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Vortex patterns in Intertype Superconductivity Regime in Thin and Nanowire superconductors

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School of Electronic Engineering

Supervisor:
Ass.Prof. Andrey S. Vasenko .

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Вихревые структуры в интертипном режиме сверхпроводимости в тонких плёнках и нанопроводах

Уилмер Йесид Кордоба Камачо

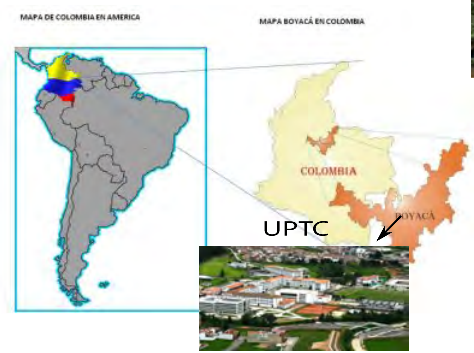
Education

- **(2014-2018) PhD in Physics** : Federal University of Pernambuco (Recife-Brazil)
- **(2012-2014) M.Sc in Physics** : Federal University of Pernambuco (Recife-Brazil)
- **(2007-2011) Bachelor in Physics** : Pedagogical and Technological University of Colombia (Tunja-Colombia)

Brazil: Pernambuco state, Recife

Colombia

- http://www.colombia.travel/en



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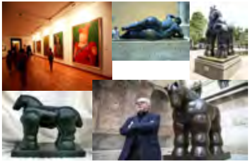


I am thankful to my coauthors

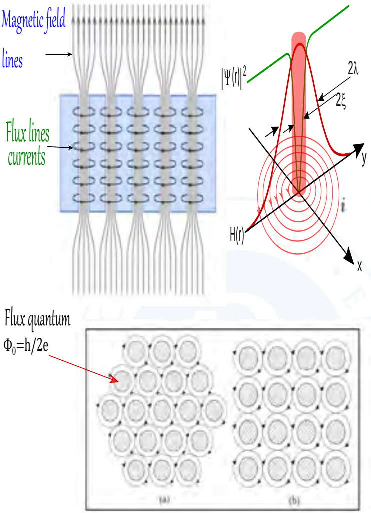
- José Albino Aguiar (UFPE-Brazil)
- Arkady Shanenko (UFPE-Brazil)
- Alexei Vagov (UB-Germany)
- Rogério M. da Silva (UFPE-Brazil)
- A.S. Vasenko (HSE-Russia)

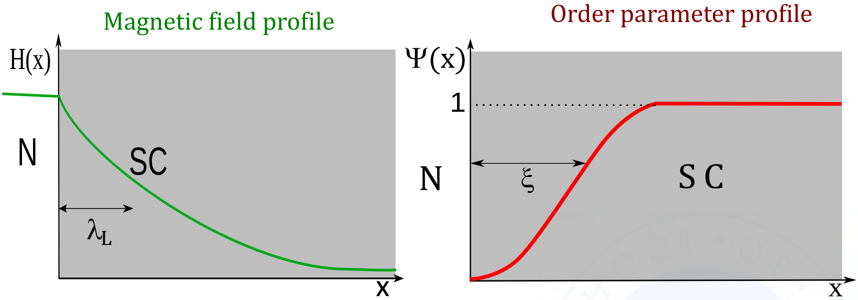
Outline

The Ginzburg-Landau theory distinguishes two types of superconductivity

- Ideally diamagnetic type-I (only diamagnetic currents, the Meissner state)
- And type-II, where a magnetic field can penetrate the superconducting condensate in the form of Abrikosov lattice of vortices

A.A. Abrikosov(1957)



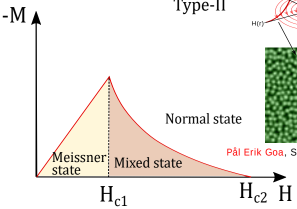


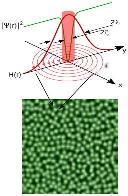
The distinction between types I and II is quantified through the ratio of the magnetic penetration depth to the coherence length, i.e., the Ginzburg-Landau parameter.

$$\kappa = \lambda/\xi \Rightarrow \begin{cases} < 1/\sqrt{2} & \text{type-I} \\ > 1/\sqrt{2} & \text{type-II} \end{cases}$$

A.A. Abrikosov(1957)

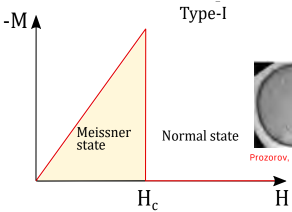
Type-II

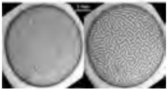




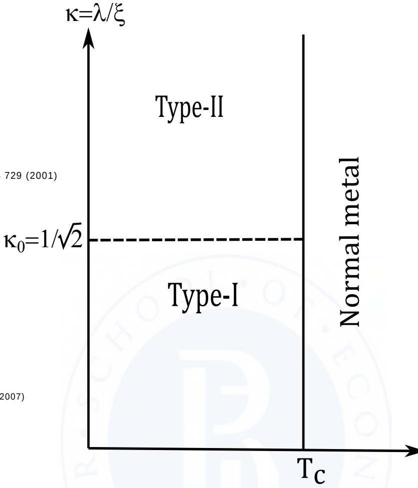
Pål Erik Goa, Supercond. Sci. Technol. 14 729 (2001)

Type-I

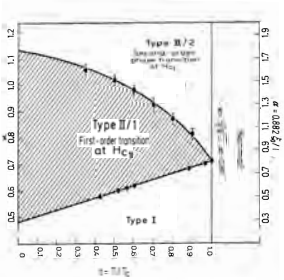


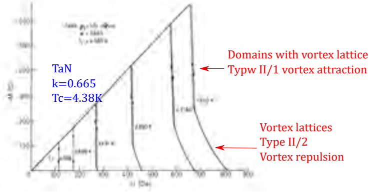


Prozorov, Phys. Rev. Lett. 98, 257001 (2007)



$$H_c(T) = \frac{\Phi_0}{2\sqrt{2}\lambda(T)\xi(T)}, \qquad H_{c1}(T) = \frac{\Phi_0}{4\pi\lambda^2(T)}\ln(k) = \frac{H_c(T)\ln(\kappa)}{\sqrt{2}\kappa}, \qquad H_{c2} = \frac{\Phi_0}{2\pi\xi^2(T)} = \sqrt{2}\kappa H_c. \tag{1}$$





J. Auer and H. Ullmaier, Phys. Rev. B 7, 136 (1973).

Intertype domain in bulk single-band superconductors

Since 1970's it is believed that the intertype mixed state in the lattice of Abrikosov vortices. The difference from type II is **non-monotonic vortex interaction** (long-range attraction and short range repulsion),

U. Krägeloh, Phys.Lett. A 28,657 (1969).
U. Essmann, Physica 55, 83 (1971).
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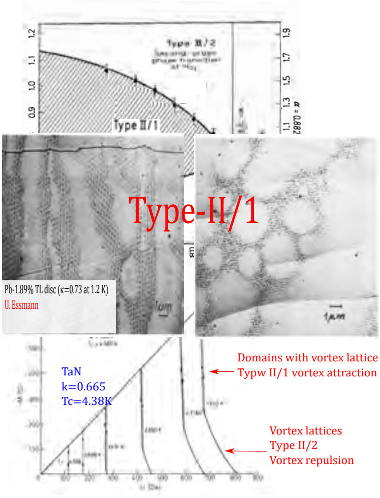
A. E. Jacobs, Phys. Rev. Lett. 26. 629 (1971).

Intertype Superconductivity



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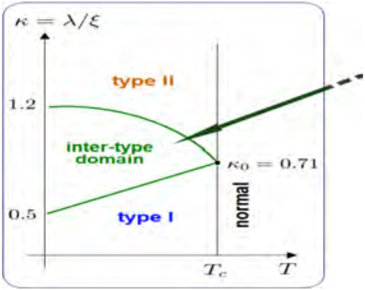

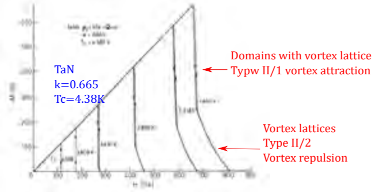

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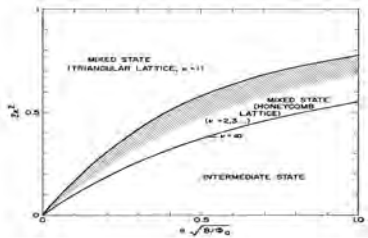
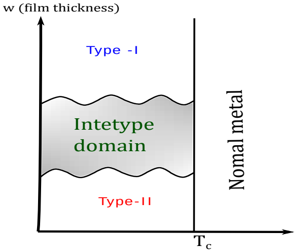
Linearized GL equations

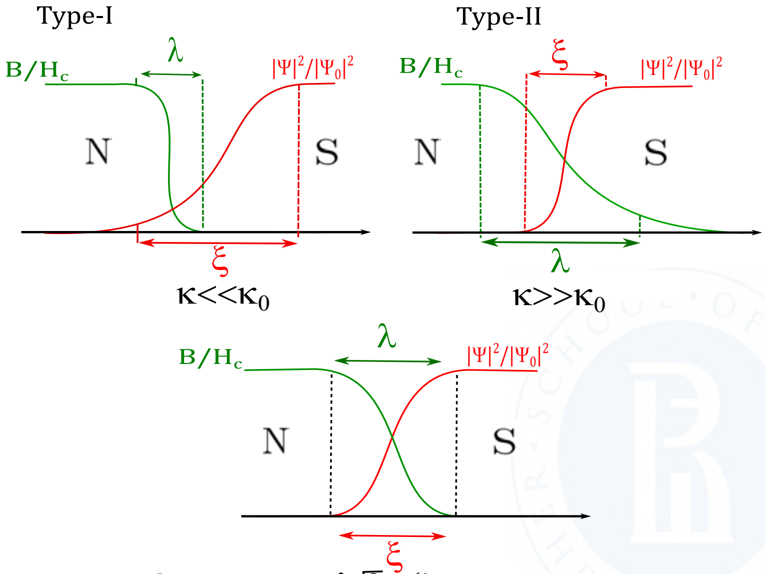


G. Lasher, Phys. Rev. 154,345, (1967).

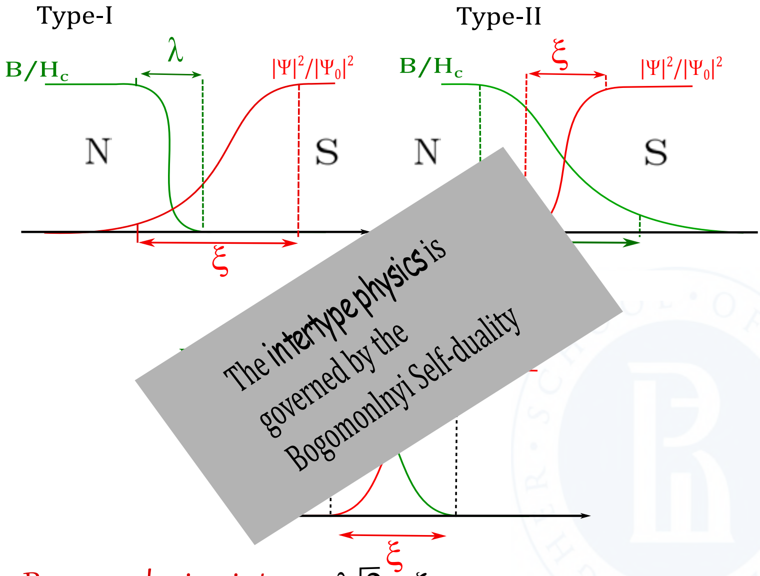


- Films made of type-I materials exhibit type-II behavior in a perpendicular magnetic field for small thicknesses.
- Switching between types occurs through the inter-type domain of film thicknesses
- The intertype domain is present but its boundaries are not well established.

M. Tinkham, Phys. Rev. 129,2413 (1963).
k. Maki, Ann. Phys. 34, 363 (1965).
G. Lasher, Phys. Rev. 154,345, (1967).
U. Essmann, Physica 55, 83 (1971).
G. J. Dolan, J. Silcox, Phys. Rev. Lett 30, 603 (1973).
S. Hasegawa et al., Phys. Rev. B. 43. 7631(1991).
H. Palonen et al. J. Phys,: Condens. Matter, 25.385702 (2013).



Bogomonlnyi point $\lambda\sqrt{2} = \xi$



Bogomonlnyi point $\longrightarrow \lambda\sqrt{2} = \xi$

Bogomolnyi self-duality equations

GL-equation

$$\alpha\Psi + \beta\Psi|\Psi|^2 - K\mathbf{D}^2\psi = 0, \qquad \mathbf{B} = (0,0,B) \quad B = H_c$$

$$\Pi^{\pm} = D_x \pm iD_y, \quad \mathbf{D}^2 = \Pi^+\Pi^- - \frac{2\pi}{\Phi_0}B$$

Bogomonlnyi point: local relation between the spatial profiles of the condensate and magnetic field

$$a\Psi + b\Psi|\Psi|^2 - K\Pi^+\underbrace{\Pi^-\Psi}_{=0} - \frac{2\pi}{\Phi_0}KB\psi = 0$$

Bogomolnyi self-duality equations (duality of the magnetic induction and condensate density) $=$

$$\Pi^-\Psi = 0, \qquad \frac{|\Psi|^2}{|\Psi_0|^2} = 1 - \frac{B}{\sqrt{2}\kappa H_c} \Rightarrow$$

$$\kappa = 1/\sqrt{2} \qquad \Pi^-\psi = 0$$

$$\psi = \Psi/\Psi_0, \qquad \mathfrak{B} = B/H_c \qquad |\psi|^2 = 1 - \mathfrak{B}$$

E. B. Bogomolnyi, Sov. J. Nucl. Phys. 24, 449 (1976)

Infinite topological degeneracy:

- Mixed states are infinity degenerate $\mathcal{G} = 0$
- Critical behavior-vortices do not interact
- Infinite number of different flux/condensate

Nonlocal effects (those beyond the Ginzburg-Landau theory)

Nonlocal effects are enhanced:

- By decreasing the temperature
- By stray fields in superconducting films
- By a long-range disorder

$\Downarrow$

Lifting the Bogomolnyi degeneracy

$\Downarrow$

As a result, the inter-type point unfolds into a finite domain between types I and II in the phase diagram.

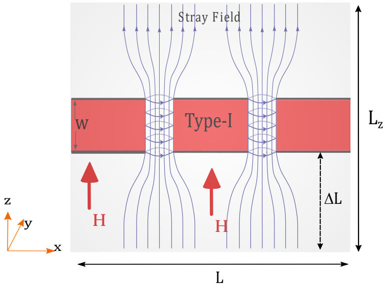
$\Downarrow$

Exotic flux/condensate configuration are expected to escape their prison and shape the mixed state in the intertype domain. Thus, the long range- attraction between

Intertype Flux Exotic States in Thin Superconductors

W. Y. Córdoba-Camacho et al., PRB,**94**,054511,(2016)

Between Types I and II: Intertype Flux Exotic States in Thin Superconductors



- $\mathbf{H} = (0, 0, H)$ (H is constant) being parallel to the z-axis. $H = 90\Phi_0/L^2$ and $H = 60\Phi_0/L^2$
- Periodic boundary condition in (x,y)
- $\kappa = 0.55$, $L_{x,y} = 50\xi_0$ and $L_z = \Delta L + w + \Delta L$
- $w/\xi_0 = 20$, and thin, $w/\xi_0 = 2$, samples

Time consuming: GPU (Graphics Processing Units) computations

Ginzburg-Landau equations.

$$(-i\boldsymbol{\nabla} - \boldsymbol{A})^2\,\Psi - (1 - T)(1 - |\Psi|^2)\Psi = 0,$$

$$\kappa^2\boldsymbol{\nabla}\times\boldsymbol{\nabla}\times\boldsymbol{A} = (1 - T)\Re\left[\Psi^*\left(-i\boldsymbol{\nabla} - \boldsymbol{A}\right)\Psi\right]$$

Boundary Conditions

$$\hat{\boldsymbol{z}}\cdot(i\boldsymbol{\nabla} + \boldsymbol{A})\,\Psi\Big|_{z=\pm w/2} = 0,$$

$$\boldsymbol{\nabla}\times\boldsymbol{A}\Big|_{z\to\pm\infty} = \mathbf{H},$$

- The modified equations are then solved by the **Link-Variable** approach
- Field cooling, $T_c < T < 0.6T_c$

M. M. Doria et al., PRB 39,9573, (1989)

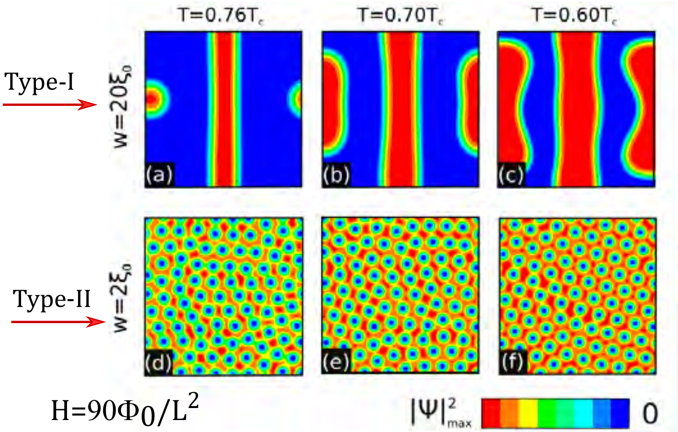
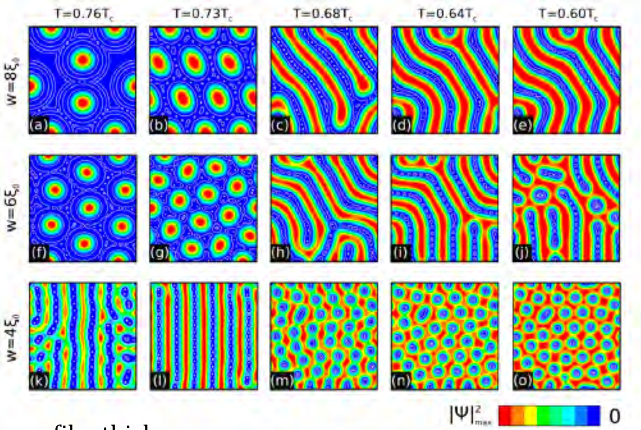


Figura: The local density of Cooper pairs $|\Psi|^2$ in films with thicknesses $w/\xi_0 = 20$ [panels (a), (b) and (c)] and $w/\xi_0 = 2$ [panels (d), (e) and (f)]

W. Y. Córdoba-Camacho et al., PRB,94,054511,(2016)



w-film thickness
$H=90\Phi_0/L^2$

Figura: The local density of Cooper pairs $|\Psi|^2$ in films with thicknesses $w/\xi_0 = 8$ [panels (a)-(e)] and $w/\xi_0 = 6$ [panels (f)-(j)], $w/\xi_0 = 4$ [panels (k)-(o)]

W. Y. Córdoba-Camacho et al., PRB,94,054511,(2016)

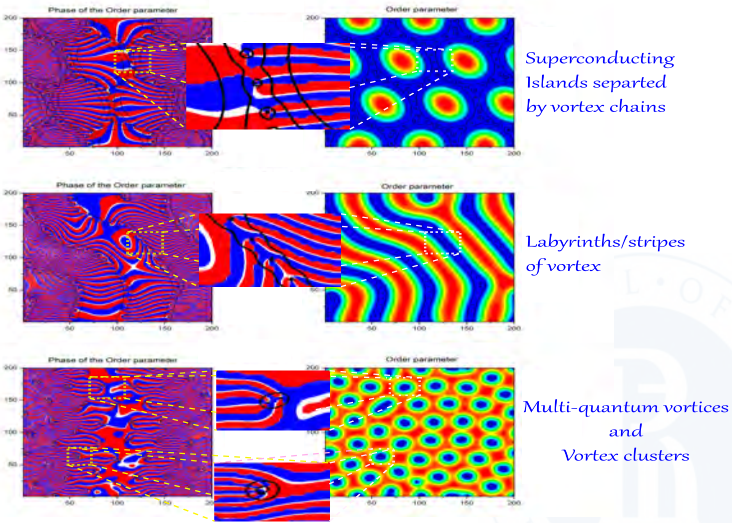
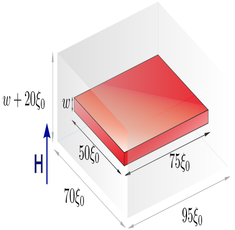
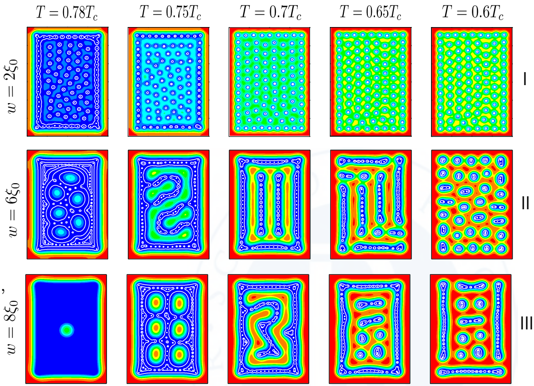


Figura: The spatially-dependent phase and amplitude of the order parameter for an island patterns

Intertype in a Rectangular Sample, $w = 2\xi_0, 6\xi_0, 8\xi_0$ **and** $\kappa = 0.55$





GL-equations

$$(-i\nabla - \boldsymbol{A})^2 \Psi - (1 - T)(1 - |\Psi|^2)\Psi = 0,$$

$$\kappa^2 \nabla \times \nabla \times \boldsymbol{A} = (1 - T)\Re\left[\Psi^* \left(-i\nabla - \boldsymbol{A}\right)\Psi\right],$$

Boundary Conditions

$$\hat{\boldsymbol{n}} \cdot (i\nabla + \boldsymbol{A})\,\Psi\Big|_{\partial\Omega_{sc}} = 0,$$

$$\nabla \times \boldsymbol{A} = \mathbf{H}.$$

W. Y. Córdoba-Camacho et al., arxiv.org. 2018. No. 1812.09621

Intertype in a Rectangular Sample, $w = 6\xi_0$ and $\kappa = 0.55$

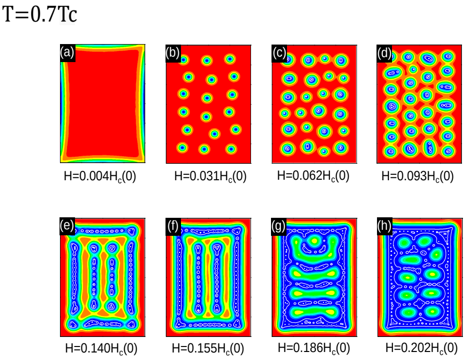


Figura: Panels (a)-(h) are color density plots of the condensate density $|\Psi|^2$, calculated for different values of the external magnetic field (shown below). Calculations are done at $T = 0.6T_c$ and for the film with thickness $w = 6\xi_0$.

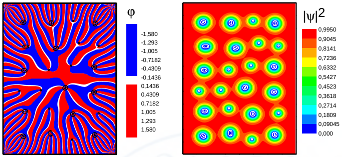


Figura: Phase portrait (left panel) corresponding to spatial profile of the condensate density (right panel), calculated at $T = 0.6T_c$ and $H = 0.062H_c(0)$. The colour scheme for the phase portrait is dichromic - blue for $\phi < 0$ and red for $\phi > 0$.

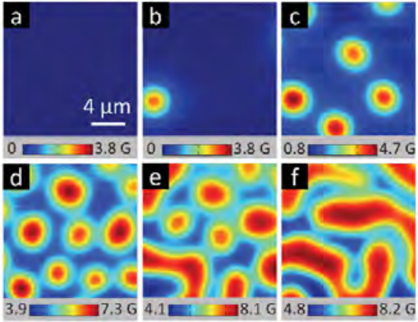


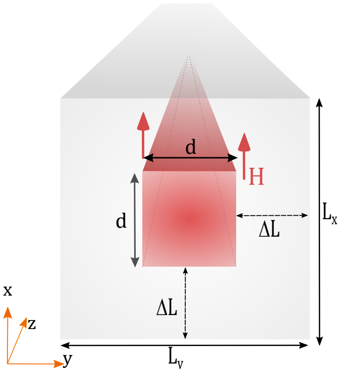
Figure 1. Typical SHPM images of type-I lead film obtained at different increasing magnetic fields after zero-field cooling (ZFC) at 6.9 K: (a) 2 Oe, (b) 2.6 Oe, (c) 4.2 Oe, (d) 7.6 Oe, (e) 12 Oe and (f) 16 Oe. Blue and red areas correspond to superconducting and normal state, respectively.

SHPM-Scanning Hall probe microscopy.

J Ge et al., New J. Phys. **15** 033013 (2013) Thick lead film of Pb with thickness of $d = 5\mu m$.

Quasi-One-Dimensional Vortex Matter in Superconducting Nanowires

W. Y. Córdoba-Camacho et al., PRB,94,054511,(2016)



GL Equations

$$(-i\boldsymbol{\nabla} - \boldsymbol{A})^2 \Psi - (1-T)(1-|\Psi|^2)\Psi = 0,$$
$$\kappa^2 \boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{A} = (1-T)\Re\left[\Psi^* \left(-i\boldsymbol{\nabla} - \boldsymbol{A}\right)\Psi\right]$$

Boundary Conditions

$$\hat{\boldsymbol{n}} \cdot (i\boldsymbol{\nabla} + \boldsymbol{A})\Psi\Big|_{\partial\Omega_{sc}} = 0,$$
$$\boldsymbol{\nabla} \times \boldsymbol{A} = \mathbf{H}.$$

- $\mathbf{H} = (H, 0, 0)$ (H is constant) being parallel to the x-axis $0 < H < 0.5H_c(0)$.
- $L \gg d$, $\Delta L = 10\xi_0$, $5\xi_0 \leq d \leq 50\xi_0$
- $T = 0.7T_c$.

- The modified equations are then solved by the link-variable approach

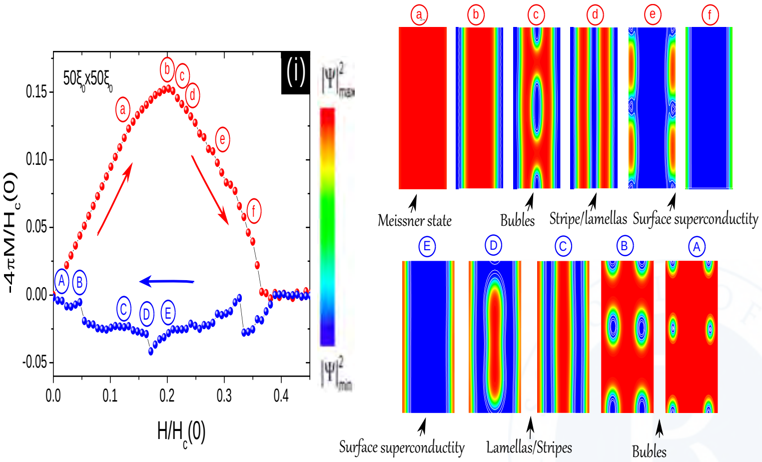


Figura: Magnetization M as a function of applied magnetic field H for wire of crossection with $L_{x,y} = 50\xi_0$. Density colour plots magnetization panels illustrate the order parameter profiles, that correspond to points in the magnetization curve.

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Quasi-One-Dimensional Vortex Matter in Superconducting Nanowires

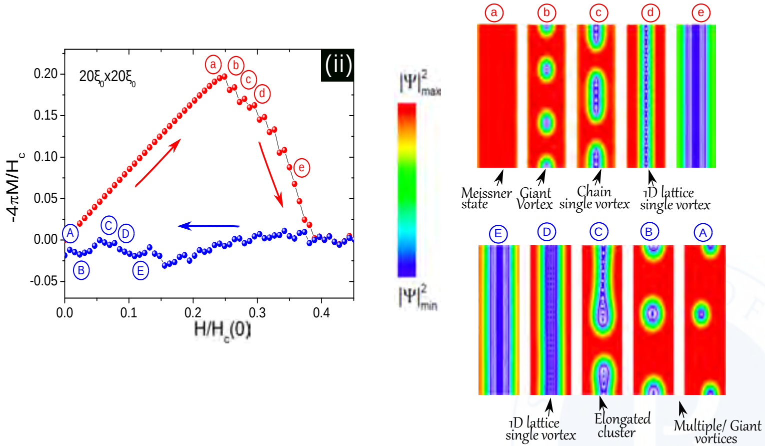

Figura: Magnetization M as a function of applied magnetic field H for wire of crossection with $L_{x,y} = 20\xi_0$. Density colour plots magnetization panels illustrate the order parameter profiles, that correspond to points in the magnetization curve.

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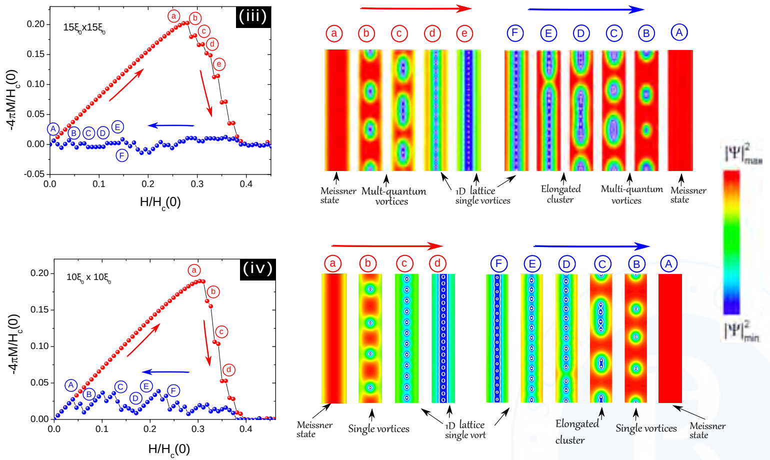

Figura: Magnetization M as a function of applied magnetic field H for wire of crossection with $L_{x,y} = 15\xi_0, 10\xi_0$. Density colour plots magnetization panels illustrate the order parameter profiles, that correspond to points in the magnetization curve.

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Quasi-One-Dimensional Vortex Matter in Superconducting Nanowires

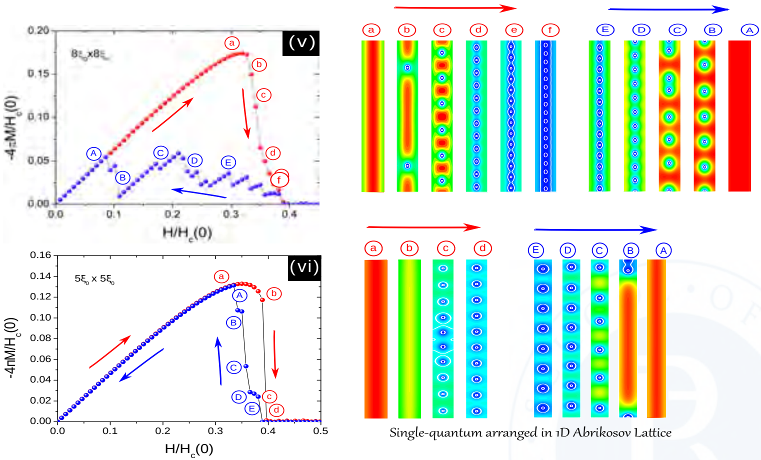

Figura: Magnetization M as a function of applied magnetic field H for wire of crossection with $L_{x,y} = 8\xi_0, 5\xi_0$. Density colour plots magnetization panels illustrate the order parameter profiles, that correspond to points in the magnetization curve.

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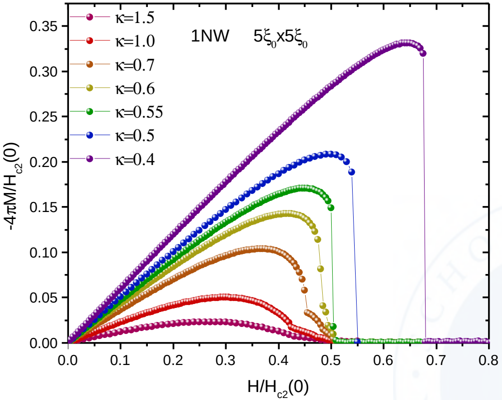


Figura: Magnetization Nano wire with cross Section $5\xi_0 \times 5\xi_0$ and different κ's values. Right:Order parameter corresponds to nanowire

Quasi-One-Dimensional Vortex Matter in Superconducting Nanowires

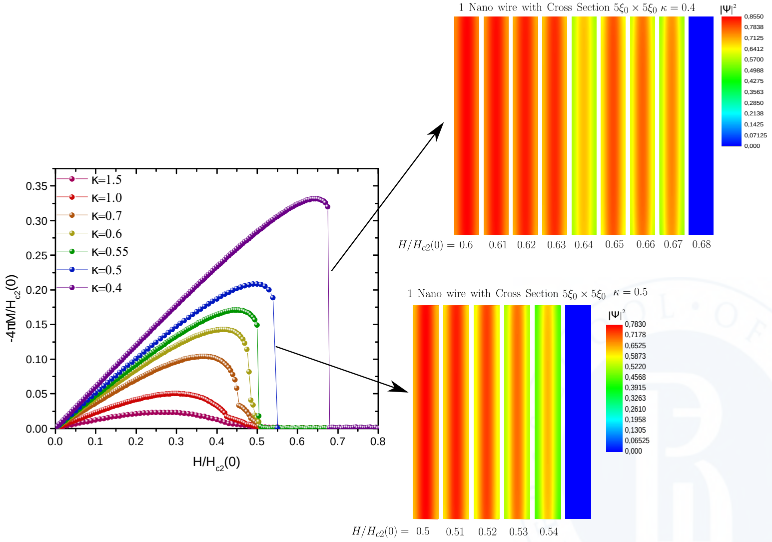


Figura: Left: Magnetization Nano wire with cross Section $5\xi_0 \times 5\xi_0$ and different κ's values. Right:Order parameter corresponds to nanowire

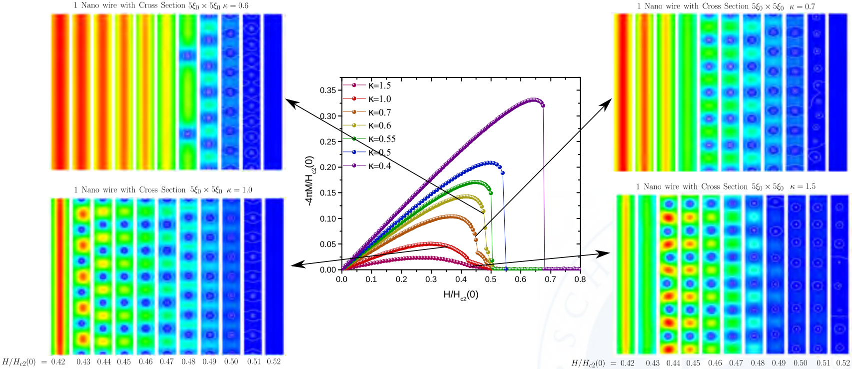
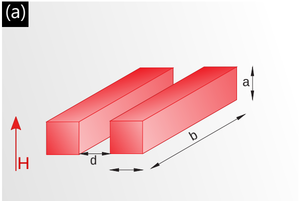


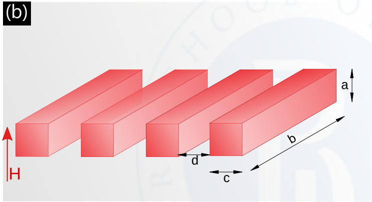
Figura: Left: Magnetization Nano wire with cross Section $5\xi_0 \times 5\xi_0$ and different κ's values. Right:Order parameter corresponds to nanowire

Our Plan and Future work

Our plan is to apply the results obtained in nanowire and thin films to design new superconducting devices with novel and unconventional properties.

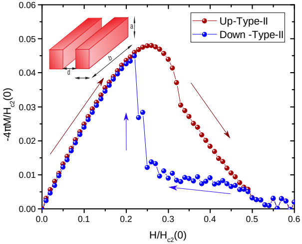
- the focuses is to investigate the magnetic response of arrays superconducting nano-wires made of a type-I and type-II material, that are arranged in matrices with different geometries.
- Introduce currents, dynamics of vortex.
- Propose to the experimental to *Obtain some patterns of vortices in some experiments superconducting samples*.

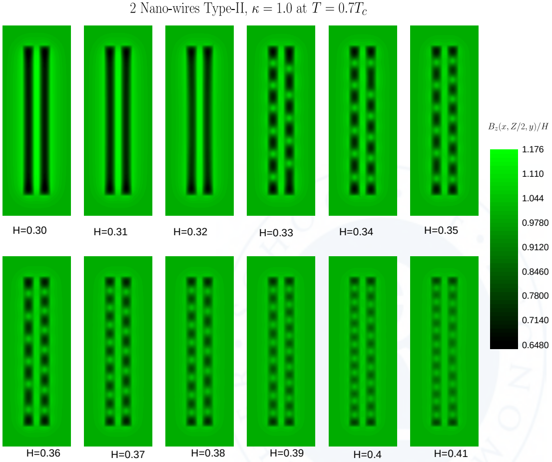




2 Nano-wires, Type-II $\kappa = 1.0$ at $T = 0.7T_c$

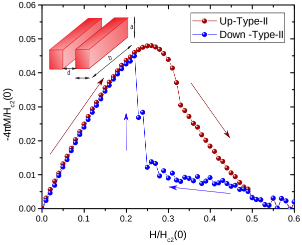
(Left) Magnetization 2-nano-wire with cross Section $4\xi_0 \times 5\xi_0$ and $d = 2\xi_0$, (Right) Profile of the magnetic field calculated in the $Z/2$ plane.

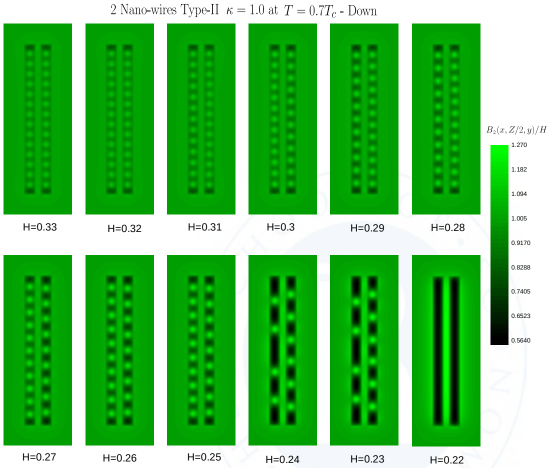




2 Nano-wires, Type-II $\kappa = 1.0$ at $T = 0.7T_c$

(Left) Magnetization 2-nano-wire with cross Section $4\xi_0 \times 5\xi_0$ and $d = 2\xi_0$, (Right) Profile of the magnetic field calculated in the $Z/2$ plane.





Conclusion

- My take has focused on the problem of superconductivity between conventional type-I and II in thin and one nanowire superconductor made of a type-I.
- The infinite degeneracy of Bogomolnyi point is removed due stray magnetic fields and the Intertype domain appears.
- A complex internal structure of the intertype domain has been found, which variety of non-standard flux/condensates patterns.
- It has been demonstrated that the magnetic response of nanowire changes when thickness decreases, sufficiently thin nanowires deviate from type I in favor of Intertype regime with multiquantum vortices and vortex cluster.

спасибо!