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Conference on Single Molecule Magnets and Hybrid Magnetic Nanostructures

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Ferromagnet-Superconductor Hybrids with Suppressed Proximity Effects

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Ferromagnet–superconductor hybrids

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Outline

- Introduction
- General formalism
- Single magnetic dot upon superconducting film
- Regular arrays of magnetic dots
- Array of magnetic dots with random magnetization
- Topological instability in the FS-bilayer

Introduction

Coexistence of ferromagnetism and superconductivity
In homogeneous systems: heavy fermions

Mutual suppression of order parameters

Heterogeneous FS systems – FS hybrids

1. FSH employing proximity effects

2.FSH with suppressed proximity

Interaction via magnetic fields

Even if magnetic field does not penetrate into superconductors,
the time-reversal symmetry is broken!

General formalism

Londons-Maxwell equations

$$H = \int \left[\frac{m_s n_s \mathbf{v}_s^2}{2} + \frac{\mathbf{B}^2}{8\pi} - \mathbf{BM} \right] d^3x$$

$$\mathbf{j}_s = e n_s \mathbf{v_s} = \frac{e\hbar n_s}{2m_s}\left(\nabla\varphi - \frac{2\pi}{\Phi_0}\mathbf{A} \right);\ \Phi_0 = \frac{\pi\hbar c}{e}$$ -- S-flux quantum

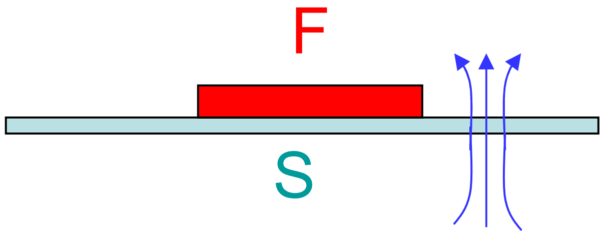
After some transformation

$$H = \int \left[\frac{n_s \hbar^2}{8m_s}(\nabla\varphi)^2 - \frac{n_s \hbar e}{4m_s c}\nabla\varphi\mathbf{A} - \frac{\mathbf{BM}}{2} \right] d^3x$$

Integration proceeds only over the volume occupied by ferromagnets and superconductors

Necessary conditions: fields and currents are zero at infinity

2d case



$$\mathbf{M}(\mathbf{r},z)=\mathbf{m}(\mathbf{r})\delta(z-d)$$

$$n_s(\mathbf{r},z)=n_s^{(2)}(\mathbf{r})\delta(z)$$

$$H=\int\left[\frac{n_s\hbar^2}{8m_s}(\nabla\varphi)^2-\frac{n_s\hbar e}{4m_s c}\nabla\varphi\mathbf{a}-\frac{\mathbf{bm}}{2}\right]d^2x$$

$$\mathbf{a}(\mathbf{r})=\mathbf{A}(\mathbf{r},z=0) \qquad \mathbf{b}(\mathbf{r})=\mathbf{B}(\mathbf{r},z=d)$$

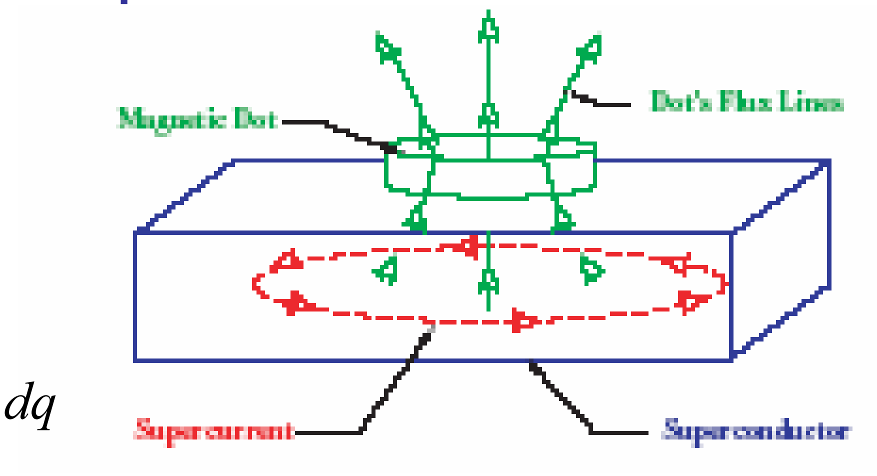
Gauge: $A_z=0$

Phase only due to vortices: $\nabla\varphi(\mathbf{r},\mathbf{r}_0)=q\dfrac{\hat{z}\times(\mathbf{r}-\mathbf{r}_0)}{|\mathbf{r}-\mathbf{r}_0|^2}$

Variables: positions of vortices, *direction of magnetization?*

Single magnetic dot upon S-film

Perpendicular magnetization



$$m_z = m\delta(z)\theta(R-r)$$

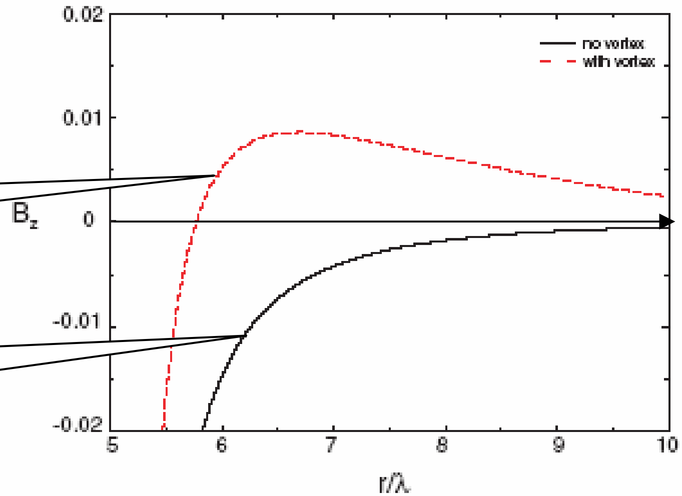
$$B_m^z(r,z) = 4\pi\lambda m R \int_0^\infty \frac{J_1(qR)J_0(qr)e^{-q|z|}}{1+2q\lambda} q^2 dq$$

$$B_m^r(r,z) = 2\pi m R \int_0^\infty J_1(qR)J_1(qr)e^{-q|z|}\left[\frac{2q\lambda}{1+2q\lambda}\theta(z)+\theta(z-d)-\theta(z)\right] q dq$$

B_z vs. distance

With vortex

Without vortex

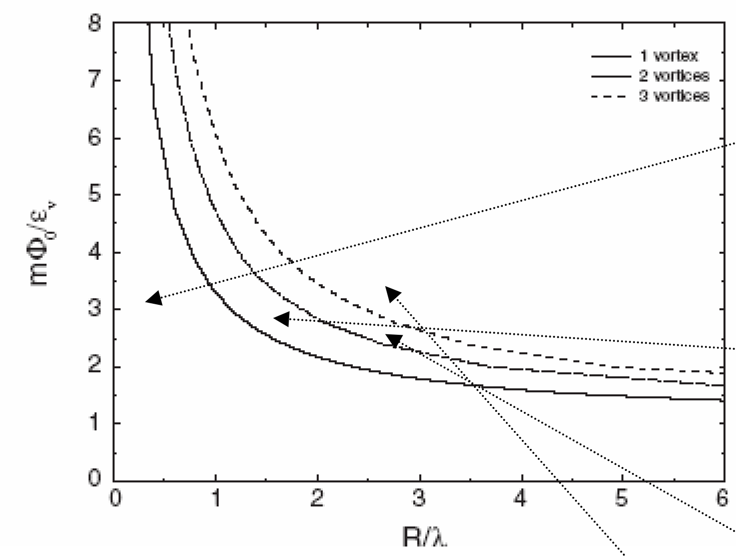


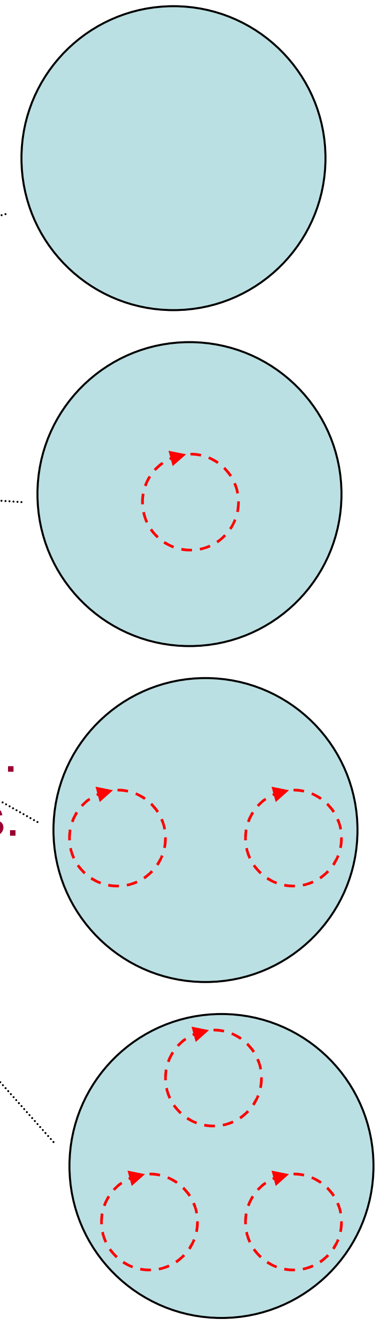
Change of sign can be used for diagnostic of vortex state

Phase Diagram

$$\varepsilon_v = \frac{\Phi_0^2}{16\pi^2\lambda}\ln\frac{\lambda}{\xi}$$

$$\lambda = \frac{\lambda_L^d}{d_s}$$





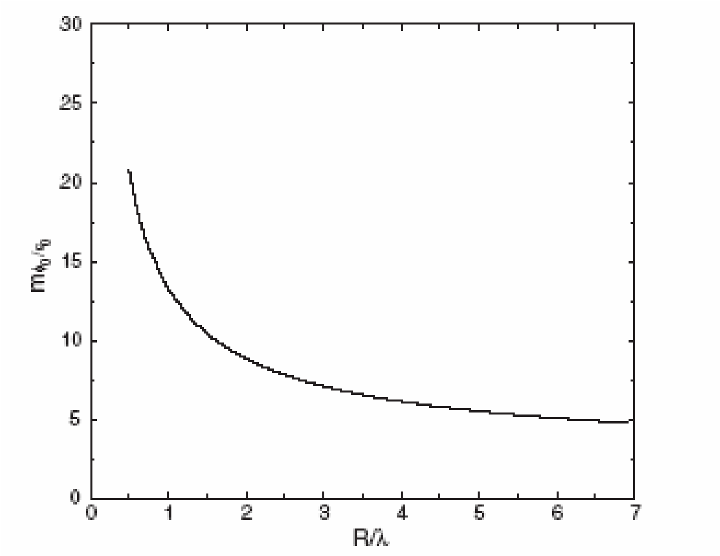
Phase diagram of a circular F-dot upon an S-film.
Lines correspond to appearance of 1, 2 or 3 dots.

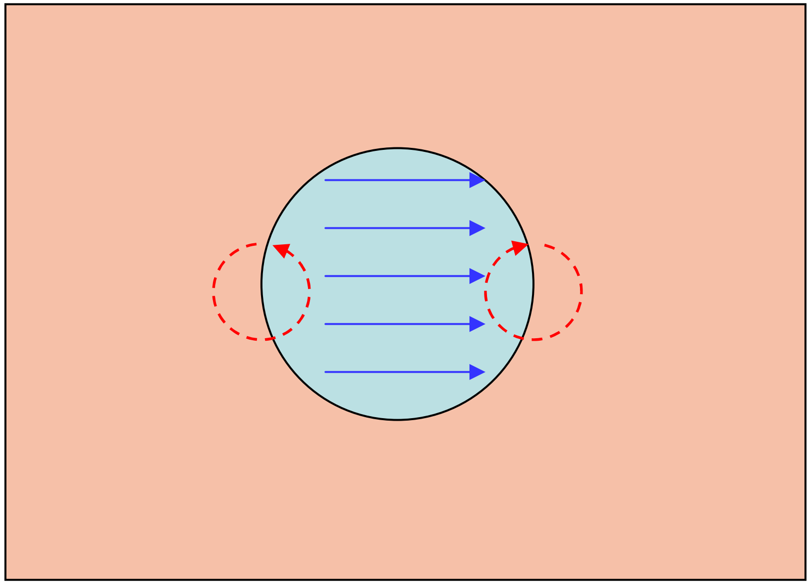
$$\text{Small } R \ll \lambda \Rightarrow \frac{mR}{\Phi_0} = const$$

$$\text{Large } R \gg \lambda \Rightarrow \frac{m\Phi_0}{\varepsilon_v} = \text{int}$$

Single magnetic dot upon S-film

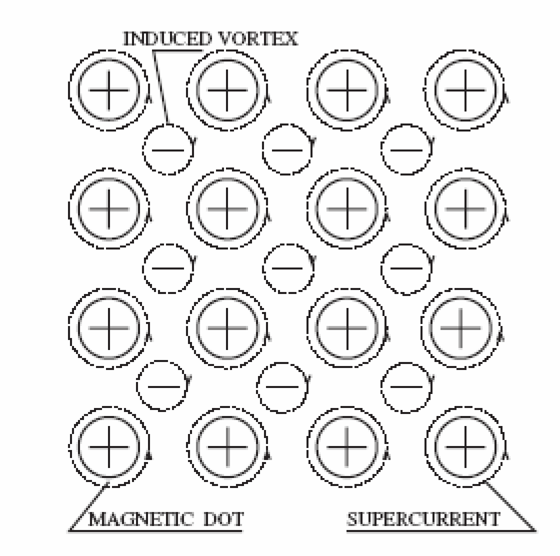
Parallel magnetization





Vortex and antivortex are centered at the opposite ends of the dot diameter

Regular arrays of magnetic dots



Total flux from a dot is zero

Vortices under dots, antivortices in interstitial positions

Strong pinning by dots, weaker for antivortices.

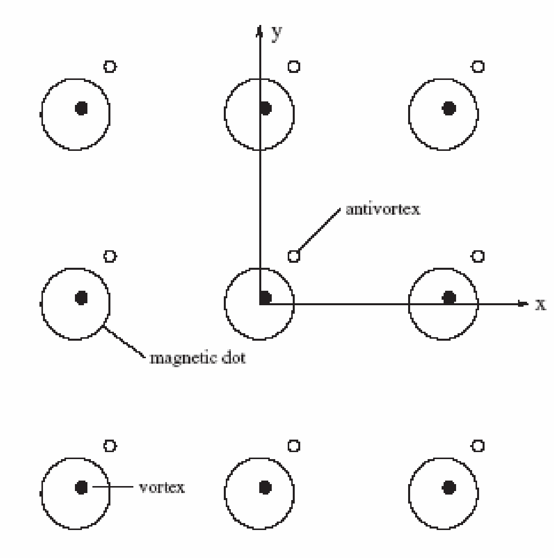
Calculation of the field generated by periodic array:

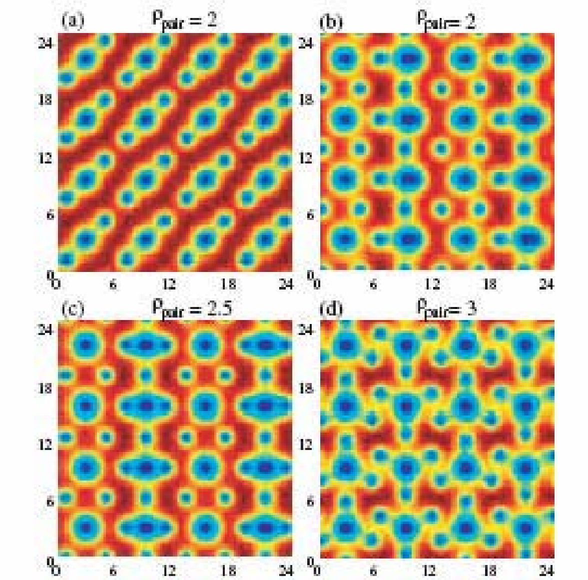
$$\mathbf{B}_m(\mathbf{G}) = \mathbf{B}_{sd}(\mathbf{q})\big|_{\mathbf{q}=\mathbf{G}}$$

$\mathbf{G}$ -vectors of reciprocal lattice

$$\mathbf{B}_s(\mathbf{G}) = \mathbf{B}_v(\mathbf{G})\left(1 - e^{i\mathbf{G}\mathbf{r}_{av}}\right)$$ ← formfactor

Spontaneous violation of lattice symmetry



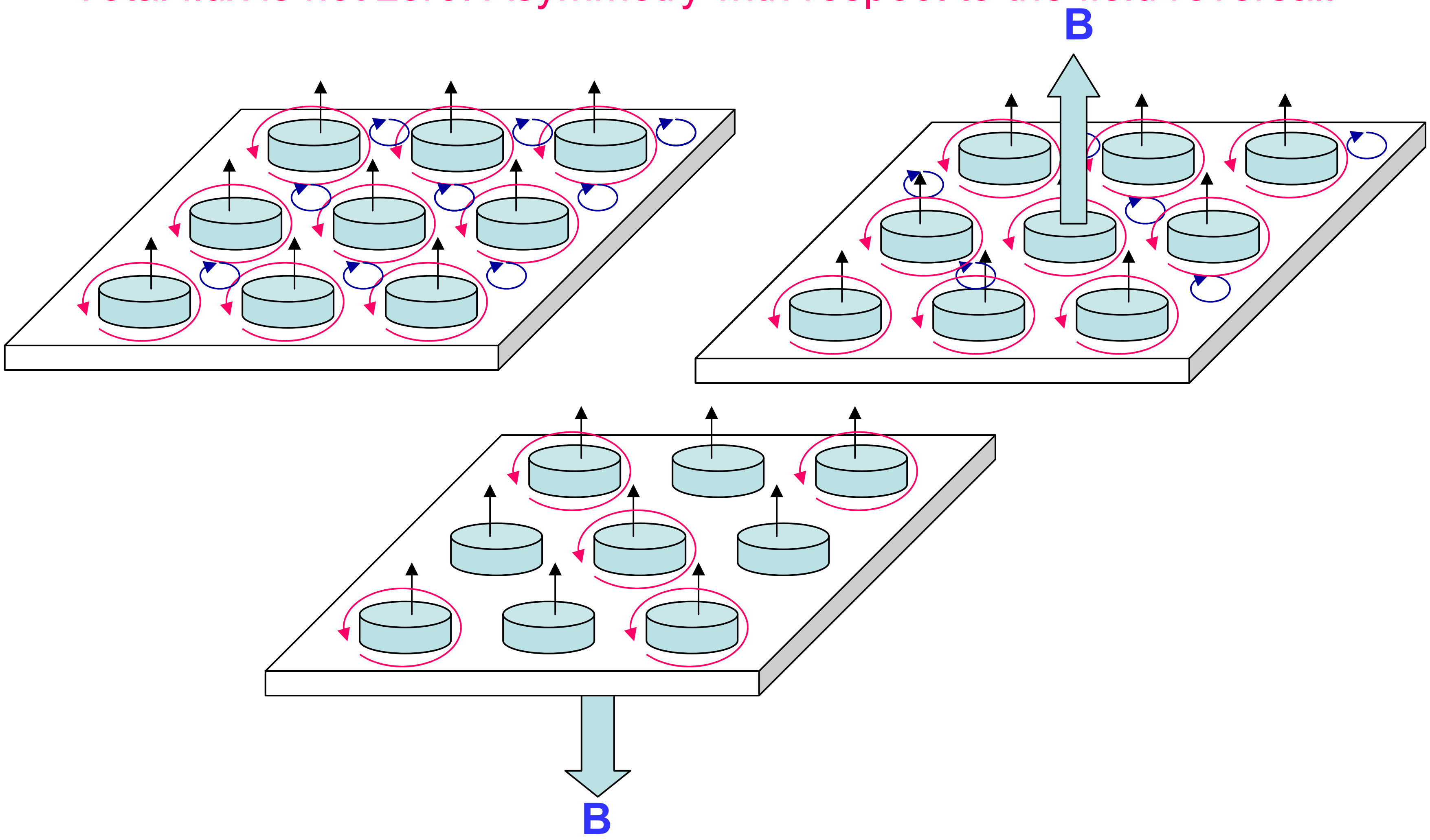


Top view of the square vortex Array with broken symmetry. Symmetry is broken at small ratio R/L<0.2. Violation of Symmetry is weak (less than 10%)
(S. Erdin, 2004).

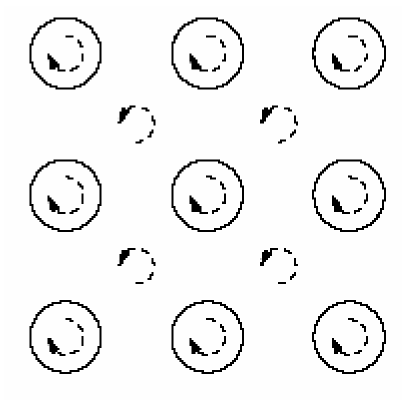
Density plots of the GL parameter Large dark spots are dots and vortices under them. Small dark spots between the dots are the antivortices. The flux under the dot is 4.10, 4.62, 4.91 and 5.62 flux quanta.
(Prior and Reftig, 2004)

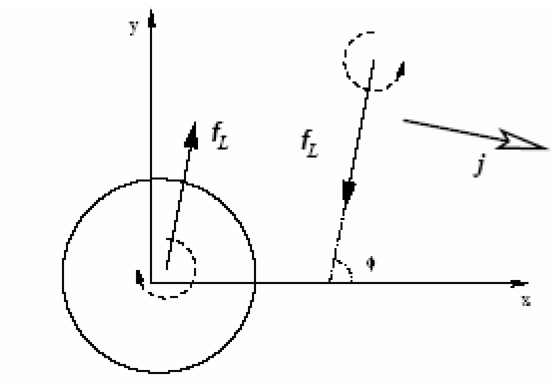
Regular dot arrays and external magnetic field

Total flux is not zero. Asymmetry with respect to the field reversal.

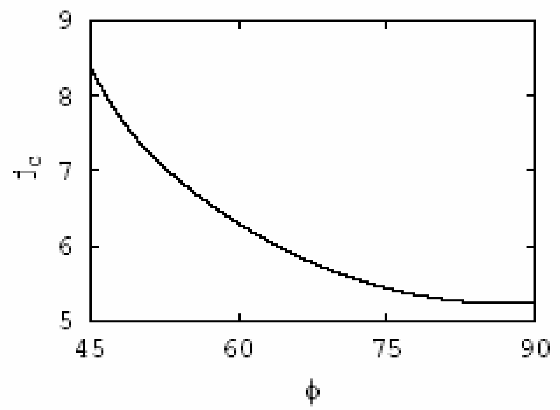


Critical currents





$$\mathbf{f}_L = \frac{\Phi_0}{c} \hat{z} \times \mathbf{j}$$



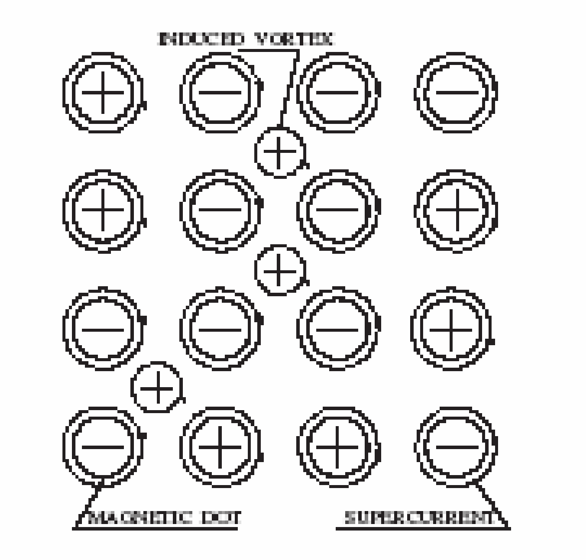
The critical current j_c vs. angle ϕ. j_c is in the unit of $\frac{mRc}{20a^2}$.

$$j_c \sim 10^6\, A/cm^2$$

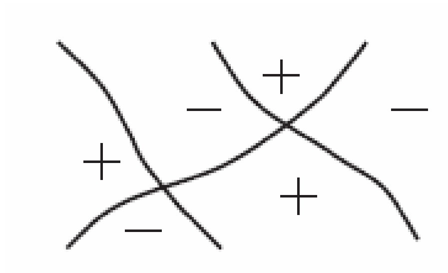
At critical current Lorenz force is equal to maximal periodic pinning force.

H. Wei, Phys. Rev. B, 2005

Array of magnetic dots with random magnetization



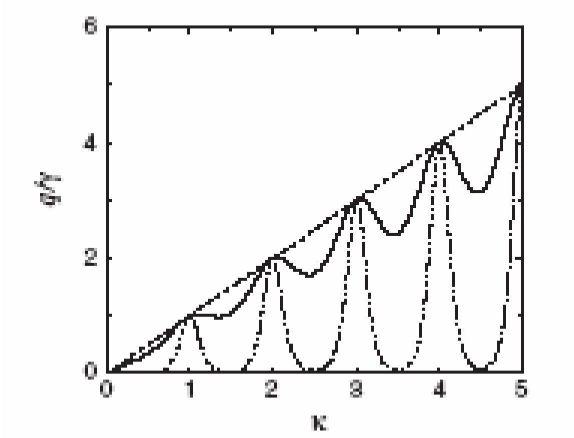
Random fields from vortices create deep random potential wells in which new vortices can appear – random checkerboard



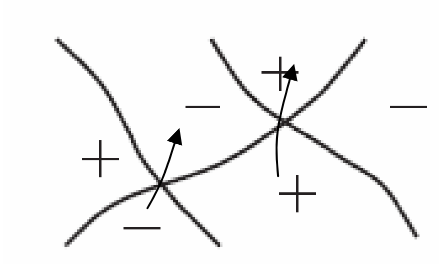
Vortices and antivortices form a dense inhomogeneous plasma to screening the random potential wells

Strong neutrality condition: sum of "charges" in each cell of the checkerboard cannot deviate from zero more than by few units

Oscillations of the occupation numbers of interstitial vortices

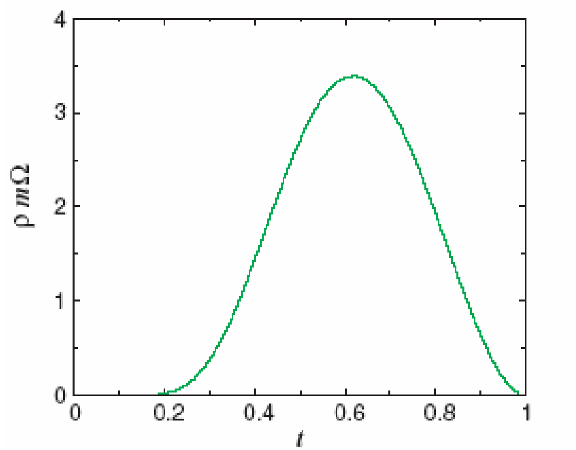


$$\kappa = \frac{m\Phi_0}{\varepsilon_v}$$



Saddle points are bottlenecks for the current flow

They are a consequence of strong neutrality and discreteness of charge

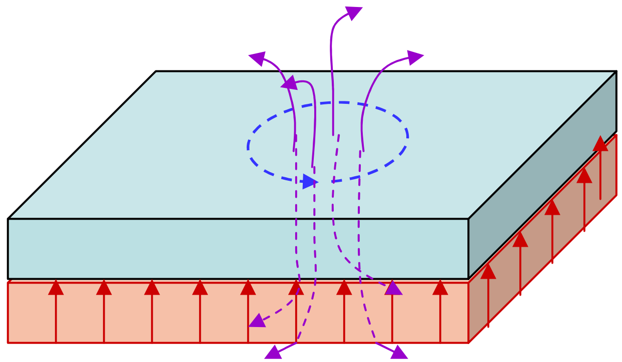


Static resistance vs. reduced temperature

D. Feldman, I. Lyuksyutov, V. Pokrovsky, V.Vinokur, 2002

Topological instability in FS-bilayer

I.Lyuksyutov and V. P., 1998



No magnetic field outside the F-layer (magnetic condenser)

$$\Delta\varepsilon = \varepsilon_v^{(0)} - m\Phi_0$$

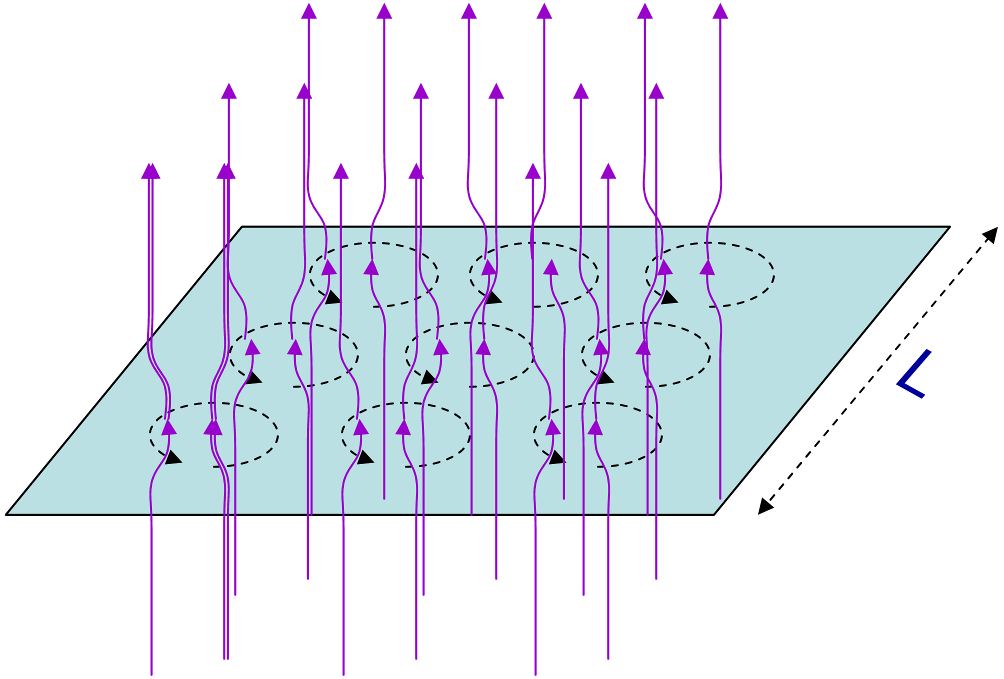
$$\varepsilon_v^{(0)} = \frac{\Phi_0^2}{16\pi^2\lambda} = \frac{\pi\hbar^2 n_s d_s}{4m_s}$$

Vortices proliferate if $\Delta\varepsilon<0$

The criterion is satisfied near transition temperature since $n_s \to 0$

Possible lower critical temperature for the vortex phase T_v

What the vortex phase looks like?

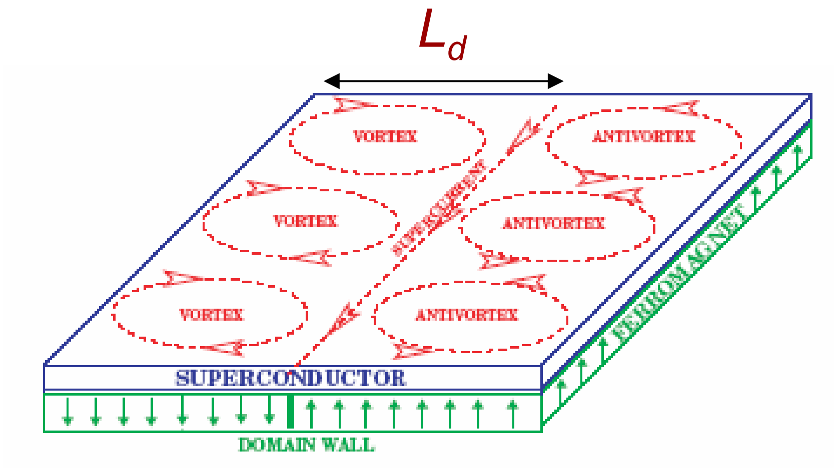


Any constant vortex density generates magnetic field in space $B_z = n_v \Phi_0$

Total energy: $E = n_v \Delta\varepsilon L^2 + \frac{B_z^2}{8\pi} L^3$

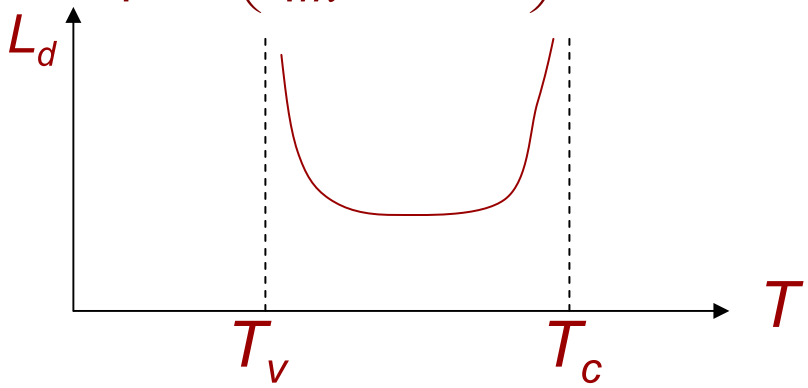
Positive in the thermodynamic limit!

Resolution of the paradox: domains



Coupled magnetic and superconducting domain walls

$$L_d = \frac{\lambda}{4}\exp\left(\frac{\varepsilon_{dw}}{4\tilde{m}^2} - C + 1\right); \qquad \tilde{m} = m - \frac{\varepsilon_v}{\Phi_0}$$

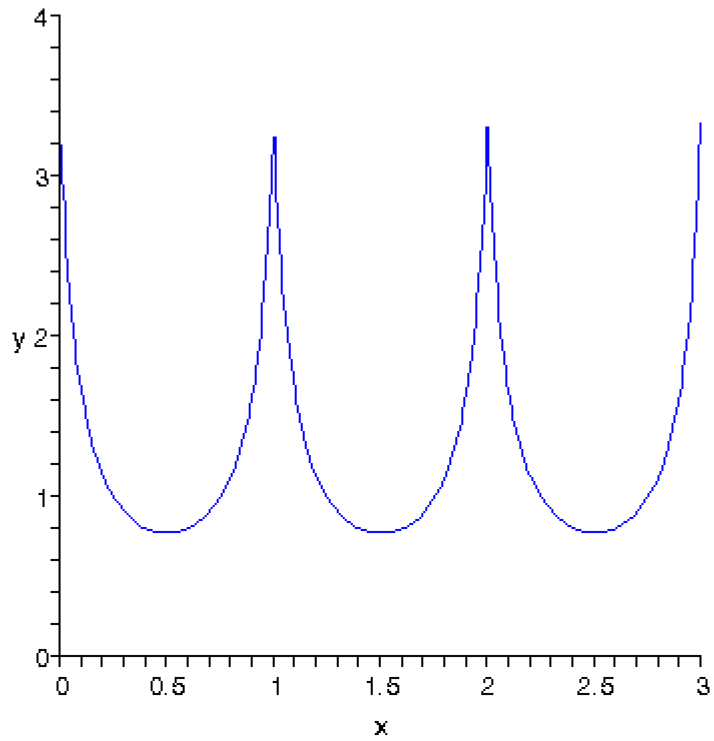


Density of vortices is strongly inhomogeneous

$$n(x) = \frac{n_0}{\sin \frac{\pi x}{L_d}}$$

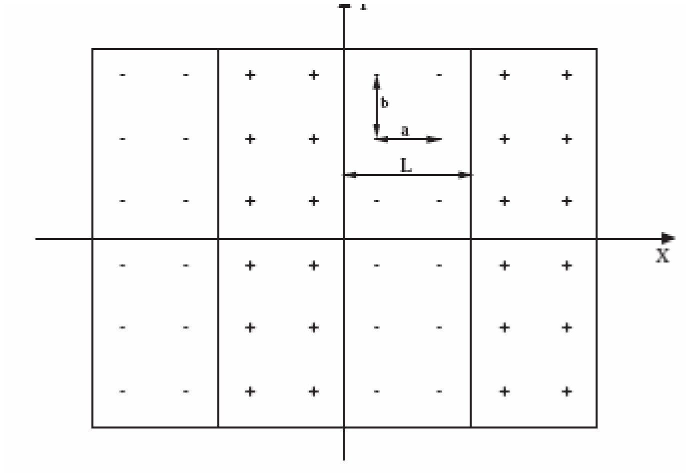
$$n_0 = \frac{4\pi\varepsilon_v}{\Phi_0^2 L_d}$$

$$y = \frac{n(x)}{n_0}$$



S. Erdin, I. Lyuksyutov, V. Pokrovsky, and V. Vinokur, 2002

Anisotropy of critical current



Schematic distribution of vortices in the FSB

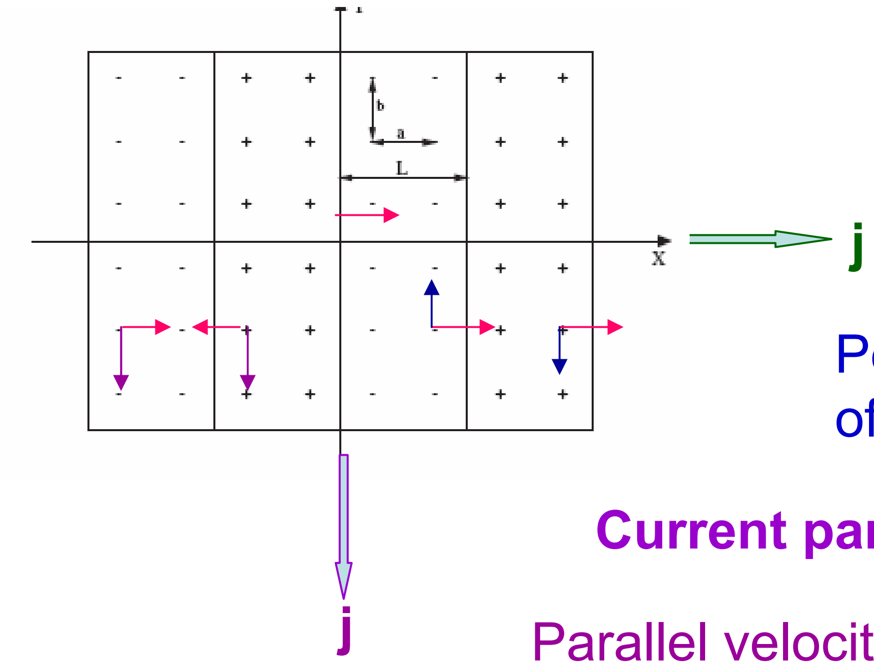
Equation of motion: $\mathbf{f} = \mathbf{f}_v + \mathbf{f}_M + \mathbf{f}_p = 0$

$\mathbf{f}_v = -\eta \mathbf{v}$ - viscous force; $\mathbf{f}_p$ - periodic pinning force

$\mathbf{f}_M = \pi \hbar n_s d_s \hat{z} \times (\mathbf{v} - \mathbf{v}_s)$ - Magnus force

$\mathbf{j} = e n_s \mathbf{v}_s$ $\eta = \dfrac{\Phi_0 H_{c2} d_s}{\rho_n c^2}$ -Bardeen-Stephen drag coefficient

Current perpendicular to domains



Parallel velocities of vortices and antivortices are equal

Domain walls move with the same speed. Quasi-Goldstone mode

Perpendicular to current components of velocity are opposite for v and av

Current parallel to domains

Parallel velocities of v and av are equal

Perpendicular to current components of velocity are opposite for v and av

Domain walls do not move. Much stronger pinning.

Conclusions

• Interaction between F and S subsystems via magnetic field is strong enough to change drastically their properties

• Even if the F-system does not generate magnetic field outside, the time reversal symmetry is broken

• Thin magnetic dots upon S-film can generate vortices. There are phase transitions between the states with different number of vortices In the plane of 2 dimensionless variables $m\Phi_0$ and R/λ

• Regular array of magnetic dots produces a regular array of vortices and antivortices. The symmetry of the latter lattice may be different than the symmetry of the dot lattice.

• In external magnetic field additional vortices appear. Generally the vortex lattice is incommensurate with the dot lattice. At commensurate values of magnetic field critical current and resistance have peaks.

• FS-bilayer is unstable to the spontaneos vortex generation followed by appearance of coupled domains in F and S layers. The domains form a stripe structure introducing strong anisotropy in the transport properties

Participants

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