Localized superconductivity and Little-Parks effect in superconductor/ferromagnet hybrids

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Outline

- **Introduction.**

Little-Parks effect. Switching between the vortex states.
Motivation: experimental data on the oscillations of the phase transition line in FS systems.

Goal: to explain experimental H – T phase diagrams

Mechanisms of interaction of superconducting order parameter with magnetic moment.

- **Electromagnetic mechanism. Localized superconductivity in SF systems. Single domain wall.**

- **2D magnetic moment distributions. Superconductivity nucleation in S film with a magnetic dot**

  Switching between vortex states. Little-Parks effect. Effect of finite film thickness

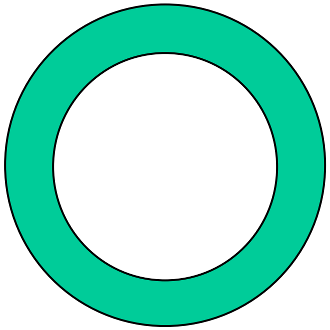
- **Exchange mechanism. Vortex states induced by proximity effect in SF hybrid structures. Little-Parks oscillations in hybrid ferromagnet–superconductor systems.**

Phys.Rev.B 2003, 2007, 2009

Little-Parks effect. Switching between the vortex states.

Multiply-connected systems

Superconducting thin-wall cylinder



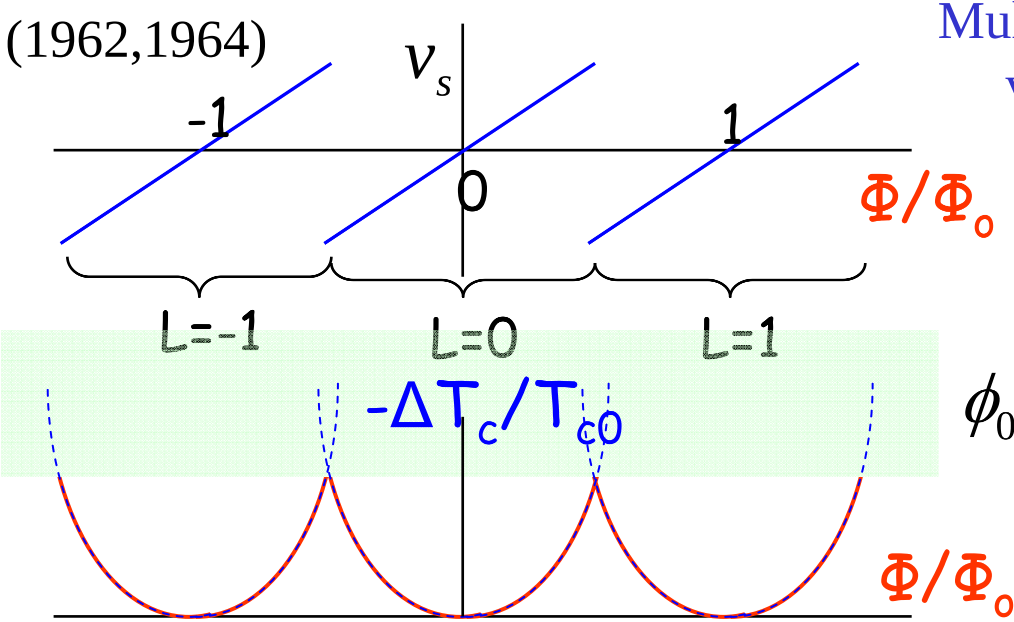
$$v_s = \frac{\hbar}{mR}\left(L - \frac{\Phi}{\Phi_0}\right)$$

$$\frac{\Delta T_c(H)}{T_{c0}} \sim \left(\frac{m v_s}{\hbar}\right)^2$$

T_c (H) oscillations

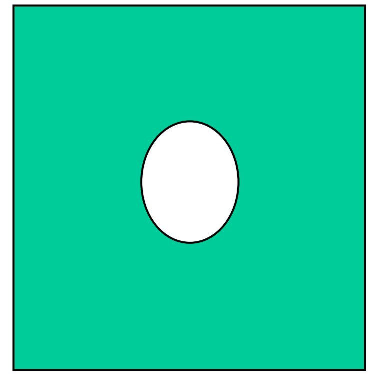
Multiquantum vortices

W.A. Little and R.D. Parks (1962,1964)



$$\phi_0 = \frac{\pi \hbar c}{e}$$

Superconductor with a columnar defect or hole



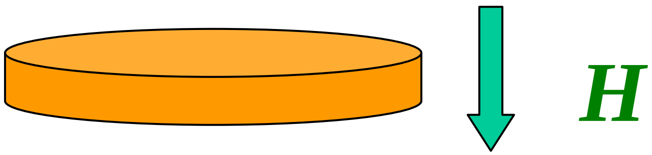
A.I.Buzdin (1993)
A.Bezryadin, A.I. Buzdin, B. Pannetier (1994)
A. Bezryadin, B. Pannetier (1995)
V.Bruyndoncx et al (1999)

Little-Parks effect

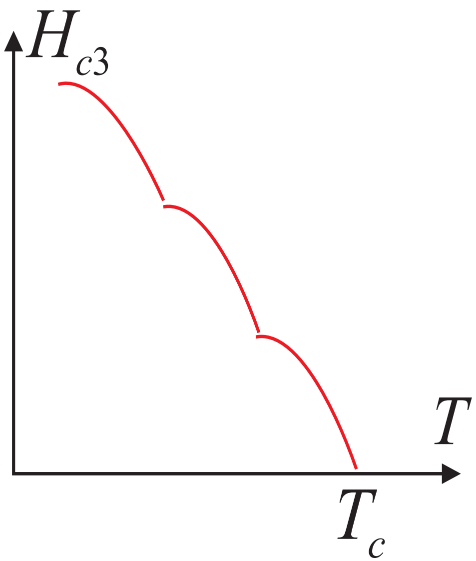
Simply-connected systems

T_c (H) oscillations   Multiquantum vortices

Mesoscopic samples
dimensions ~ several coherence lengths



O.Buisson et al (1990)
R.Benoist, W.Zwerger (1997)
V.A.Schweigert, F.M.Peeters (1998)
H.T.Jadallah, J.Rubinstein, Sternberg (1999)



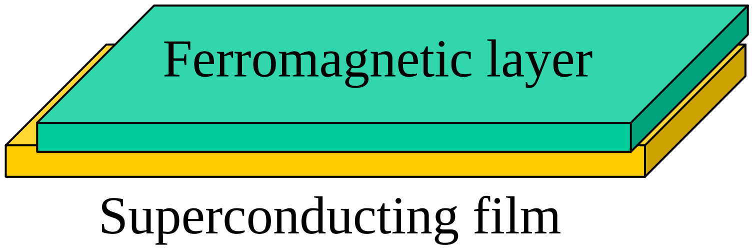
Multiquantum vortices around magnetic dots

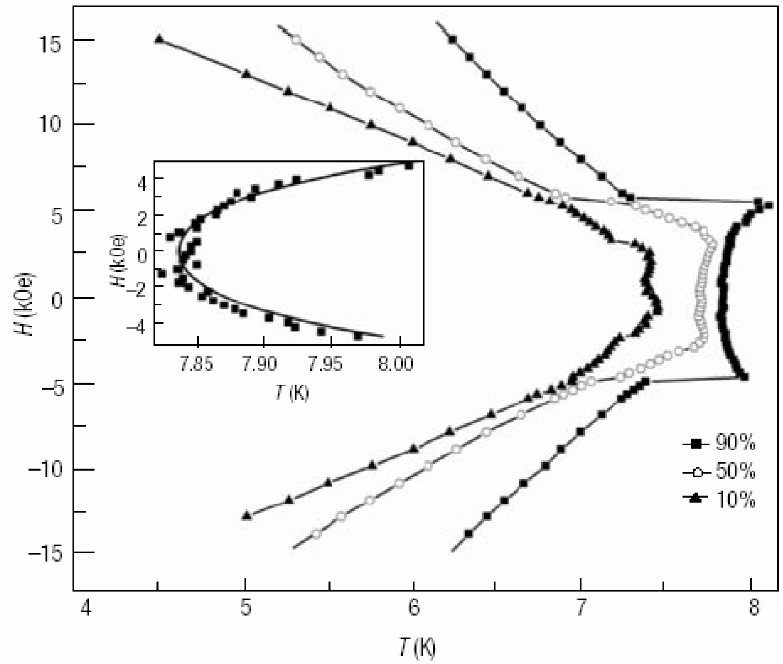
I.K. Marmorkos, A. Matulis, F.M. Peeters (1996)
S.-L. Cheng, H.A. Fertig (1999)
M.V. Milosevic, S.V.Yampolskii, F.M. Peeters (2002)
M.V. Milosevic, F.M. Peeters (2003)

Origin of T_c oscillations:
Transitions between the states with different vorticity L

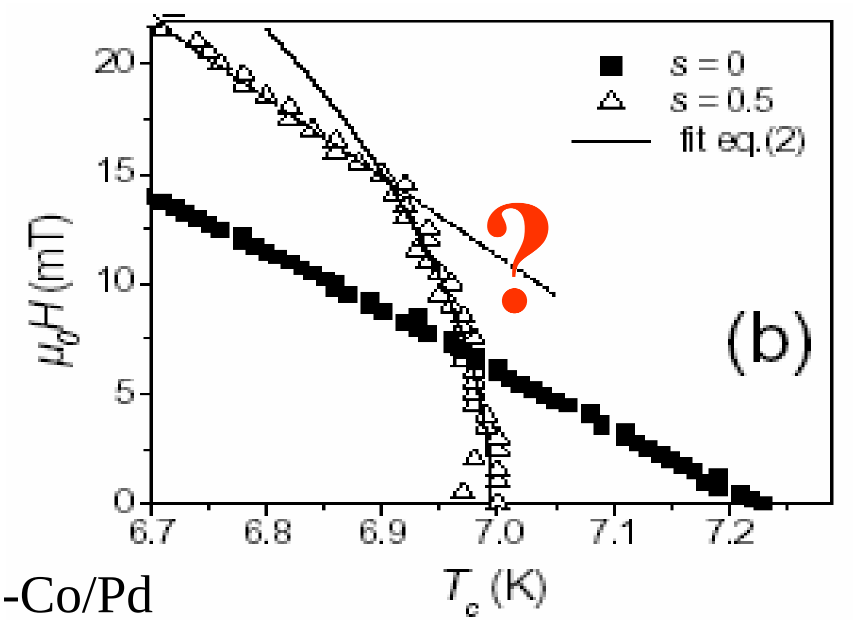
Superconductor - ferromagnet systems: unusual H-T phase diagrams

Z.Yang, M.Lange, A.Volodin, R.Szymczak, V.Moshchalkov (2004)





M.Lange, M.J. Van Bael, and V.V.Moshchalkov (2003)



Pb-Co/Pd

Figure 5 Superconducting phase diagram of Nb/$BaFe_{12}O_{19}$. The diagram was obtained from the $R(T)$ curves shown in Fig. 4 by defining the critical temperature with three different resistance criteria. The inset shows an enlarged view of the H–T phase diagram for the resistance criterion of R_{cri} = 90% R_n. The solid line is a fit to equation (1) with fitting parameter E_{min} = 0.37. In the fitting, H_d is taken as 5.4 kOe corresponding to the field where $R(H)$ displays a minimum at 8.15 K and $T_c(0)$ is taken as 7.84 K. From the linear fitting for $|H| > 6$ kOe, we know that 5.4 kOe can shift the critical temperature by 0.6 K, $\Delta T_c^{orb} \sim 0.6$ K. For $|H| > 6$ kOe, the linear behaviour of the phase diagram can be fitted by $H_{c2}(T) = \Phi_0/2\pi\xi^2(T)$ with $\xi(0)$ = 6.67 nm and T_{c0} = 8.06 K, where Φ_0 is the superconducting flux quantum, $\xi(T) = \xi(0)/(1 - T/T_{c0})^{1/2}$ the temperature-dependent coherence length in the dirty limit, and T_{c0} the critical temperature at zero total field ($\vec{H}_t = \vec{H}_a + \vec{H}_d = 0$). The coherence length at 7.84 K is about 40.4 nm.

H-T phase diagrams are strongly affected by the domain structure

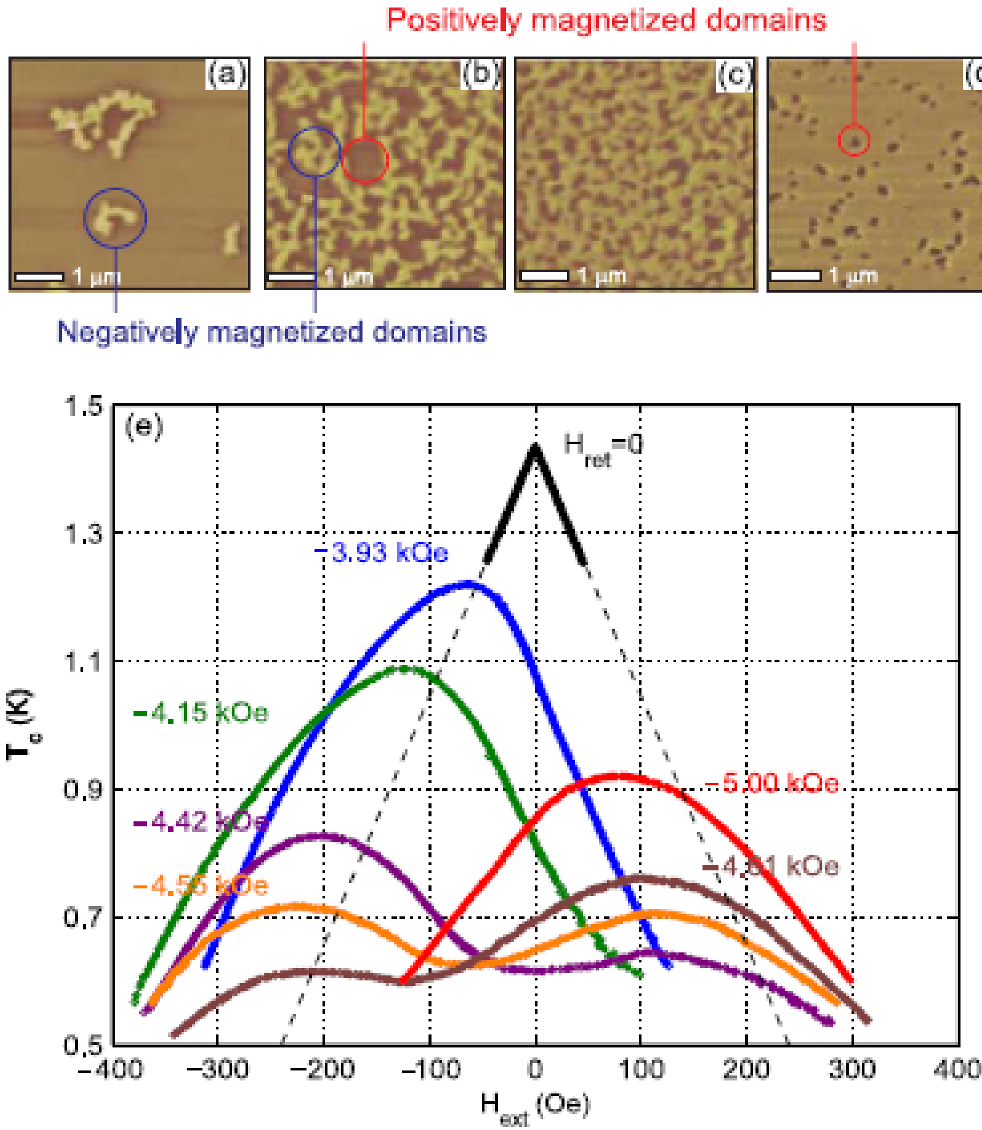
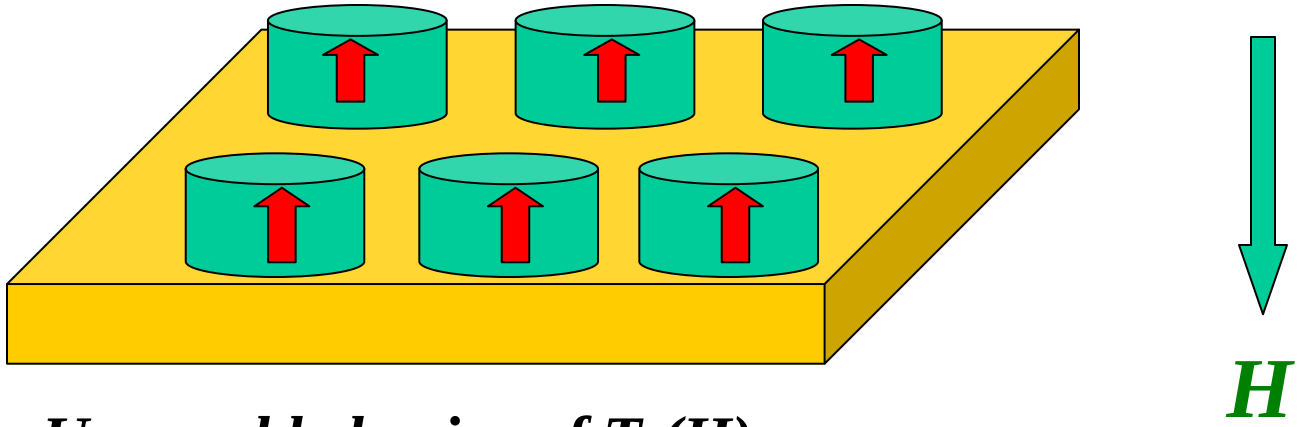


Figure 7. (a)–(d) MFM images obtained at $T = 300$ K for H_{ret} values equal to −1.75 kOe (a), −2.00 kOe (b), −2.50 kOe (c), −3.00 kOe (d), the coercive field $H_c^{300\,K} = 1.91$ kOe. The dark (bright) color represents domains with positive (negative) magnetization. (e) A set of experimental phase boundaries $T_c(H_{ext})$ obtained for the same bilayered S/F sample (a superconducting Al film on top of a Co/Pt multilayer) in various magnetic states measured after the procedure of an incomplete demagnetization: $H_{ext} = 0 \Rightarrow H_{ext} = 10$ kOe $\Rightarrow H_{ext} = H_{ret} \Rightarrow H_{ext} = 0$ for various returning fields H_{ret} indicated on the diagram, the coercive field $H_c^{5\,K} = 3.97$ kOe. All these plots were adapted with permission from Gillijns *et al* 2007 *Phys. Rev.* B 76 060503 [96]. Copyright (2007) by the American Physical Society.

Superconducting films with arrays of ferromagnetic dots



Unusual behavior of $T_c(H)$:

Y.Otani, B.Pannetier, J.P.Noziers, D.Givord (1993)

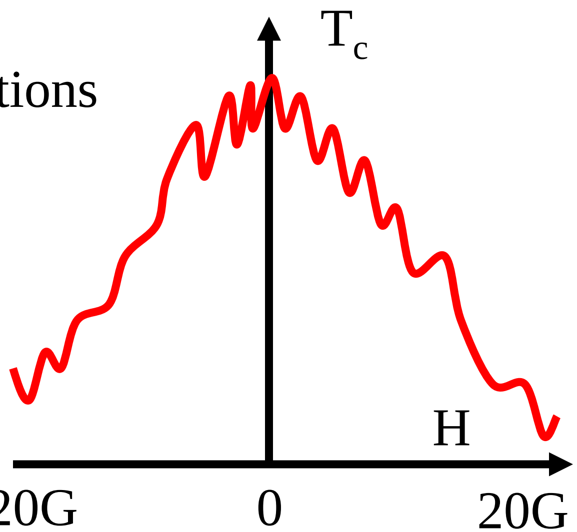
M.Lange, M.J. Van Bael, Y.Bruynseraede, V.V.Moshchalkov (2002)

Nonlinear Tc(H)

Magnetic field induced superconductivity

Tc(H) oscillations

Nb-Gd/Co



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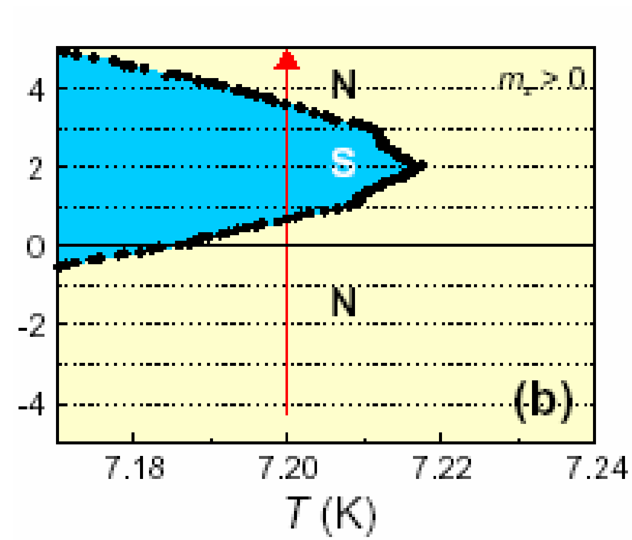


Pb-Co/Pd

W.Gillijns, A. Silhanek, V.Moshchalkov (2006)

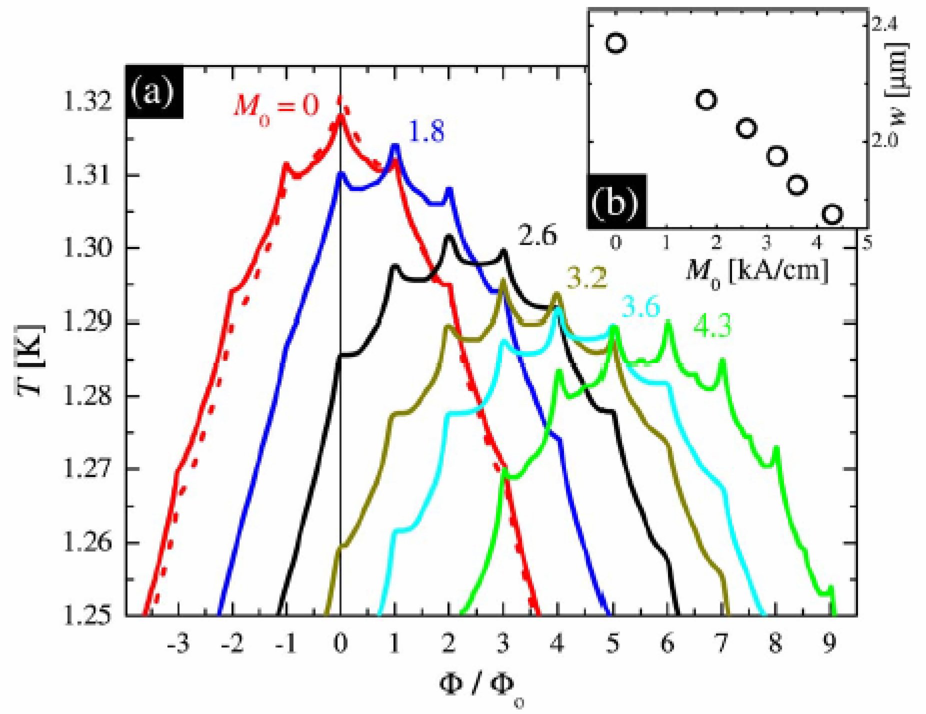
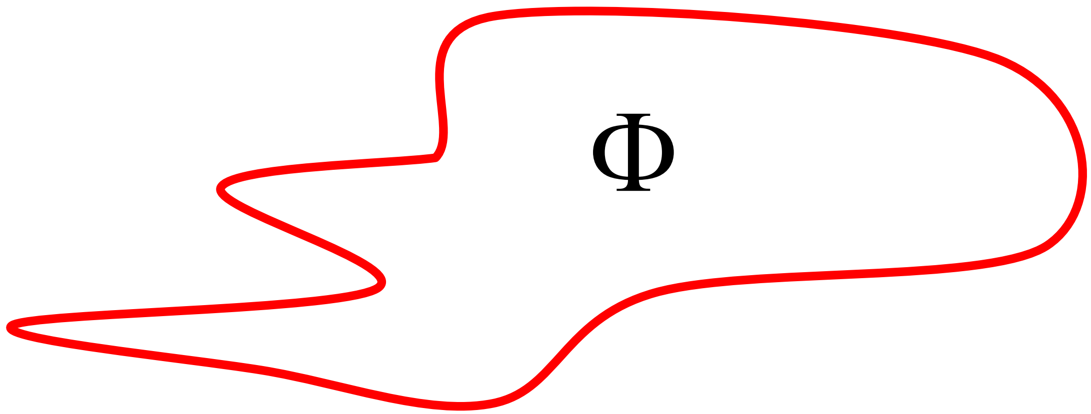


FIG. 2. (Color online) (a) Superconducting transition $T_c(H)$ of the Al film for different magnetic states of the dots. By increasing the magnetization a clear shift of $T_c(H)$ and a decrease of T_c^{max} is observed. (b) Lateral dimension w of the nucleation of superconductivity as a function of the magnetization of the dots.

Electromagnetic mechanism of T_c oscillations.

Question: We need localized superconducting channels which form closed loops. How can we get localized S channels in FS structures?



Mechanisms of interaction of superconducting order parameter with magnetic moment

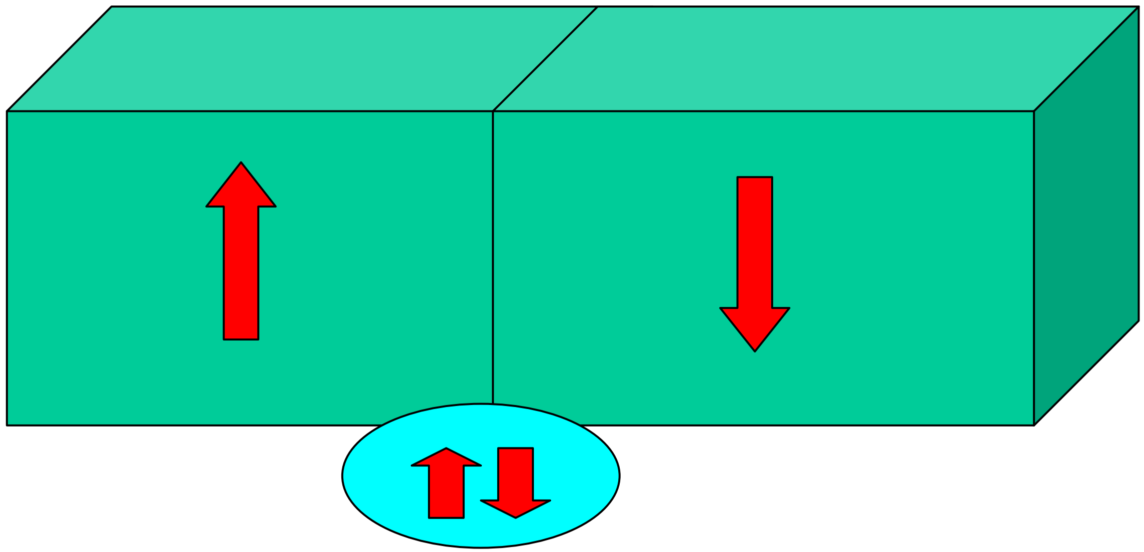
Electromagnetic mechanism
(breakdown of Cooper pairs by magnetic field induced by magnetic moment)

V.L.Ginzburg (1956)

Breakdown of singlet Cooper pairs caused by the exchange interaction

Matthias, Suhl, Corenzwit (1958)

Localized superconducting channels. Domain wall superconductivity



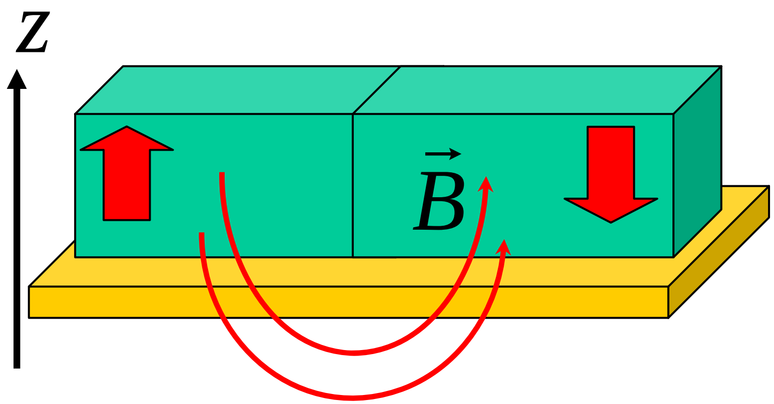
Cooper pair

Matthias, Suhl (1960)
Kopaev (1965)
Buzdin, Bulaevskii, Panyukov (1984)
…….

Electromagnetic (orbital) mechanism. Phenomenological Ginzburg-Landau theory

External field H + **Inhomogeneous magnetic field induced by magnetic moments**

$$-\left(\nabla + \frac{2\pi i}{\Phi_0}\vec{A}(\vec{r})\right)^2 \Psi = \frac{1}{\xi^2(T)}\Psi$$

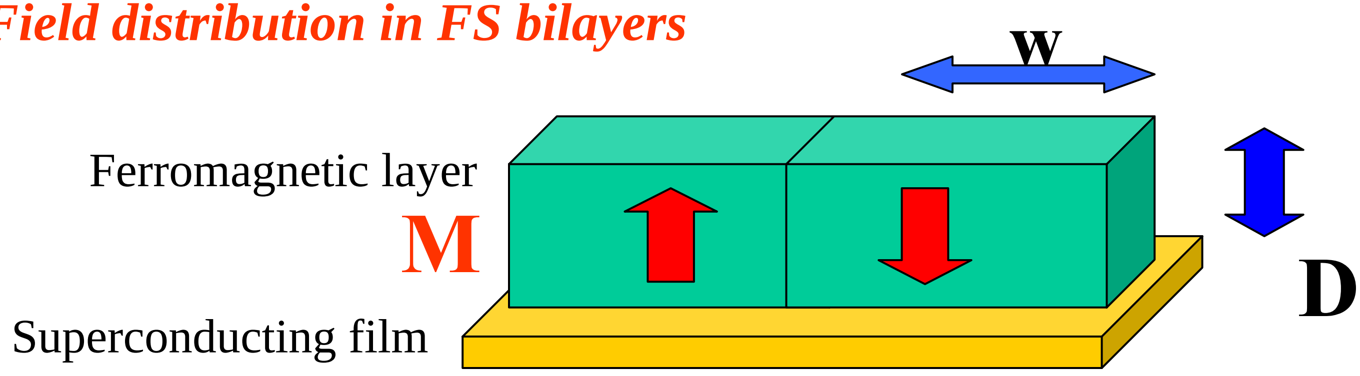


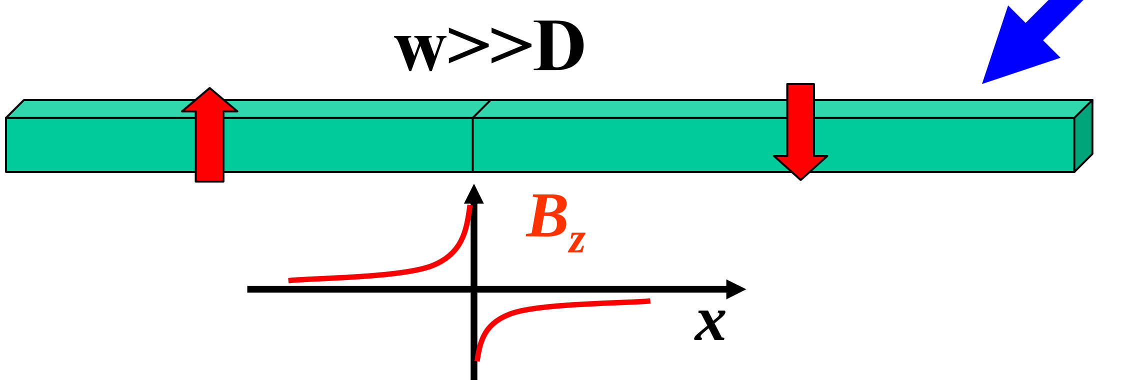
$$H_{c2}^{\perp} << H_{c2}^{\parallel}$$

Thin superconducting films: Only B_z field component is important

Assumption: Domain walls are pinned

Field distribution in FS bilayers

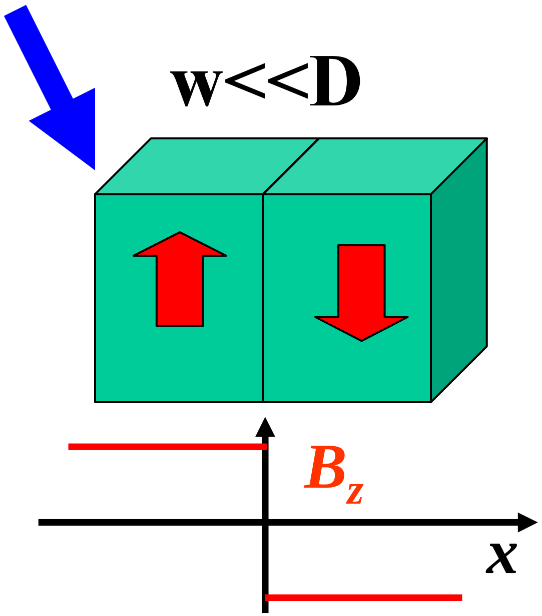




Magnetic field decays inside the domains

Domain walls suppress superconductivity [E.B.Sonin (1988)]

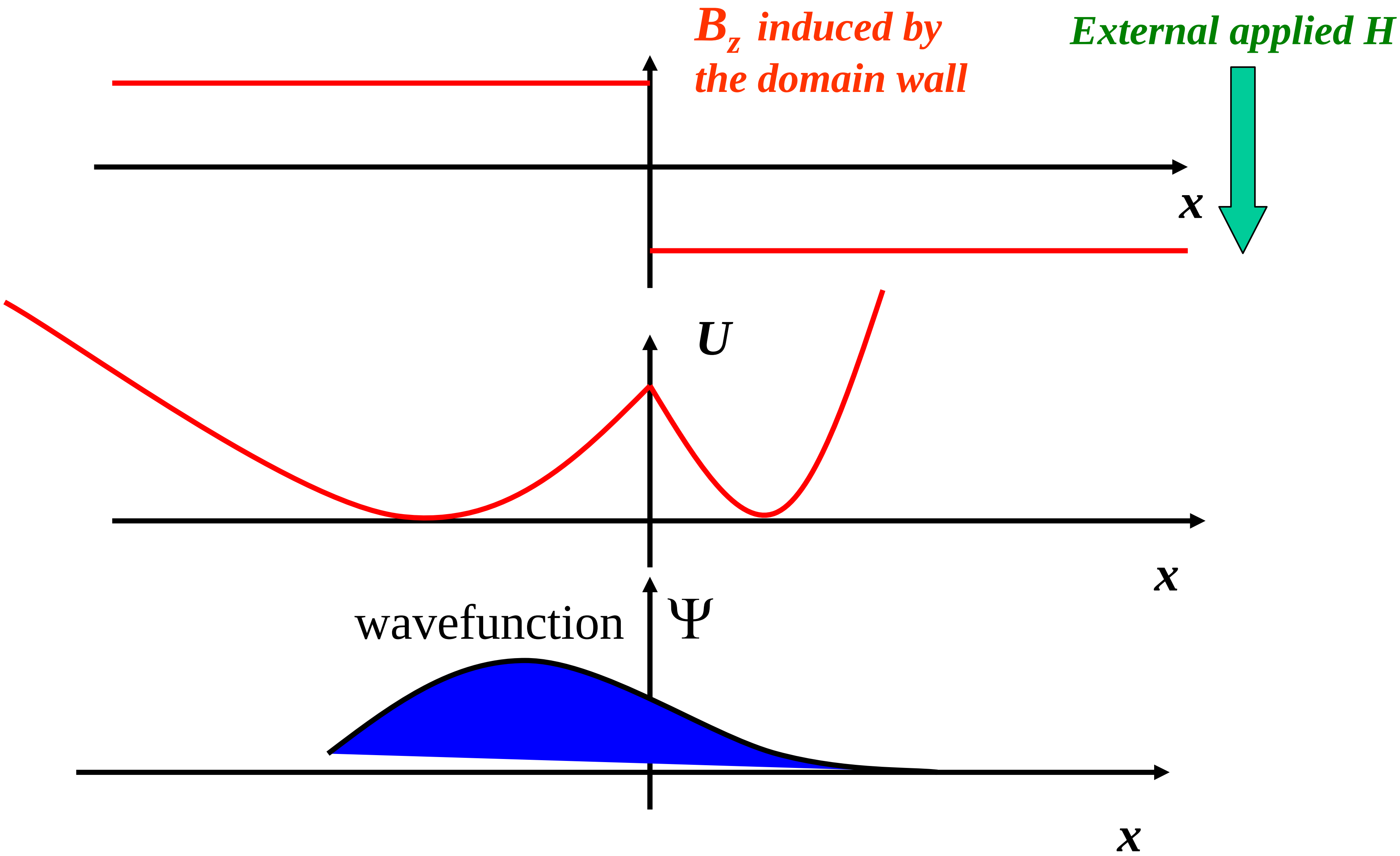
The position of superconducting nucleus
is controlled by the external field



Magnetic field is almost
homogeneous inside the domains

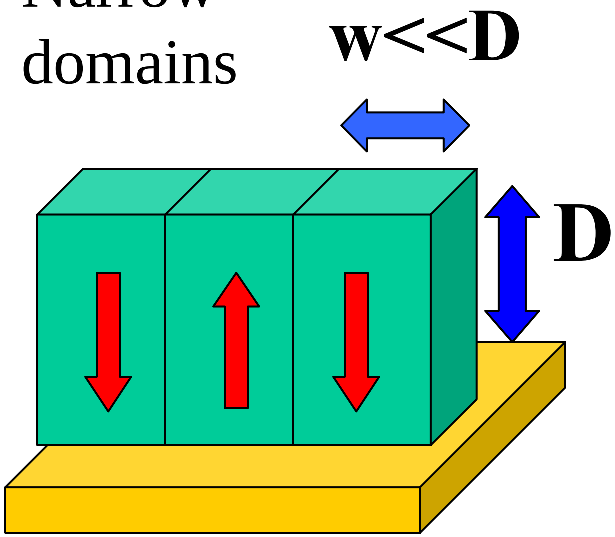
Domain walls stimulate
superconductivity nucleation

Superconductivity nucleation in a step-like profile of the magnetic field component B_z

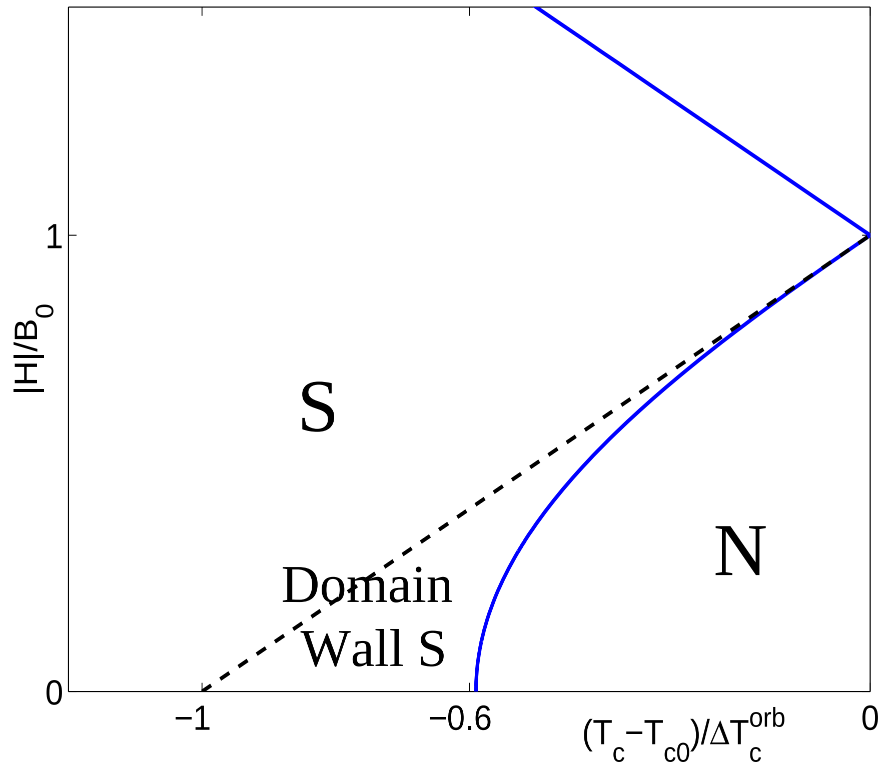


Superconductivity nucleation in S/F bilayers

Narrow domains



T_c of a nucleus localized at a single domain wall



Nb/F

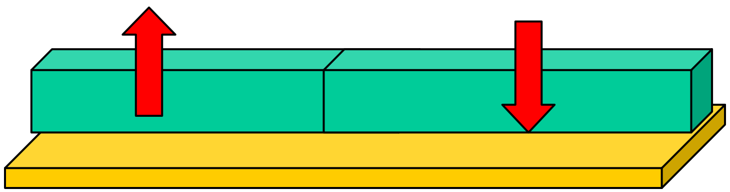
$$4\pi M \sim 1-10\,kOe \qquad \frac{dH_{c2}}{dT} \sim 0.5 kOe / K$$

$$T_c \sim 9\,K \qquad \delta T_c \sim 1-3\,K$$

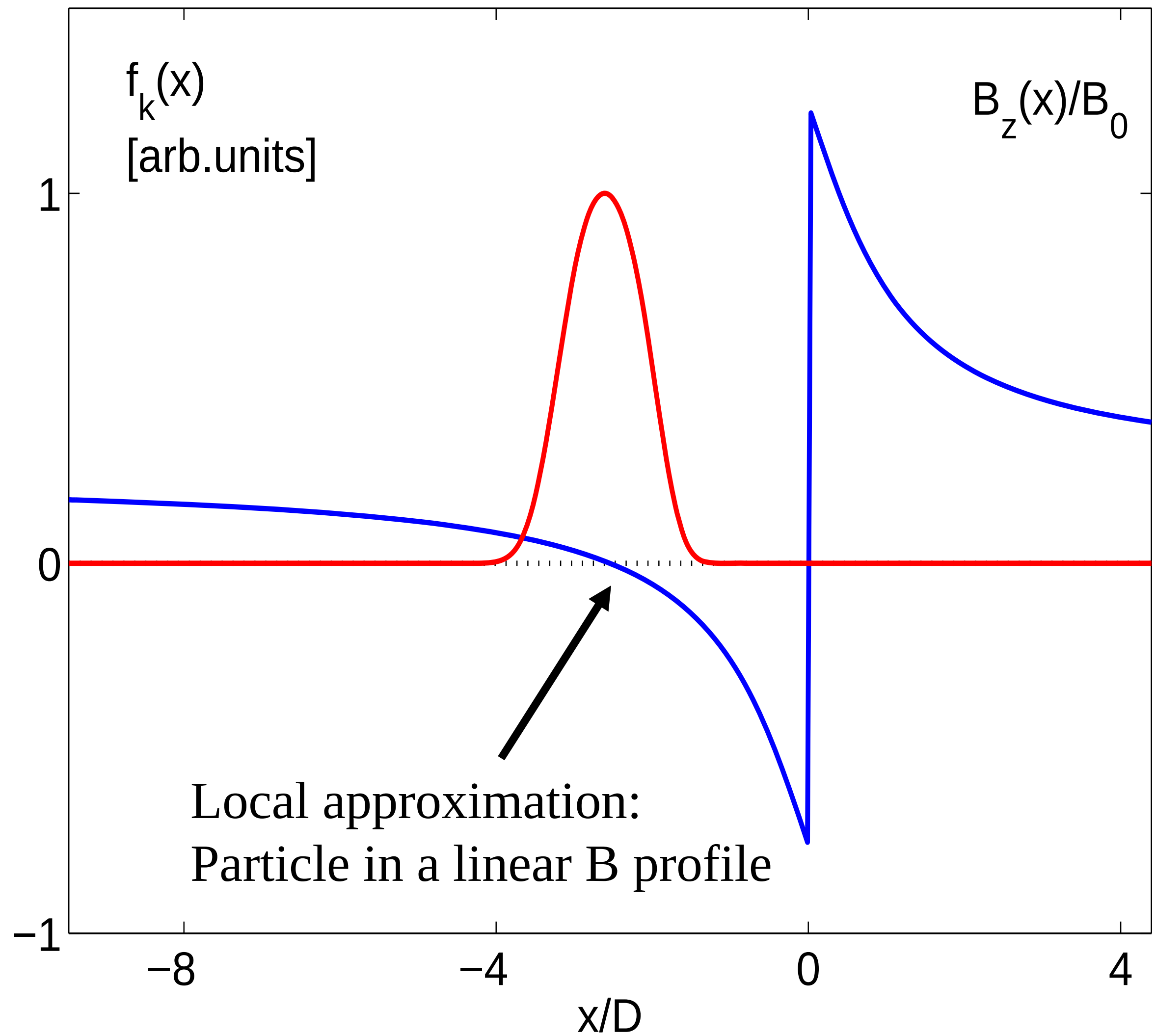
Superconductivity nucleation at an isolated domain wall

Thick domains

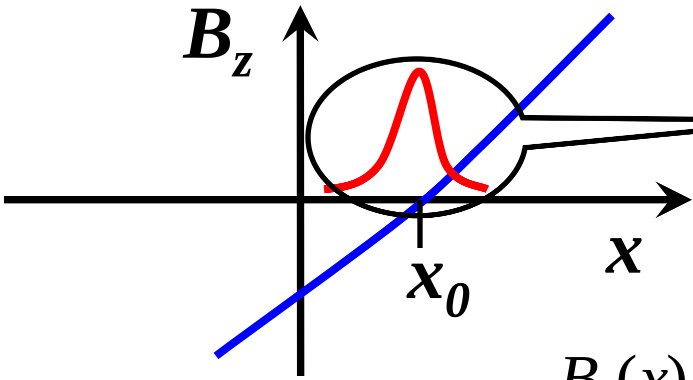
w>>D



B_0-maximum field induced by the domain wall



Particle in a linear $B_z(x)$ profile



$$B_z(x_0) = 0$$

$$B_z(x) \approx \frac{dB_z(x_0)}{dx}(x - x_0)$$

$$\Psi(x, y) = f_k(x) e^{iky}$$

$$\left| \frac{B_z''(x_0)}{B_z'(x_0)} \ell \right| << 1$$

$$x - x_0 = \ell \cdot t$$

Characteristic length:

$$\ell = \sqrt[3]{\frac{\Phi_0}{\pi |B_z'(x_0)|}}$$

$$-\frac{d^2\psi}{dt^2} + \left(t^2 - Q\right)^2 \psi = E\psi$$

$$E = \frac{\ell^2}{\xi_0^2}\left(1 - \frac{T_c}{T_{c0}}\right) \xrightarrow[\min Q]{} 0.904$$

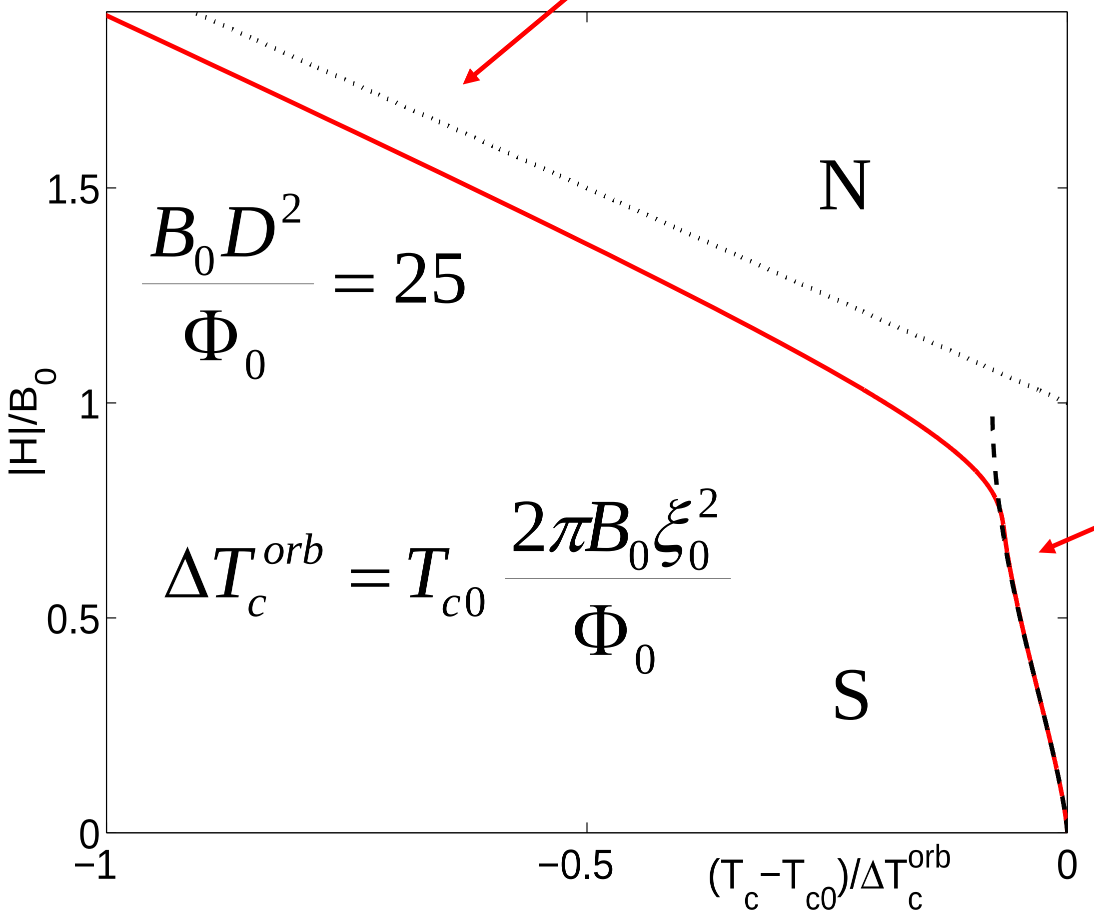
$$Q = \sqrt[3]{\frac{\Phi_0}{\pi B_z'(x_0)}}\left(k - \frac{2\pi}{\Phi_0} A(x_0)\right)$$

Key parameter: $\dfrac{\text{F film thickness}}{\text{Intervortex distance for } B_0} = \sqrt{\dfrac{B_0 D^2}{\Phi_0}}$

High fields H: $\dfrac{T_{c0} - T}{\Delta T_c^{orb}} \approx 1 - \dfrac{|H|}{B_0}$

Low fields H:

$$\frac{T_{c0} - T}{\Delta T_c^{orb}} \approx \frac{1}{\pi}\left(\frac{\Phi_0}{2B_0 D^2}\right)^{1/3}\left[\sin\left(\frac{\pi |H|}{2B_0}\right)\right]^{4/3}$$

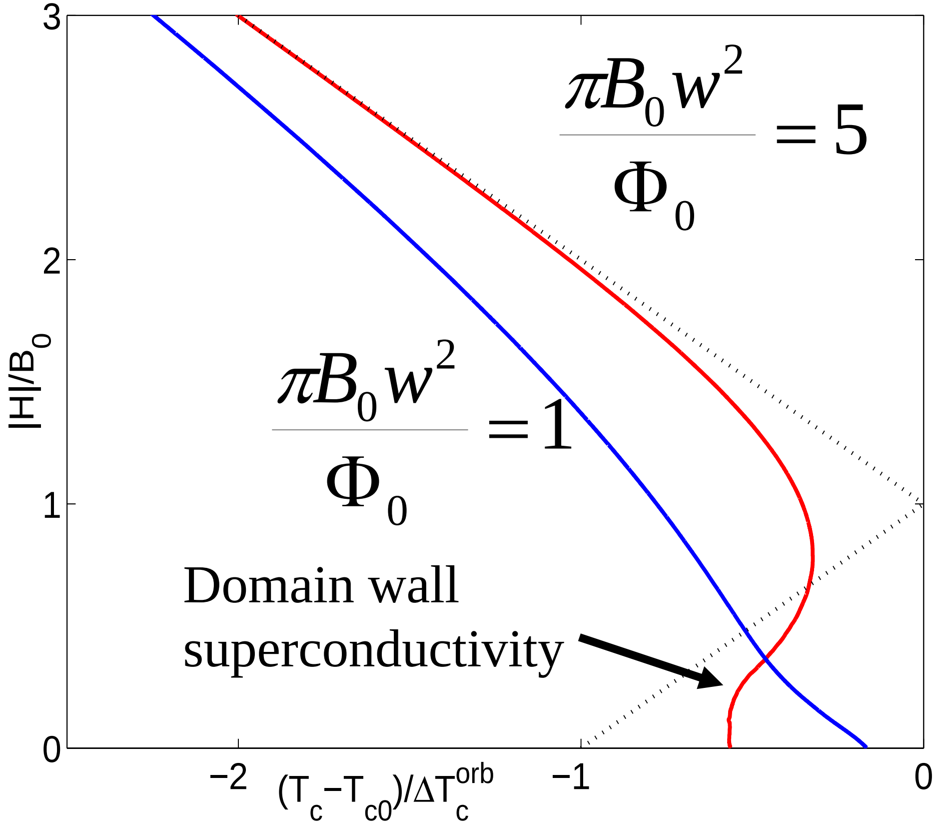


$$\frac{B_0 D^2}{\Phi_0} = 25$$

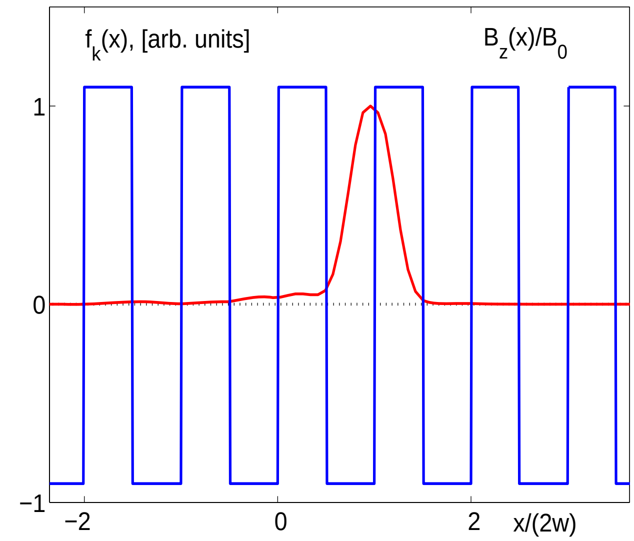
$$\Delta T_c^{orb} = T_{c0}\,\frac{2\pi B_0 \xi_0^2}{\Phi_0}$$

Superconducting nucleus in a periodic domain structure in an external field

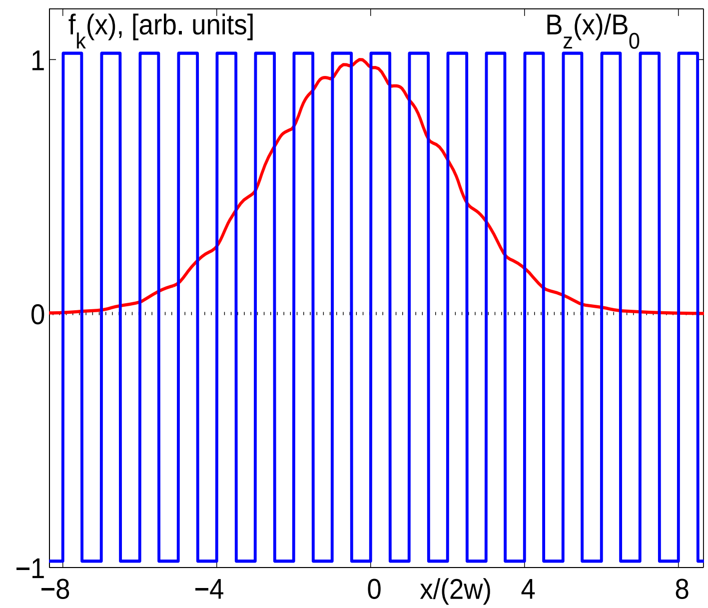
$$H \neq 0$$



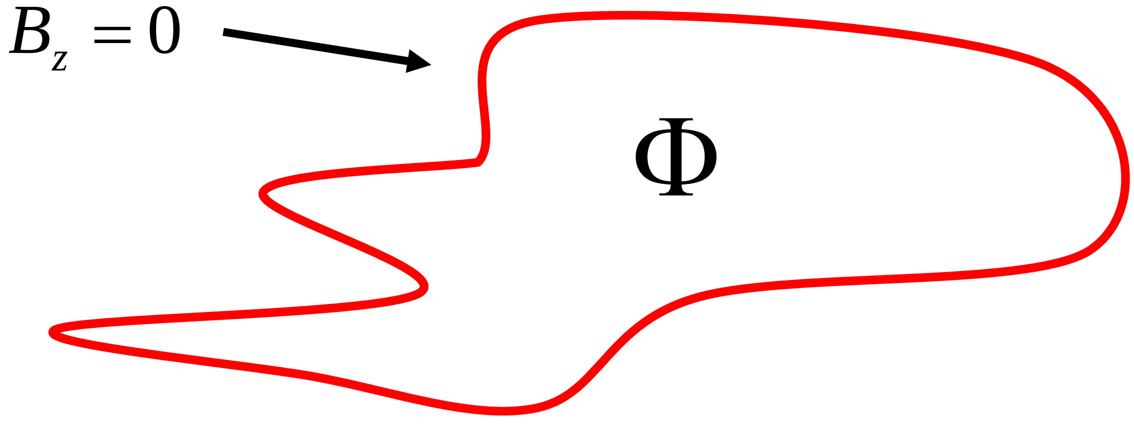
$$\frac{B_0 w^2}{\Phi_0} >> 1$$



$$\frac{B_0 w^2}{\Phi_0} << 1$$



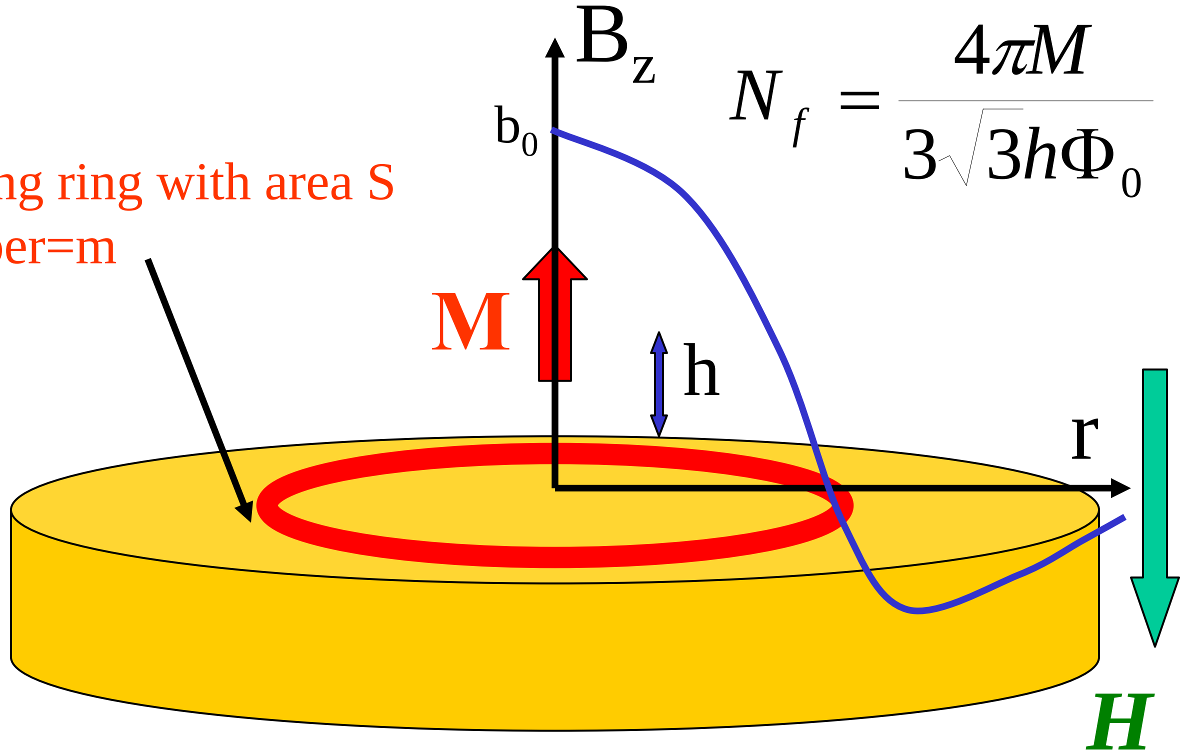
2D magnetic moment distributions
Little-Parks effect ?



Little-Parks effect and multiquanta vortices in a hybrid S/F system
Axially symmetric field profile

Example: magnetic dot (dipole) above S film

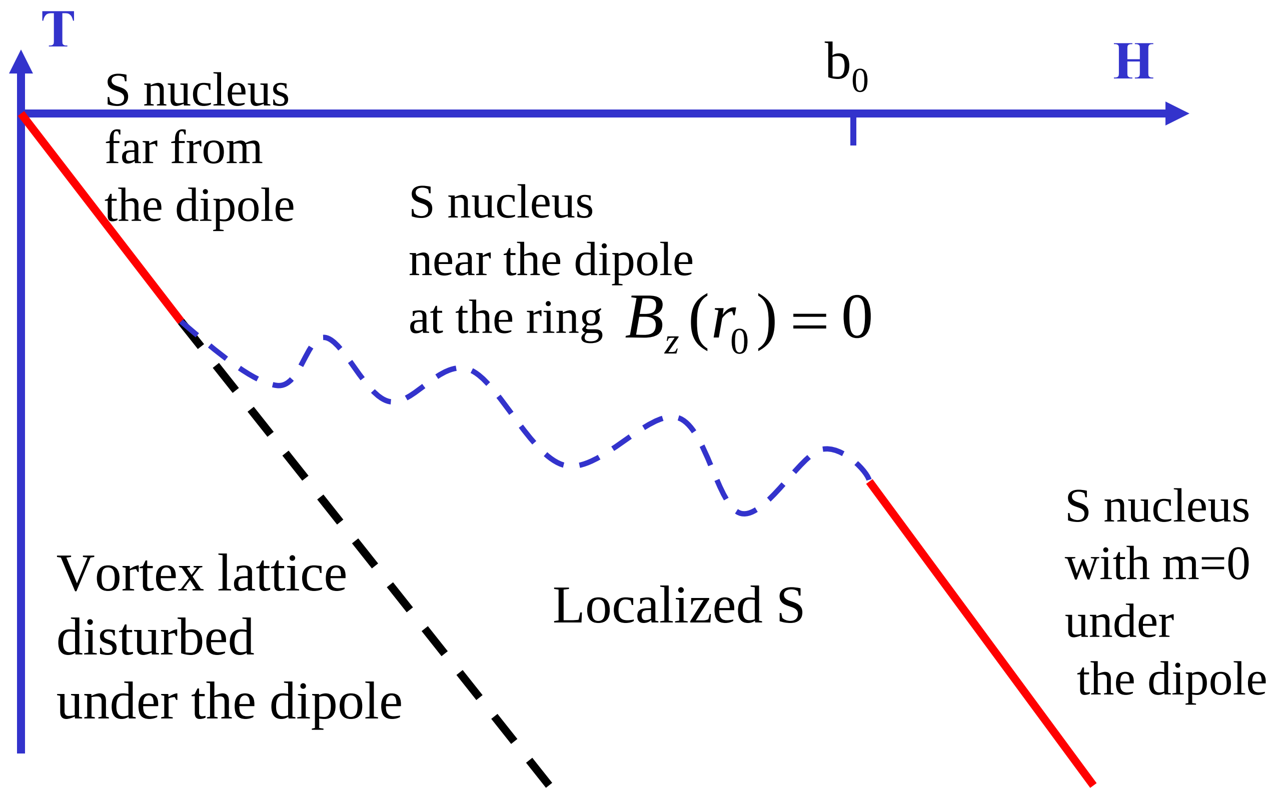
Superconducting ring with area S
Winding number=m



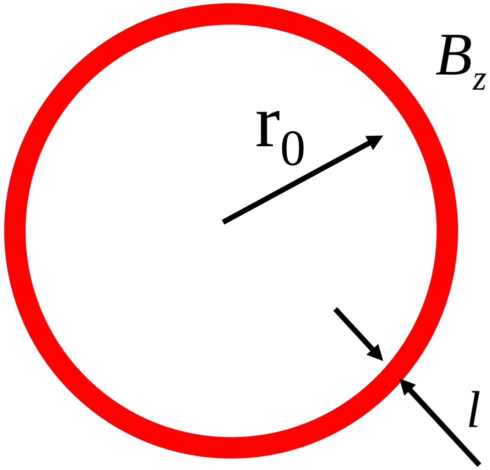
$$N_f = \frac{4\pi M}{3\sqrt{3}h\Phi_0}$$

T_c (H) oscillations are caused by the quantization of flux through the area S

Schematic phase diagram



Magnetic dot assisted superconductivity.
T_c oscillations for a nucleus at the ring

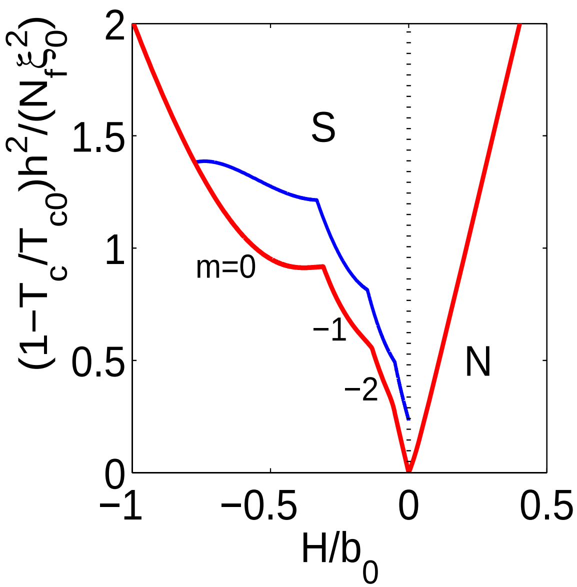


$B_z(r_0) = 0$

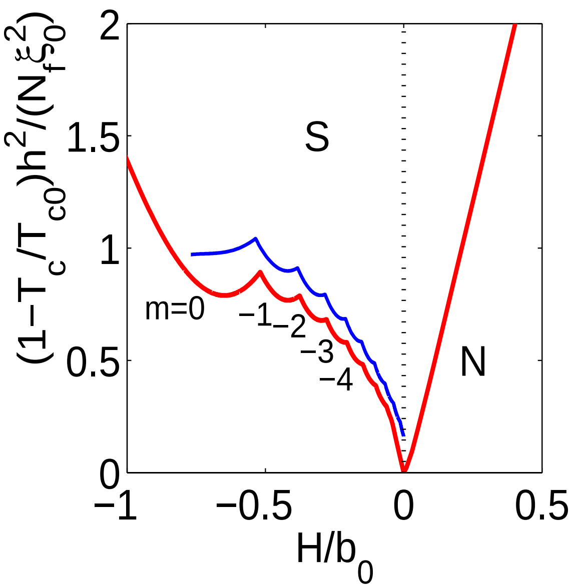
Local approximation: $l \ll r_0$

S nucleus in a linear B profile

$$l = \sqrt[3]{\frac{\Phi_0}{\pi\,|B_z'(r_0)|}}$$



$N_f = 4$



$N_f = 10$

F particle 300 x 300 x 300 nm, magnetization ~ 10^3 G, h~300 nm

$M \sim 3\cdot10^{-11}\,G\cdot cm^3$

$b_0 \sim 10^3\,G$ $\qquad N_f \sim 10$

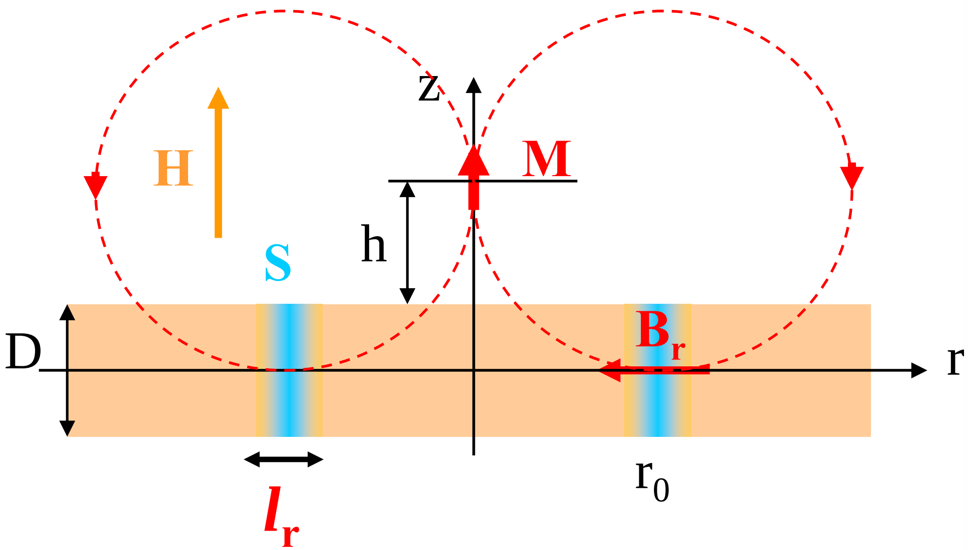
Nb film: $T_{c0} \sim 9\,K$

$\xi_0 \sim 40\,nm$

$\Delta H \sim 100\,G$

$\Delta T_c \sim 0.1K$

Effect of finite superconducting film thickness



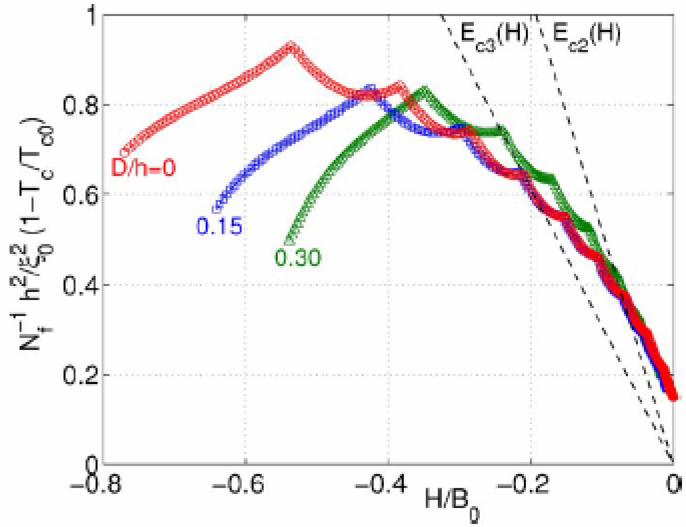


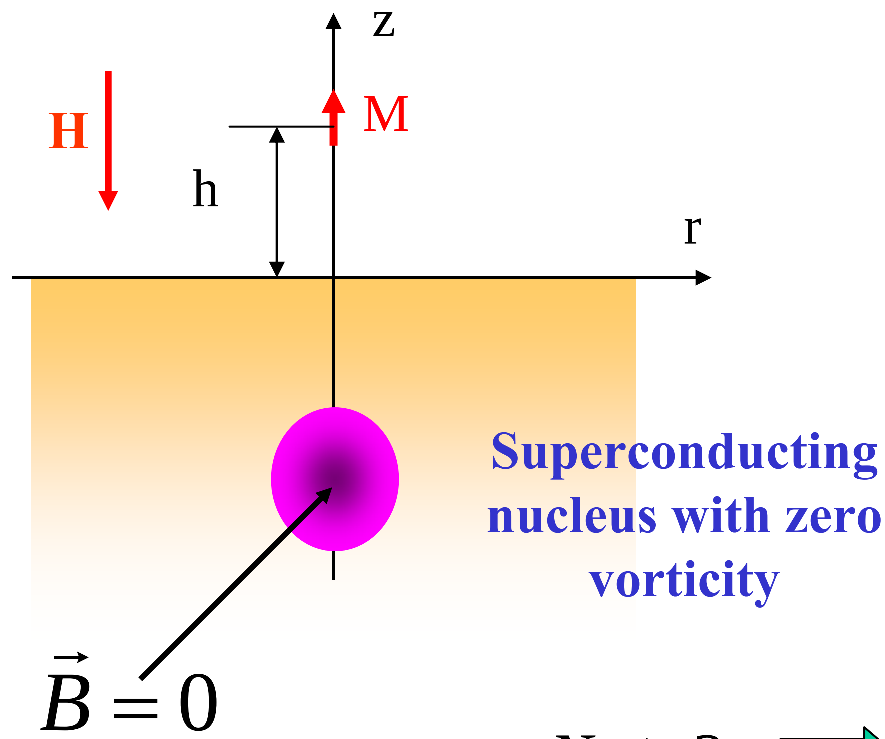
FIG. 2. (Color online) The phase boundaries $T_c(H)$ for the S/F hybrid with $N_f=10$ and $D/h\to 0$ (○), $D/h=0.15$ (□), and $D/h=0.30$ (△), obtained from Eq. (8). The dashed lines show the reference dependencies $E_{c2}(H)=(h^2/\xi_0^2)[1-T_{c2}(H)/T_{c0}]$ and $E_{c3}(H)=(h^2/\xi_0^2)[1-T_{c3}(H)/T_{c0}]$, corresponding to OP nucleation either far from the edges in a bulk sample or near the sample edges, respectively.

Localized superconducting nuclei are suppressed by the magnetic field component parallel to the film surface

→

Decrease in the number of observable Little-Parks oscillations

Thick superconducting films



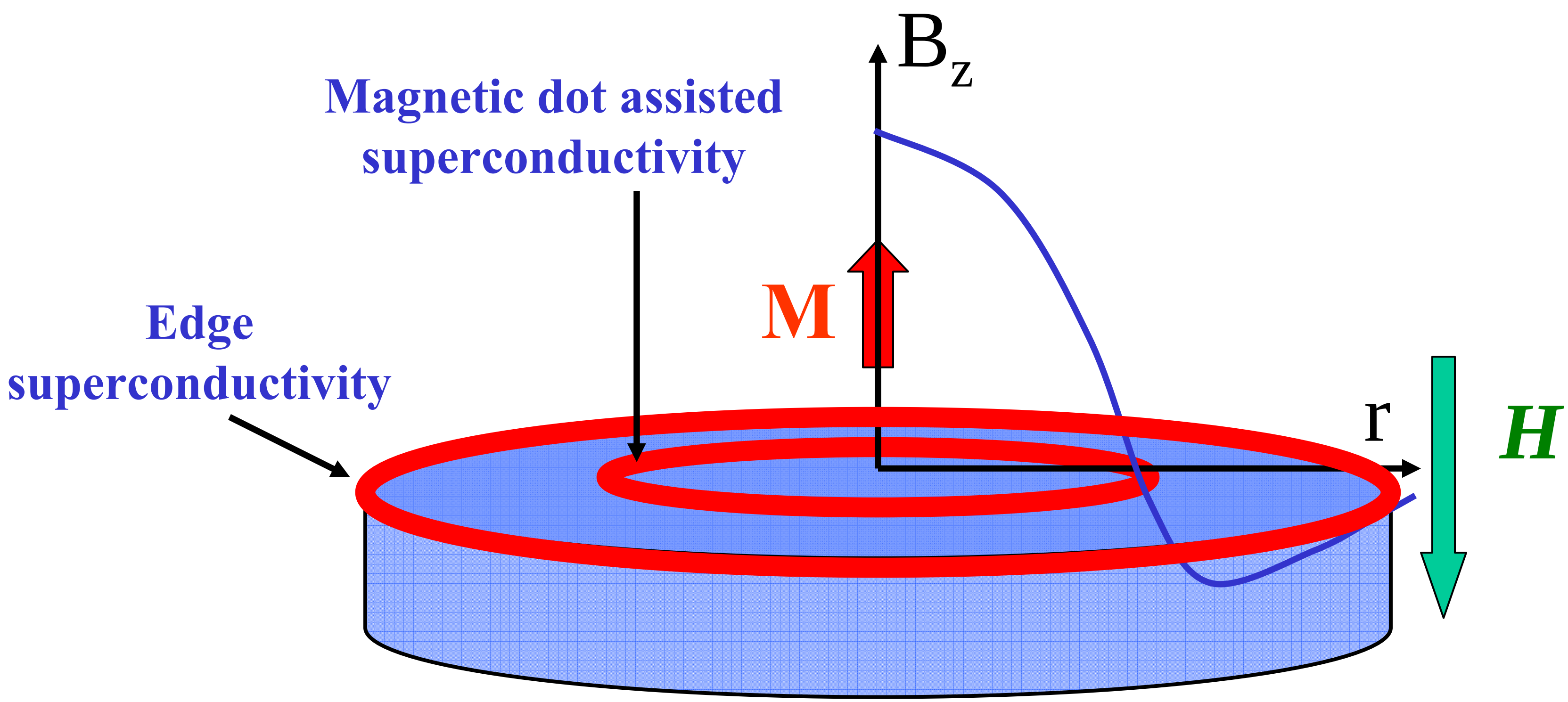
$$\frac{\delta T_c}{T_c} \sim \frac{\xi_0^2}{h^2} N_f^{2/3} \left(\frac{|H|}{b_0} \right)^{8/9}$$

$$N_f = \frac{4\pi M}{3\sqrt{3} h \Phi_0}$$

$N_f \geq 3$ ⇨ **Magnetic dot assisted superconductivity dominates even for thick films**

$N_f \leq 3$ ⇨ **Magnetic dot assisted superconductivity appears only for rather thin films**

Mesoscopic samples: interplay between the magnetic dot assisted superconductivity and edge superconductivity



Change in the period of Little-Parks oscillations with the increase in the sample thickness

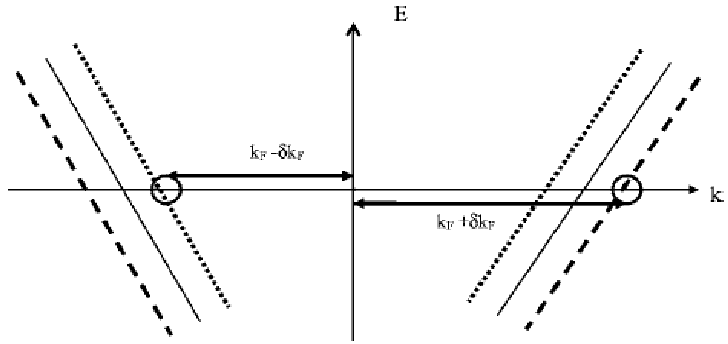
Exchange mechanism. Proximity effect in FS structures.

Question: Is it possible to affect vortex states by the exchange field?

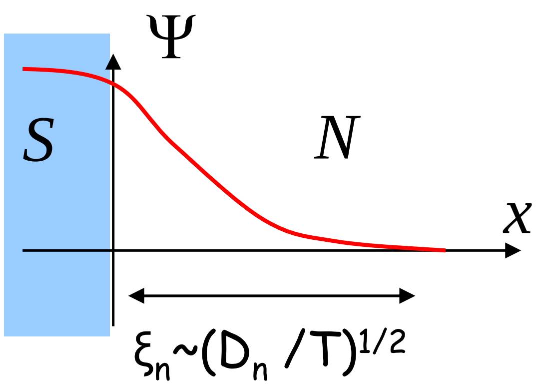
$$\delta\hat{H} = \vec{h}\,\hat{\vec{\sigma}}$$

Inhomogeneous superconductivity induced by the exchange field:

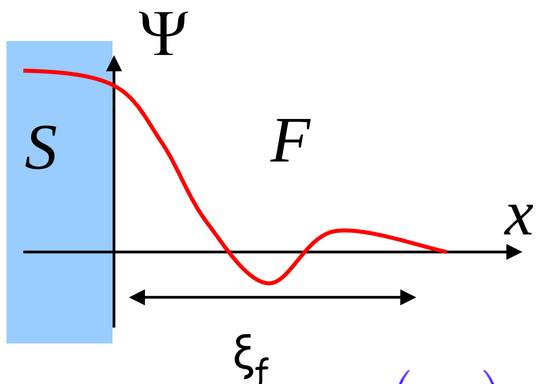
1. FFLO state



2. Interference effects for Cooper pairs in FS layered structures



Damped oscillatory dependence of pair wave function in ferromagnets



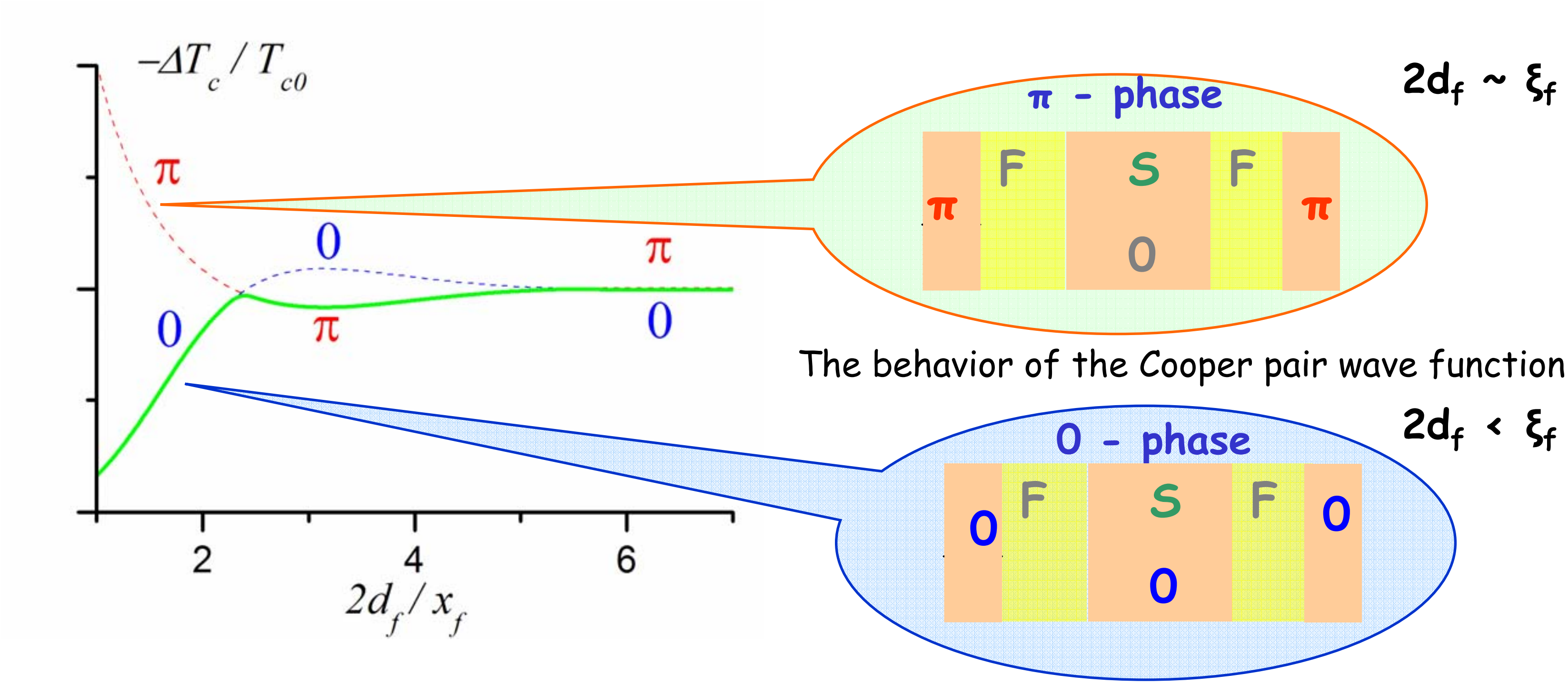
$$\Psi \sim \Delta \exp\left(-\frac{x}{\xi_f}\right) \cos\left(\frac{x}{\xi_f}\right)$$

h= exchange energy

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

Examples. π – Superconductivity in FS multilayer

Commensurability effects between the period of the order parameter oscillation ξ_f and the thickness of FM layer d_f

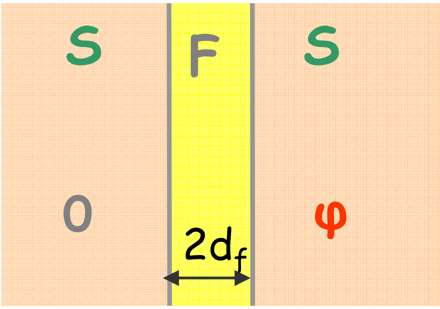


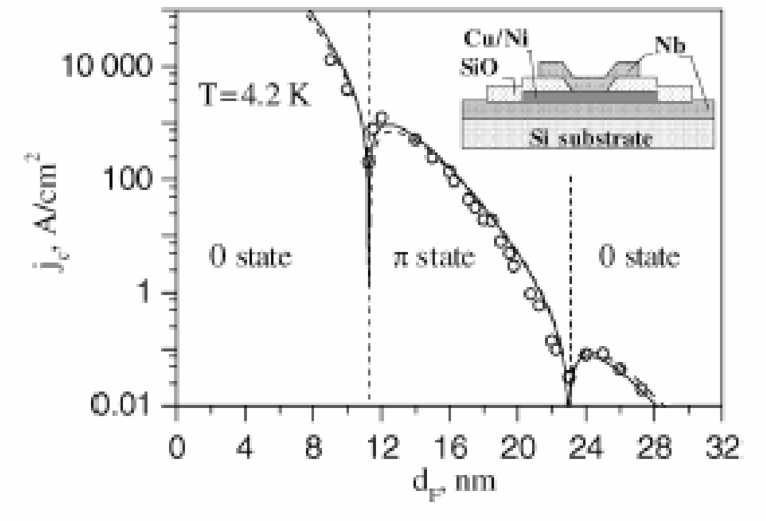
Theory: A.I.Buzdin, M.V.Kuprianov, JETP Lett. 1990

Z.Radovic, et al., PRB 1991

Experiments: J.S.Jiang et al., PRL 1995

Examples. Superconductor-Ferromagnet-Superconductor (SFS) Josephson junction: π-Junction





[Oboznov et al (2006)]

$E_J = (\Phi_0 I_c/2\pi c)\,(1-\cos\varphi)$

I_c – Josephson critical current

The Current-Phase Relation:

$I_s(\varphi) = (2e/\hbar)\,\partial E_J/\partial\varphi = I_c \sin\varphi$

$I_c > 0 \rightarrow \varphi = 0$ - **0-Junction** $(2d_f < \xi_f)$

$I_c < 0 \rightarrow \varphi = \pi$ - **π-Junction** $(2d_f \sim \xi_f)$

Ni: $h \sim 1000$ K -> $\xi_f < 10$ A

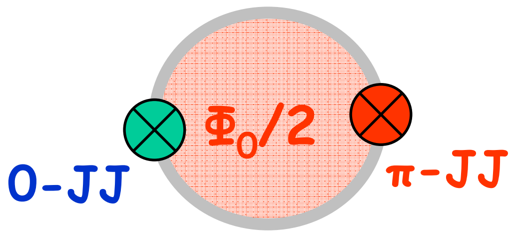
Cu_xNi_{1-x}: $h \sim 100$ K -> $\xi_f \sim 30\text{-}50$A

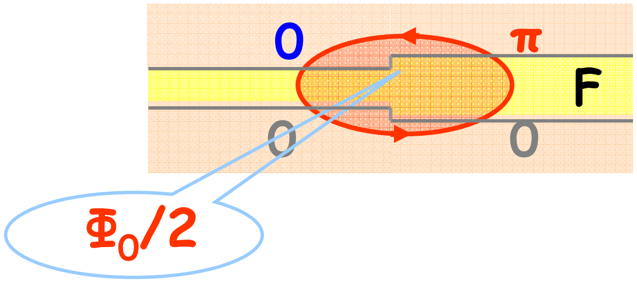
L.N.Bulaevskii, V.V.Kuzii, and A.A.Sobyanin (1977) - barrier with magnetic impurities
A.V.Andreev, A.I.Buzdin, and R.M.Osgood III (1991) - SFS
V.V.Ryazanov, et al., (2001) - SFS, experiment

Spontaneously generated fluxes in SFS Josephson systems.

Half-Fluxon : $\Phi_0/2$

Theory:
L.N.Bulaevskii, V.V.Kuzii, and A.A.Sobyanin (1978)
R.G.Mints (1998)
E.Goldobin, D.Koelle, R.Kleiner (2002)





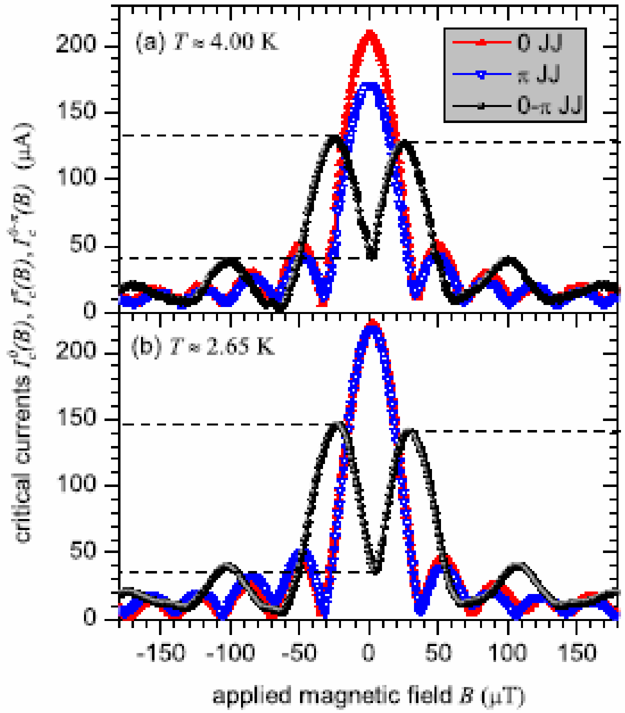
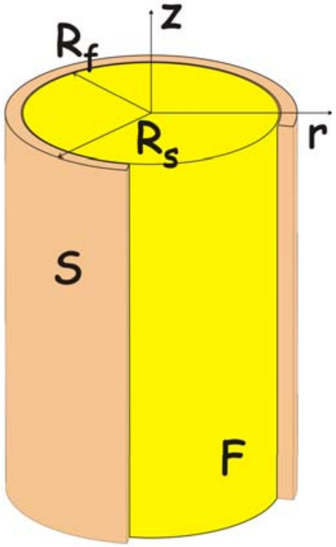


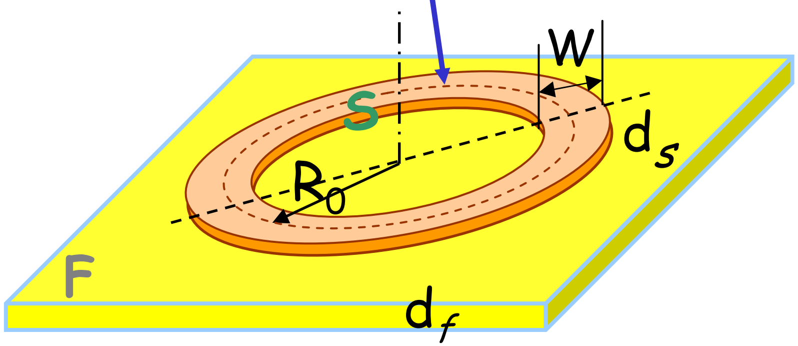
FIG. 3 (color online). $I_c(B)$ of 0 JJ (red filled triangles), π JJ (blue open triangles), and 0-π JJ (black spheres) measured at (a) $T \simeq 4.2$ K and (b) $T \simeq 2.65$ K.

Experiment:
S.M.Frolov, et al., PRB 2006
M.Weides, et al., PRL 2006

$Nb/Al_2O_3/Ni_{0.6}Cu_{0.4}/Nb$

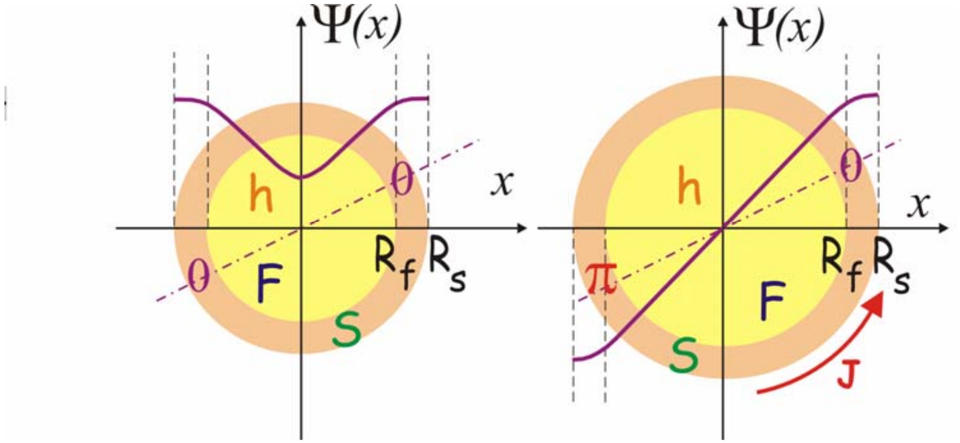
Little-Parks effect and vortex states induced by proximity effect in SF hybrid structures





Ferromagnetic layer

The Key Idea:
Exchange effect vs Orbital effect



Pi- state

Linearised Usadel Equations ($h \gg T_{c0}$; $hl/v_f \ll 1$)

$$-\frac{D_f}{2}\left(\nabla + \frac{2\pi i}{\Phi_0}\mathbf{A}\right)^2 F_f + (|\omega| + i\, h \,\mathrm{sgn}\,\omega)\, F_f = 0\,,$$

$$-\frac{D_s}{2}\left(\nabla + \frac{2\pi i}{\Phi_0}\mathbf{A}\right)^2 F_s + |\omega| F_s = \Delta(\mathbf{r})\,.$$

$$\omega = (2n+1)\,\pi T_c$$

-Matsubara frequency

self-consistency equation:

$$\Delta(\mathbf{r})\,\ln\frac{T_c}{T_{c0}} + \pi T_c \sum_{\omega}\left(\frac{\Delta(\mathbf{r})}{|\omega|} - F_s(\mathbf{r},\omega)\right) = 0.$$

Δ -pairing potential

boundary conditions:

$$\partial_{\mathbf{n}} F_{f,s} = 0\,,$$

at outer surfases

interface between F & S metals

$$\sigma_s\, \partial_{\mathbf{n}} F_s = \sigma_f\, \partial_{\mathbf{n}} F_f;$$

$$F_s = F_f - \gamma_b \xi_n\, \partial_{\mathbf{n}} F_f$$

$$\xi_{s(n)} = \sqrt{D_{s(f)}/2\pi T_{c0}}$$

$$\gamma_b \xi_s = R_b \sigma_f$$

simplifications:

$$d = R_s - R_f \ll \xi_s$$

$$h \gg \pi T_{c0}$$

$$\mathrm{B} = \mathrm{rot}\,\mathbf{A}, \quad \mathrm{B} = \mathrm{H} + 4\pi \mathrm{M}$$

$$\Phi_M \sim 4\pi^2 R_f^2 M \ll \Phi_0$$

$$B \simeq H \qquad A_\theta = rH/2.$$

$$a_H = \sqrt{\Phi_0/2\pi H}$$

$$\phi = 2\pi r A_\theta/\Phi_0 = r^2/2a_H^2$$

Switching between the vortex states induced by proximity effect in SF hybrid structures. Zero external magnetic field.

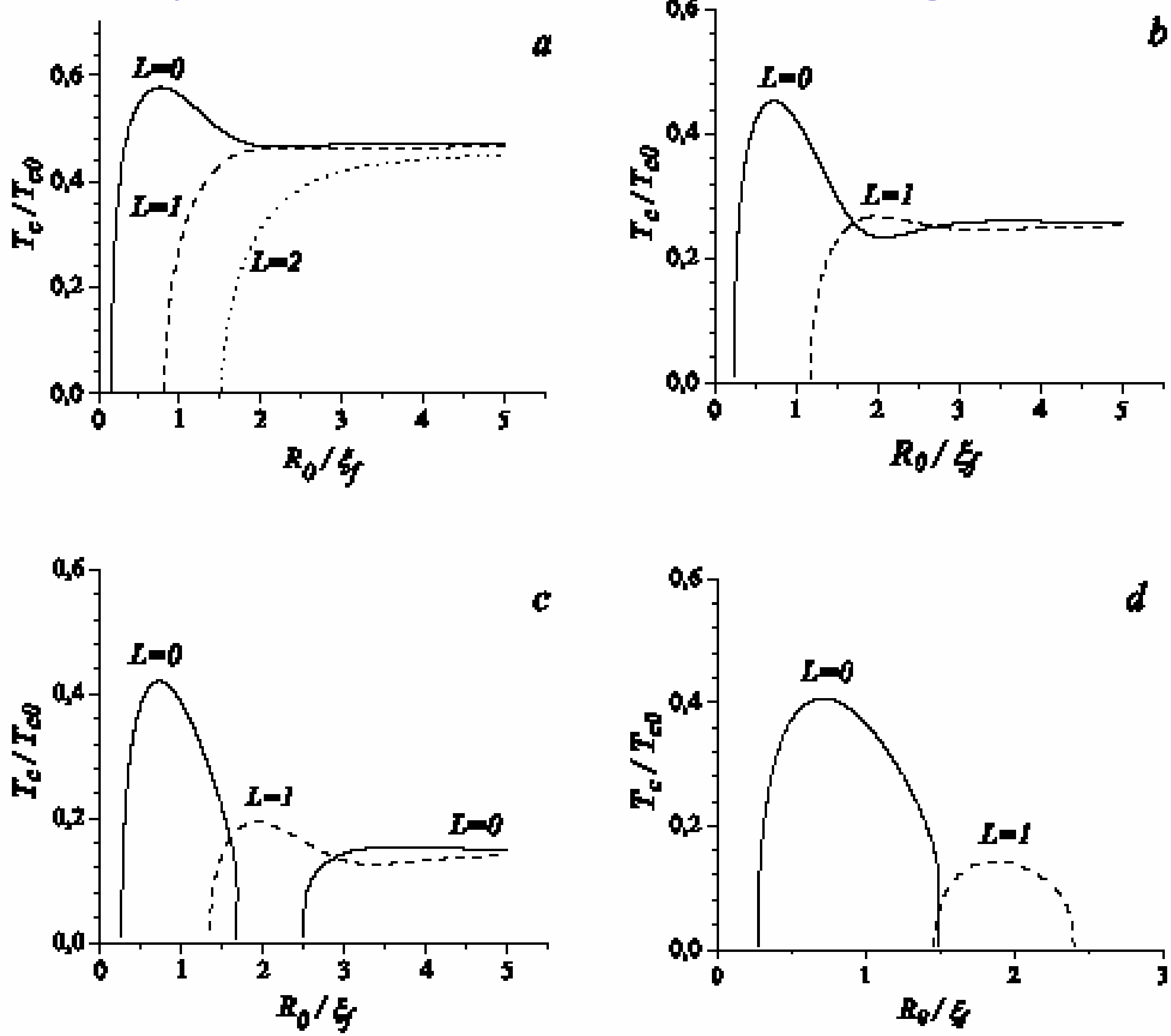


FIG. 6: The dependence of the critical temperature T_c on the S ring radius R_0 for different values of the vorticity $L = 0$ (solid line), $L = 1$ (dashed line) and , $L = 2$ (dotted line). Here we choose $d_s/d_f = 1$, $W = 0.5\xi_s$, $\xi_s/\xi_f = 0.1$: a) $\sigma_s/\sigma_f = 2.5$; b) $\sigma_s/\sigma_f = 2.1$; c) $\sigma_s/\sigma_f = 2.03$; d) $\sigma_s/\sigma_f = 2.0$

Switching between the vortex states in SF hybrid structures. Interplay between the orbital and exchange effects.

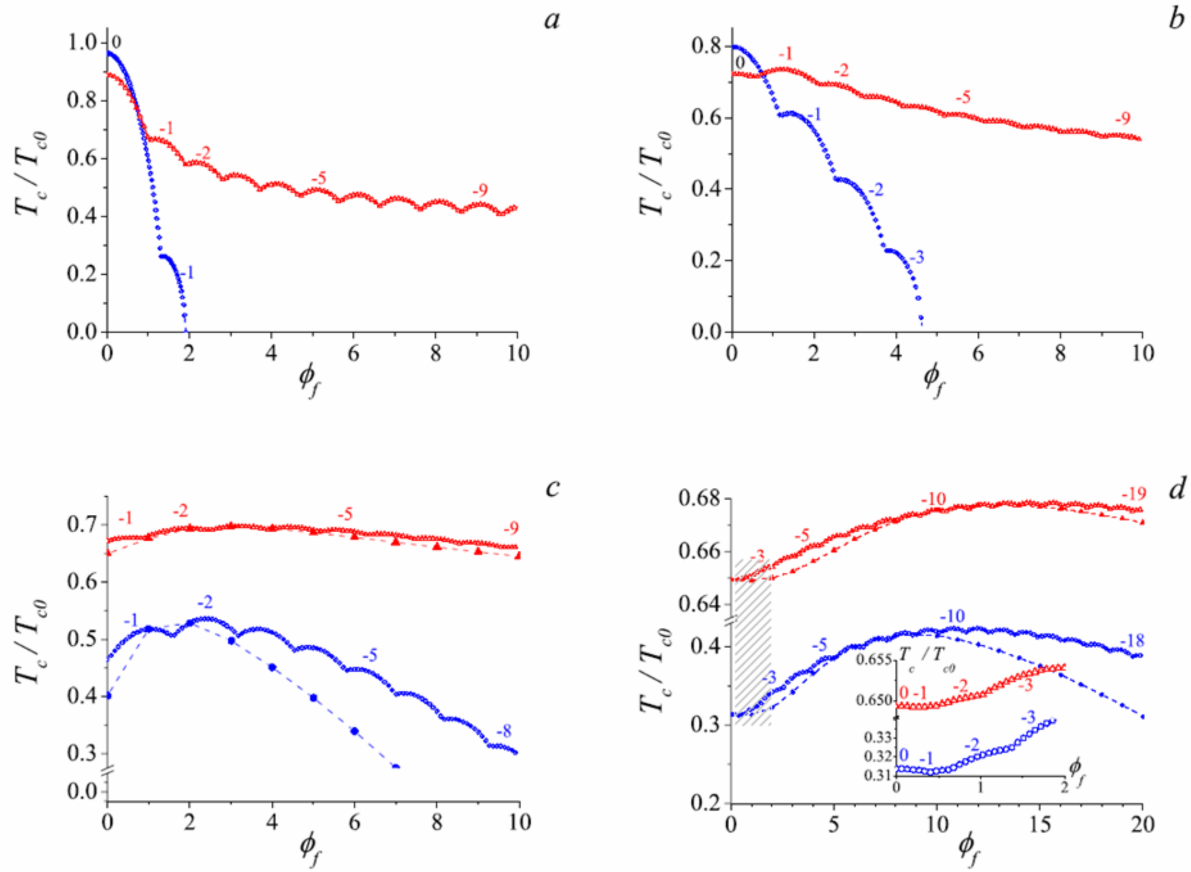
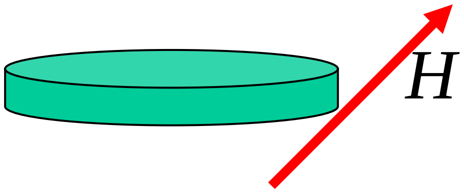


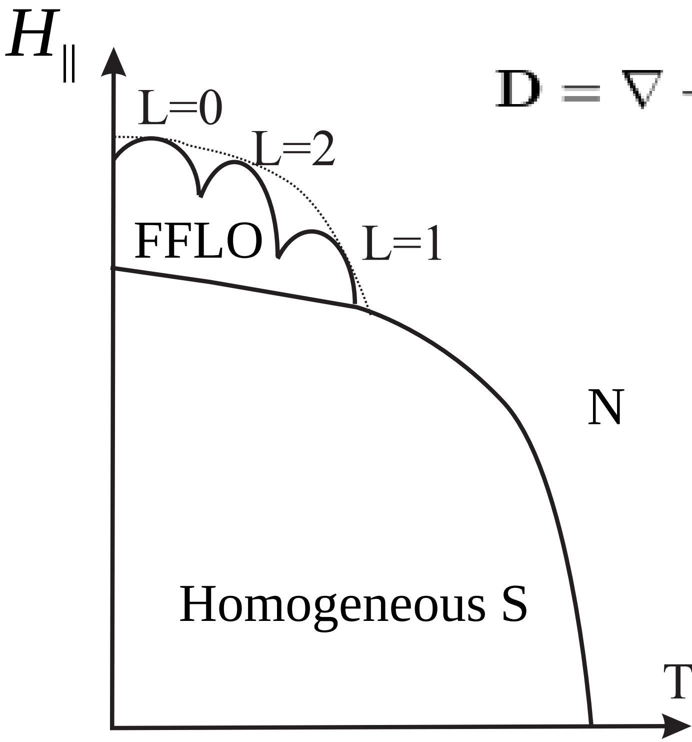
FIG. 3: (Color online) The typical dependences of the critical temperature T_c on the external magnetic field H for differen values of the interface resistance γ_b: $\gamma_b = 0$ (○); $\gamma_b = 0.2$ (△). The magnetic field H is measured in the units of the magneti flux ϕ_f enclosed in F cylinder. The numbers near the curves denote the corresponding values of vorticity L. Here we choos $W = 0.5\xi_s$; $\xi_s/\xi_f = 0.1$; $\xi_n/\xi_f = 4.0$; $\sigma_s/\sigma_f = 1$, and different values of the F cylinder radius $R_f/\xi_f =$ (a) 0.5, (b) 1, (c) 2 (d) 4. The inset in panel (d) gives the zoomed part of the $T_c(H)$ line, marked by the shaded box. The dashed lines in panel (c, d) are guides for eye which connect the points corresponding to the T_c values found for $\phi_f = -L$, when the orbital effect i the depairing parameter (17) is cancelled.

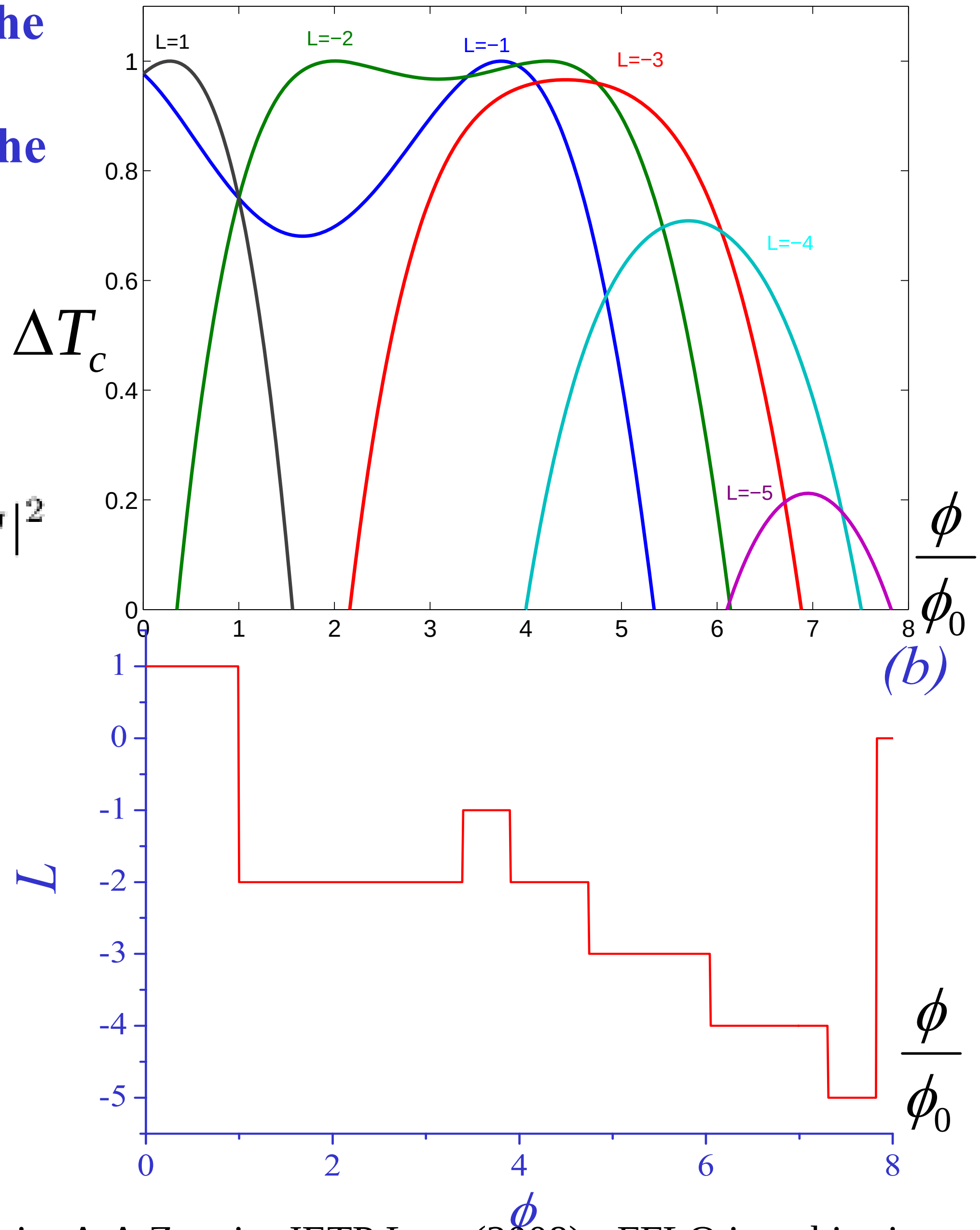
Switching between the vortex states in the FFLO phase in finite size samples. Another example of interplay between the orbital and exchange effects.



$$G = a|\Psi|^2 - \beta|\mathbf{D}\Psi|^2 + \gamma|\mathbf{D}^2\Psi|^2$$

$$\mathbf{D} = \nabla + \frac{2\pi i}{\Phi_0}\mathbf{A}_{\parallel}$$





A.Yu.Zyuzin, A.A.Zyuzin, JETP Lett. (2008) - FFLO in a thin ring

Results

Orbital mechanism.

Little-Parks effect for closed superconducting channels along the domain walls in FS bilayers and S films with magnetic dot arrays.

Exchange mechanism.

Switching between the vortex states induced by the exchange field