects at S-F structures. Results

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

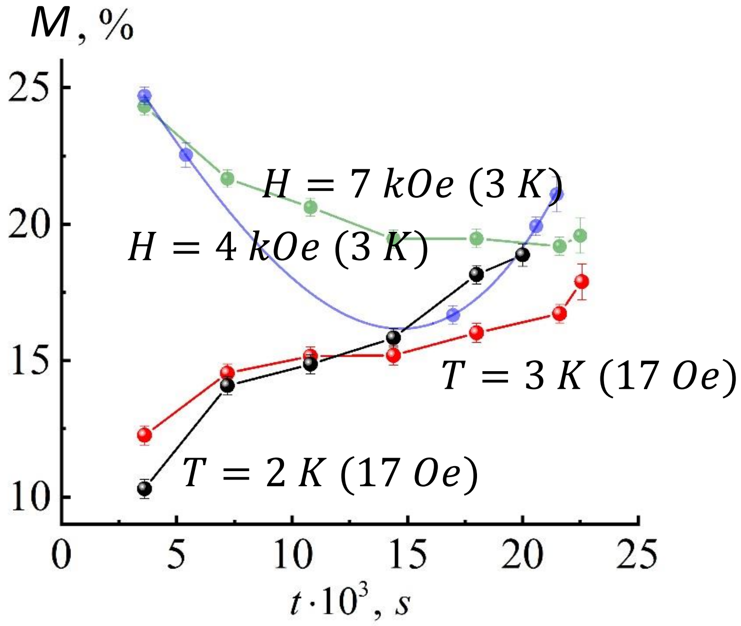


Nominal structures





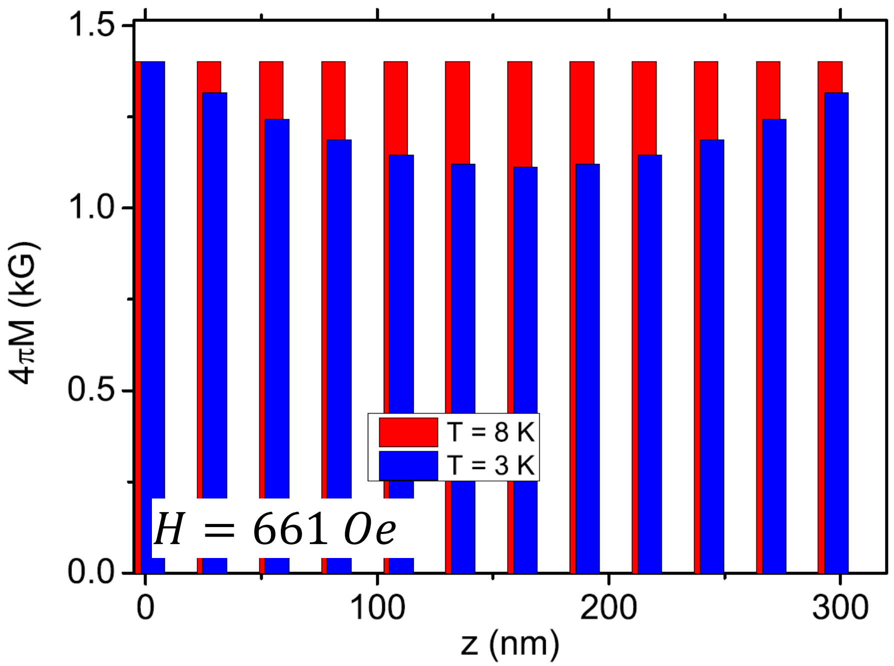
Small-angle scattering of synchrotron radiation in grazing geometry



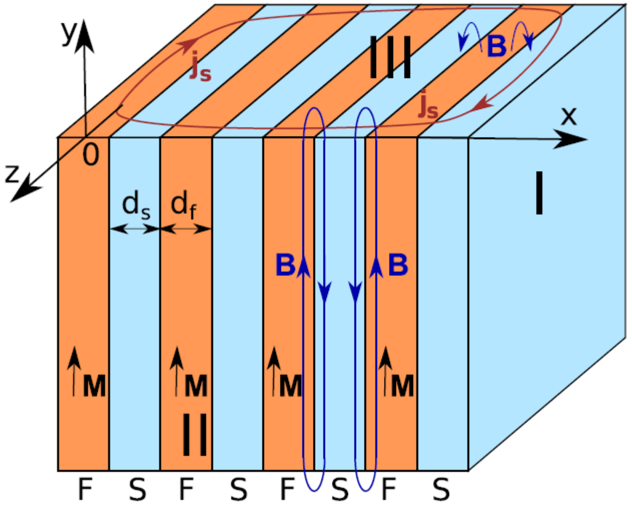
Magnetic moment relaxation of the structure with ferromagnet FeV

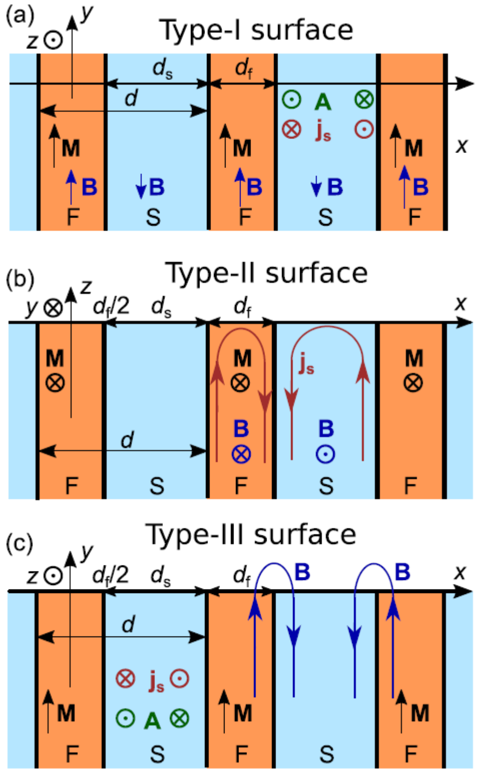
Diamagnetism of a periodic ferromagnetic-superconducting structure

- 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



Results of experimental data fitting





Giant electromagnetic proximity effect in superconductor/ferromagnet superlattices

A.V. Putilov, S.V. Mironov, A.S. Mel’nikov, A.I. Buzdin *2022*

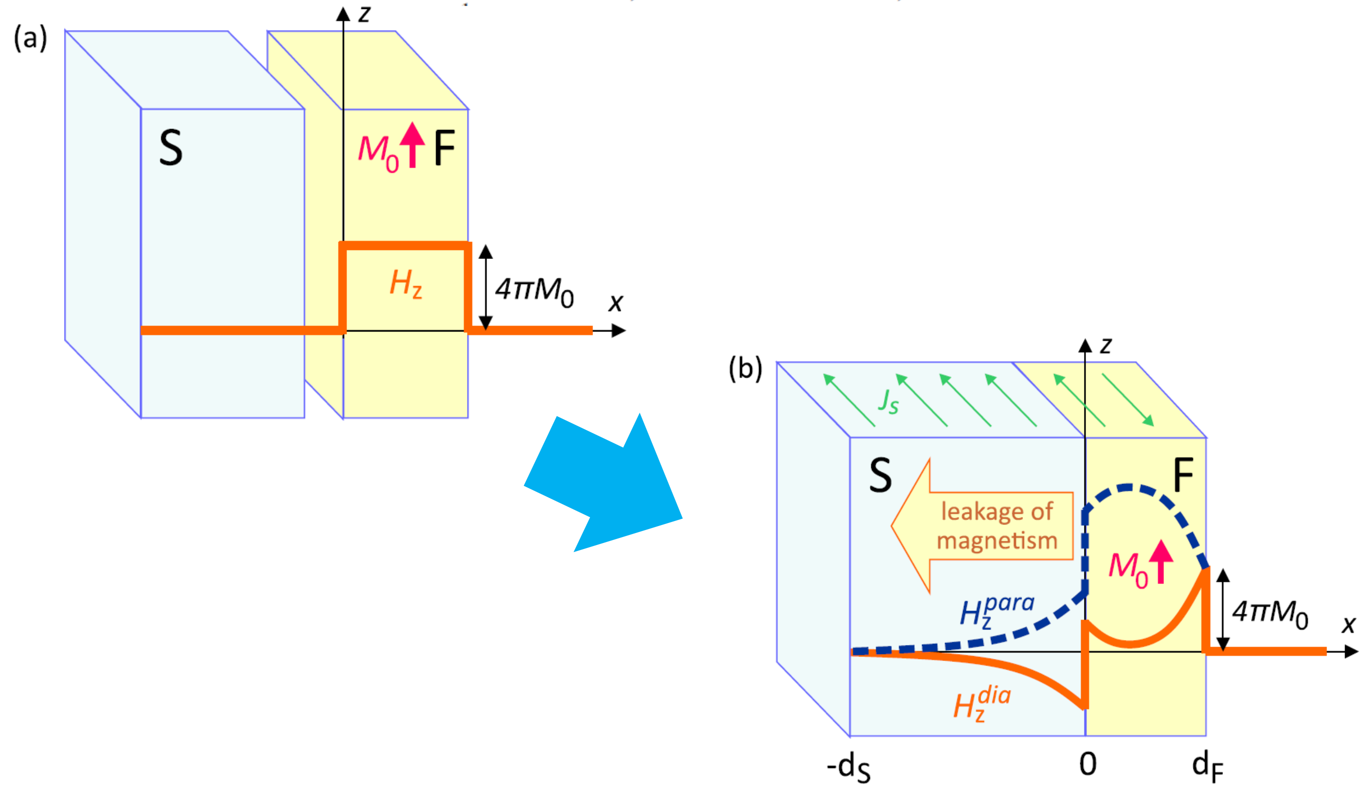
Electromagnetic proximity effect

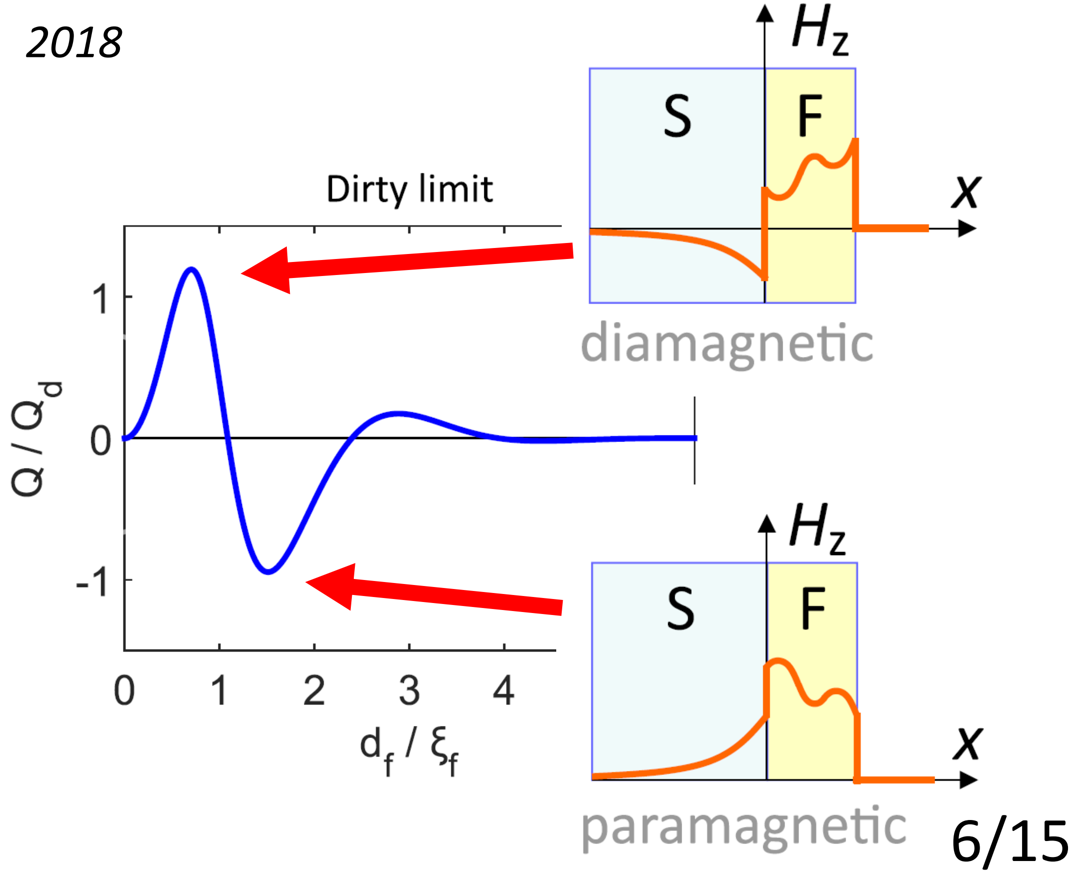
Recently, a new proximity effect has been described in ferromagnetic-superconducting layered nanostructures, which is characterized by a large scale (10 nm) of the interaction of superconductivity and magnetism, and which takes place for any ferromagnets.

Electromagnetic proximity effect in planar superconductor-ferromagnet structures

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

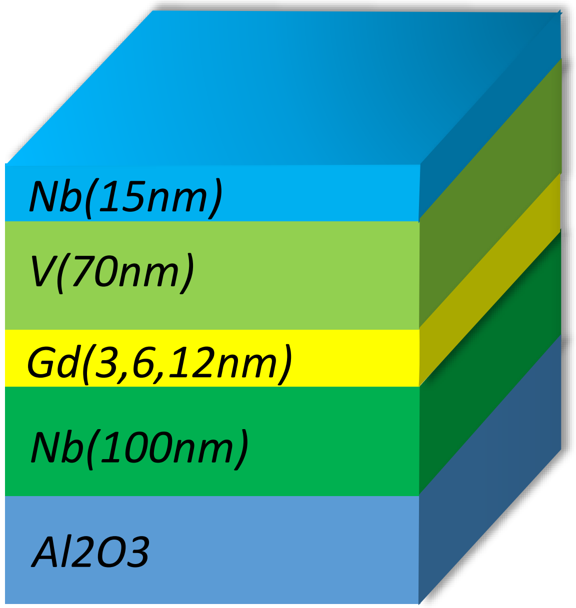
2018





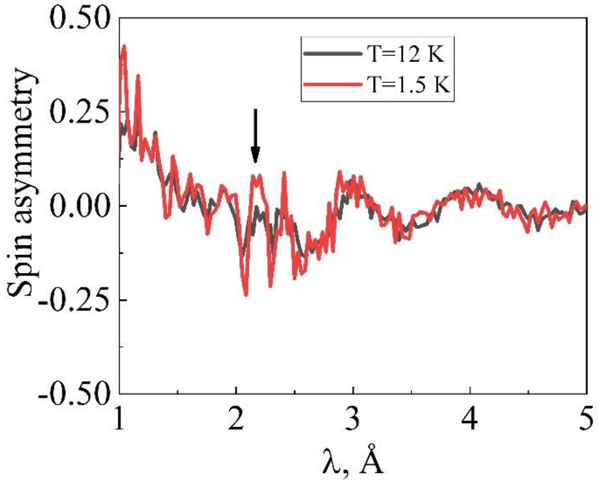
Electromagnetic proximity effect. Results.

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.



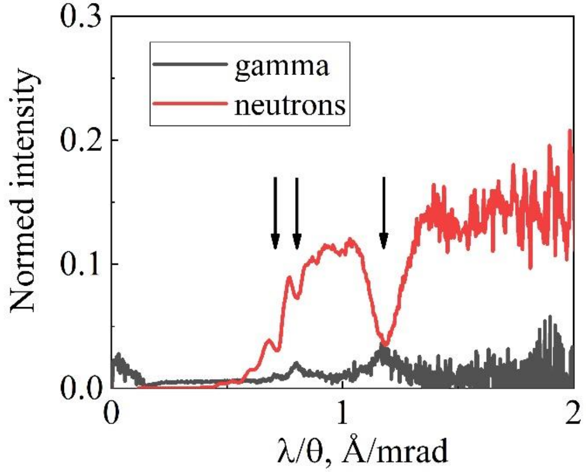
Polarized neutrons

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



Polarized neutrons reflectometry

Determined potential
- sum for all isotopes

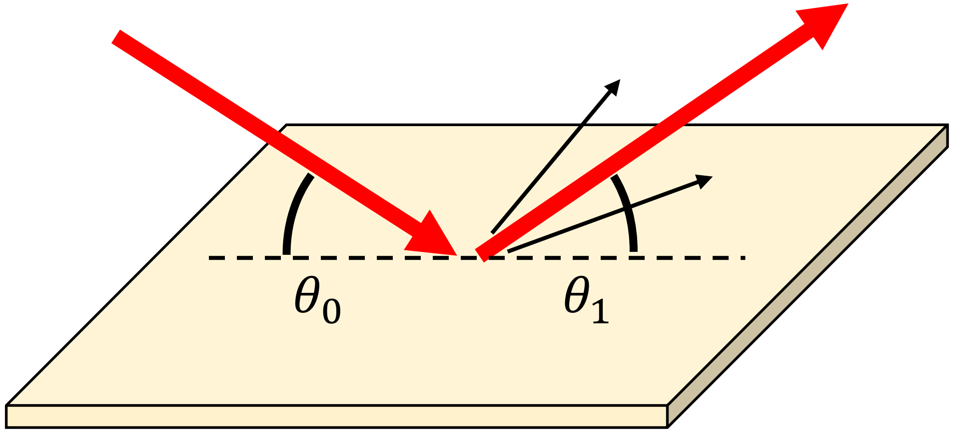
$$U = \sum U_i \propto \sum N_i \, b_i$$

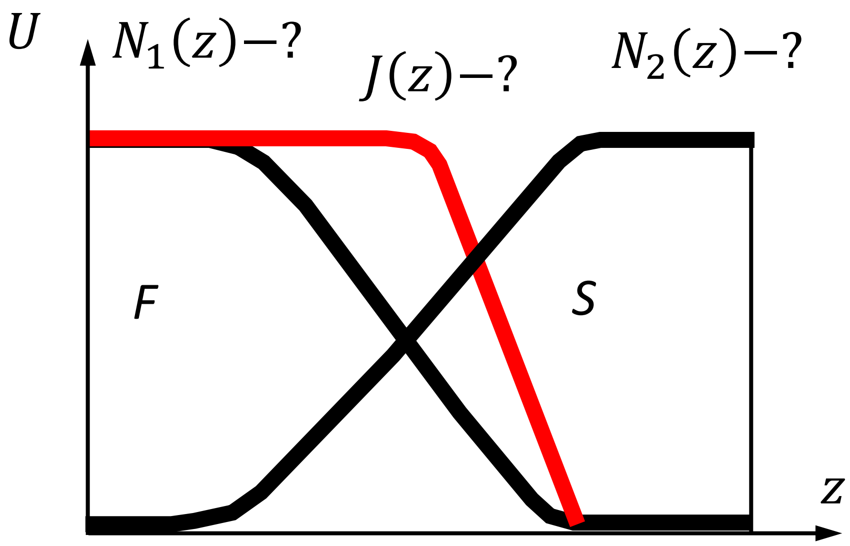
$$U = U_{nuc} + U_{mag}$$

$$U_{nuc} = V - iW$$

$$W = 10^{-5} \div 10^{-3} \, V$$

$$\Delta U(z) \Leftrightarrow \Delta N_i(z) \ ?$$





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

Standing wave regime

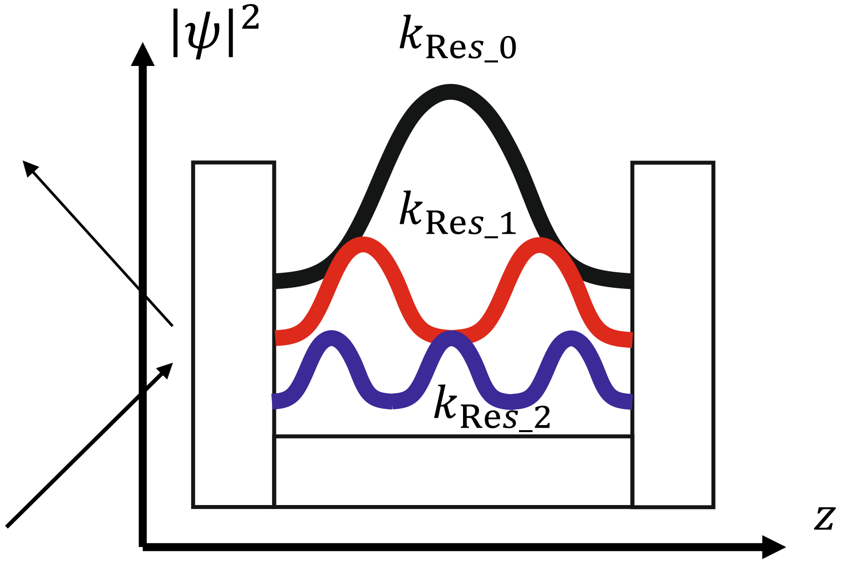
$$W = 10^{-5} \div 10^{-3}\, V$$

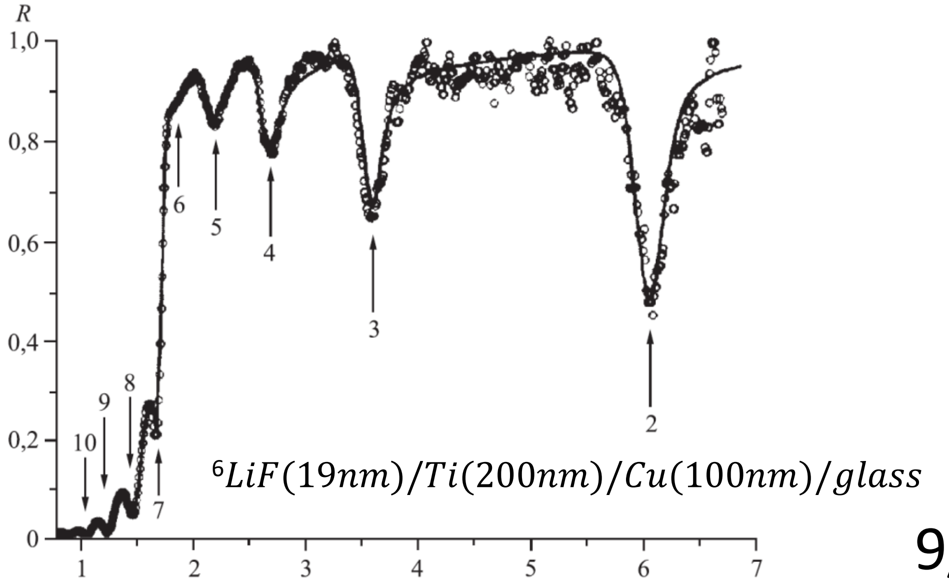
$$|\psi(z,k)|^2 = |\psi_d(z,k) + \psi_b(z,k)|^2$$

$$\eta_{\max}(nucl.\ density) \approx 10^5$$

Secondary radiation calculation:

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



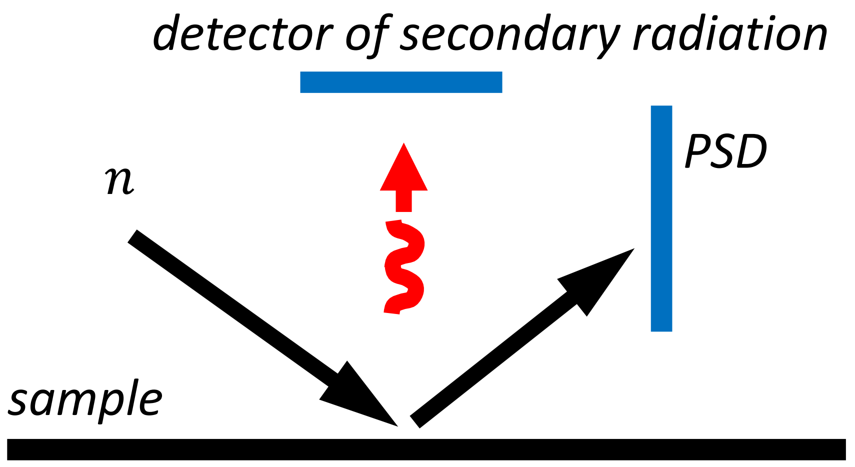


Registration of secondary radiation

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

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*

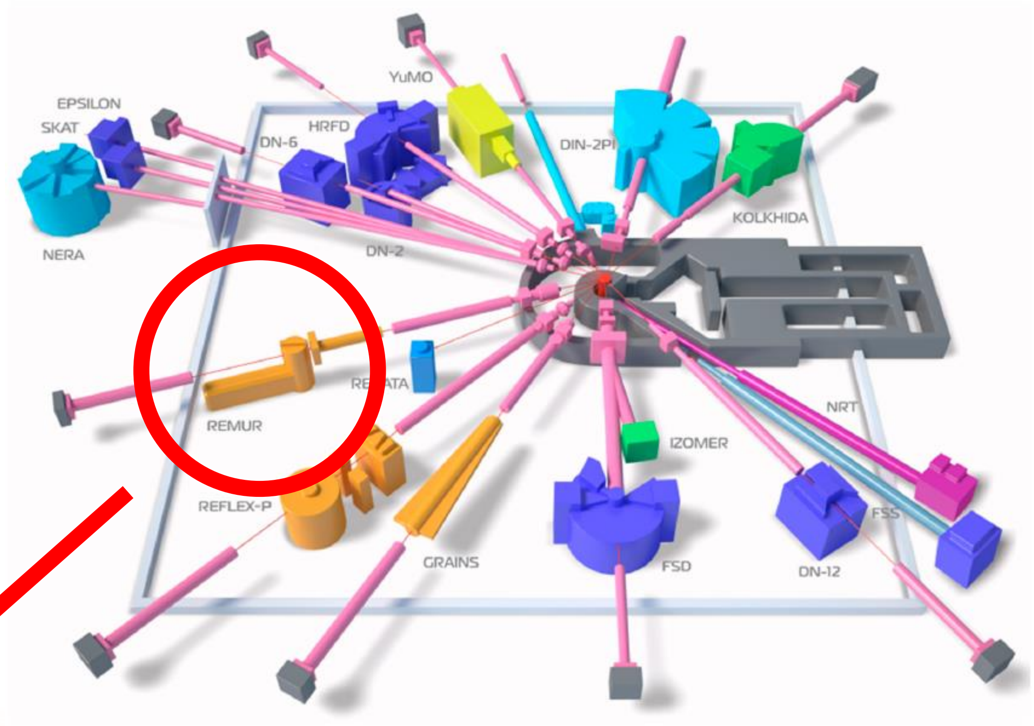


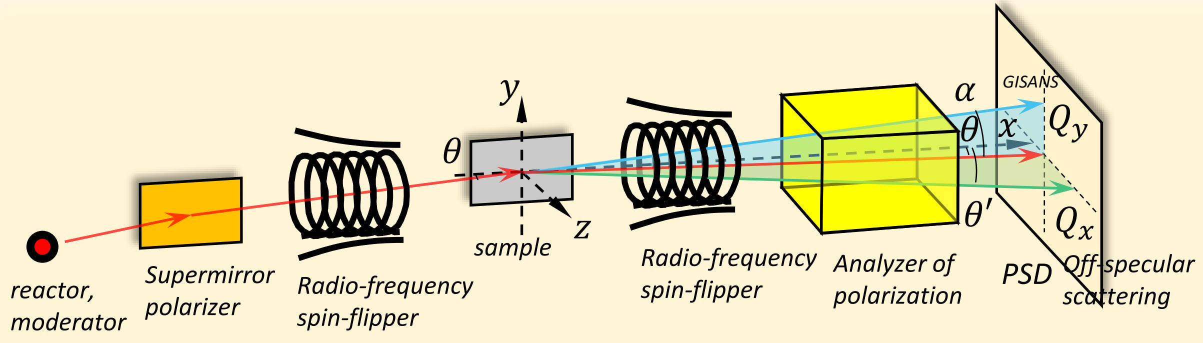
$$M_{i,j}(k_{z0}) \sim \int \frac{|\psi(z,k_{z0})|^2 \cdot Im(u)}{|\psi_0(k_{z0})|^2 \cdot k_0} N_i(z)dz$$

Reflectometer REMUR

Some options

- Sample plane - vertical
- Scattering plane - horizontal
- Neutron wavelength 0.9 – 15 Å
- Wavelength resolution δλ = 0.015 Å

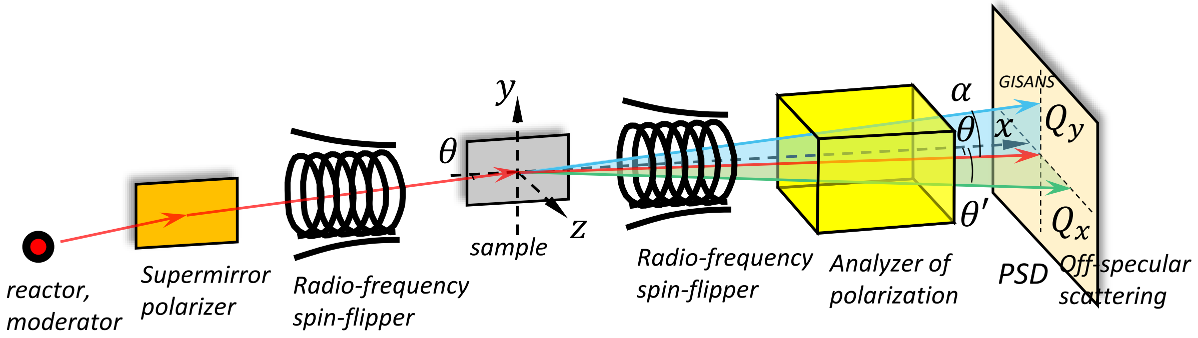




- Scattering angles range 1 – 100 mrad
- Sample-detector distance 0.7 – 4.9 m
- Resolution of PSD 2.5 mm

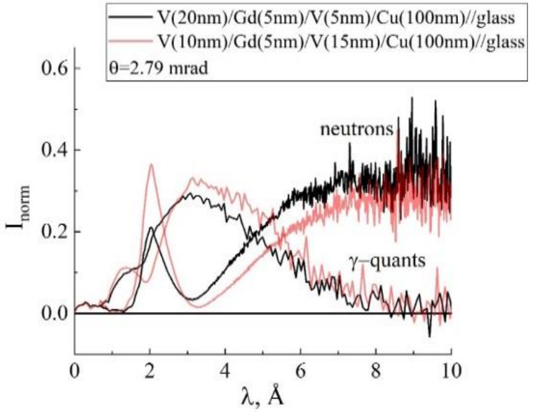
Secondary radiation registration at REMUR

Schema of the REMUR spectrometer at the IBR-2 reactor



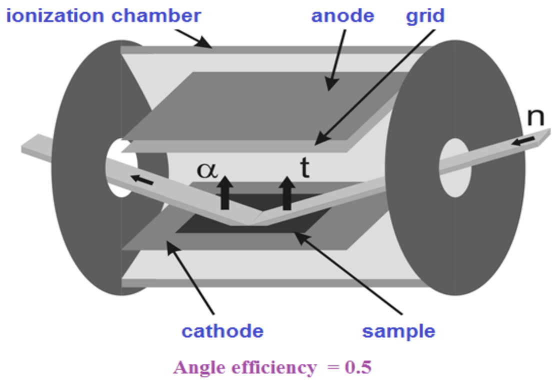
Gamma-quanta registration channel

Gamma-quanta registration channel and position of the sample

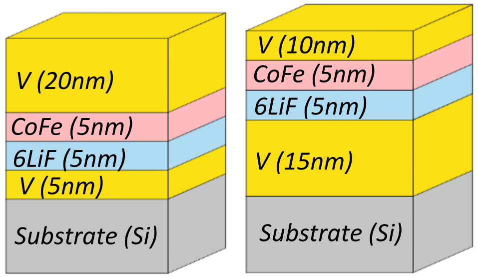


Neutron reflectivity and gamma-quanta spectra

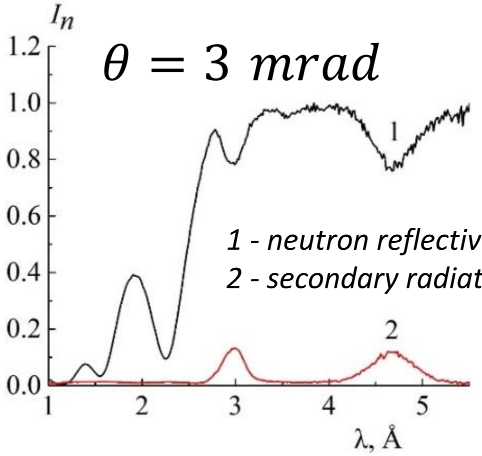
Charged particles and polarized neutrons registration channels



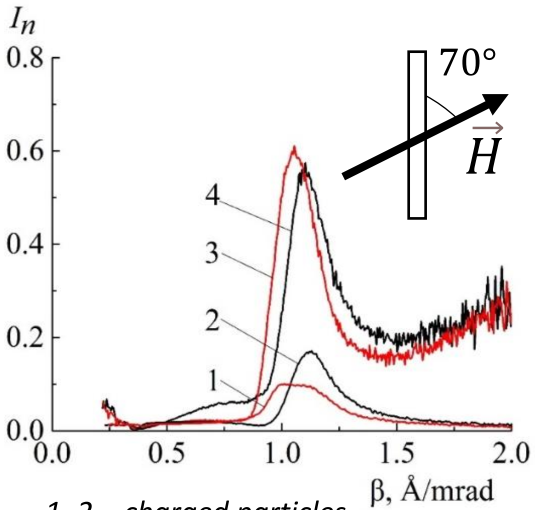
Measurements scheme



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



Neutron reflectivity and charged particles spectra

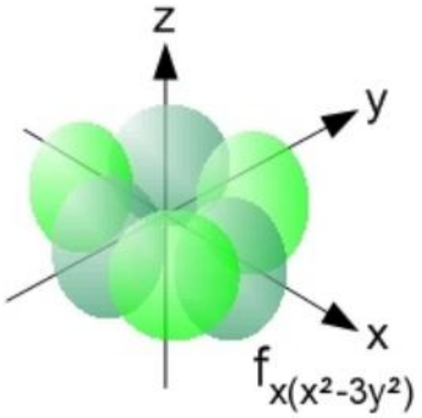


1, 2 – charged particles
3, 4 – spin-flip neutrons

Actinide heterostructures

Motivation

- *Nanograms of matter*
- *Low-dimensional effects*
- *Complex magnetism*
- *Superconductivity*
- *Coexistence of superconductivity and ferromagnetism*
- *Source of fission fragments and gamma quanta*

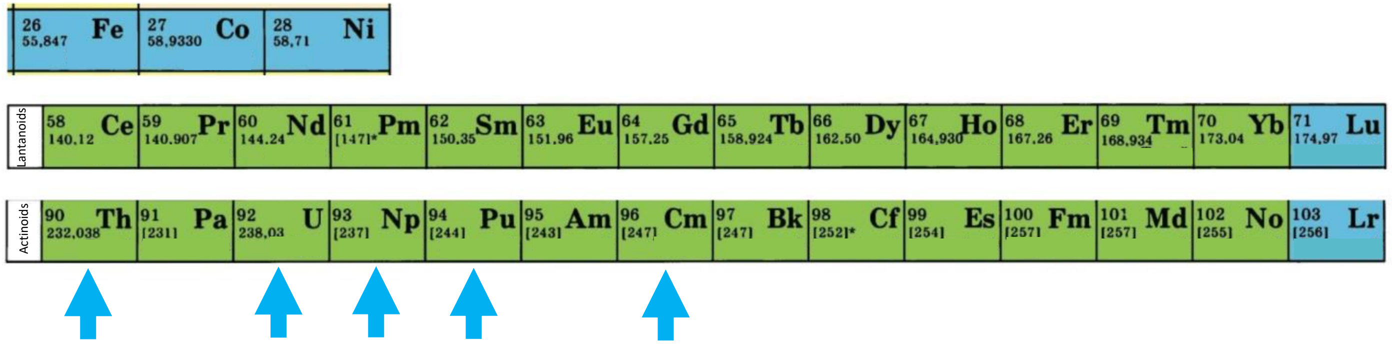


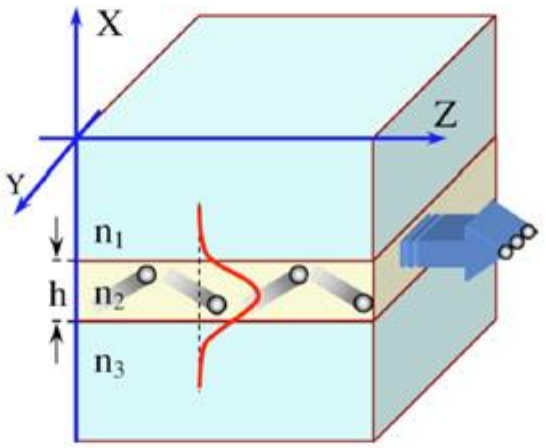
Ferromagnetism does not suppress the superconductivity with triplet pairing, hence, there is no reason for the formation of a cryptomagnetic state. Indeed, no traces of a space modulation of magnetic moments directions on the scale smaller than the coherence length has been revealed [4, 10–12]. On the other hand, the neutron depolarization measurements on UGe_2 down to 4.2 K (that is in the ferromagnet but not superconducting region) establish, that the magnetic moment strictly aligned along the *a*-axis, with a typical domain size in the *bc*-plane of the order 4.4×10^{-4} cm [13] that is about two orders of magnitude larger than the largest superconducting coherence length in the *b*-direction $\xi_b \approx 7\times10^{-6}$ cm. Similar size of domains has been recently measured in UCoGe.[14]

V.P. Mineev. Superconductivity in uranium ferromagnets // Uspekhi fizicheskikh nauk, vol. 187, no. 2

Tasks

- *Targets for the synthesis of superheavy elements*
- *Search for cryptoferromagnetism in uranium superconducting ferromagnets*
- *Uranium thin-film waveguides*





S.P. Pogossian. Enhanced neutron concentration in uranium thin film waveguides // Journal of Applied Physics 102, 104501 (2007)

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. Diamagnetism of a periodic ferromagnetic-superconducting structure [Nb/Gd] was investigated. Rare-earth elements perspective for investigation of proximity effects at SF heterostructures.
3. At the structure Al_2O_3//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.
4. 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. At the moment, the following values have been achieved for a layer with a thickness of 5 nm: for the channel of charged particles σ_{min} = 0.025 barn (22 isotopes), for the channel of gamma quanta σ_{min} = 0. 3 barn (> 100 isotopes), for magnetic elements B_{min} = 1 Gs (Fe, Co, Ni, Gd, Dy, Tb, Ho, Er, Tm)

Thank you for your attention!