Odd triplet superconductivity in superconductor-ferromagnet structures.

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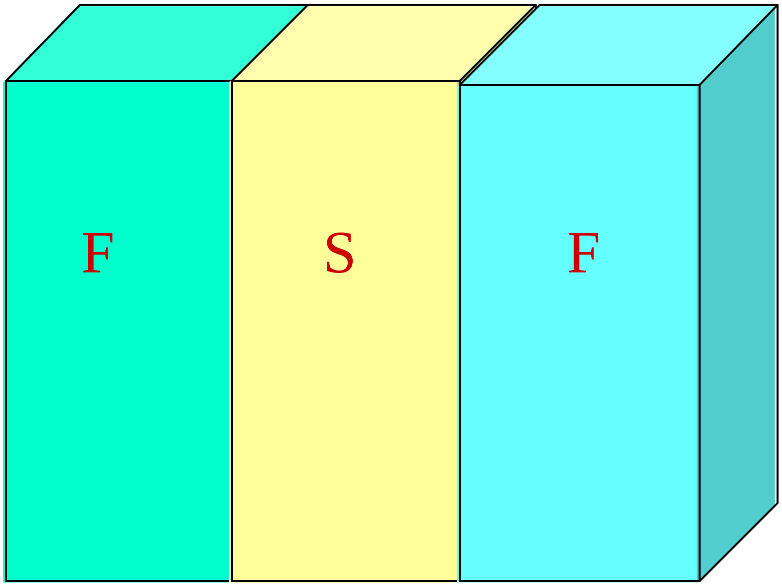
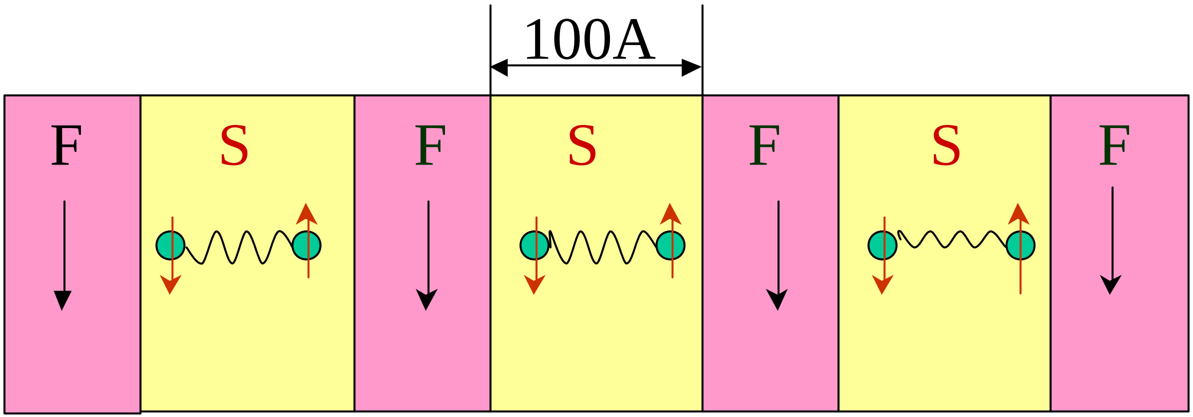


S-superconductor, F-ferromagnet

Common knowledge:
Exchange field destroys superconductivity. (?)

Superconductor-Ferromagnet multilayers



$$T_K = 1000K$$

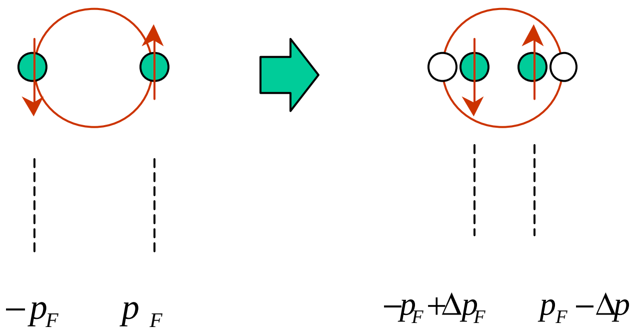
$$T_C = 1-10K$$

Due to proximity effects the superconductor and the ferromagnet act on each other!

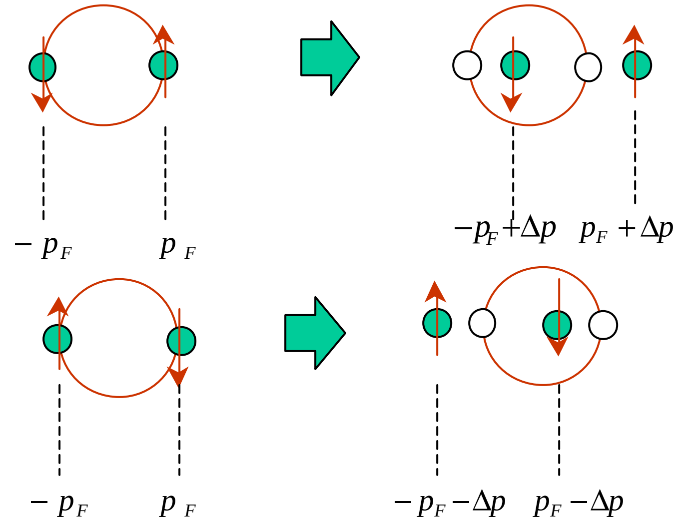
Zeeman splitting is most important. Effect of the magnetic field on the orbital motion is neglected.

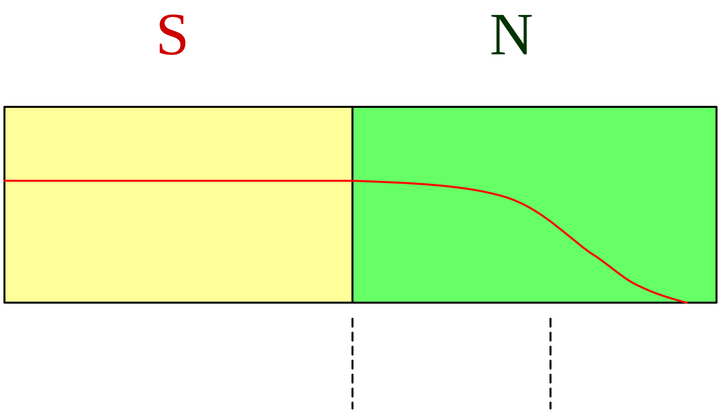
No chance for Cooper pairs to penetrate the ferromagnet.(?)

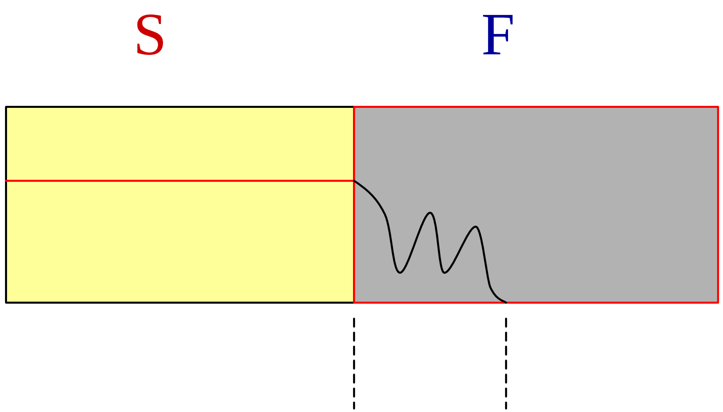
Superconductor/Normal Metal



Superconductor/Ferromagnet







$$x_T = \sqrt{D/2pT}$$

$$x_T \geq x_J$$

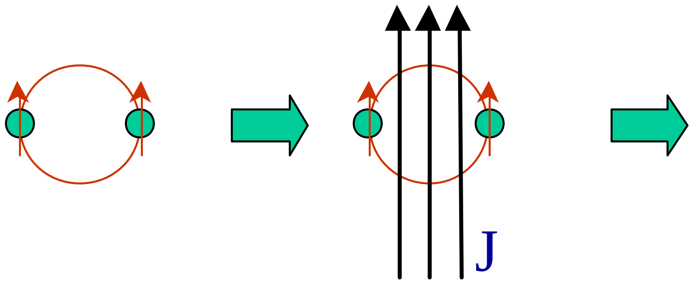
$$x_J = \sqrt{D/J}$$

T-Temperature

J-Exchange energy

Q. Can the superconducting condensate penetrate the ferromagnet over distances exceeding ξ_J or it is absolutely impossible?

A. It can if it is a triplet one.



No destruction of Cooper pairs: everything is as in a normal metal!

How to get a triplet condensate?

It can be generated "by hand" making the magnetization of different layers non-collinear to each other!

Known types of superconductivity in nature:

1. Singlet s-wave pairing (conventional, observed in traditional superconductors).
2. Triplet p-pairing (superfluid He^3, Sr_2RuO_4)
3. Singlet d-pairing (high T_c cuprates)

Triplet pairing has been possible because the condensate function F_t is odd in momentum $\Longrightarrow$ no contradiction with Pauli principle.

$$F(r,t;r',t') = < \Psi_\uparrow(r,t)\Psi_\uparrow(r',t') >$$

$$\Delta(r,r';t) = V(r-r')F(r,t;r',t)$$

The function $\Delta(r,r',t)$ vanishes at coinciding coordinates and times.

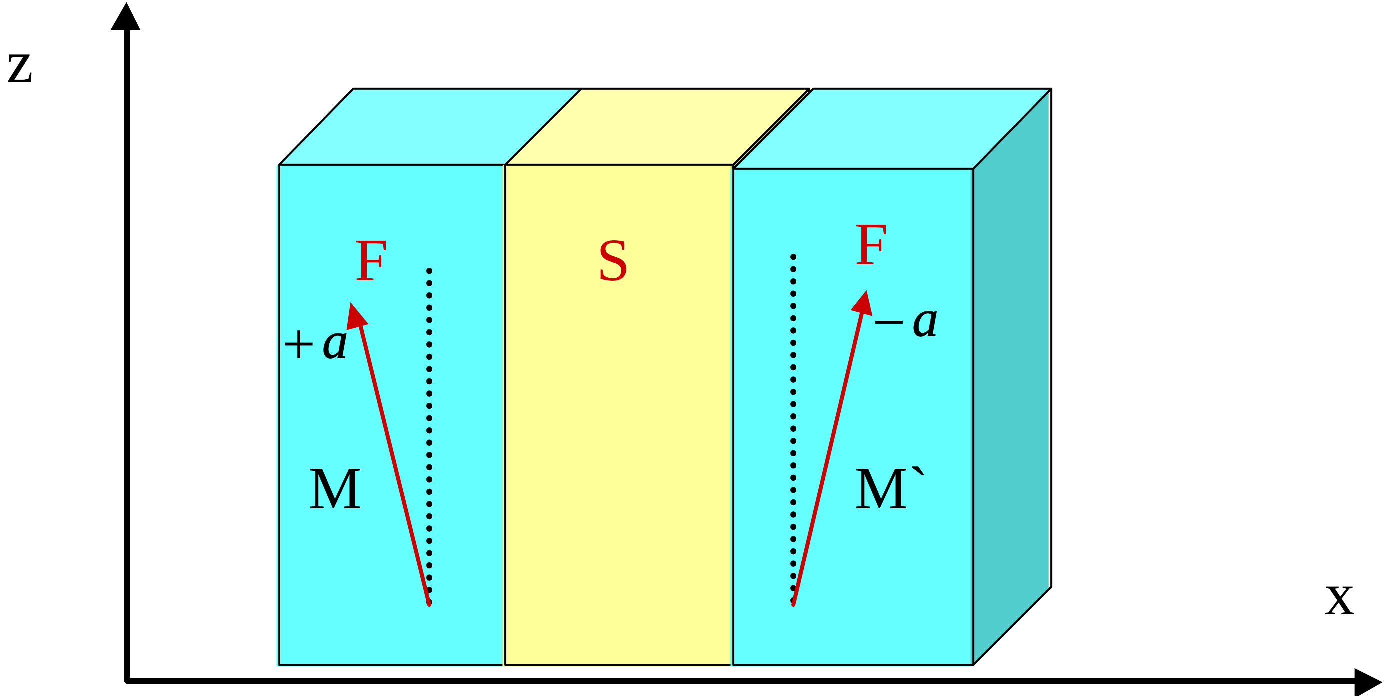
However, another proposal:

V depends on time, $\Delta(r,r',t,t')$ is odd with respect to t $\rightleftarrows$ t\`(s-wave).

Berezinskii (1975), Balatskii, Abrahams (1992) (odd gap superconductivity).

Now: odd triplet condensate can be created in the ferromagnet (s-wave pairing, not sensitive to potential impurities). No gap, but superconductivity is possible!

Triplet condensate (the simplest structure)



M and **M`** are not collinear ($+a$ and $-a$)

Model:

$$H = H_{BSC} + H_Z$$

$$H_{BCS} = \int \left(\sum_{a=\uparrow,\downarrow} y_a^+(\mathbf{r})\left(e(-i\nabla) - e_F\right) y_a(\mathbf{r}) - g y_\uparrow^+(\mathbf{r}) y_\downarrow^+(\mathbf{r}) y_\downarrow(\mathbf{r}) y_\uparrow(\mathbf{r}) \right) d\mathbf{r}$$

$$H_Z = -J \sum_{a=\uparrow,\downarrow} \int y_a^+(\mathbf{r}) \mathbf{m}\, \mathbf{s}_{ab} y_b(\mathbf{r})\, d\mathbf{r}$$

It is assumed that:
g>0, J=0 in the superconductor, g=0, J>0 in the ferromagnet, **m** is a unit vector directed along the magnetization.

In the main approximation one has the standard singlet coupling in the superonductor and no condensate in the ferromagnet.

However, proximity effects! Triplet component appears.

Method of quasiclassical (4x4) Green functions: in the limit $Jt \leq 1$ Usadel equation.

$$-D\nabla_{\mathbf{R}}(\hat{g}_0 \nabla_{\mathbf{R}} \hat{g}_0) + [(w\hat{r}_3 - i\hat{\Delta}(\mathbf{R}) + i\hat{V}_0(\mathbf{R})), \hat{g}_0(\mathbf{R}, w)] = 0$$

$$\hat{g}_0^2 = 1$$

D is the classical diffusion coefficient

Normal g and anomalous f 2x2 Green functions: equation in the ferromagnets

$$D\partial_X^2 \hat{f} - 2|w|\hat{f} + i\,\mathrm{sgn}(w)\left(\hat{f}\hat{V}^* - \hat{V}\hat{f}\right) = 0$$

$$\hat{V} = J\begin{pmatrix} \cos a & \pm i \sin a \\ \mp i \sin a & -\cos a \end{pmatrix}$$

Structure of the functions f:

$$f = i\hat{t}_2 (f_3(x)\hat{s}_3 + f_0(x)) + i\hat{t}_1\hat{s}_1 f_1(x)$$

s, t -Pauli matrices (spin, Nambu)

$$f_3 \propto \langle y_\uparrow y_\downarrow \rangle - \langle y_\downarrow y_\uparrow \rangle$$ -Singlet condensate

$$f_0 \propto \langle y_\uparrow y_\downarrow \rangle + \langle y_\downarrow y_\uparrow \rangle$$ -Triplet condensate (with projection 0 on z-axis)

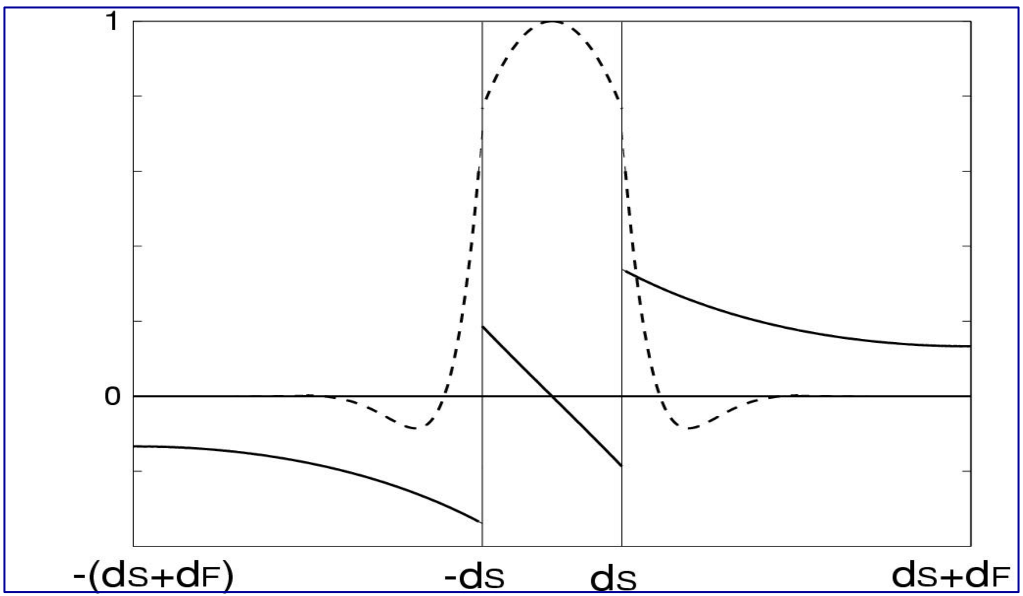
$$f_1 \propto \langle y_\uparrow y_\uparrow \rangle \propto \langle y_\downarrow y_\downarrow \rangle$$ -Triplet condensate (with projection +1,-1)

Properties of the triplet component:

1) The singlet component f_3 penetrates the ferromagnetic region over a short distance $x_J = \sqrt{D_F / J}$ (even function in w, symmetric in momentum).

2) f_0 and f_1 are odd functions of w (odd condensate!) and are symmetric functions in the momentum space. They penetrate the ferromagnetic region over a long distance $x_T = \sqrt{D_F / 2pT}$. At $J >> T$ long range penetration.

3) The maximum is achieved at $a = p / 4$. No contribution at $a = 0, p$.



Spatial dependence of Im(SC) (dashed line) and Re(TC) (solid line). Only the long range part of TC is represented (which is the reason for the discontinuity).

Local Density of States

Performing the measurement on the outer side of the ferromagnet ⇨ only the triplet component contributes.

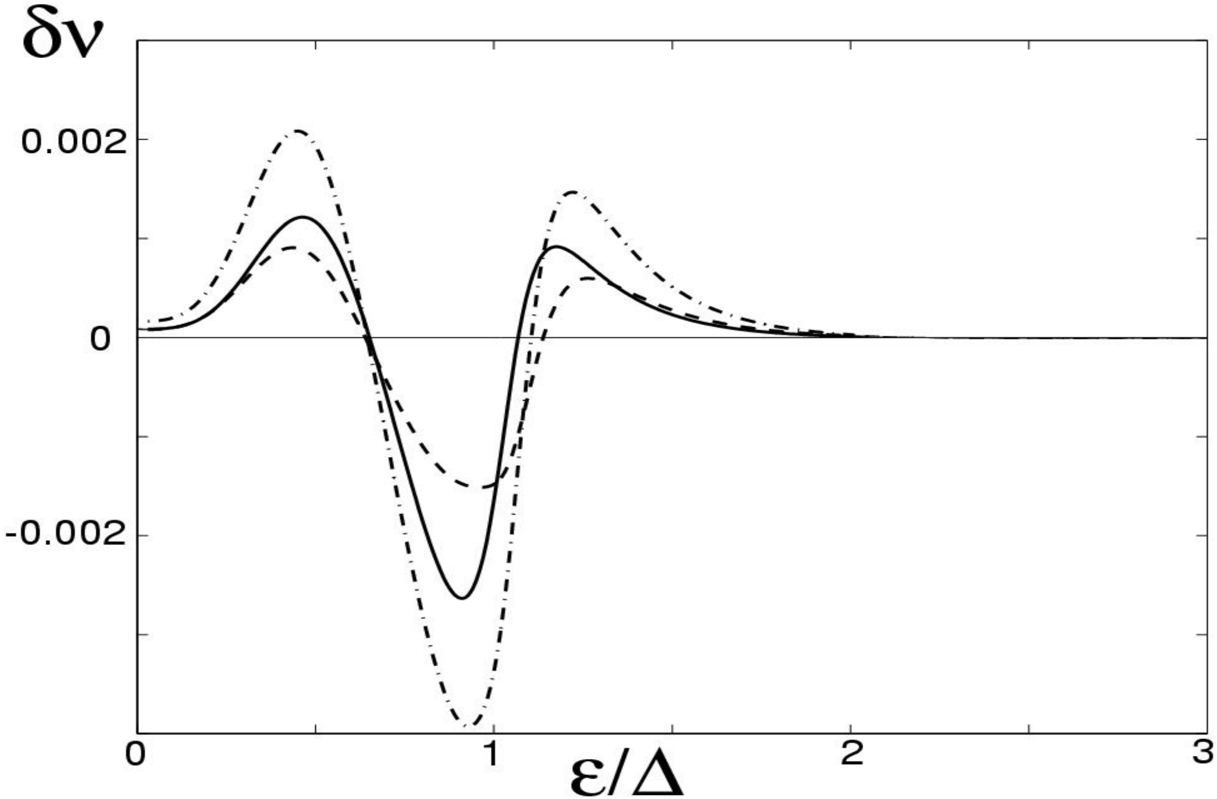
$$dn = \frac{1}{8} Tr(t_3(g_e^R(r,r) - g_e^A(r,r))$$

The condensate function f in the superconductor

$$f_S^R = \frac{\Delta}{\sqrt{(e + i\Gamma)^2 - \Delta^2}}$$

Γ -is a small damping

In the ferromagnet the deviation dn from the density of states of the normal metal is small!

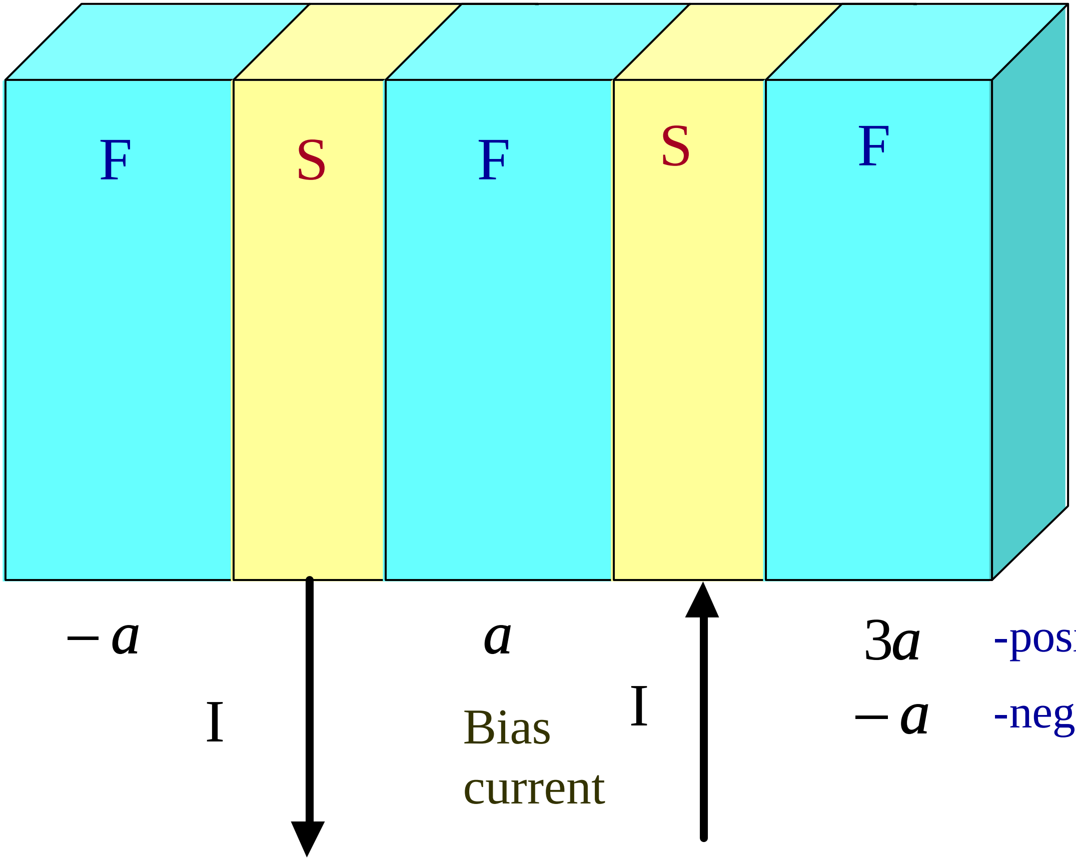


DOS at $d_F = x/2$ for $a = 3p/8$ (solid line), $a = p/8$ (dashed line), and $a = p/4$ (point-dashed line).

This value of DOS is small but can be measured!

Josephson current in a F/S/F/S/F structures.

Q. Can one have a supercurrent through a ferromagnet?
A. Josephson effect is possible!



$3a$ -positive chirality

$-a$ -negative chirality

$$\boxed{I = I_c \sin \varphi}$$

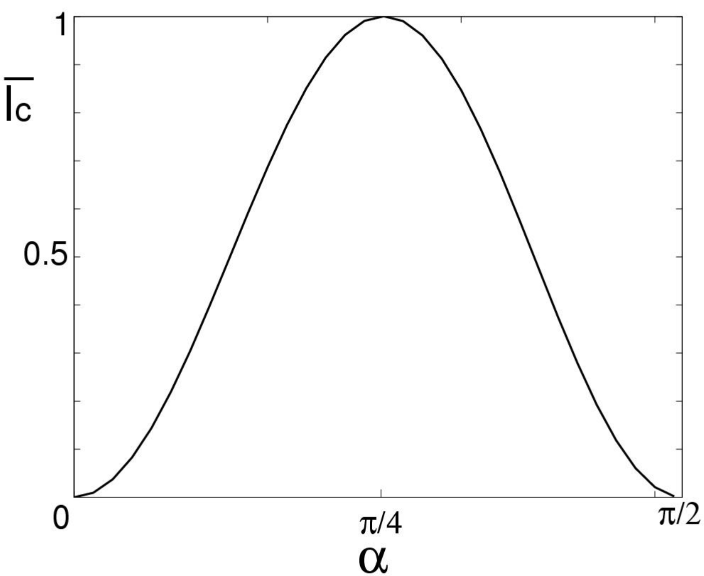
I_c -critical current

$$eR_F I_c = \pm 2\pi T \sum_{\omega} \frac{d_F b_1^2}{\xi_T} (1 + \tan^2 \alpha) \exp(-d_F / \xi_T)$$

b_1 -is the amplitude of the triplet condensate,

R_F -resistivity of the ferromagnetic layer.

``+`` positive chirality, ``-`` negative chirality (π -contact)



CONCLUSIONS

1. Non-homogeneous magnetization generates a triplet component of the superconducting condensate in superconductor-ferromagnet layers.

2. The triplet component is odd in frequency and even in momentum (odd superconductivity). It can penetrate the ferromagnet over long distances (like the singlet component penetrates a normal metal).

3. This is a s-wave pairing and the triplet component is not sensitive to conventional impurities.

4. The penetration of the superconducting condensate into the ferromagnet manifests in the Josephson effect and changes the local density of states.