Institute of Physics and
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Spontaneous currents in ferromagnet-superconductor heterostructures

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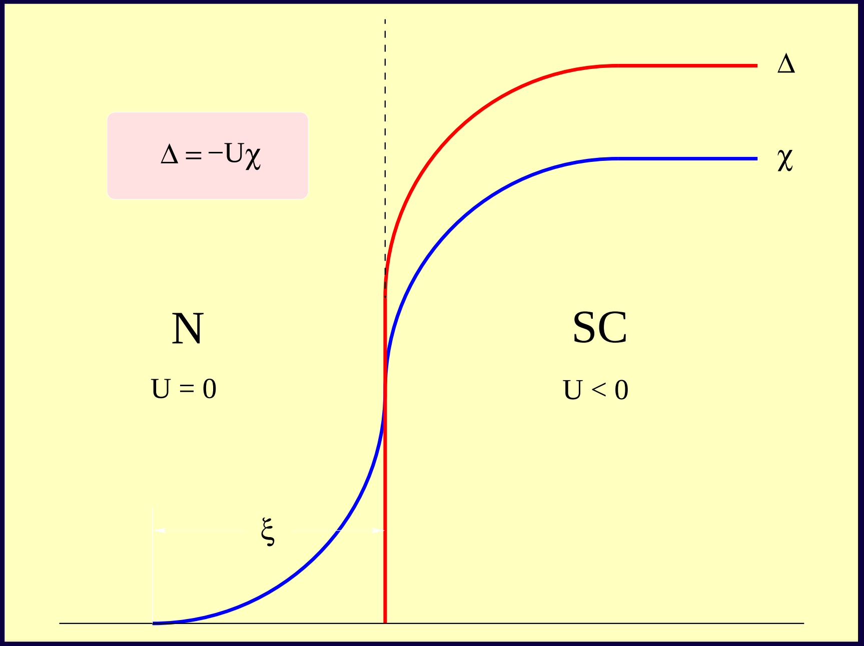
Outline

- Proximity effect - basic facts
- Some remarkable experiments
- SC electrons in an exchange field - FFLO state
- Andreev bound states
- Self-consistent theory: negative U Hubbard model
- Current carrying ground state
- Effect of the normal metal slab
- Conclusions

- % % % -

Proximity effect – basic facts



N-S

- Holm et al, Z. Phys. (1932):
  vanishing of the resistance of the
  S-N-S system (Josephson effect)
- Cooper, PRL (1961):
  first microscopic theory of the N-S system
- Andreev, JETP (1964):
  Andreev reflections

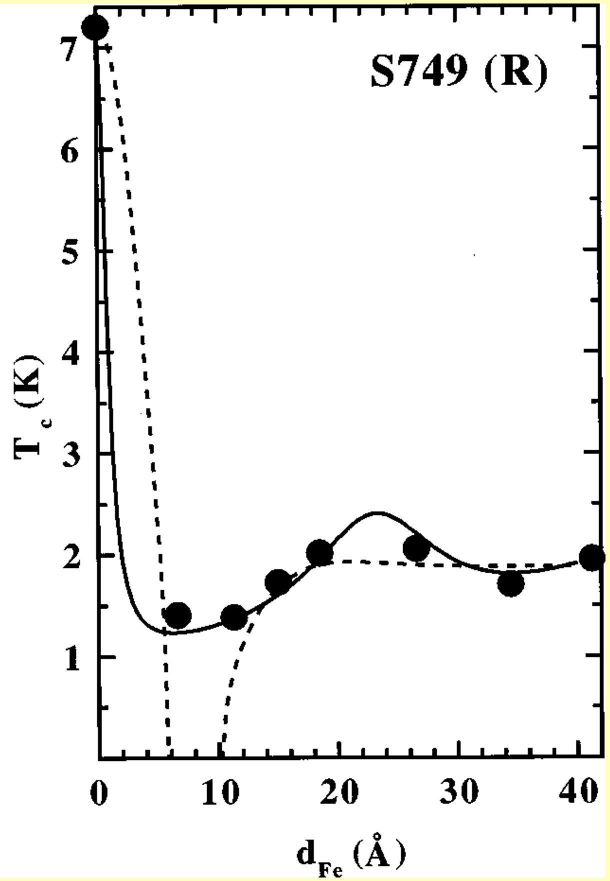
F-S

- pair breaking ⇒ short superconducting
  proximity effect
- de Jong & Beenakker, PRL (1995):
  suppression of the Andreev reflections
- Clogston, PRL (1962):
  $E_{ex} > \Delta/\sqrt{2} \Rightarrow$ no superconductivity

Some remarkable experiments

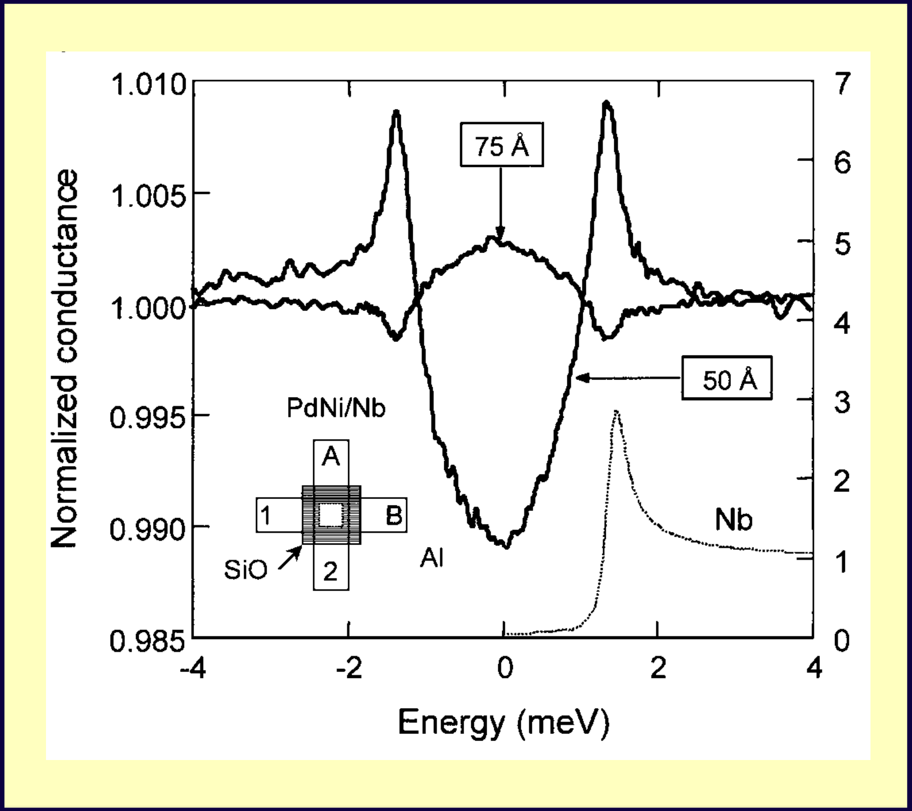
superconducting transition temperature   Lazar *et al.*, PRB (2000)

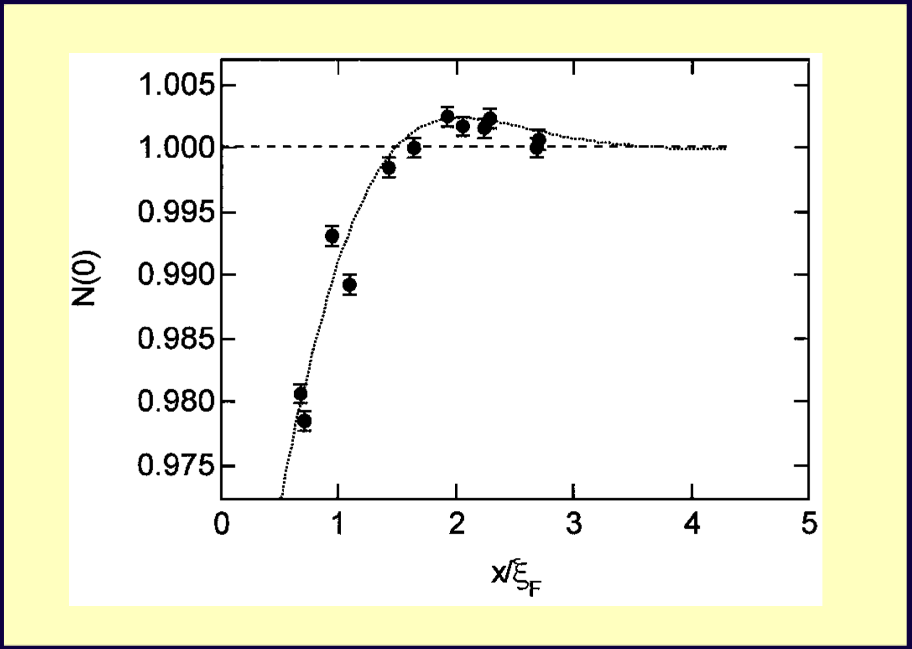
- Fe/Pb/Fe
- resistivity + AC suceptibility



differential conductance Kontos *et al.*, PRL (2001)

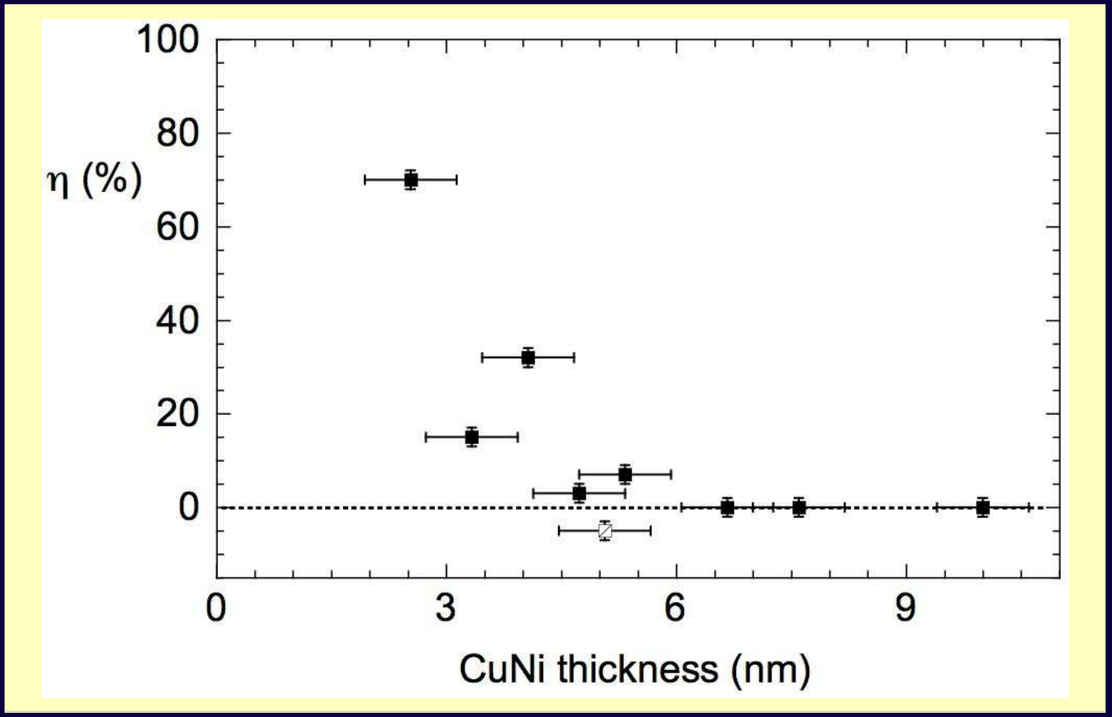
- $Nb/PdNi/Al_2O_3/Al$
- planar tunneling spectroscopy





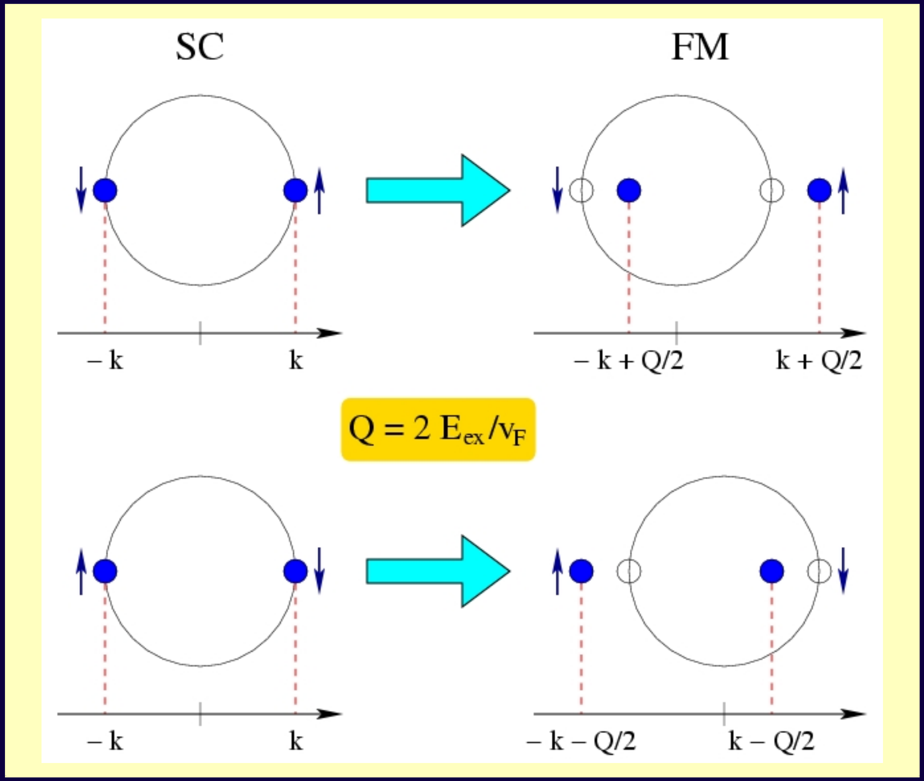
density of states Cretinon *et al.*, PRB (2005)

- Nb/CuNi
- scanning tunneling microscopy (STM)

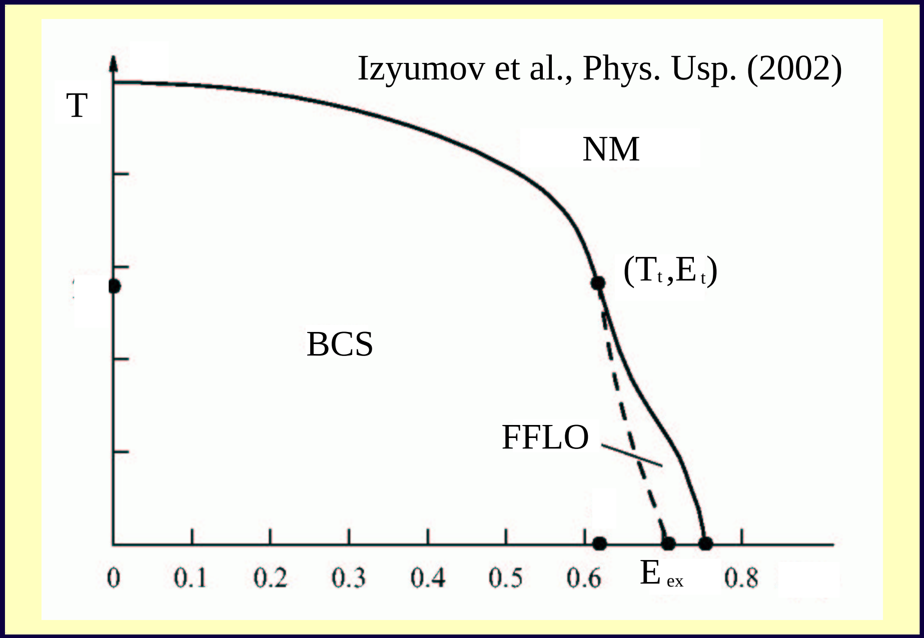


Superconducting electrons in an exchange field - FFLO state

- Δe^{iQr} — Fulde & Ferrel, Phys. Rev. (1964)
- $\Delta cos(Qr)$ — Larkin & Ovchinnikov, Sov. Phys. JETP (1965)
- F-S — Demler *et al.*, PRB (1997)
  Proshin & Khusainov, JETP Lett. (1997)



phase diagram

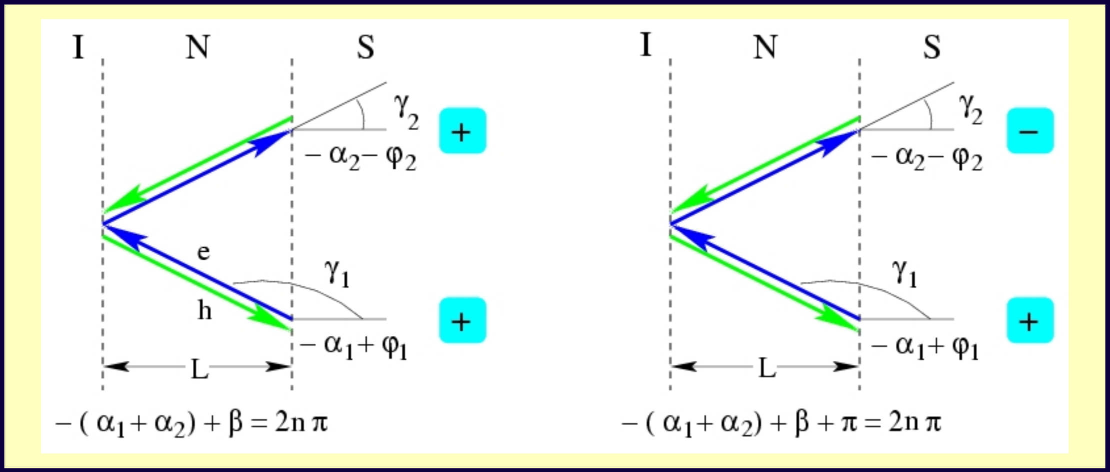


properties of the FFLO state

- spatially dependent order parameter $\Delta(\vec{r})$
- non-zero pairing momentum in the BCS theory
- spin polarization
- almost normal Sommerfeld specific heat
- almost normal single-electron tunneling characteristics
- unusual anisotropic electrodynamic behavior
- spontaneously generated current
- sensitivity to disorder
- strong dependence on the shape of the Fermi surface

Andreev bound states

I-N-S



Bohr-Sommerfeld:

$$-(\alpha_1+\alpha_2)\mp\delta\varphi+\beta(\omega)=2n\pi$$

$0:\ \Longrightarrow \omega/\Delta=\pm cos\left(\frac{2\omega L}{\Delta\xi cos(\gamma_2)}\right)$

de Gennes & Saint-James, PL (1963)

$\pi:\ \Longrightarrow \omega/\Delta=\pm sin\left(\frac{2\omega L}{\Delta\xi cos(\gamma_2)}\right)$

Hu, PRL (1994)

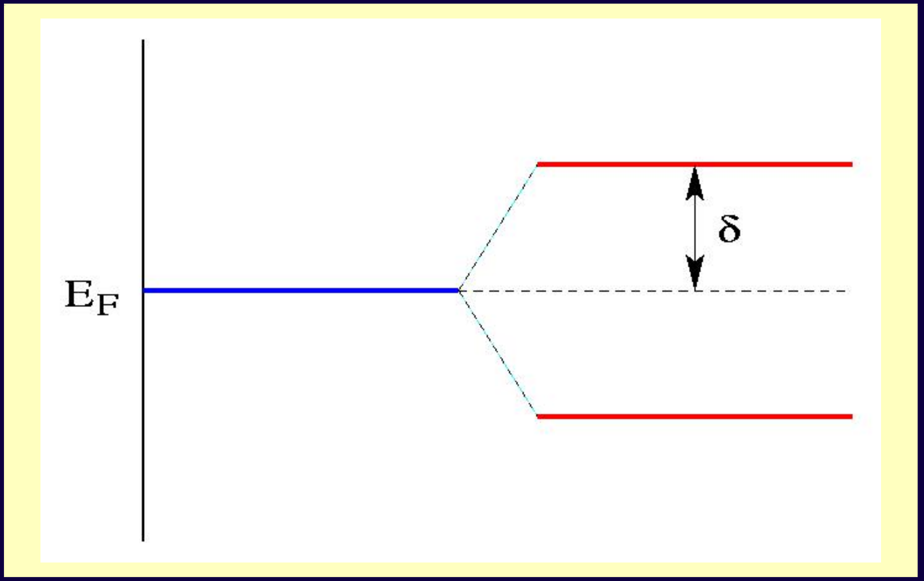
I-F-S

$$\omega_{n\sigma}(\varphi)=\sigma cos((\gamma(\varphi)+\sigma l_n/\xi_F)/2)$$

Kuplevakhskii & Fal‘ko, JETP Lett. (1990)

– $cos(\gamma(\varphi))=1-2cos(\varphi/2)$
– $\sigma=\pm1$
– $\xi_F=\hbar v_F/E_{ex}$

splitting of the zero-energy states



self-induced Doppler shift:

$$\omega \to \omega \pm \delta = \omega \pm e v_F A$$

below $T^{\star} \approx (\xi/\lambda)\, T_c$

linear current response

total current:

$$J = J_{dia} + J_{para}$$

diamagnetic:

$$J_{dia} = -\frac{e^2 n}{mc} A$$

paramagnetic:

$$J_{para} = \frac{e^2 n}{mc} A \int d\omega \left(-\frac{df}{d\omega}\right) \frac{N(\omega)}{N_0}$$

0 :

$\Rightarrow$ $\rho(\varepsilon_F) = 0$

$\Rightarrow$ $J_{para} = 0$ at $T = 0$

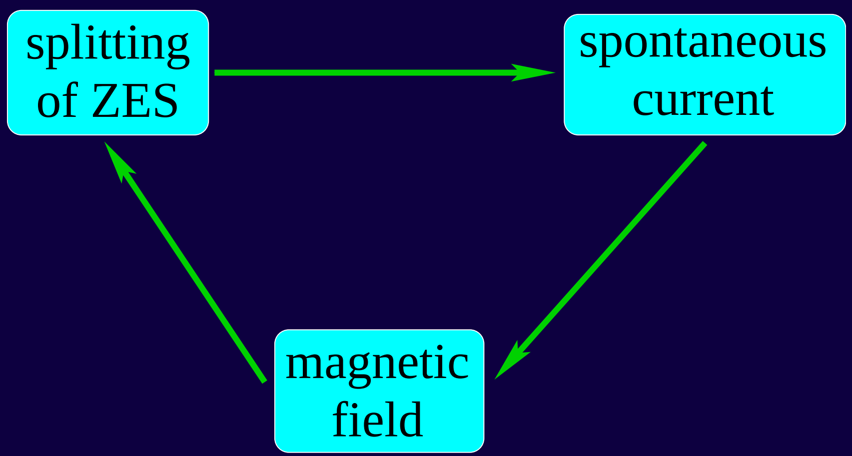
π :

$\Rightarrow$ sharp peak at E_F

$\Rightarrow$ overcompensation of the diamagnetic response

$\Rightarrow$ instability: $\delta F = -J\delta A < 0$

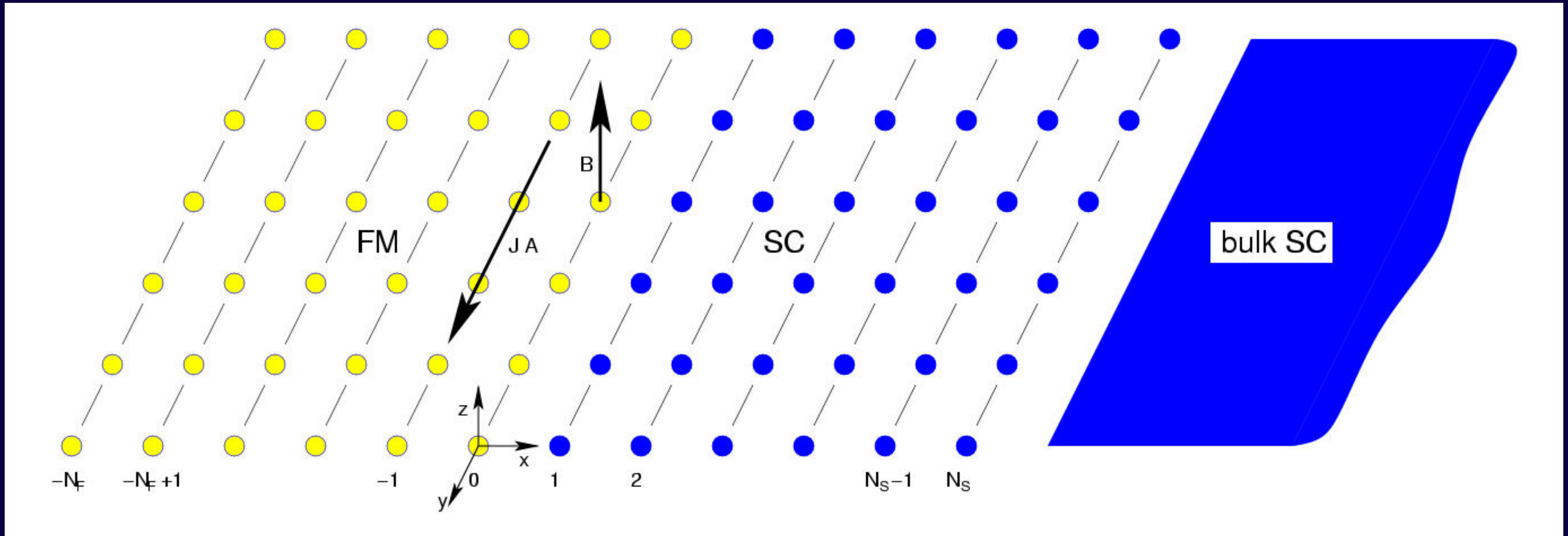
$\Rightarrow$ **spontaneous current**



Self-consistent theory: negative U Hubbard model

M. K., B. L. Györffy & J. F. Annett, PRB (2002); EPJB (2003); Physica C (2003); PRB (2004); Physica C (2005)

model $$H = \Sigma_{ij\sigma}\left[t_{ij} + (\varepsilon_{i\sigma} - \mu)\delta_{ij}\right] c^{+}_{i\sigma} c_{j\sigma} + \Sigma_{i\sigma} \frac{U_i}{2} \widehat{n}_{i\sigma} \widehat{n}_{i-\sigma}$$



- hopping integral: $t_{ij} = -te^{-ie\int_{\vec{r}_i}^{\vec{r}_j} \vec{A}(\vec{r})\cdot d\vec{r}}$
- Coulomb interaction: $U_i = 0$ (FM) and $U_i < 0$ (SC)
- site energies: $\varepsilon_{i\sigma} = \frac{1}{2}E_{ex}\sigma$ (FM) and $\varepsilon_{i\sigma} = 0$ (SC)
- magnetic field: $\vec{B} = (0, 0, B_z(x)) \ \Rightarrow \ \vec{A} = (0, A_y(x), 0)$

SPHFG equations

$$\Sigma_{m' k_y} \left(\omega \hat{\tau}_0 \delta_{nm'} - \hat{H}_{nm'}(k_y) \right) \hat{G}_{m'm}(\omega, k_y) = \delta_{nm}$$

$$\hat{H}_{nm}(k_y) = \begin{pmatrix} \frac{1}{2}E_{ex}\delta_{nm} - T_- & -\Delta_n \delta_{nm} & 0 & 0 \\ -\Delta_n \delta_{nm} & \frac{1}{2}E_{ex}\delta_{nm} + T_+ & 0 & 0 \\ 0 & 0 & -\frac{1}{2}E_{ex}\delta_{nm} - T_- & \Delta_n \delta_{nm} \\ 0 & 0 & \Delta_n \delta_{nm} & -\frac{1}{2}E_{ex}\delta_{nm} + T_+ \end{pmatrix}$$

$$T_{\pm} = (t cos(k_y \pm eA_y(n)) + \mu)\delta_{nm} + t\delta_{n,n+1}$$

- principal layer technique   Turek et al., *Electronic structure* ..., Boston (1997)

- finite temperature method   Litak et al., Physica C (1995)

$$\langle \hat{O} \rangle = \frac{2}{\pi} \sum_{\nu=0}^{2N-1} \mathrm{Re} G(\omega_\nu) e^{(2\nu+1)\pi i/2N}$$

$$\omega = \sigma \left(e^{(2\nu+1)\pi i/2N} - 1 \right) \;\; ; \;\; N = \beta\sigma/2 \;\; ; \;\; \sigma > W/2$$

self-consistency and the Ampere's law

- electron concentration: $n_n = n_{n\uparrow} + n_{n\downarrow}$

  $n_n = \frac{2}{\beta}\Sigma_{k_y\nu}\text{Re}\left\{\text{Tr}(\widehat{G}_{nn}(\omega_\nu, k_y))e^{(2\nu+1)\pi i/2N}\right\}$

- spin polarization: $m_n = n_{n\uparrow} - n_{n\downarrow}$

  $m_n = \frac{2}{\beta}\Sigma_{k_y\nu}\text{Re}\left\{\text{Tr}(\widehat{G}_{nn}(\omega_\nu, k_y)\widehat{\tau}_3)e^{(2\nu+1)\pi i/2N}\right\}$

- SC order parameter: $\Delta_n = U_n\Sigma_{k_y}\langle c_{n\downarrow}(k_y)c_{n\uparrow}(k_y)\rangle$

  $\Delta_n = \frac{2U_n}{\beta}\Sigma_{k_y\nu}\text{Re}\left\{G^{12}_{nn}(\omega_\nu, k_y)e^{(2\nu+1)\pi i/2N}\right\}$

- current in the y direction: $J_y^{tot}(n) = J_{y\uparrow}(n) + J_{y\downarrow}(n)$

  $J_y^{tot}(n) = \frac{4et}{\beta}\Sigma_{k_y\nu}sin(k_y - eA_y(n))\text{Re}\left\{\text{Tr}(\widehat{G}_{nn}(\omega_\nu, k_y))e^{(2\nu+1)\pi i/2N}\right\}$

- polarization of the current: $\Delta J_y(n) = J_{y\uparrow}(n) - J_{y\downarrow}(n)$

  $\Delta J_y(n) = \frac{4et}{\beta}\Sigma_{k_y\nu}sin(k_y - eA_y(n))\text{Re}\left\{\text{Tr}(\widehat{G}_{nn}(\omega_\nu, k_y)\widehat{\tau}_3)e^{(2\nu+1)\pi i/2N}\right\}$

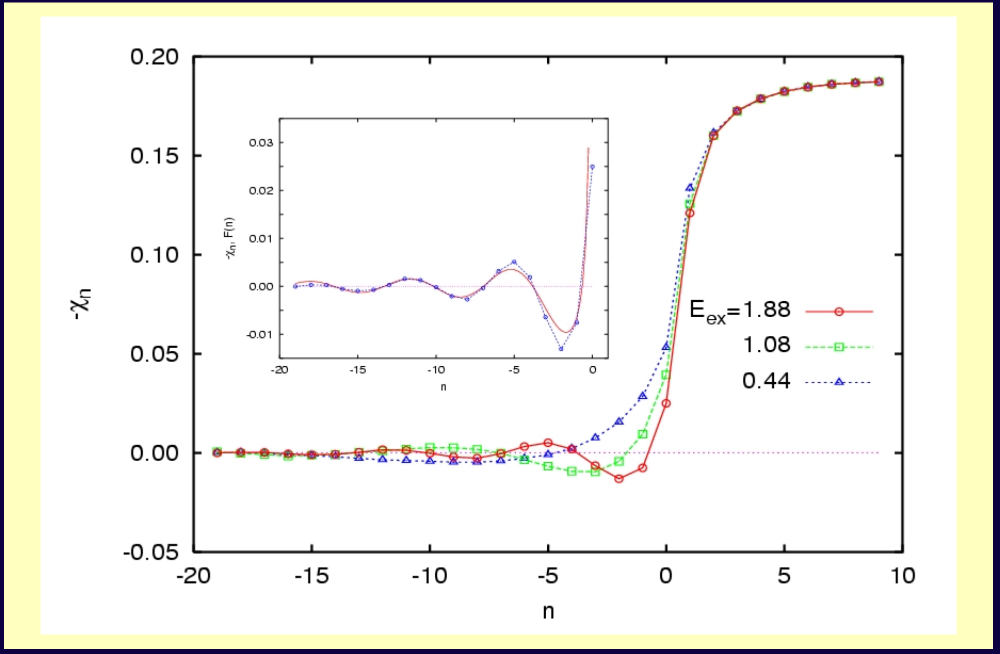
- Ampere's law on a lattice: $\vec{\nabla} \times \vec{\nabla} \times \vec{A}(\vec{r}) = \mu_0\vec{j}(\vec{r})$

  $A_y(n+1) - 2A_y(n) + A_y(n-1) = -\mu_0 J_y(n)$

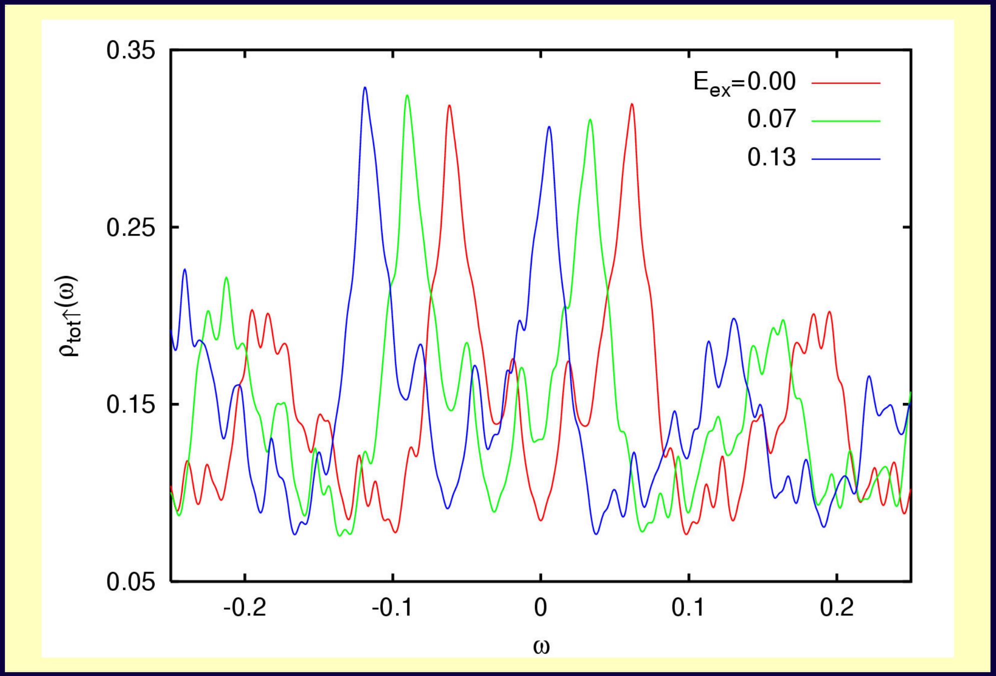
Current carrying ground state

pairing amplitude

$$\chi_n \propto \frac{sin(n/\xi_F)}{(n/\xi_F)}$$



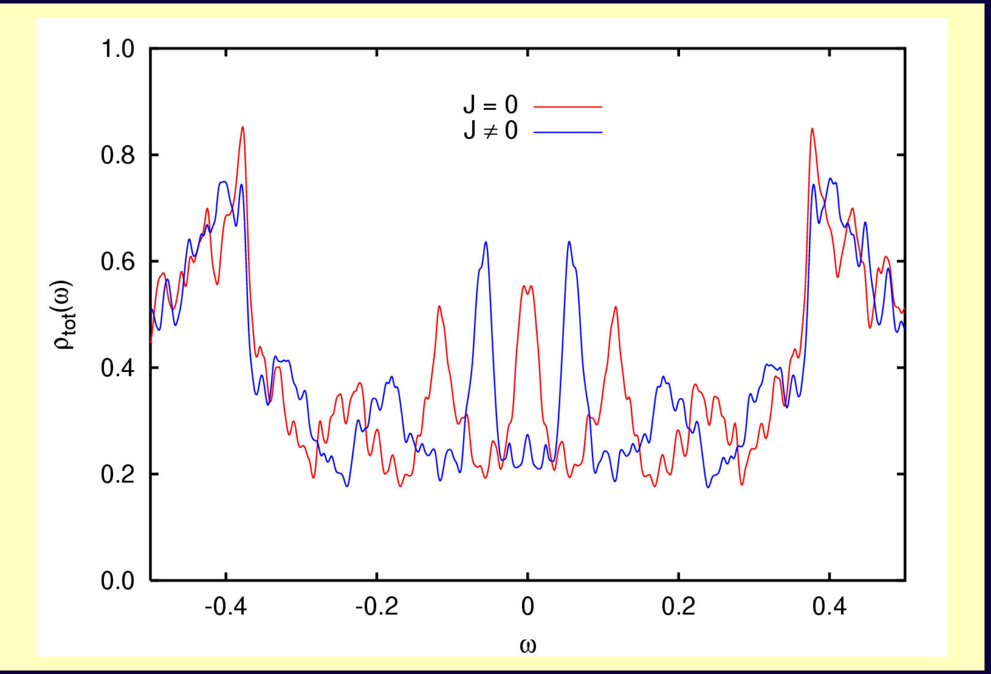
Andreev bound states



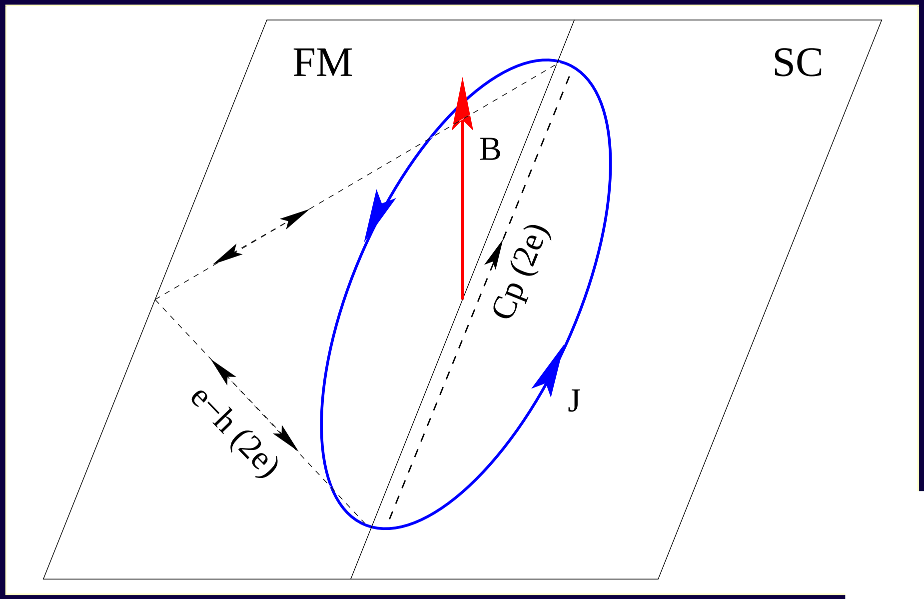
zero-energy bound states (ZES):

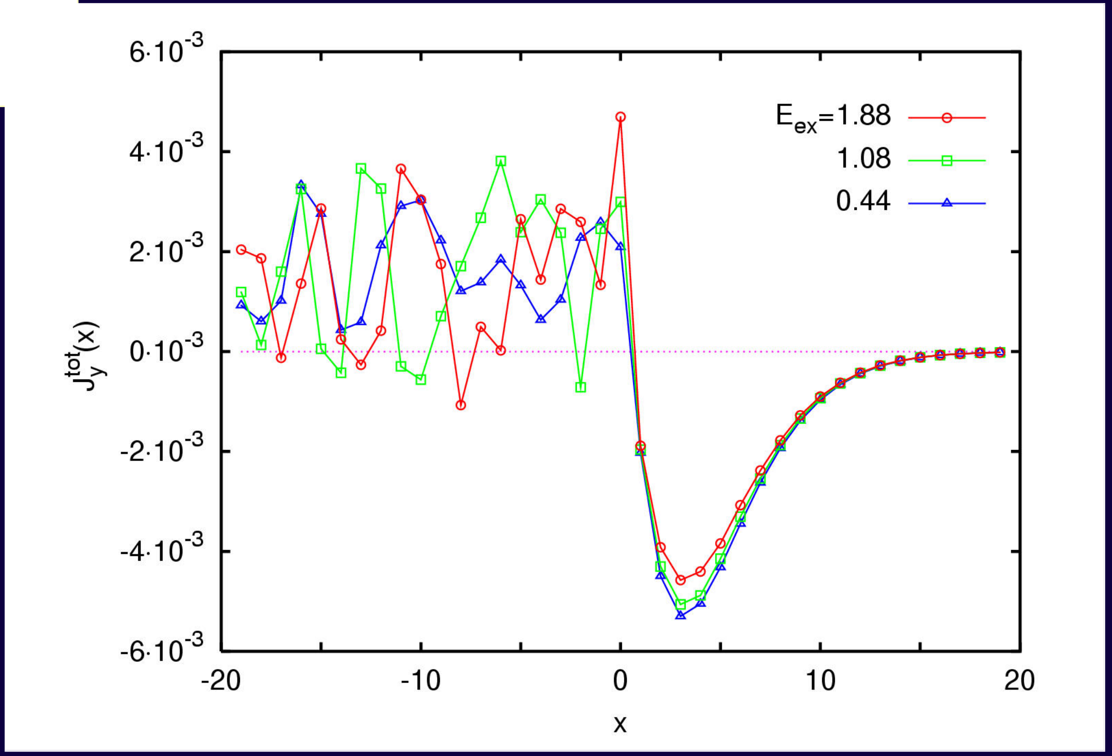
- splitting of the ZES

$$\delta \approx 2et\bar{A}_y$$



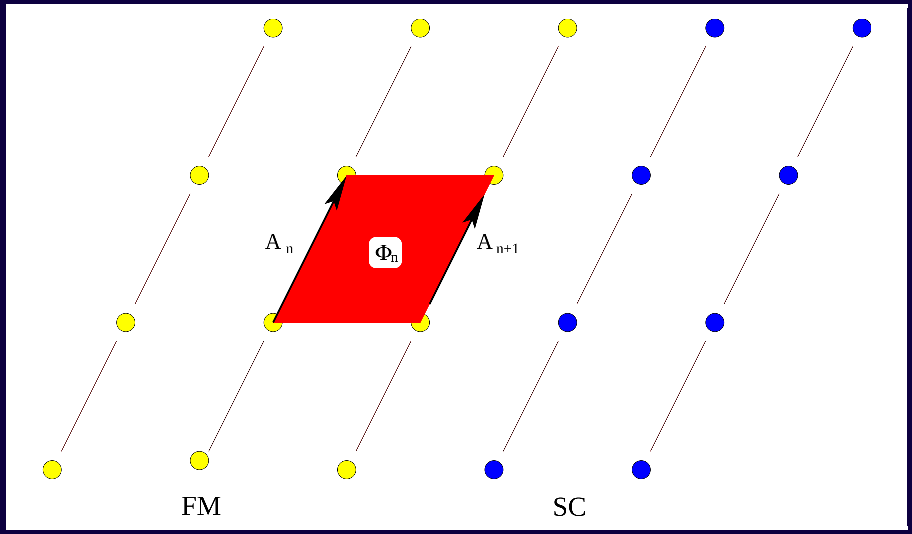
spontaneous current



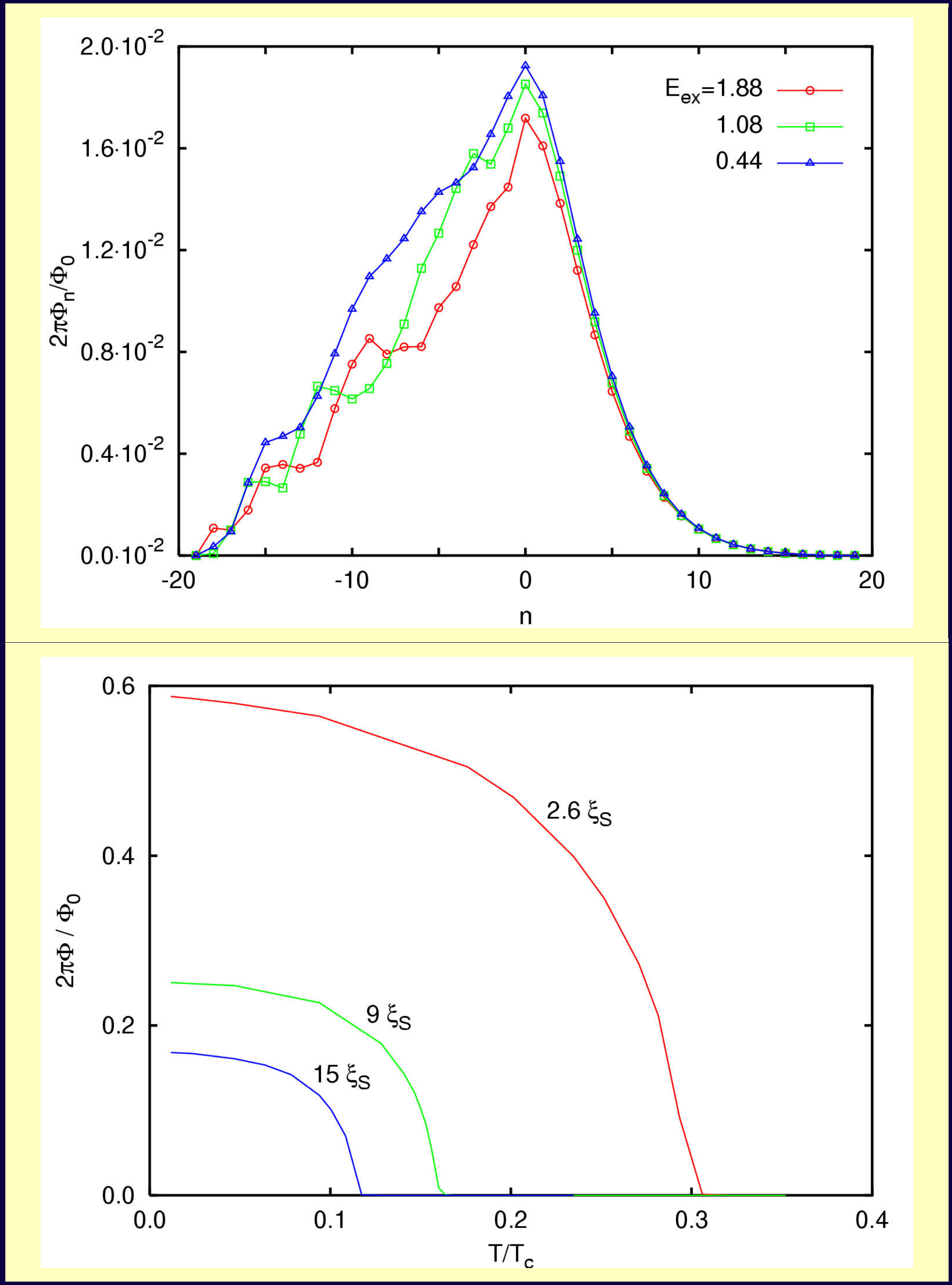


spontaneous magnetic field

$$\Phi(n) = A_y(n+1) - A_y(n)$$

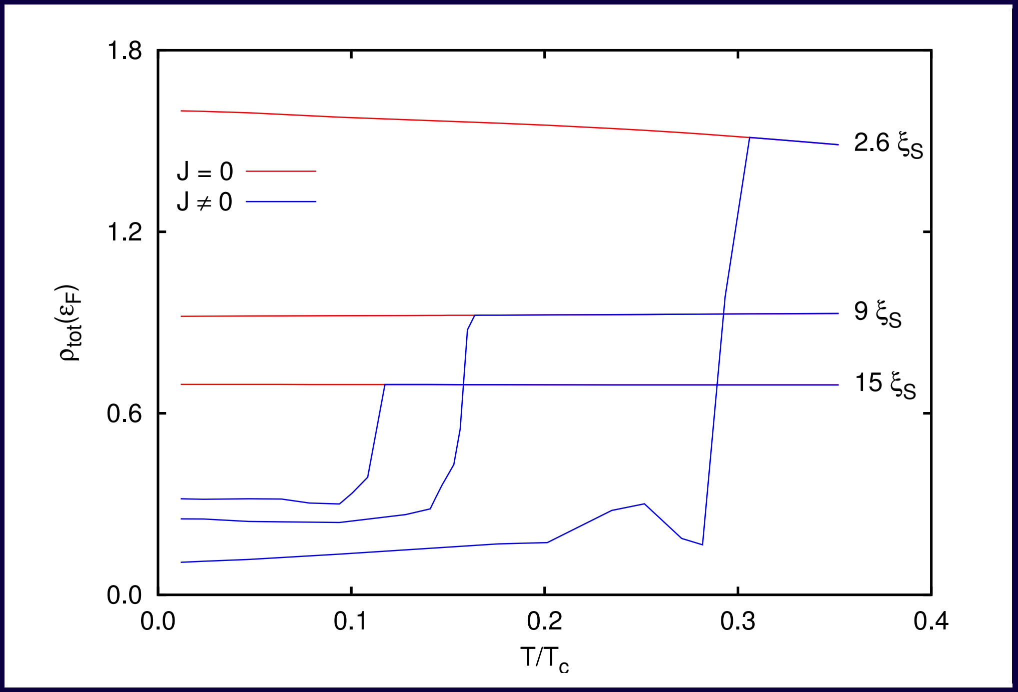


$$H \sim 10^{-2} H_{c2}^{bulk}$$



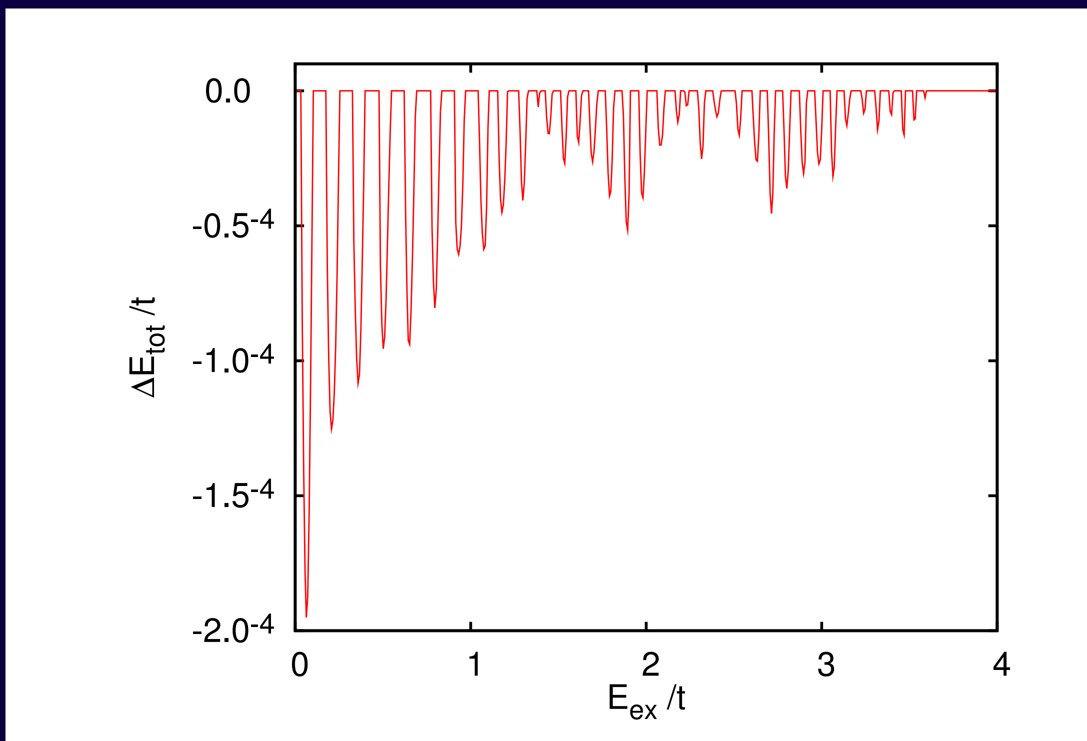
density of states vs temperature

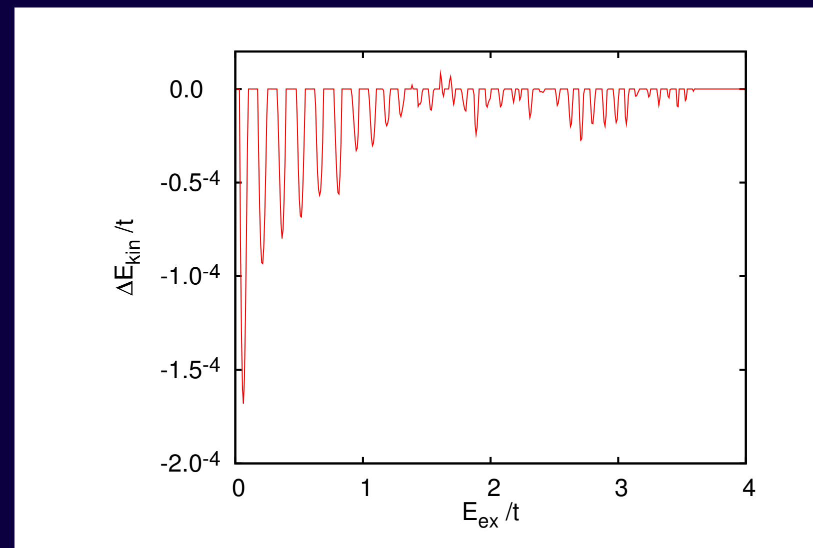
$T^\star < T_c \Rightarrow$ spontaneous current

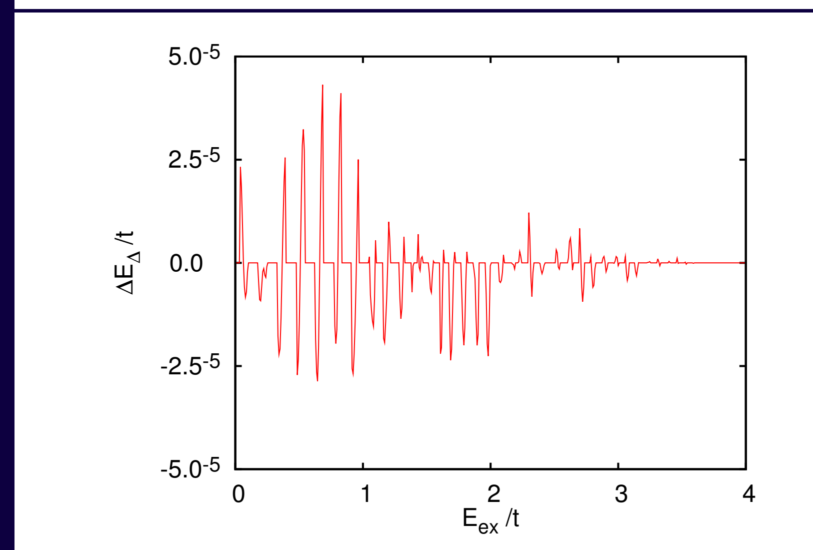


ground state energy

$\Delta E = E_J - E_0 < 0 \Rightarrow$ true ground state



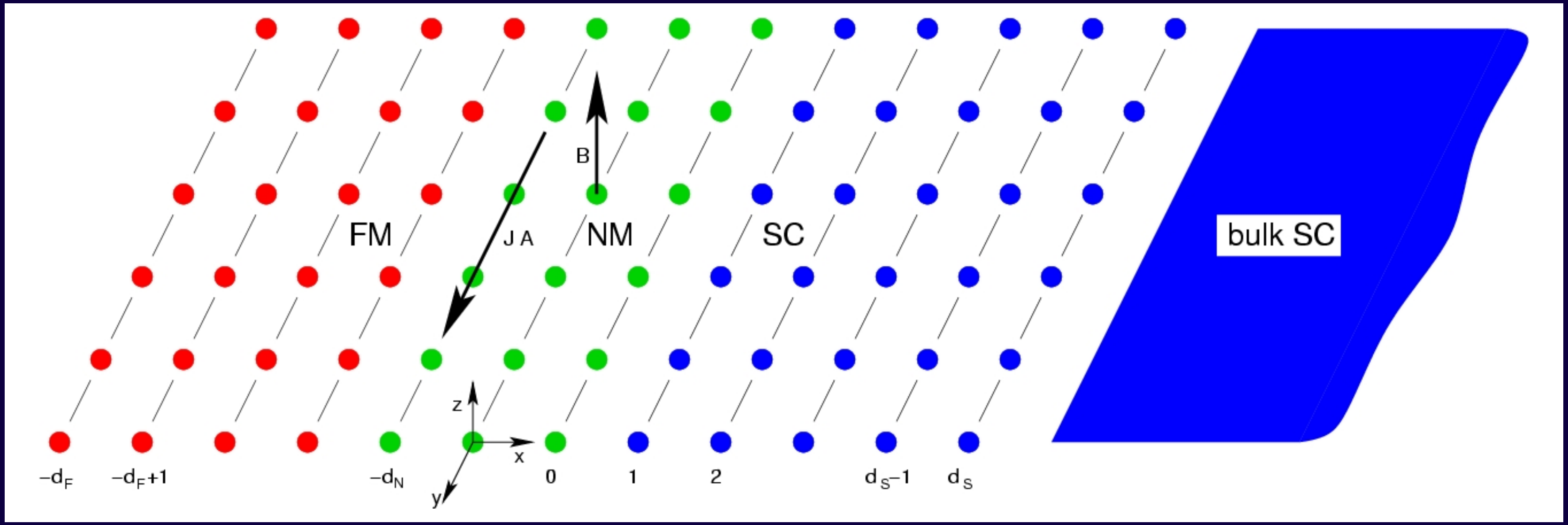




Effect of the normal metal slab (F-N-S)

M. K., J. F. Annett & B. L. Györffy, cond-mat (2005)

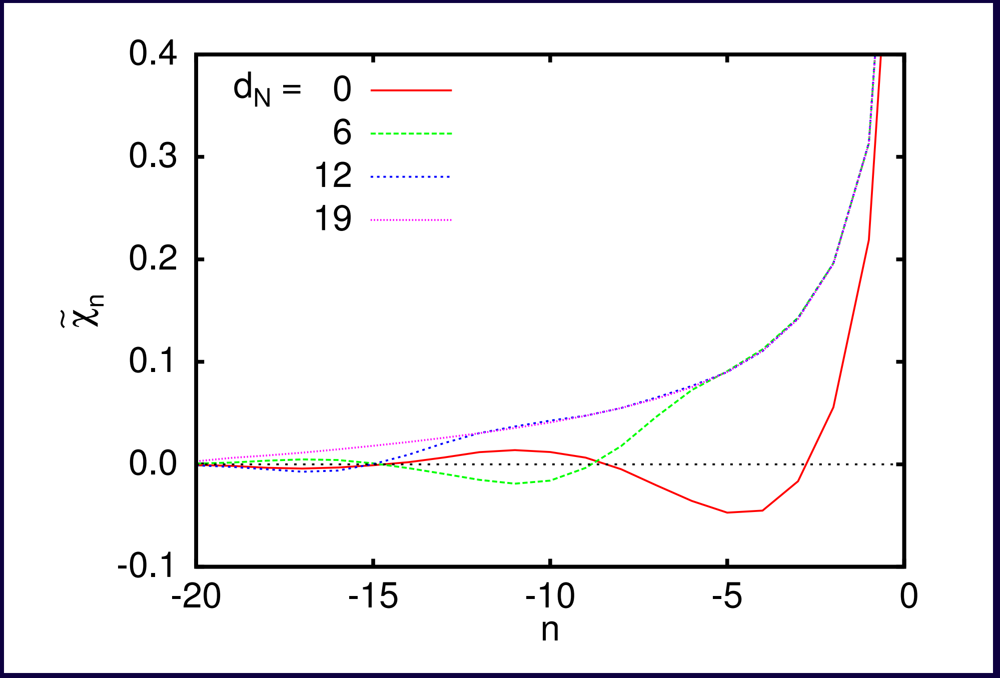
model $H = \Sigma_{ij\sigma}\left[t_{ij} + (\varepsilon_{i\sigma} - \mu)\delta_{ij}\right] c_{i\sigma}^{+} c_{j\sigma} + \Sigma_{i\sigma}\frac{U_i}{2}\hat{n}_{i\sigma}\hat{n}_{i-\sigma}$



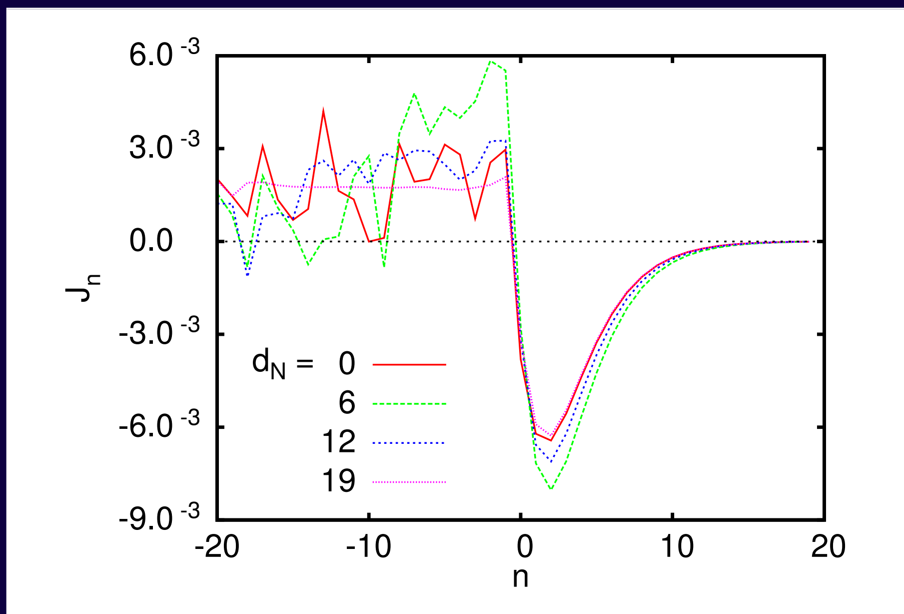
- hopping integral: $t_{ij} = -te^{-ie\int_{\vec{r}_i}^{\vec{r}_j}\vec{A}(\vec{r})\cdot d\vec{r}}$
- Coulomb interaction: $U_i = 0$ (FM and NM) and $U_i < 0$ (SC)
- site energies: $\varepsilon_{i\sigma} = \frac{1}{2}E_{ex}\sigma$ (FM) and $\varepsilon_{i\sigma} = 0$ (NM and SC)
- magnetic field: $\vec{B} = (0, 0, B_z(x)) \Rightarrow \vec{A} = (0, A_y(x), 0)$

pairing amplitude

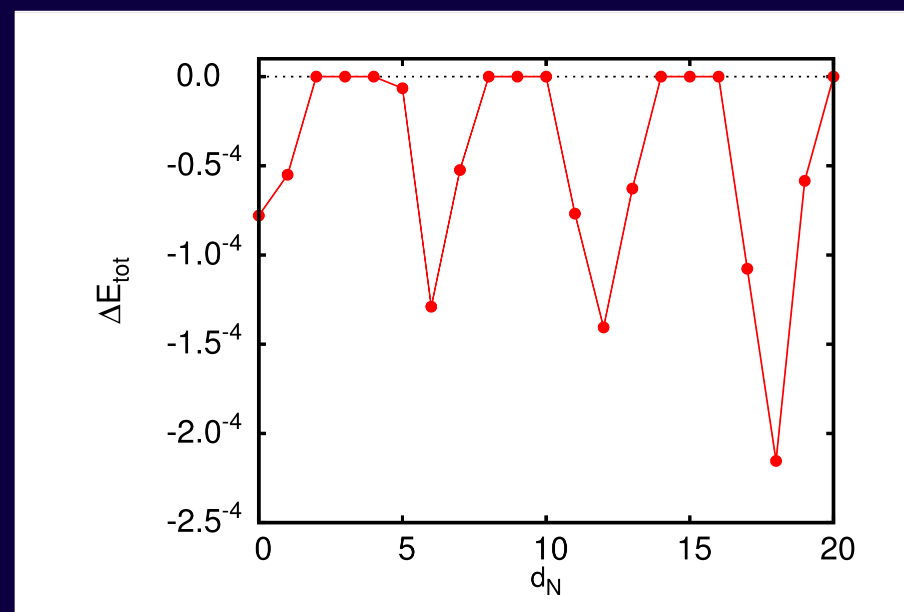
$$\chi_n \propto \frac{sin(n/\xi_F)}{(n/\xi_F)}$$



spontaneous current



ground state energy



Conclusions

F-S

- oscillatory behavior of the pairing amplitude
- zero-energy Andreev bound states in FM
- spontaneous current and magnetic field
- true ground state

F-N-S

- pairing amplitude in FM: $\chi_{FNS} \approx \chi_{FS}$
- difference in the GS energy: $|\Delta E_{FNS}| > |\Delta E_{FS}|$
- $NM \neq$ transparency of the interface