Direct Evidence of Abrikosov Vortex Cores in a Nonsuperconducting Metal

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Laboratory of topological quantum phenomena in superconductors

Moscow Institute of Physics and Technology

Unique equipment:

Low temperature high vacuum JT-STM SPECS

Cryogenic system AFM/MFM AttoDRY1000

1952

Type II superconductivity

A. A. Abrikosov, Doklady Akademii Nauk SSSR 86 (1952) 489.

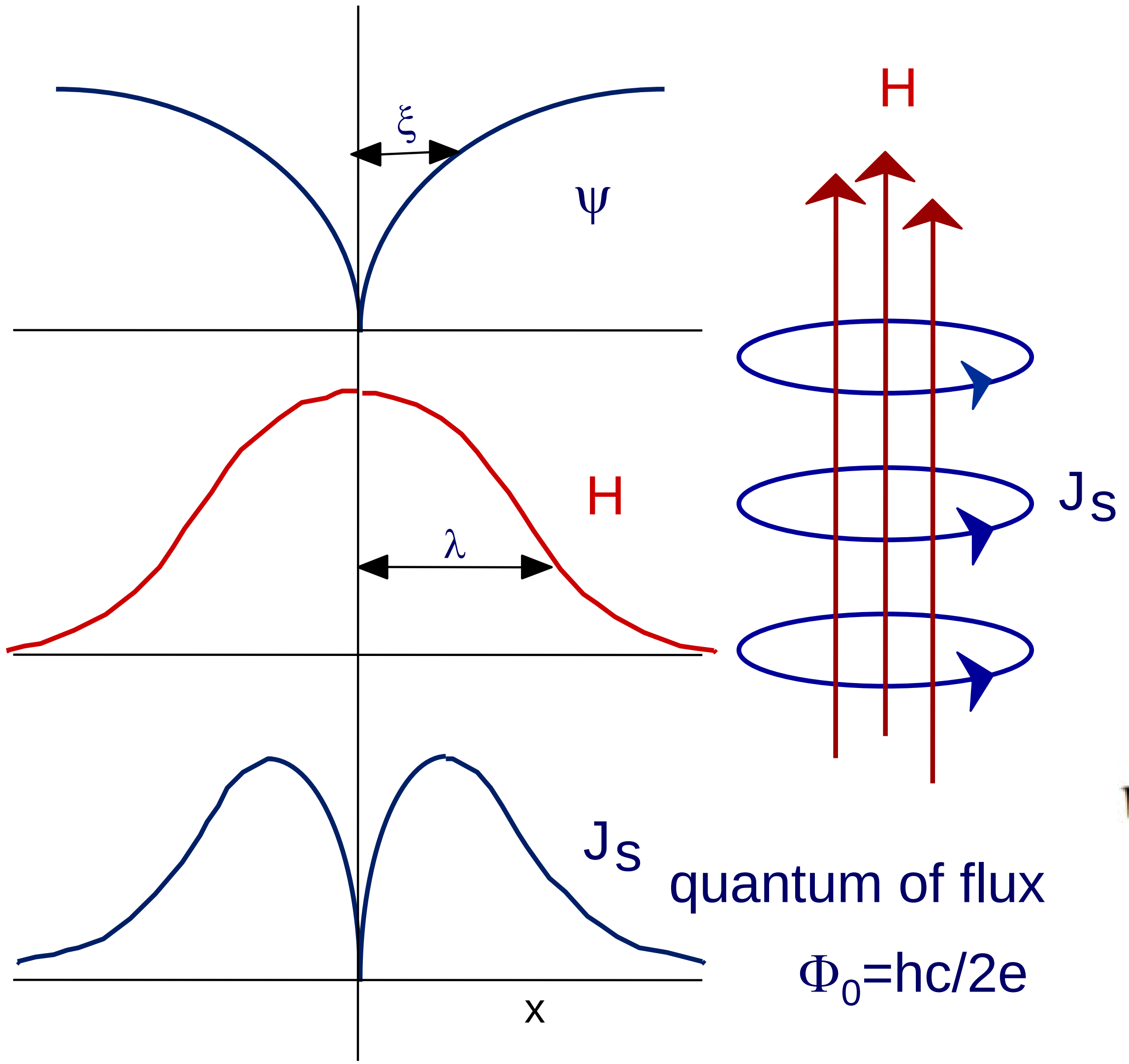
This work was submitted to “Doklady” by L. D. Landau

Verifying the predictions of the GL theory, Nikolay Zavaritskii undertook measurements of the critical field of thin films.

N.V. Zavaritskii, Dokl. Akad. Nauk SSSR 86 (1952) 501

Abrikosov explored the consequences of the possibility of $\kappa > 1/\sqrt{2}$ where the normal metal-superconductorsurface energy becomes negative.
The resulting theory nicely described the experimental data; in particular, it showed that the superconducting transition became of second order for any thickness.

Abrikosov vortex



quantum of flux

$\Phi_0 = hc/2e$

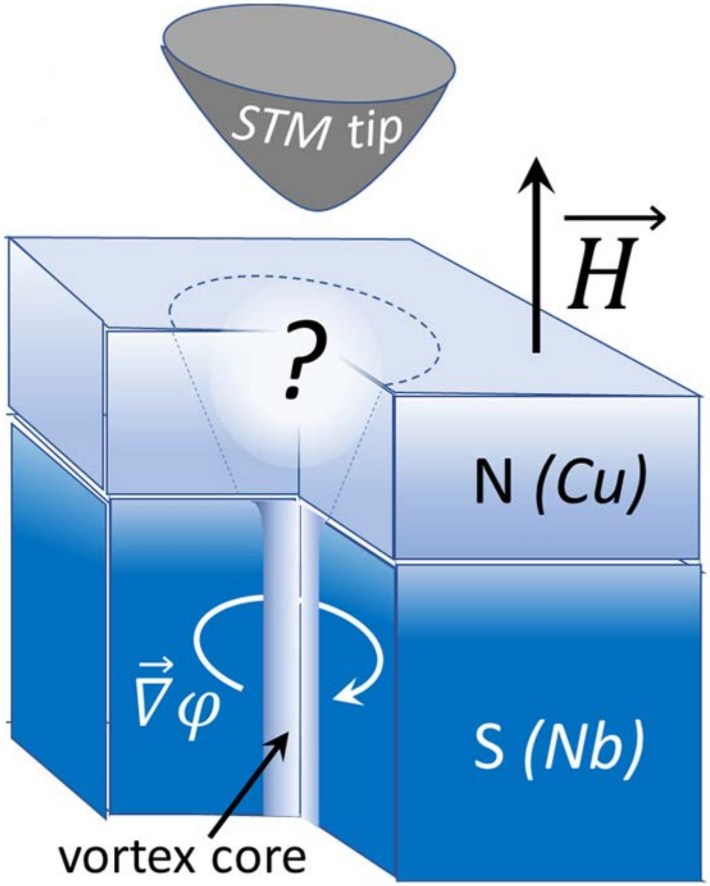
$$j = e n_s v_s$$

$$v_s = \hbar/(2mr)$$

$$\lambda \gg \xi$$

Abrikosov vortex in the structure normal metal - superconductor

V. S. Stolyarov, *et. al.*, "Expansion of a superconducting vortex core into a diffusive metal",
Nature Communications 9, 2277 (2018)

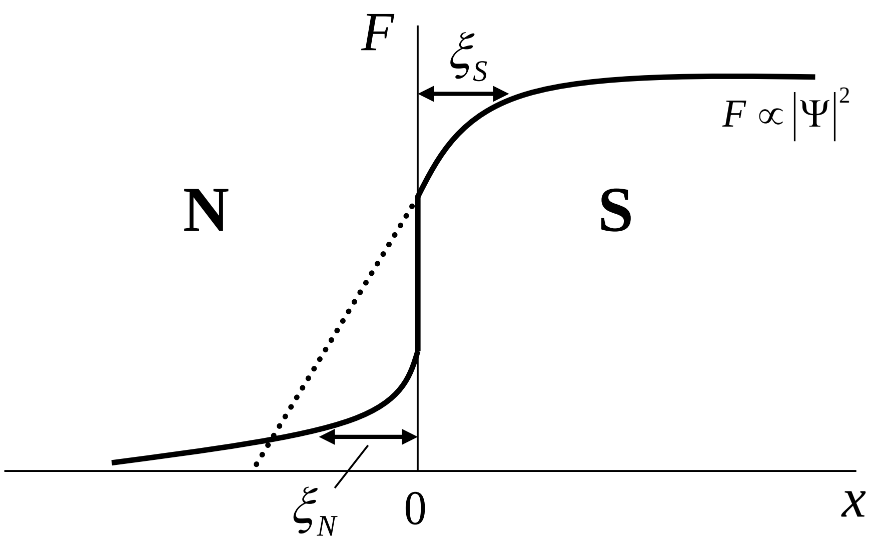


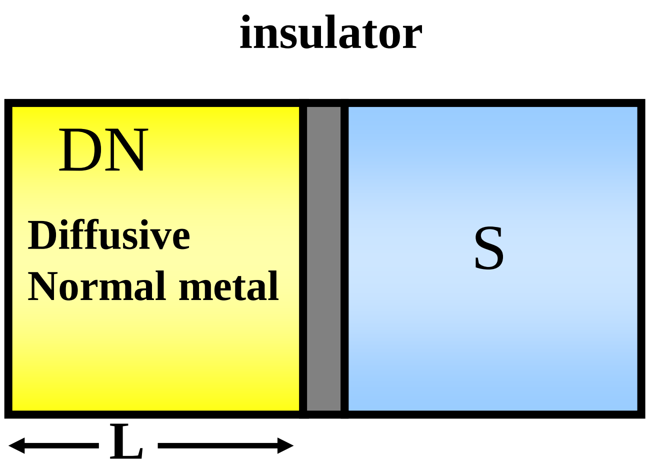
- how does the vortex evolve in an N-layer?
- do these vortices have cores, like Abrikosov vortex in superconductors?
- what does fix the core size?

Proximity effect

Pair amplitude $$F = \langle \Psi_\uparrow \Psi_\downarrow \rangle$$

Normal metal $$F \propto \exp\left(-\frac{|x|}{\xi_N} \right)$$





ξ **: coherence length**

"minigap" is induced in DN,
which scales with the Thouless energy

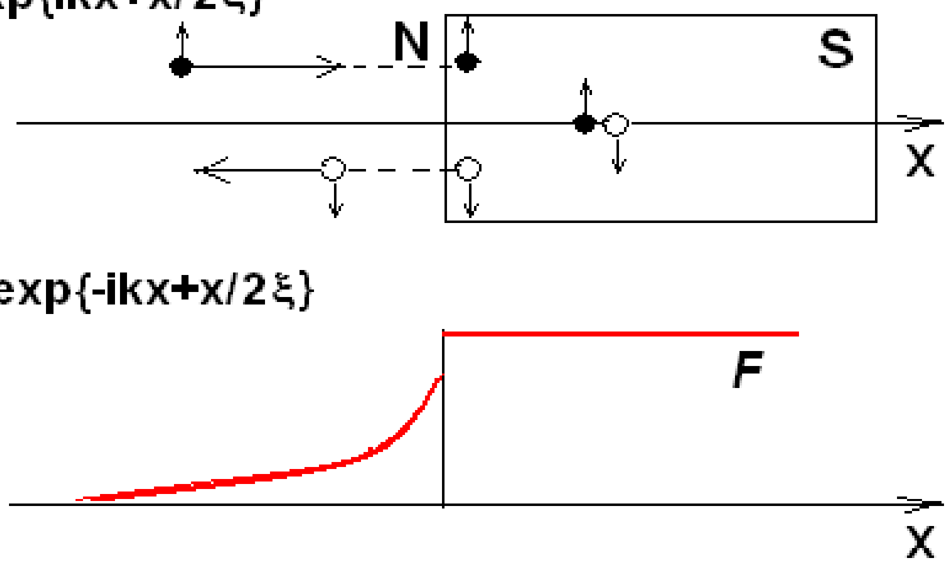
$$E_T = \hbar D / L^2$$

Proximity effect in normal metal - superconductor (NS) structures

$$\Psi(\vec{r}) = \begin{Bmatrix} u \\ v \end{Bmatrix} = \begin{Bmatrix} u_p \\ v_p \end{Bmatrix} \exp\{i\vec{p}\vec{r}\} \qquad p^2 = 2m\mu \pm \sqrt{\varepsilon_p^2 - |\Delta|^2}$$

Andreev reflection at SN interface

$u \sim \exp\{ikx + x/2\xi\}$

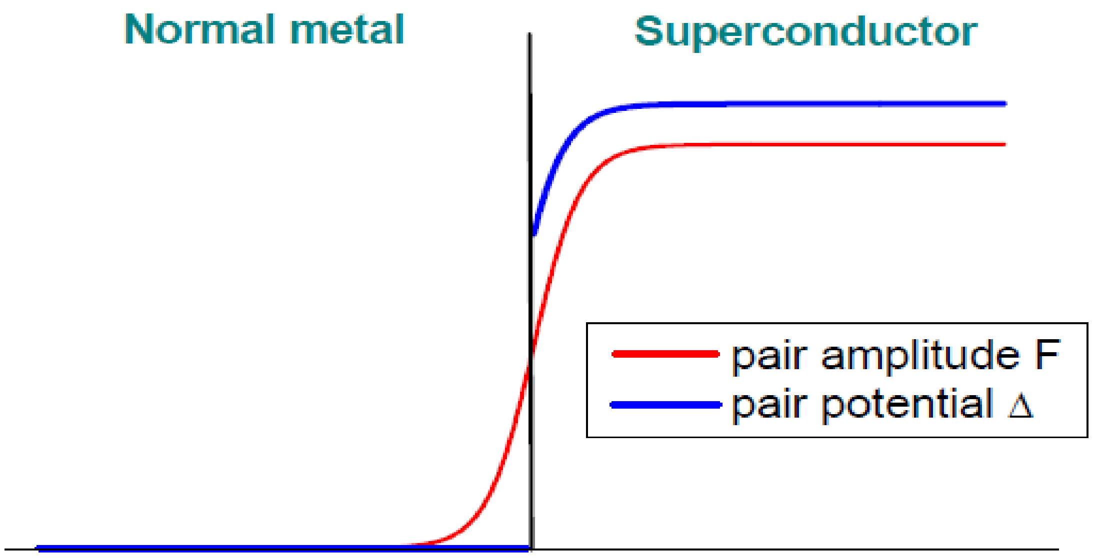


$v \sim \exp\{-ikx + x/2\xi\}$

$\Delta \sim F \sim uv \sim \exp\{x/\xi\}$

dephasing between
an electron and a hole

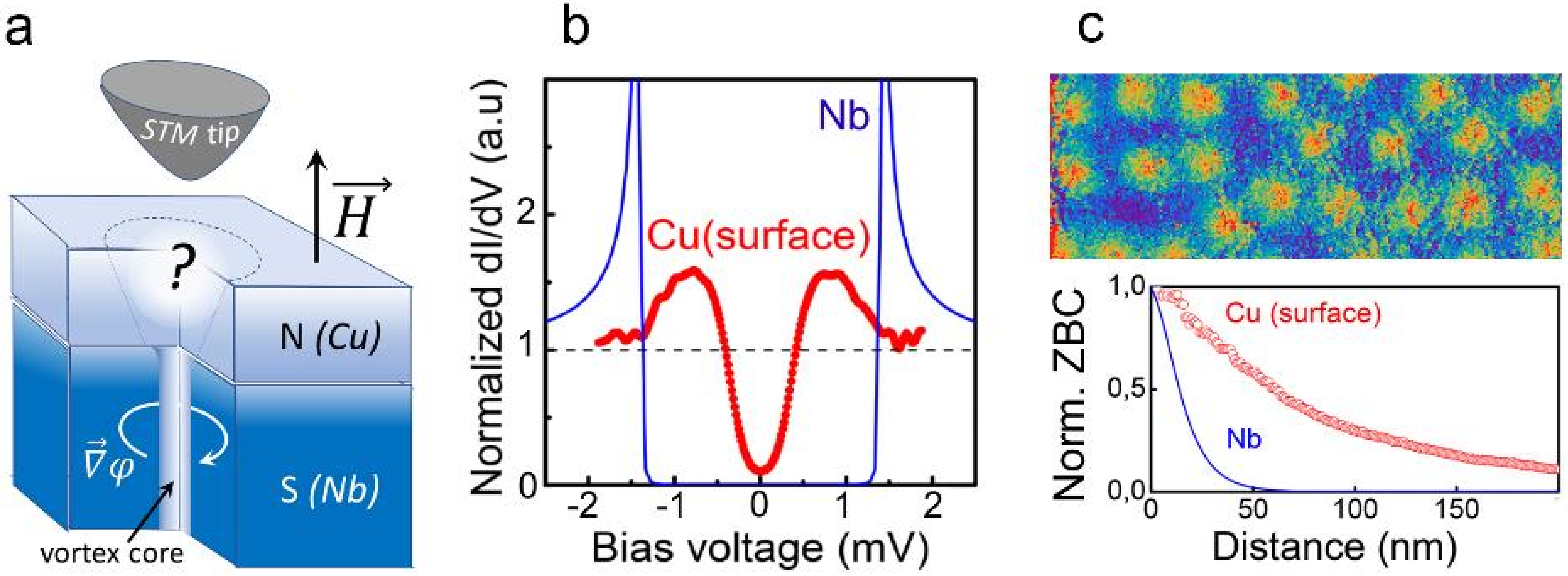
Proximity effect:
pair potential Δ & pair amplitude F (order parameter)



Pair amplitude exists in N, but pair potential Δ vanishes

At the same time, the "minigap" δ is induced in N,
which scales with the Thouless energy $E_T = \hbar D / L^2$

STM experiment

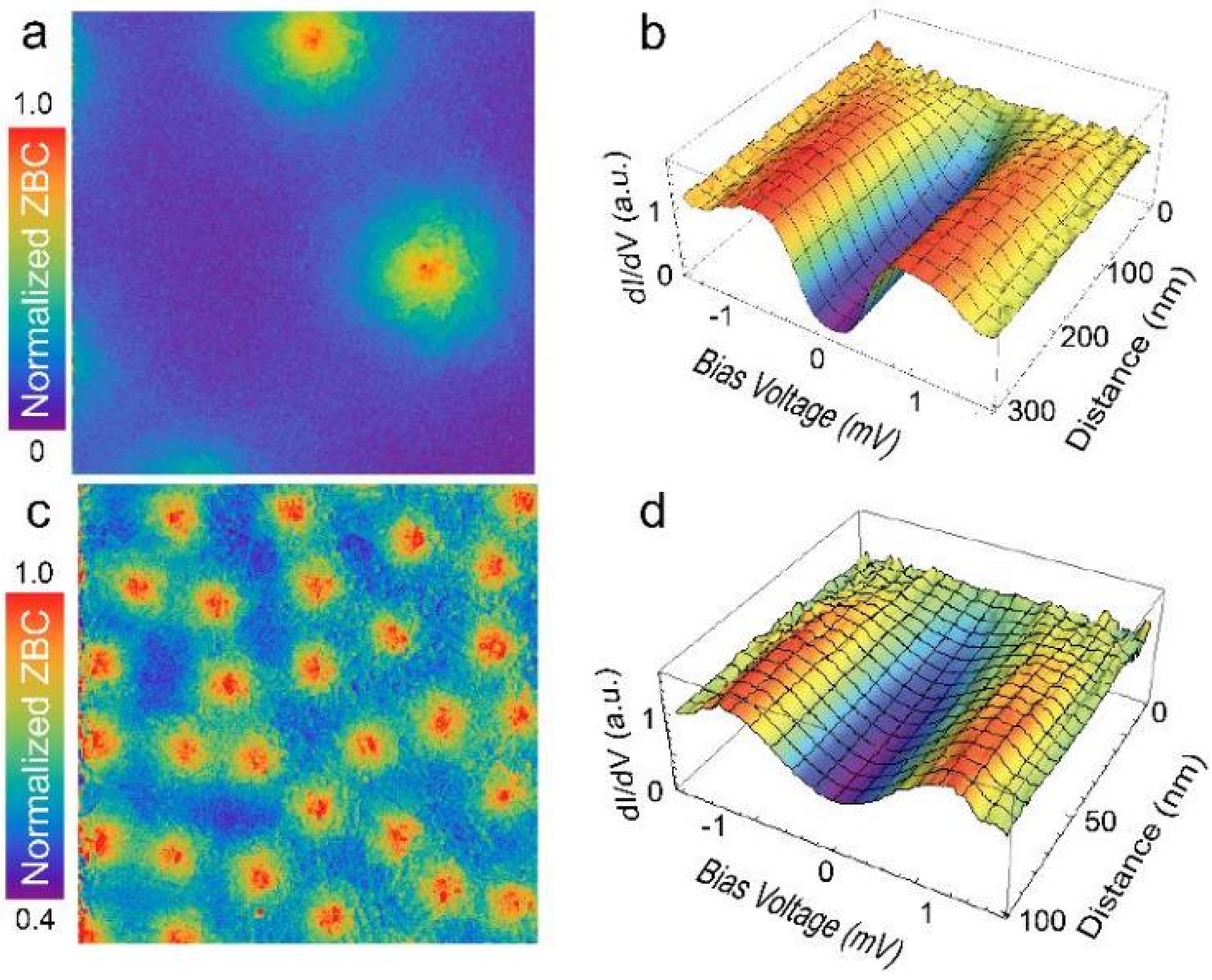


Local tunneling characteristics are probed at the surface of 50 nm thick Cu-film backed with a 100 nm-thick Nb.

(b) tunneling conductance measured at Cu-surface exhibits a minigap 0.5 meV;

(c) - upper image: 800 nm x 250 nm color-coded dI/dV (V = 0) map acquired in the magnetic field of 120 mT reveals proximity vortices; lower plot: radial variation of the ZBC from the vortex center defines the vortex core profile (red data points). The minigap vanishes in the vortex cores; blue line - expected radial ZBC evolution at the Abrikosov vortex core in Nb-film

800 nm x 800 nm ZBC maps acquired at 300 mK in magnetic fields of 5 mT and 55 mT, respectively



Theoretical formulation:

- Quasiclassical approximation

- Dirty limit in N and S materials

=> the Usadel equations are applicable

$$D\frac{\partial}{\partial x}[\check{G}_N(x)\frac{\partial \check{G}_N(x)}{\partial x}] + i[\check{H}, \check{G}_N(x)] = 0,$$

$$\check{H} = \begin{pmatrix} \hat{H}_0 & 0 \\ 0 & \hat{H}_0 \end{pmatrix}, \quad \hat{H}_0 = \epsilon\tau_3.$$

$\check{G}_N(x)$ is angular averaged Green's function

D is the diffusion constant

- We developed the self-consistent method of solution of the Usadel equations in three-dimensional geometry of a vortex lattice in arbitrary magnetic field

- The local density of states was calculated from the Green's function

Technically, the problem is reduced to solving the coupled equations for the Green's functions in N and S layers in 3D (θ-parametrization):

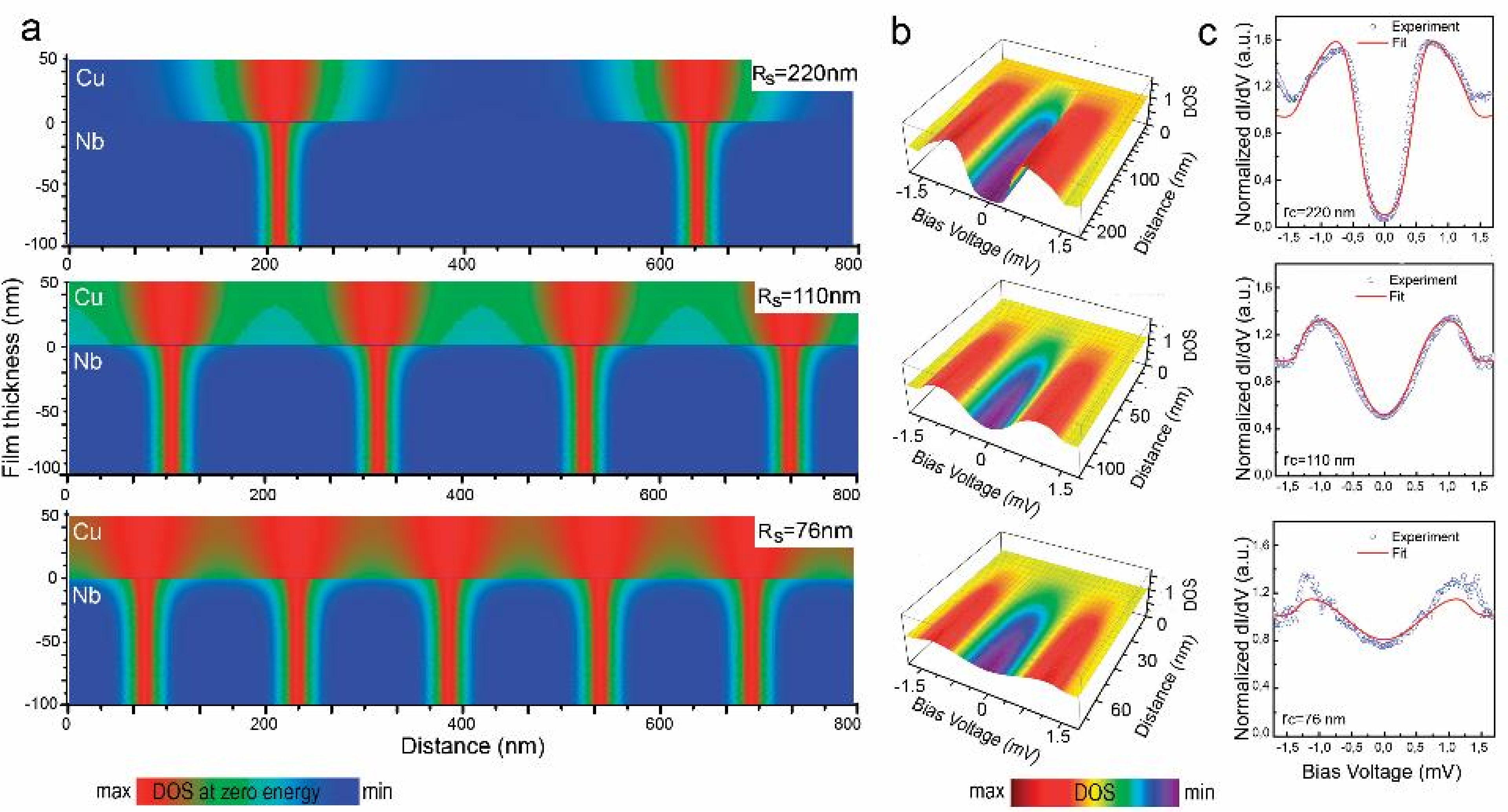
$$\frac{d^2\theta_S}{dz^2}+\frac{1}{r}\frac{d}{dr}\left(r\frac{d\theta_S}{dr}\right)-(\Omega+Q^2\cos\theta_S)\sin\theta_S=-\Delta\cos\theta_S, \tag{2}$$

$$\frac{d^2\theta_N}{dz^2}+\frac{1}{r}\frac{d}{dr}\left(r\frac{d\theta_N}{dr}\right)-\frac{\Omega+k^2Q^2\cos\theta_N}{k^2}\sin\theta_N=0, \tag{3}$$

$$Q=\frac{1}{r}\left(1-\frac{r^2}{r_S^2}\right), \tag{4}$$

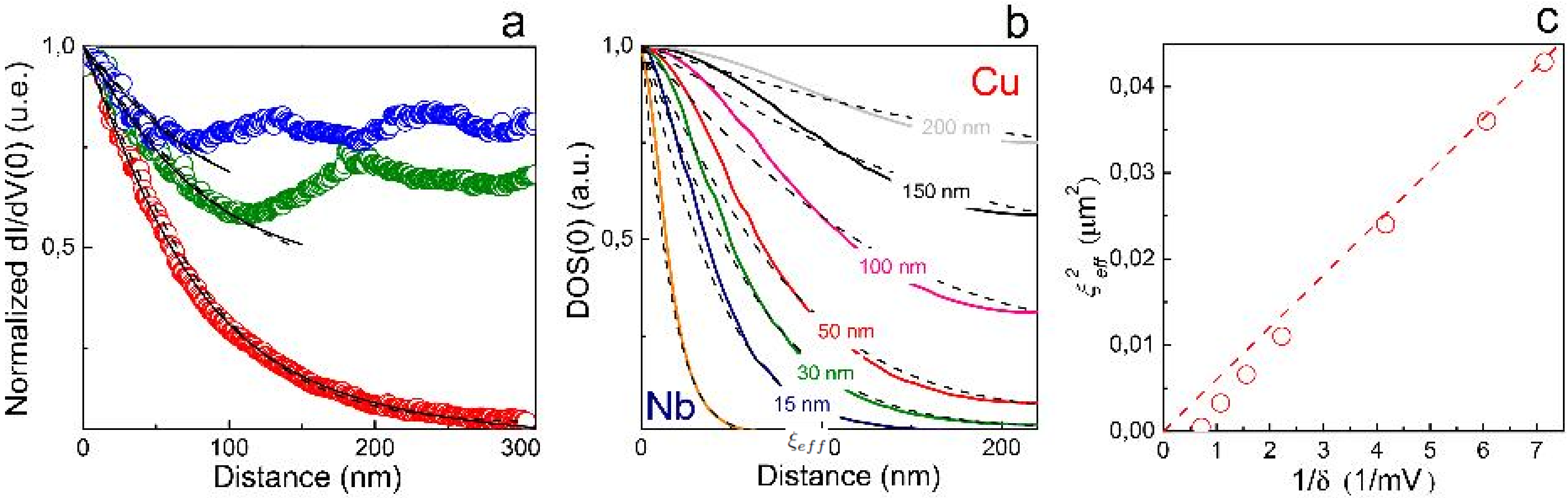
$$\Delta\ln t+2t\sum_{\Omega\geq 0}^{\infty}\left(\frac{\Delta}{\Omega}-\sin\theta_S\right)=0. \tag{5}$$

Comparison with the quasiclassical theory (the Usadel equations):



the only fitting parameter is Nb/Cu interface resistance

Extracting the effective coherence length in Cu



Red, green and blue data points:
radial ZBC proles of proximity vortex at 5 mT, 55 mT and 120 mT, respectively.
Fits provide the effective core size ξ_{eff} = 110 nm.

(b) Color lines: vortex core profiles (zero-bias conductance) calculated within Usadel framework for different thicknesses of Cu-lm in 5 mT field.

(c) Scaling of the effective core size with the minigap δ

Summary

- The existence of a well-defined core of Abrikosov vortex induced from a superconductor (Nb) into a normal metal (Cu) is demonstrated experimentally

- Good quantitative agreement between theory and experiment is achieved

- The vortex core size is controlled by the proximity minigap in Cu

- The developed method enables extracting relevant physical properties of the buried S/N interfaces

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