Vortices in superconductors
IV. Hybrid systems

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Magnetic impurities

$T_c$ decreases with increasing impurity density

Origin: *exchange interaction* between electron and impurity: $\Gamma (\mathbf{r}_i-\mathbf{r}_e) \mathbf{S}_i \cdot \mathbf{s}_e$

the two electrons of a Cooper pair have opposite *spins* $\rightarrow \Gamma$-coupling acts with opposite sign

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Magnetic field

Transition temperature decreases with increasing magnetic field

Origin: orbital effect: $(\mathbf{p} \cdot \mathbf{A} + \mathbf{A} \cdot \mathbf{p})/2m$

the two electrons of a Cooper pair have opposite *momentum* $\rightarrow$ orbital effect acts with opposite sign
Nanostructured ferromagnets + superconducting film


Ferromagnets \(\rightarrow\) create inhomogeneous magnetic fields with \(<H>=0\)
- will locally destroy superconductivity \(\rightarrow\) pinning centra
- \(<H>\) \(\rightarrow\) vortex/antivortex pairs can be created
Single magnetic disk on top of a superconducting film
Superconducting Wigner vortex molecule
Single magnetic dot on top of a SC film


Evolution of vortex-antivortex configurations with increasing $m$ – the *baby* vortex-antivortex pair
The equilibrium vortex phase diagram: solid lines illustrate transitions between different vortex configurations for different size ($R_d$) and magnetic moment ($m$) of the dot. Dashed lines denote the formation of a new ring of anti-vortices. $N$ is the number of the anti-vortices involved. Note that the total vorticity is always equal zero. In shaded area, the multivortex state under the dot is energetically favorable (giant vortex splits into individual vortices).
Magnet geometry imposed vortex-antivortex configurations
The ferromagnet-vortex interaction

\[ U_{mv} = \frac{1}{2c} \int \left[ \vec{j}_m \cdot \vec{\Phi}_v \right] d\nu^{(1)} - \frac{1}{2} \int \left[ \vec{h}_v \cdot \vec{M} \right] d\nu^{(fm)} \]

Out-of-plane magnetized FM – vortex interaction

- Vortex *attracted* by the disk for the parallel magnetization-vortex orientation and vice-versa, independently on the parameters*

* Found for magnetic disks, all regular polygons, triangles, squares, etc.

\[ m/m_0 = 10.0 \]

\[ d/\lambda = 0.5 \]

\[ x/\lambda = \{ -0.9000, -0.8100, -0.7200, -0.6300, -0.5400, -0.4500, -0.3600, -0.2700, -0.1800, -0.0900 \} \]

\[ y/\lambda = \{ -2, -1, 0, 1, 2 \} \]
A regular lattice of Ni magnetic dots, with \( R_d = 60 \text{nm} \), \( d_d = 110 \text{nm} \), under a 95nm thick Nb film.
Asymmetric flux pinning

Strong pinning

\( \overrightarrow{H_0} \uparrow \quad \overrightarrow{m} \)

\( H_1 \quad H_2 \quad H_3 \quad H_4 \)

Weak pinning

\( \overrightarrow{H_0} \downarrow \quad \overrightarrow{m} \)

\( H_{-1} \quad H_2 \quad H_3 \)
Asymmetric flux pinning

A square lattice of 400nm x 400nm Co/Pt magnetic dots, under a 50nm thick Pb film

Field-polarity dependent pinning by in-plane magnets

Larger magnetization – magnet induces a vortex-antivortex pair

vortex - antivortex attraction vs. vortex - magnet interaction
Field polarity dependent flux pinning by in-plane magnetic dipoles

A regular lattice of 540nm x 360nm Co magnetic dipoles, under a 50nm thick Pb film

$H_{\text{ext}} = 0$

$H_{\text{ext}} = H_{1/2}$

Field polarity & magnetization dependent flux pinning

\[ \frac{d}{\lambda} = 0.5 \]
\[ \frac{D}{\lambda} = 0.35 \]
\[ \frac{S_y}{\lambda^2} = 4.86 \]
\[ \frac{t}{\lambda} = 0.2 \]
Vortex-Antivortex Ionic Crystals in Superconducting Films with Magnetic Pinning Arrays

\( a/\xi = 2.0 \)
\( D/\xi = 2.0 \)
\( l/\xi = 0.1 \)
\( d/\xi = 0.2 \)
\( \kappa = 1.2 \)
Effects of the applied homogeneous magnetic field on the critical parameters
Magnetic-field-enhanced critical current

\[ \frac{J_c}{J_0} - \frac{M}{H_{c2}} \]

- \( \text{H}_{\text{ext}} = 0 \)
- \( \text{H}_{\text{ext}} = \text{H}_1 \)

- \( L/y = 6.25 \)
- \( a/y = 2.0 \)
- \( D/y = 2.0 \)
- \( l/y = 0.1 \)
- \( d/y = 0.2 \)
- \( l = 1.2 \)
Magnetic-field-induced superconductivity

A square lattice of 800nm x 800nm Co/Pd magnetic dots, on top of the 85nm thick Pb film


\[ \Phi^+/\Phi_0 = 2.28 \]

\[ H/H_1 = 0 \]

\[ H/H_1 = 2 \]
Magnetic-field-induced superconductivity (theory vs. experiment)
- Critical field enhancement by magnetic nanostructuring

*M Same qualitative behavior observed for $\Phi^+/\Phi_0 = 2.21 - 3.22$
Summary

• Magnets with out-of-plane magnetization attract parallel aligned vortices, and vice versa. The origin of the magnetic pinning of vortices lies in the interactions with the Meissner currents.

• In the case of a regular array of weakly magnetized dots we found matching configurations (both integer and rational). Asymmetric flux pinning is explained, depending on the polarity of the external field.

• For a superconducting film with a single magnetic disk on top, the total vorticity always equals zero - a central core of vortices (under the disk) is surrounded by antivortex shells → Wigner vortex molecule, with size-magnetization-controlled “magic numbers”.

• For stronger magnetized dots, their stray field perturbs the order parameter in the vicinity of the dots. Regular vortex-antivortex lattices are formed, with vortices under the dots and antivortices at interstitial sites → First and second order configurational transitions, fractional vortex-antivortex states, lattice effects on the vortex nucleation, …

• External flux lines compensate the existing antivortices in the sample → external-field-enhanced critical current and critical field. Therefore, magnetic nano-engineering, and local defining of the magnetic field in the sample is a powerful tool for controlling the critical parameters of the superconductor.