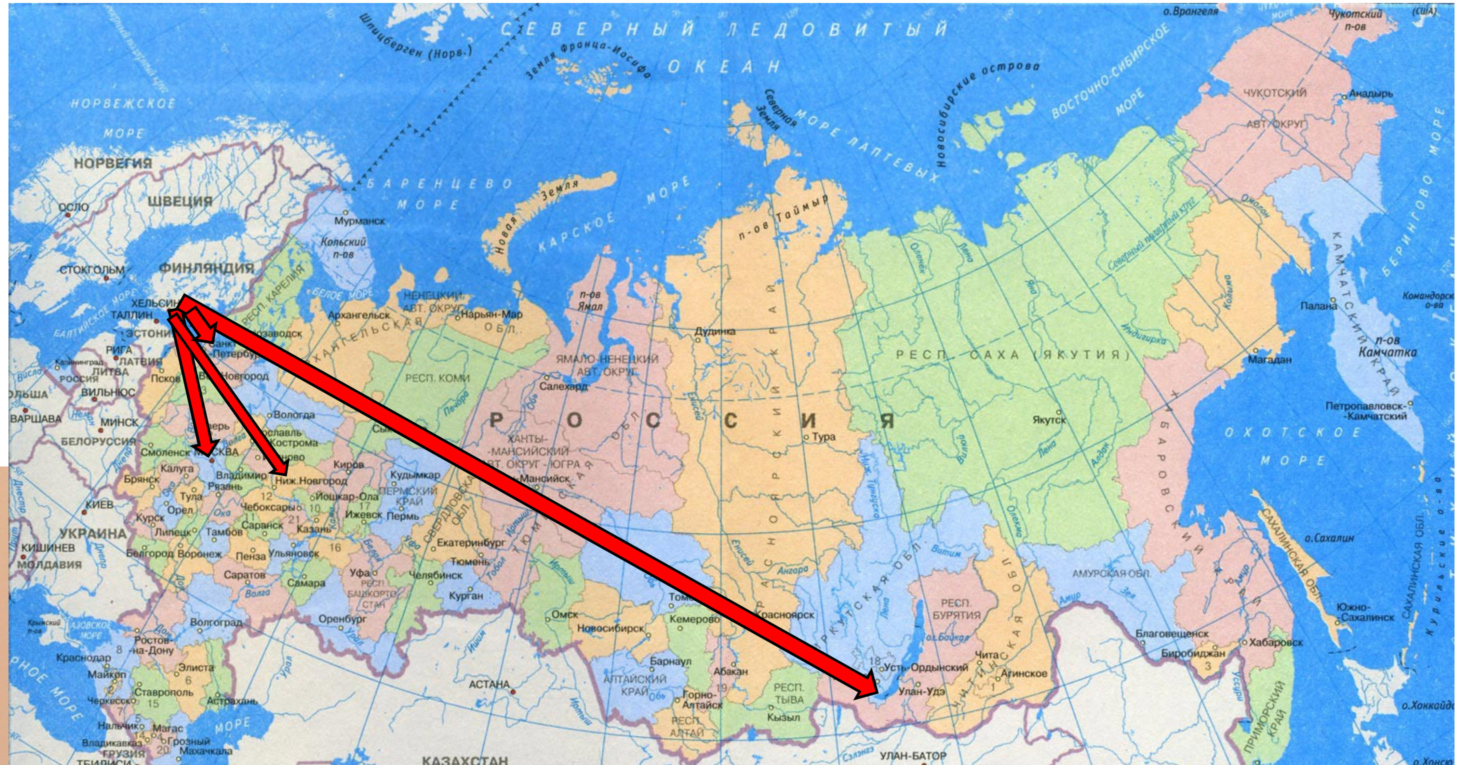
Jukka in Russia



Happy birthday!

ELECTROMAGNETIC PROXIMITY EFFECT IN PLANAR SUPERCONDUCTOR-FERROMAGNET STRUCTURES

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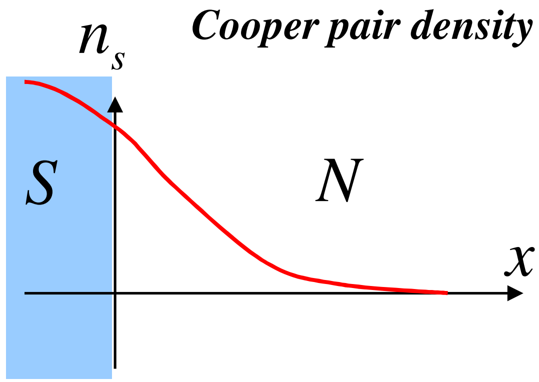
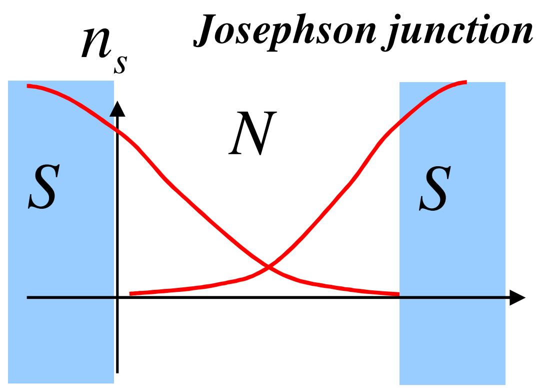
Outline

- **Proximity effect and inverse proximity effect in SF systems**
- **Spread of the stray magnetic field in SF bilayer**
- **Role of the vector potential.**
- **Electromagnetic proximity effect in dirty and clean limits.**
- **Discussion of some experiments**

Proximity effect.





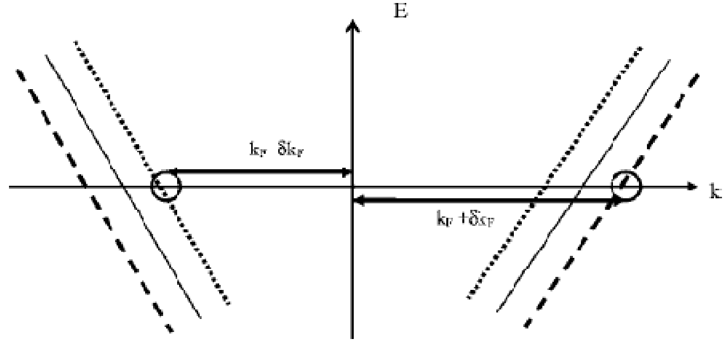
Proximity effect in FS structures.

$$\delta\hat{H} = \vec{h}\,\hat{\vec{\sigma}}$$

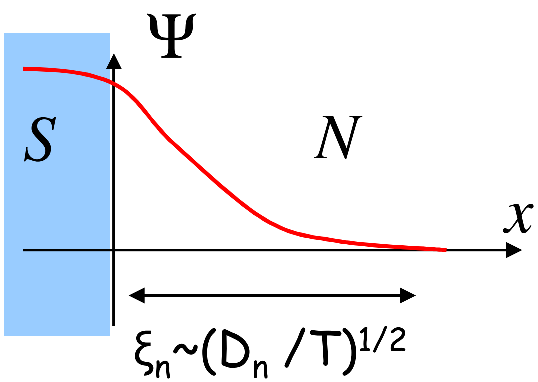
h= exchange energy

Inhomogeneous superconductivity induced by the exchange field:

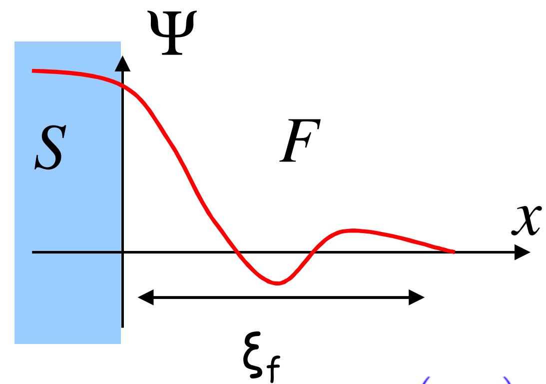
1. FFLO state



2. Interference effects for Cooper pairs in FS layered structures



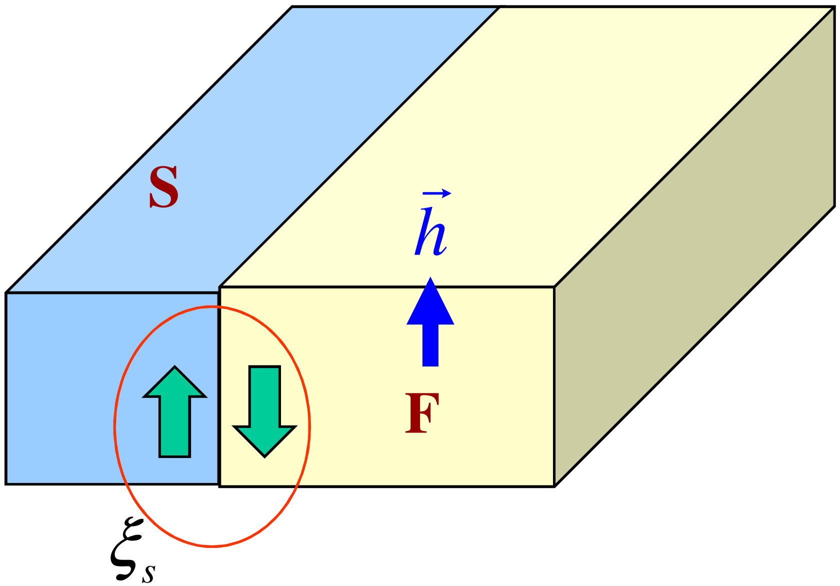
Damped oscillatory dependence of pair wave function in ferromagnets



$$\Psi \sim \Delta \exp\left(-\frac{x}{\xi_f}\right)\cos\left(\frac{x}{\xi_f}\right)$$

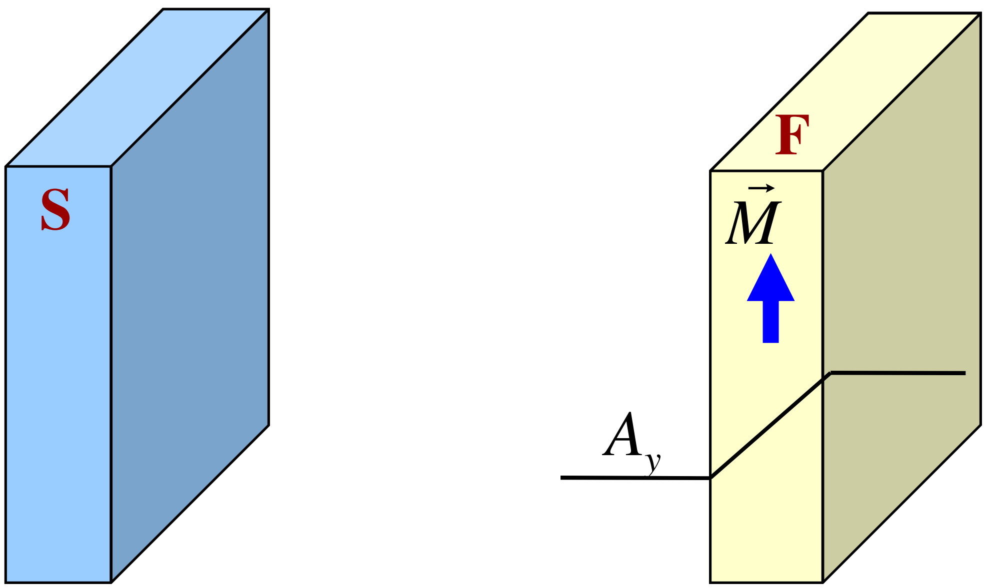
in dirty limit: $\xi_f = \sqrt{\frac{D_f}{h}}$

Inverse proximity effect in S/F bilayers.
Electron spin polarization near the surface.

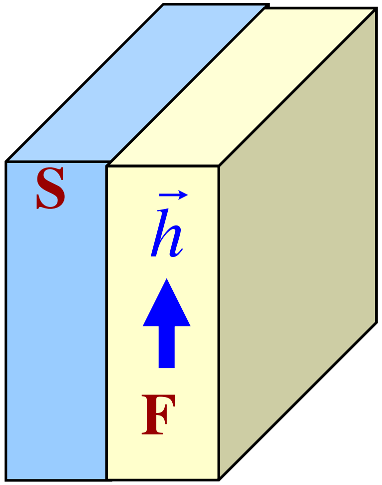


Bergeret, F. S., Volkov, A. F. & Efetov, K. B. Induced ferromagnetism due to superconductivity in superconductor-ferromagnet structures. *Phys. Rev. B* **69**, 174504 (2004).

Electromagnetic proximity effect in S/F bilayers. Aharonov-Bohm effect?



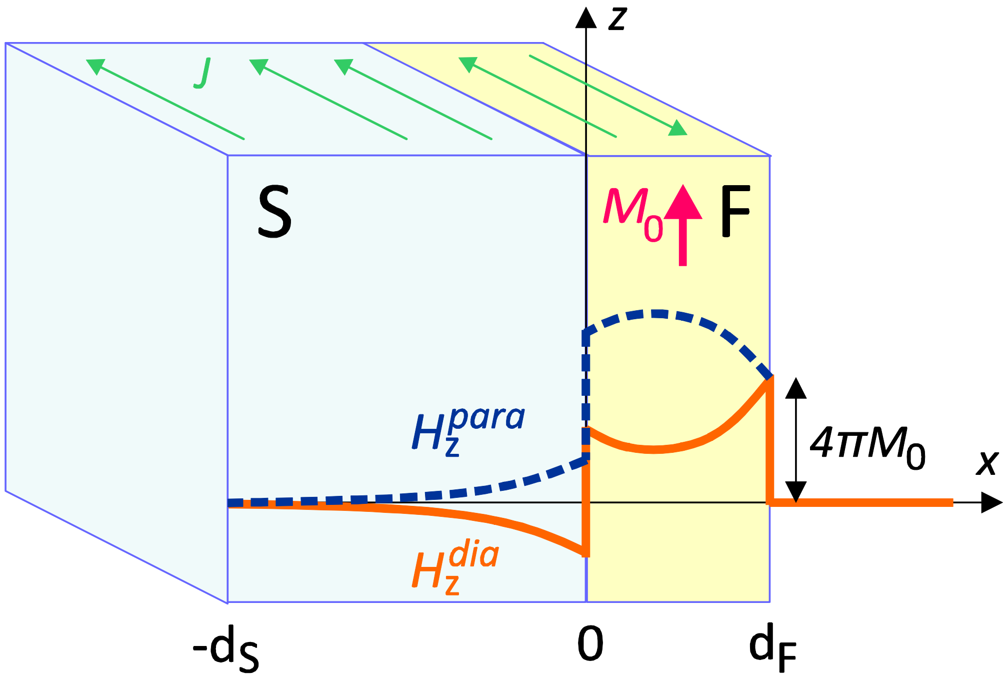
Can the magnetic field (not just vector potential !) escape from ferromagnet to superconductor at large distances?



London equation

$$\vec{j} = -\frac{e^2 n_s}{mc}\vec{A}$$

Spontaneous currents in S/F bilayers. Electromagnetic proximity effect.



$$\mathrm{rot}\ \mathrm{rot}\,\mathbf{A} = \frac{4\pi}{c}(\mathbf{j}_s + \mathbf{j}_m)$$

$$\mathbf{j}_s(x) = -\frac{c}{4\pi}\frac{1}{\lambda^2(x)}\mathbf{A}(x)$$

$$A_y(x) = A_0 \exp(x/\lambda_0)$$

$$A_y(x) = A_0 + 4\pi M_0 x$$

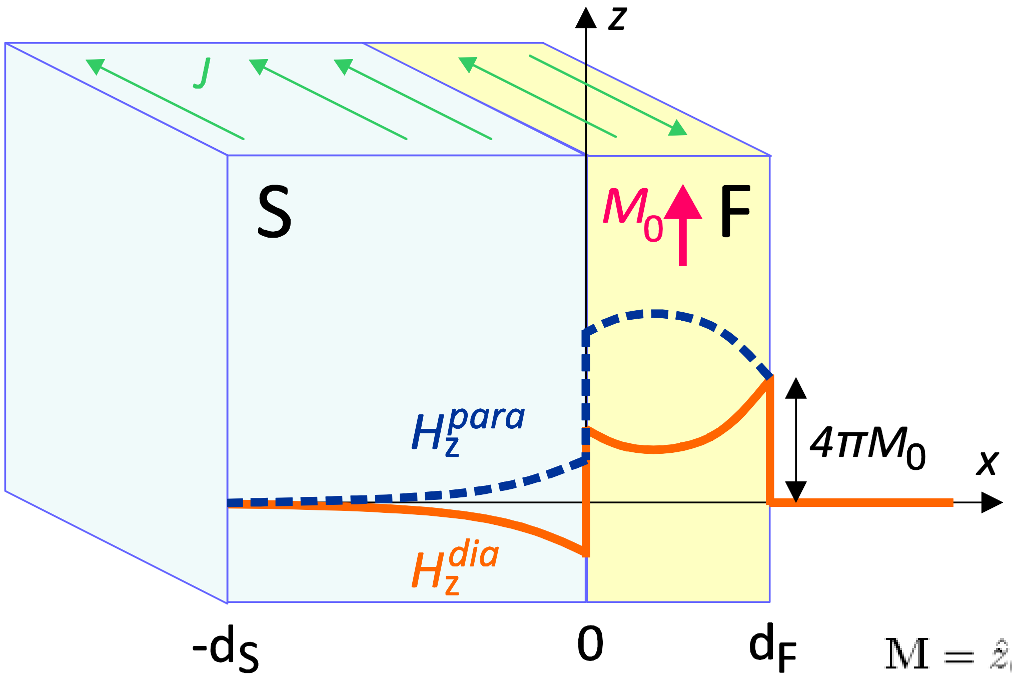
$$B_z = -4\pi M_0 Q \exp(x/\lambda_0)$$

$$B_z(d_f) - B_z(0) = A_0 \int_0^{d_f} \frac{dx'}{\lambda^2(x')} + 4\pi M_0 \int_0^{d_f} \frac{x' dx'}{\lambda^2(x')}$$

$$Q = \int_0^{d_f} \lambda^{-2}(x') x' dx'$$

$$Q \sim (\xi_f/\lambda)^2 \sim 10^{-2}$$

Spontaneous currents in S/F bilayers.
Electromagnetic proximity effect.



$$\mathrm{rot}\ \mathrm{rot}\,\mathbf{A} = \frac{4\pi}{c}\left(\mathbf{j}_s + \mathbf{j}_m + \mathbf{j}_{surf}\right)$$

$$\mathbf{M} = \hat{z}_0 M_0 d_f \delta(x), \quad \mathbf{j}_{surf} = -\frac{c}{4\pi}\int_{-\infty}^{d_f} \mathbf{A}(x')R(x')dx'\delta(x).$$

$$\mathbf{j}_{surf} = -\hat{\mathbf{y}}_0 \frac{c}{4\pi}\delta(x)\left(A_0 P + 4\pi M_0 Q\right),$$

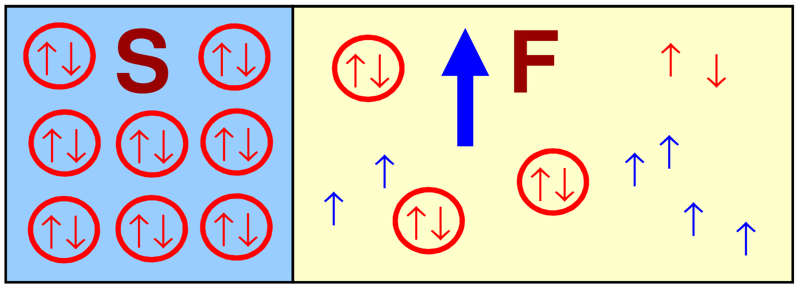
$$m_s = \int_{-d_s}^{0} \frac{B_z}{4\pi}dx = -M_0 Q\lambda \tanh\left(\frac{d_s}{2\lambda}\right)$$

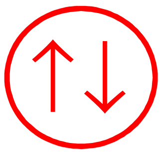
$$P = \int_{-\infty}^{d_f} R(x')dx', \quad Q = \int_{0}^{d_f} x'R(x')dx'.$$

$$B_z = -\frac{4\pi M_0 Q}{\sinh\left(d_s/\lambda\right)}\sinh\left(\frac{x+d_s}{\lambda}\right)$$

Proximity effect in S/F systems

Exchange field (energy) in the ferromagnet: $\hat{H} = \ldots + \vec{h}\,\hat{\vec{\sigma}}$





$\uparrow\downarrow$ **Cooper pairs**

$\uparrow\uparrow$ **exchange field**

Singlet: $\uparrow\downarrow - \downarrow\uparrow$

$S = 0$

Triplet:

$S = 1$

$\uparrow\downarrow + \downarrow\uparrow \quad S_z = 0$

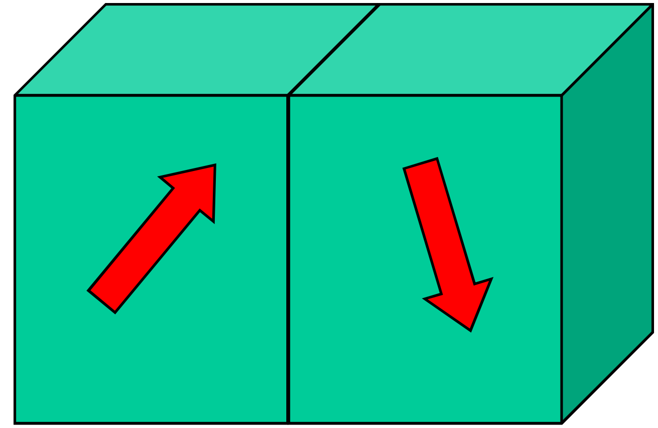
$\uparrow\uparrow$

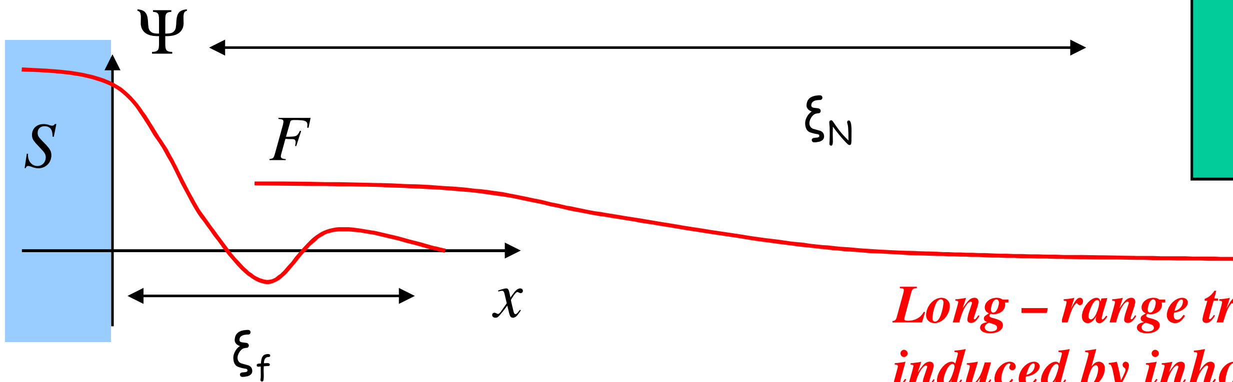
$\downarrow\downarrow \quad S_z = \pm 1$

Long – range triplet proximity effect in dirty SF systems

Bergeret – Volkov – Efetov (2001)

Kadigrobov- Shekhter- Jonson (2001)

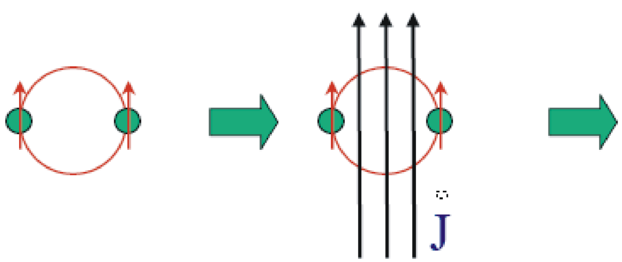




Long – range triplet component induced by inhomogeneous exchange field

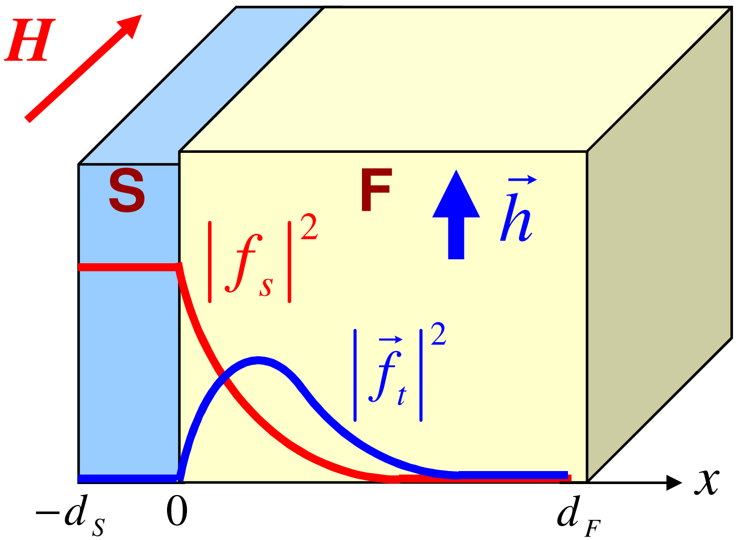
$$\left(\frac{D}{2}\nabla^2 - \omega_n\right) f_s = -\mathbf{h}\mathbf{f}_t$$

$$\left(\frac{D}{2}\nabla^2 - \omega_n\right) \mathbf{f}_t = \mathbf{h} f_s$$



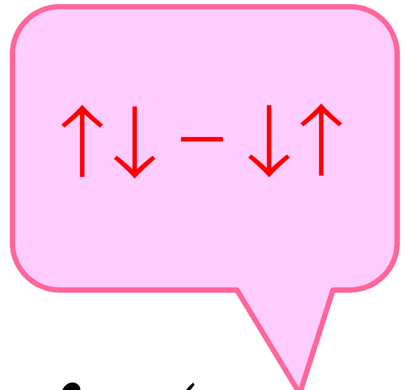
Exchange field does not destroy triplet Cooper pairs

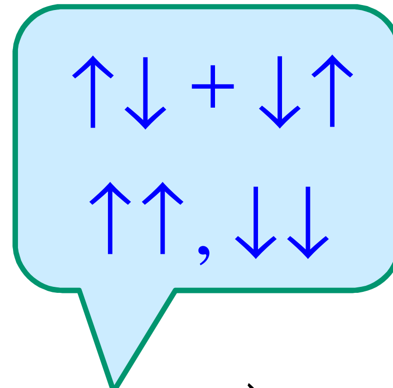
Paramagnetic Meissner effect in dirty S/F bilayers



$$\vec{j} = -\frac{1}{4\pi}\lambda^{-2}\vec{A}$$

$$\hat{f} = \left(f_s + \vec{f}_t\hat{\vec{\sigma}}\right)i\hat{\sigma}_y$$





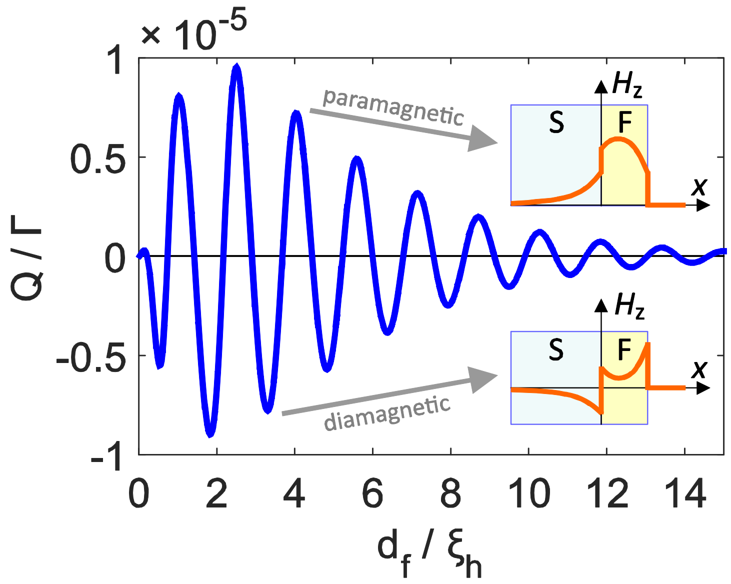
$$\lambda^{-2} = \frac{16\pi^2 T_c}{d_0}\sum_{n=0}^{\infty}\int \sigma\left(|f_s|^2 - |\vec{f}_t|^2\right)dx$$

$$|\vec{f}_t|^2 > |f_s|^2 \Rightarrow \lambda^{-2}(x) < 0$$

Local paramagnetic response

Can the superfluid density change its sign?

Meissner effect in clean S/F bilayers



$$\mathbf{j}_s(x) = -\frac{c}{4\pi}\int \mathbf{A}(x')K(x,x')dx'$$

$$Q = \int_{-x_0}^{d_f} dx \int_0^{d_f} dx' x' \left[K(x,x') - \lambda_0^{-2}\delta(x-x')\theta(-x)\right]$$

$$Q = \Gamma\left(\frac{Td_f}{\hbar v_F}\right)^2 \mathrm{Re}\sum_{\omega>0}\frac{T}{\Omega}\left\langle \frac{v_y^2}{v_F^2}\frac{1+kd_f}{\cosh^2(pd_f+\chi)}\right\rangle$$

where $\Omega = \sqrt{\omega^2+\Delta^2}$, $\sinh\chi = \omega/\Delta$, $k = 2\Omega/\hbar|v_x|$, $p = 2(\omega+ih)/\hbar|v_x|$
$\Gamma = 8\pi^2 e^2\nu_0\hbar^2 v_F^4/(c^2T^2)$.

Effect of misalignment of magnetic moments

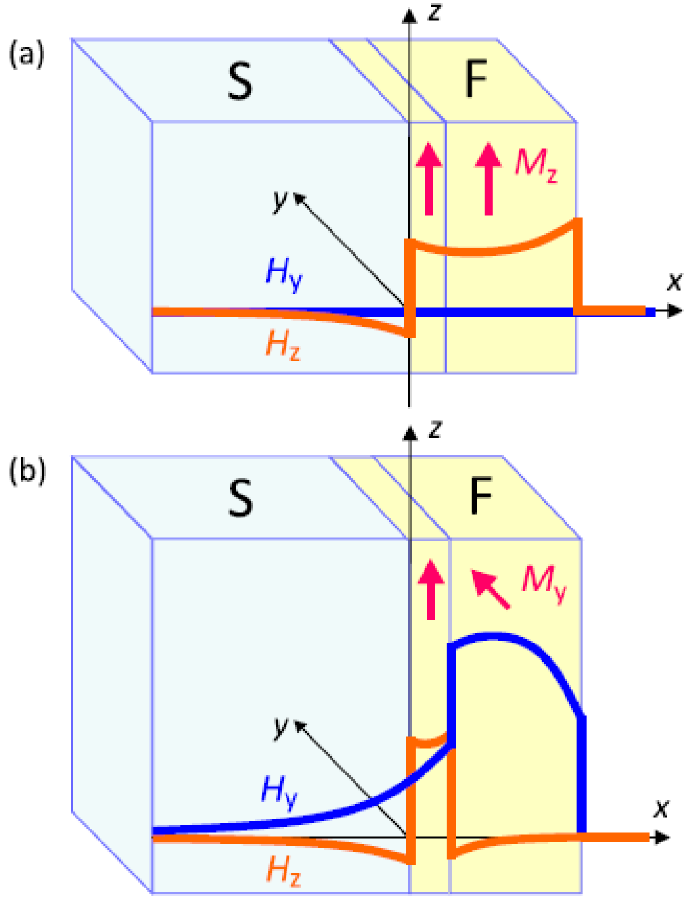


FIG. 3. The profiles of the spontaneous magnetic field in the superconductor-ferromagnet-ferromagnet trilayer when the magnetic moments in the two F layers are (a) parallel to each other and (b) perpendicular to each other.

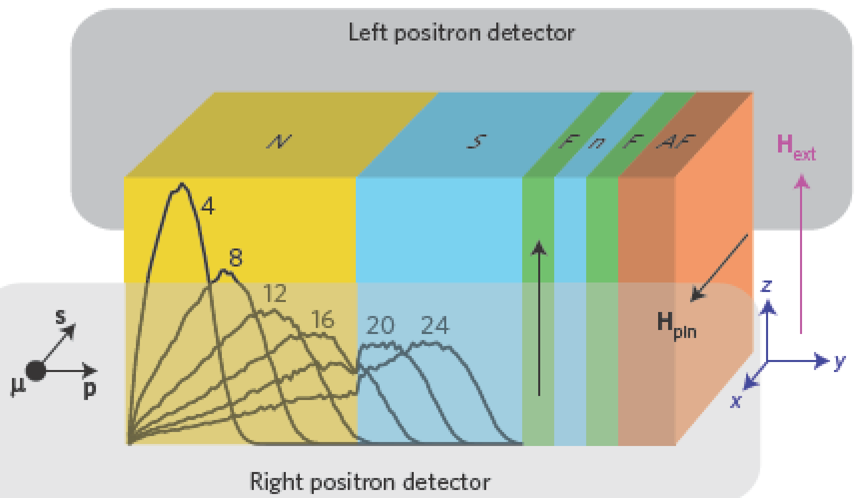
nature physics

LETTERS

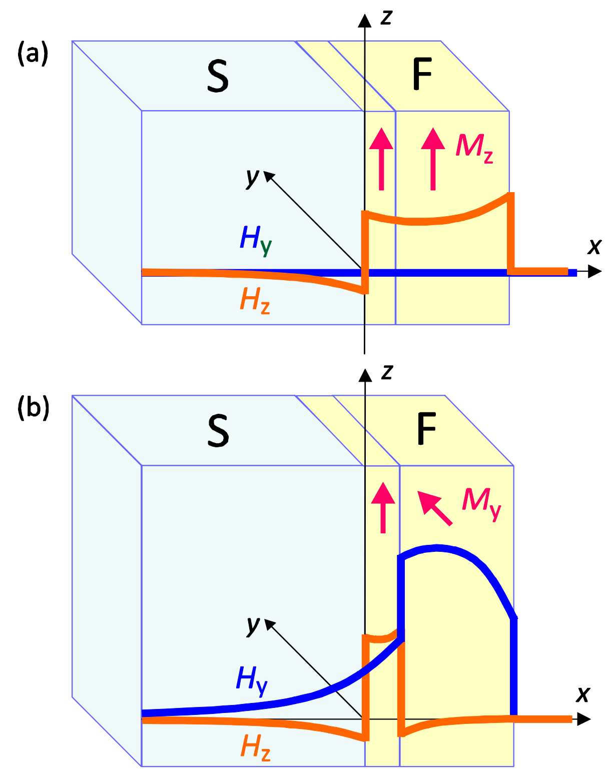
PUBLISHED ONLINE: 5 OCTOBER 2015 | DOI: 10.1038/NPHYS3486

Remotely induced magnetism in a normal metal using a superconducting spin-valve

M. G. Flokstra[1]*, N. Satchell[2], J. Kim[2], G. Burnell[2], P. J. Curran[3], S. J. Bending[3], J. F. K. Cooper[4], C. J. Kinane[4], S. Langridge[4], A. Isidori[5], N. Pugach[5,6], M. Eschrig[5], H. Luetkens[7], A. Suter[7], T. Prokscha[7] and S. L. Lee[1]



Evidence for the long-range triplet component



For our experiments we use superconducting spin-valve structures Au(x)/Nb(50)/Co(2.4)/Nb(3)/Co(1.2)/IrMn(4)/Co(3)/Ta(7.5)/Si-substrate with numbers indicating the layer thicknesses in nm and $x = 5$ or 70. They consist of an S/F interface with an

PHYSICAL REVIEW LETTERS **120,** 247001 (2018)

Editors' Suggestion

Observation of Anomalous Meissner Screening in Cu/Nb and Cu/Nb/Co Thin Films

M. G. Flokstra,[1,*] R. Stewart,[1] N. Satchell,[2] G. Burnell,[3] H. Luetkens,[4] T. Prokscha,[4]
A. Suter,[4] E. Morenzoni,[4] S. Langridge,[2] and S. L. Lee[1]

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(Received 3 March 2018; published 14 June 2018)

Pis'ma v ZhETF, vol. 98, iss. 2, pp. 116 – 120

On the feasibility to study inverse proximity effect in a single S/F bilayer by polarized neutron reflectometry

Yu. N. Khaydukov[a,b1)], *B. Nagy*[c], *J.-H. Kim*[b], *T. Keller*[b], *A. Rühm*[d], *Yu. V. Nikitenko*[e], *K. N. Zhernenkov*[f], *J. Stahn*[g], *L. F. Kiss*[c], *A. Csik*[h], *L. Bottyán*[c], *V. L. Aksenov*[a,e,i]

V(40 nm)/Fe(1 nm)

ЖЭТФ, 2016, том 149, вып. 4, стр. 852–863

МАГНИТНЫЙ ЭФФЕКТ БЛИЗОСТИ НА ГРАНИЦЕ КУПРАТНОГО СВЕРХПРОВОДНИКА С ОКСИДНЫМ СПИНОВЫМ КЛАПАНОМ

Г. А. Овсянников [a,b*], *В. В. Демидов* [a], *Ю. Н. Хайдуков* [c,d], *Л. Мустафа* [c],
К. И. Константинян [a], *А. В. Калабухов* [b,d], *Д. Винклер* [b]

ISSN 1063-7745, Crystallography Reports, 2007, Vol. 52, No. 3, pp. 381–386. © Pleiades Publishing, Inc., 2007.
Original Russian Text © V.L. Aksenov, Yu.V. Nikitenko, A.V. Petrenko, V.M. Uzdin, Yu.N. Khaidukov, H. Zabel, 2007, published in Kristallografiya, 2007, Vol. 52, No. 3, pp. 403–409.

MAGNETISM AND STRONGLY CORRELATED ELECTRONIC SYSTEMS

Features of the Magnetic State of the Layered Fe–V Nanostructure of the Superconductor–Ferromagnet Type

V. L. Aksenov[a, b], Yu. V. Nikitenko[b], A. V. Petrenko[b], V. M. Uzdin[c], Yu. N. Khaidukov[b], and H. Zabel[d]

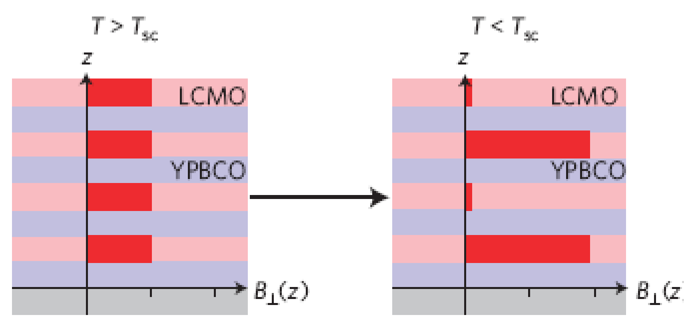
nature materials

LETTERS

PUBLISHED ONLINE: 15 FEBRUARY 2009 | DOI: 10.1038/NMAT2383

Giant superconductivity-induced modulation of the ferromagnetic magnetization in a cuprate–manganite superlattice

J. Hoppler[1,2], J. Stahn[2]*, Ch. Niedermayer[2], V. K. Malik[1], H. Bouyanfif[1†], A. J. Drew[1†], M. Rössle[1], A. Buzdin[3], G. Cristiani[4], H.-U. Habermeier[4], B. Keimer[4] and C. Bernhard[1]*



Josephson-type experiment to observe electromagnetic proximity effect

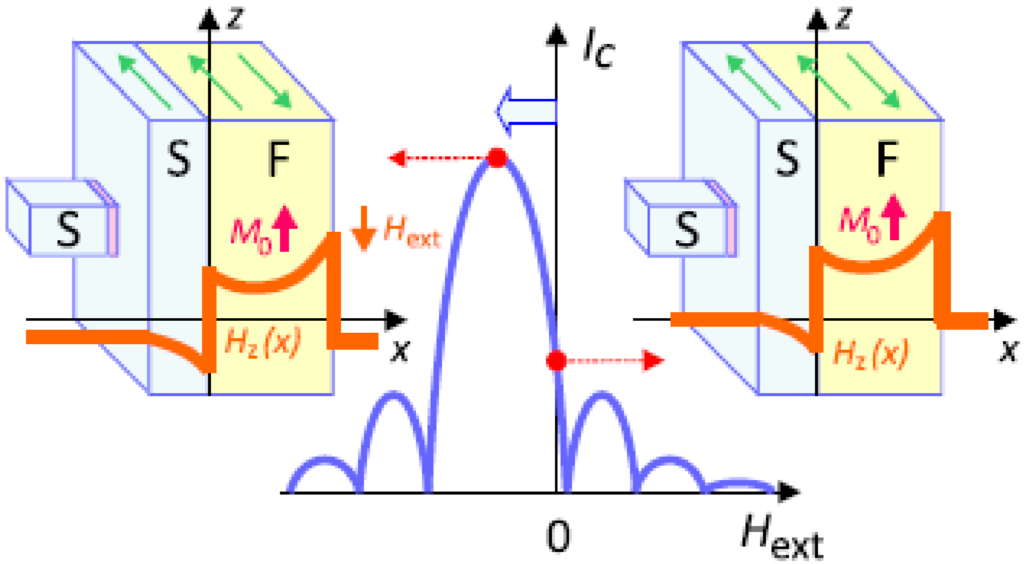
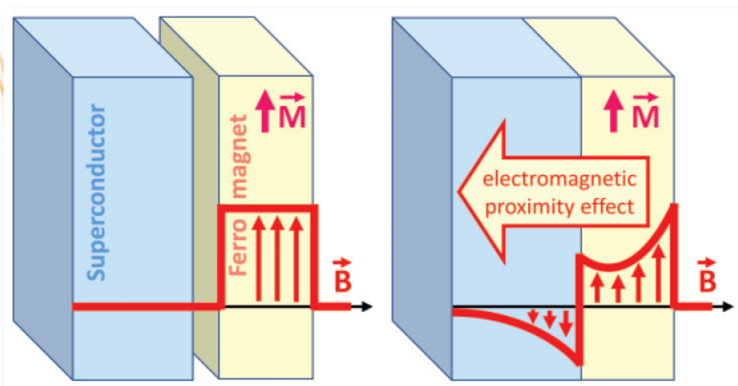


FIG. 4. Shift in the Fraunhofer critical current oscillations for the Josephson junction with one electrode being covered by the ferromagnetic layer.

9 July 2018 Volume 113 Number 2

Applied Physics Letters



Electromagnetic proximity effect in planar superconductor-ferromagnet structures

DOI: 10.1063/1.5037074

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