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and Hybrid Magnetic Nanostructures**

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Transport Properties of Ballistic Superconductor-Ferromagnet Heterostructures

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TRANSPORT PROPERTIES OF BALLISTIC SUPERCONDUCTOR-FERROMAGNET HETEROSTRUCTURES

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Landau Institute, Moscow

Outline

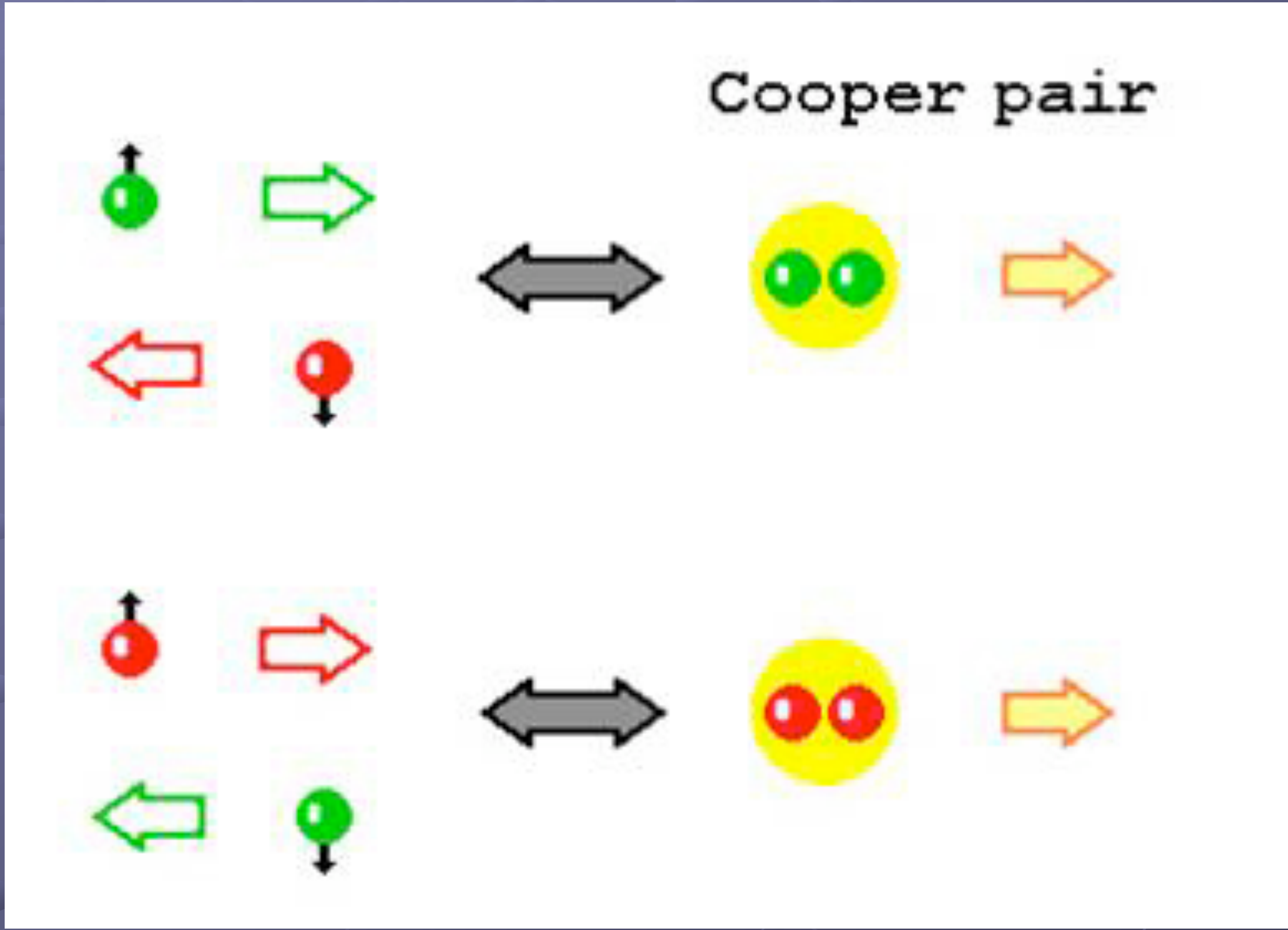
- Coherent transport in clean FISIF junctions:
  - Differential conductances (charge and spin)
  - Proximity effect
  - Ballistic spectroscopy
- Coherent transport in clean SIFIS junctions :
  - dc Josephson current
  - Coexistence of 0 and p states –
    modulation period of $\phi_0/2$ in SQUIDs.
  - Temperature-induced 0-π transition
  - Transmission resonances triggering 0- π transitions

Why FSF and SFS double barrier ballistic-junctions?

- Resonant tunneling (resonant amplification of the Andreev process)
- Ballistic spectroscopy of superconductors by spin-polarized currents
- π-SQUIDs for quantum electronics and spintronics
- Superposition of macroscopically distinct quantum states:
  LCs in quantum computers ?

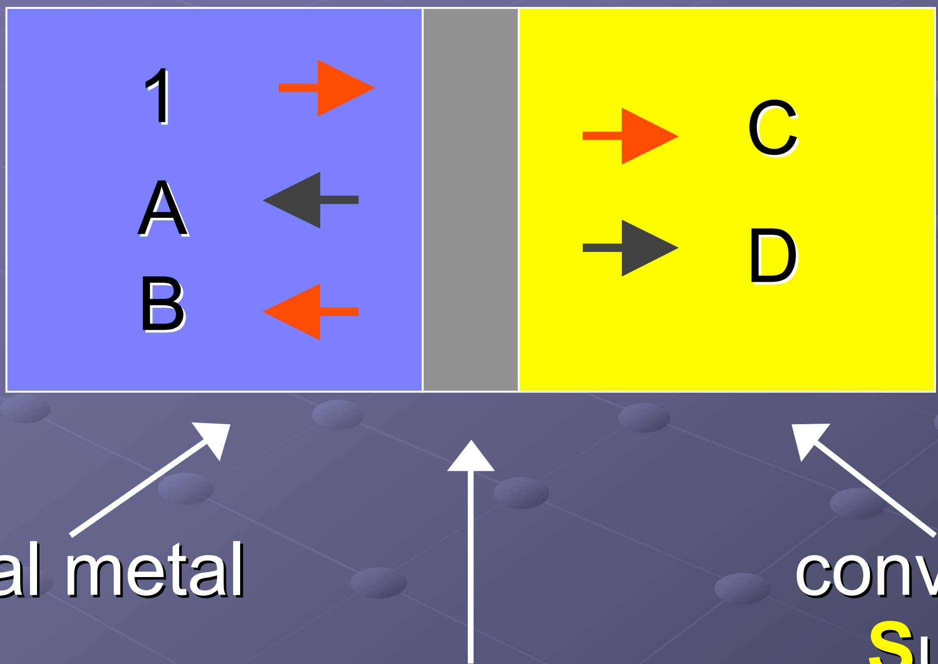
Andreev reflection

A. F. Andreev, Sov. Phys. JETP **19**, 1228 (1964).



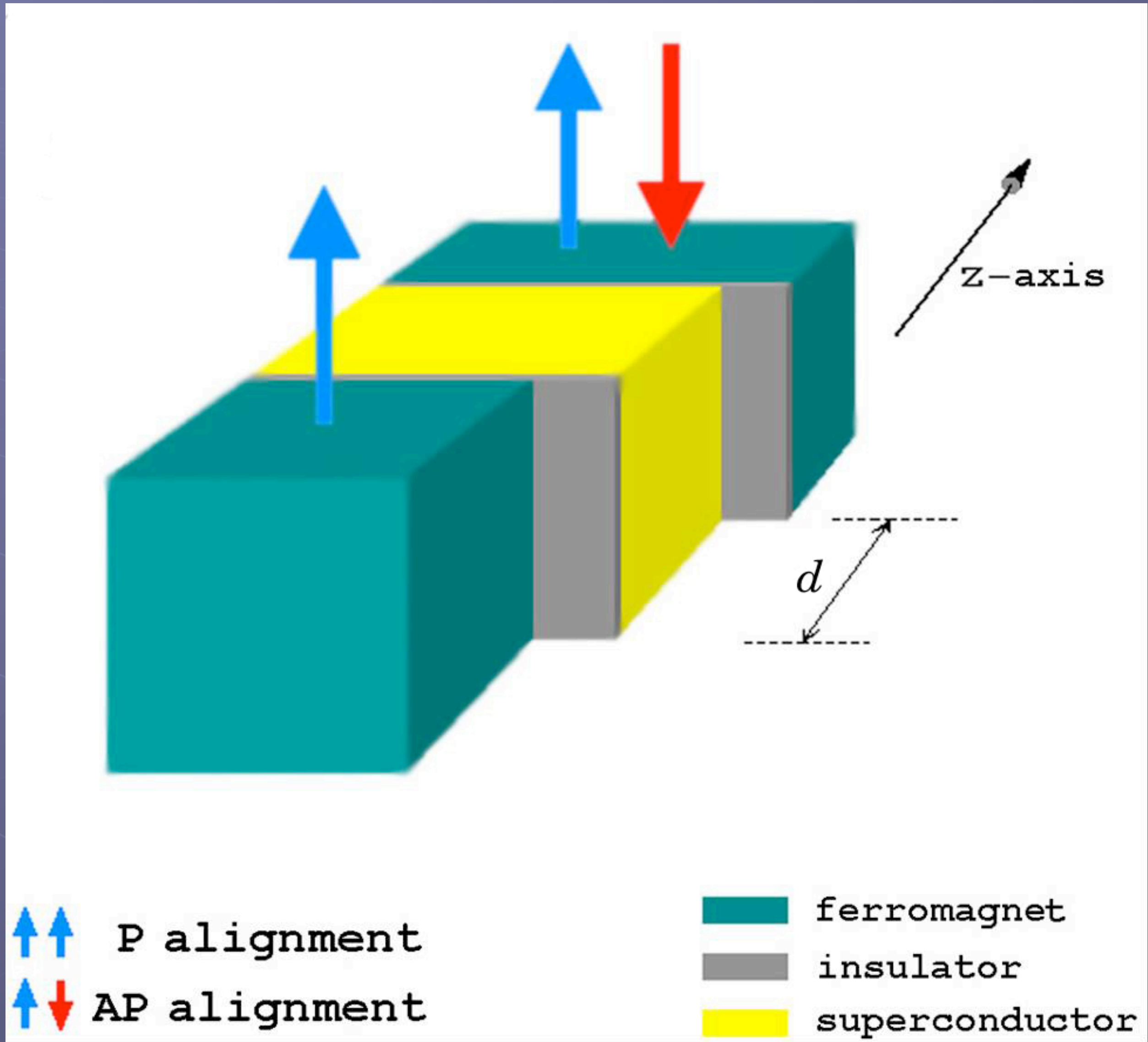
The BTK model

G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B **25**, 4515 (1982).



$$G = G_0 \, (1 + A - B)$$

The Model (FISIF)



BdG Equations

$$\begin{pmatrix} H_0(\mathbf{r}) - \rho_\sigma h(\mathbf{r}) & \Delta(\mathbf{r}) \\ \Delta^*(\mathbf{r}) & -H_0(\mathbf{r}) + \rho_{\bar{\sigma}} h(\mathbf{r}) \end{pmatrix} \Psi_\sigma(\mathbf{r}) = E\,\Psi_\sigma(\mathbf{r})$$

$$\Psi_\sigma(\mathbf{r}) \equiv \begin{pmatrix} u_\sigma(\mathbf{r}) \\ v_{\bar{\sigma}}(\mathbf{r}) \end{pmatrix} = \exp(i\mathbf{k}_{||,\sigma} \cdot \mathbf{r})\ \psi(z)$$

Exchange energy $h(\mathbf{r})/E_F^{(F)} = X[\Theta(-z) \pm \Theta(z-d)]$

Stepwise pair potential $\rho_{\uparrow,\downarrow} = \pm 1$

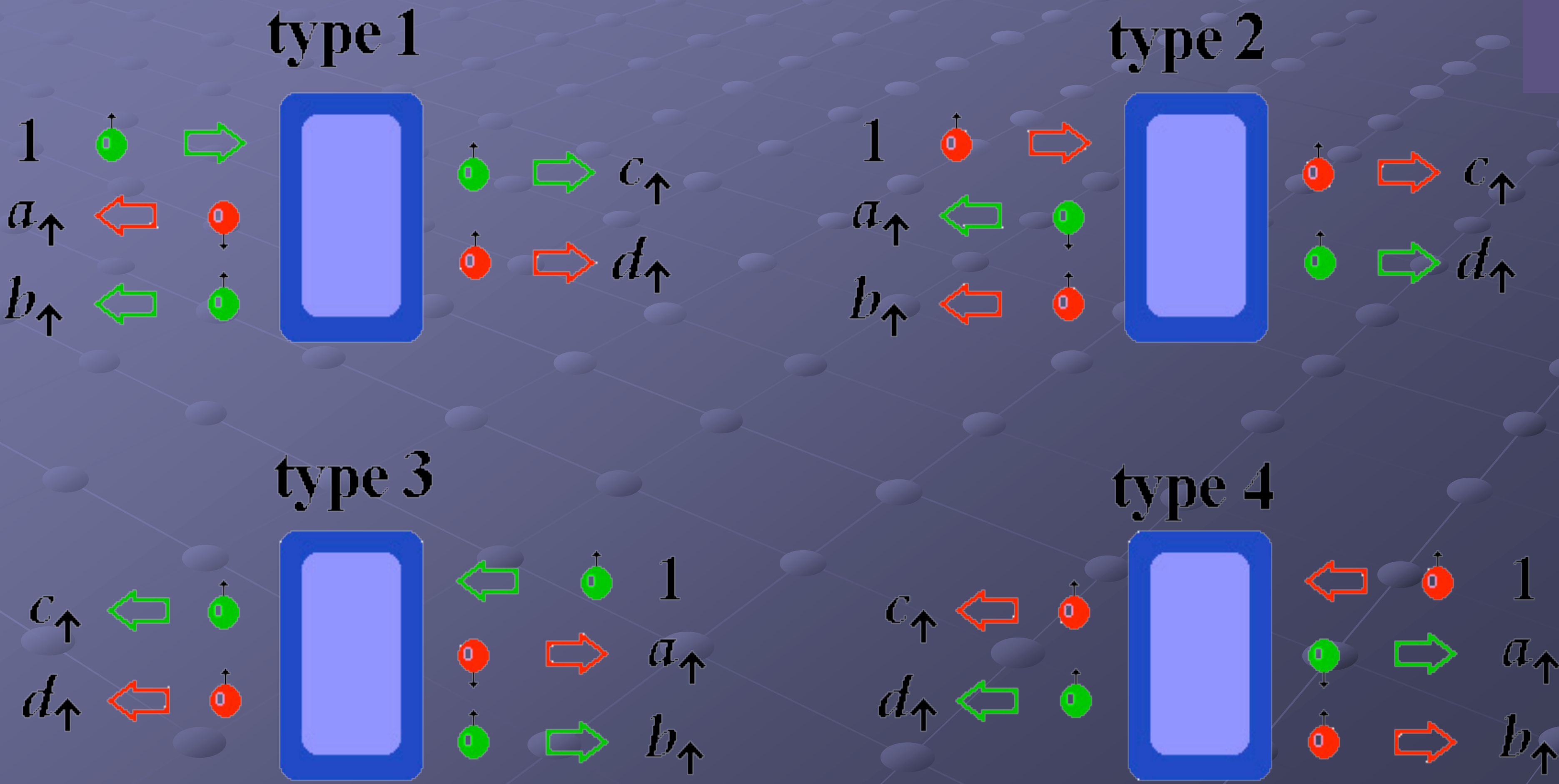
Interface potential $\hat{W}[\delta(z) + \delta(d-z)]$ $Z = 2m\hat{W}/\hbar^2 k_F^{(S)}$

FWVM parameter $\kappa = k_F^{(F)}/k_F^{(S)}$

Scattering Problem

A. Furusaki and M. Tsukada,
Solid State Commun. **78**, 299 (1991).

W.J. Beenakker and H. van Houten,
Phys. Rev. Lett. **66**, 3056 (1991).



Two limits

- Metallic limit (Z = 0)
  Andreev reflection vanishes at geometrical resonances:

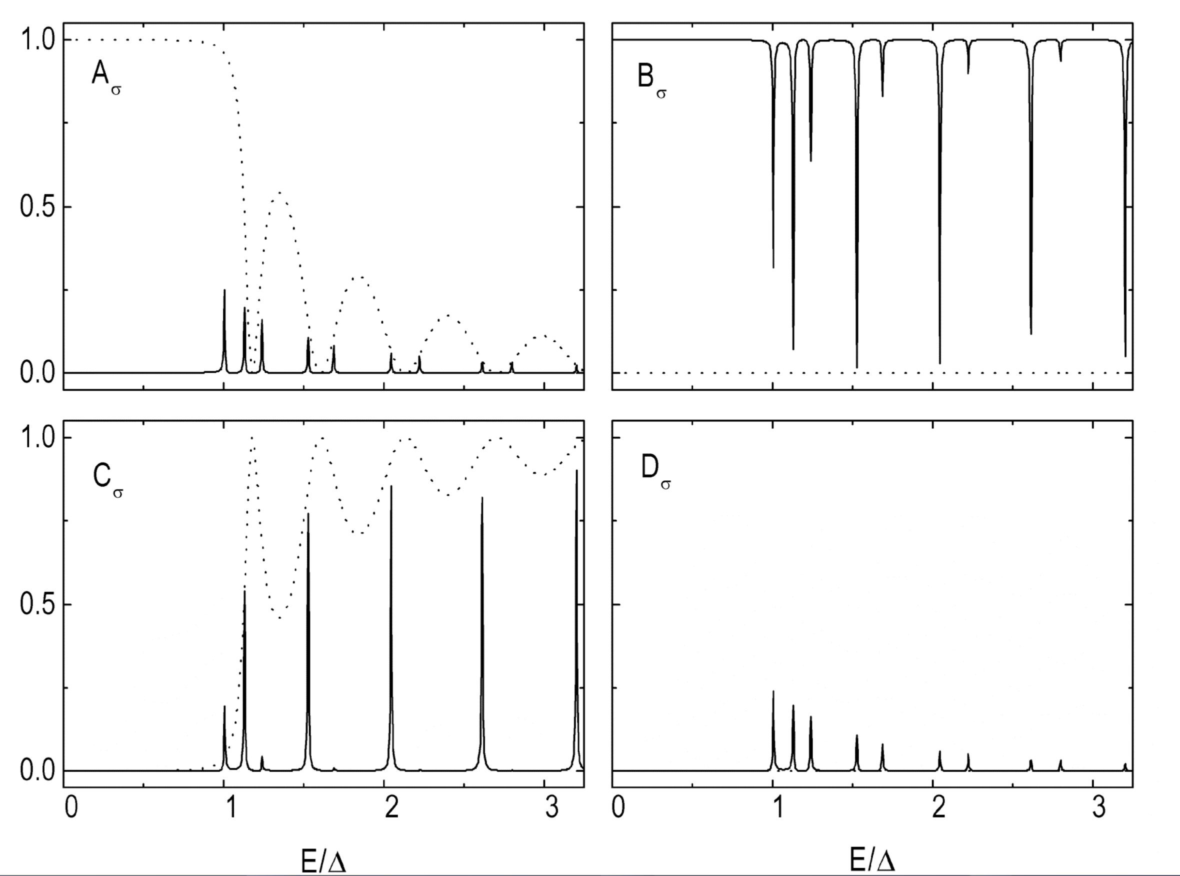
$$A_\sigma = D_\sigma = 0 \quad \text{when} \quad d(q_\sigma^+ - q_\sigma^-) = 2n\pi$$

$$q_\sigma^\pm = \sqrt{(2m/\hbar^2)(E_F^{(S)} \pm \Omega) - \mathbf{k}_{||,\sigma}^2} \qquad \Omega = \sqrt{E^2 + \Delta^2}$$

- Tunnel limit ($Z \to \infty$)
  Transport through bound states of an isolated S film:

$$dq_\sigma^+ = n_1\pi \qquad dq_\sigma^- = n_2\pi \qquad n_1 - n_2 = 2n$$

NSN junction: metallic to tunnel limit



$$X = 0$$

$$dk_F^{(S)} = 10^4 \quad [d/\xi_0 \approx 10]$$

$$\theta = 0$$

$$\kappa = 1\ ,\ \ \Delta/E_F^{(S)} = 10^{-3}$$

Z=0 dotted curves
Z=10 solid curves

M. Božović and Z. Radović in *Supercond. and Rel. Ox.: Phys. and nanoeng. V, Proc. of SPIE, vol. 4811* (Seattle, 2002), p. 216.

Differential conductances

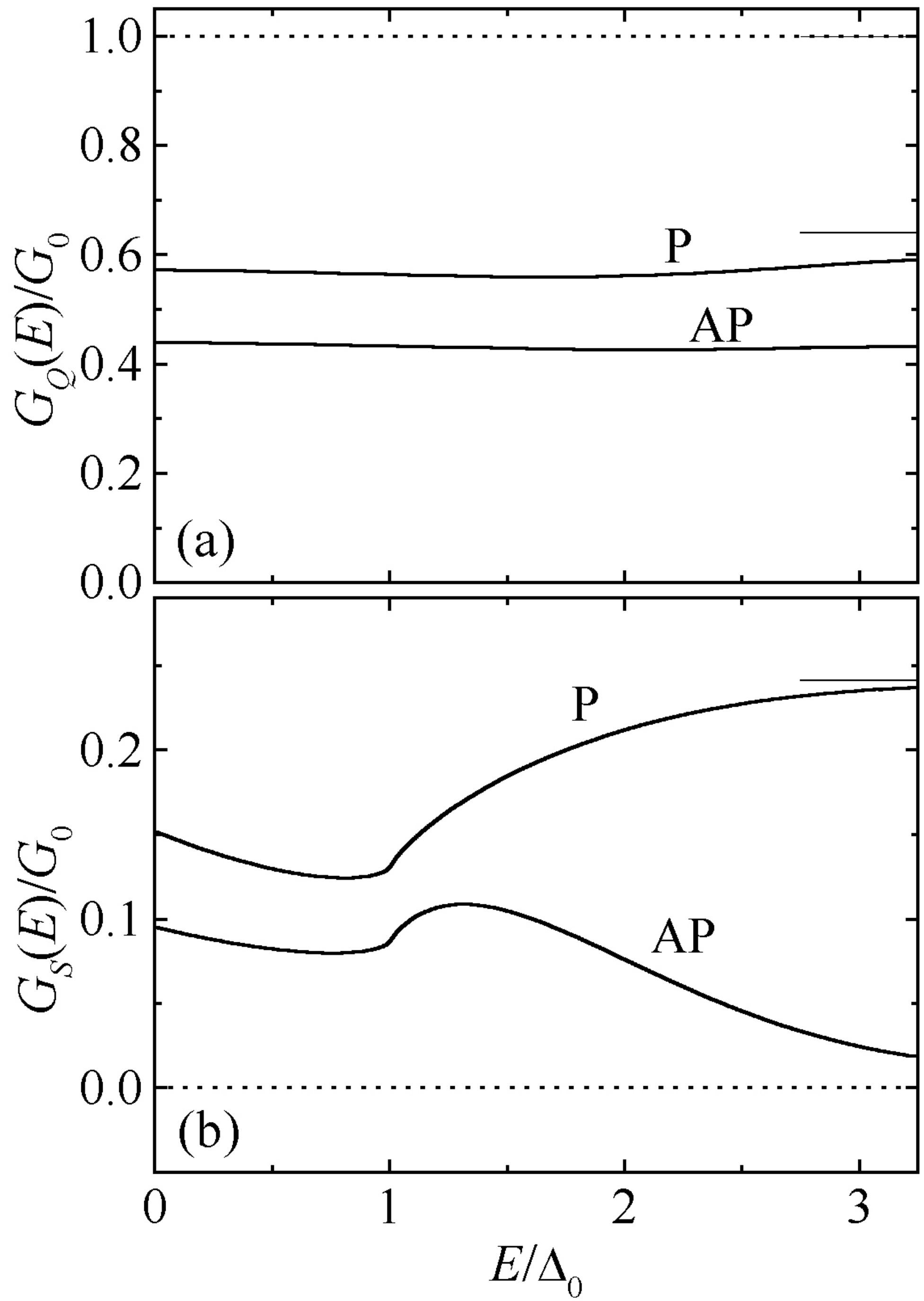
charge

$$G_Q(E) = \frac{e^2}{h} \sum_{\sigma} \lambda_{\sigma}^2 \int_0^{\theta_{c1,\sigma}} d\theta \sin\theta \cos\theta \; [A_{\sigma}(E,\theta) + C_{\sigma}(E,\theta)]$$

spin

$$G_S(E) = \frac{e^2}{h} \sum_{\sigma} \rho_{\sigma} \lambda_{\sigma}^2 \int_0^{\theta_{c1,\sigma}} d\theta \sin\theta \cos\theta \; [1 - A_{\sigma}(E,\theta) - B_{\sigma}(E,\theta)]$$

$$\lambda_{\sigma} = \kappa \sqrt{1 + \rho_{\sigma} X} \qquad \theta_{c1,\uparrow} = \arcsin(1/\lambda_{\uparrow}) \qquad \theta_{c1,\downarrow} = \pi / 2$$



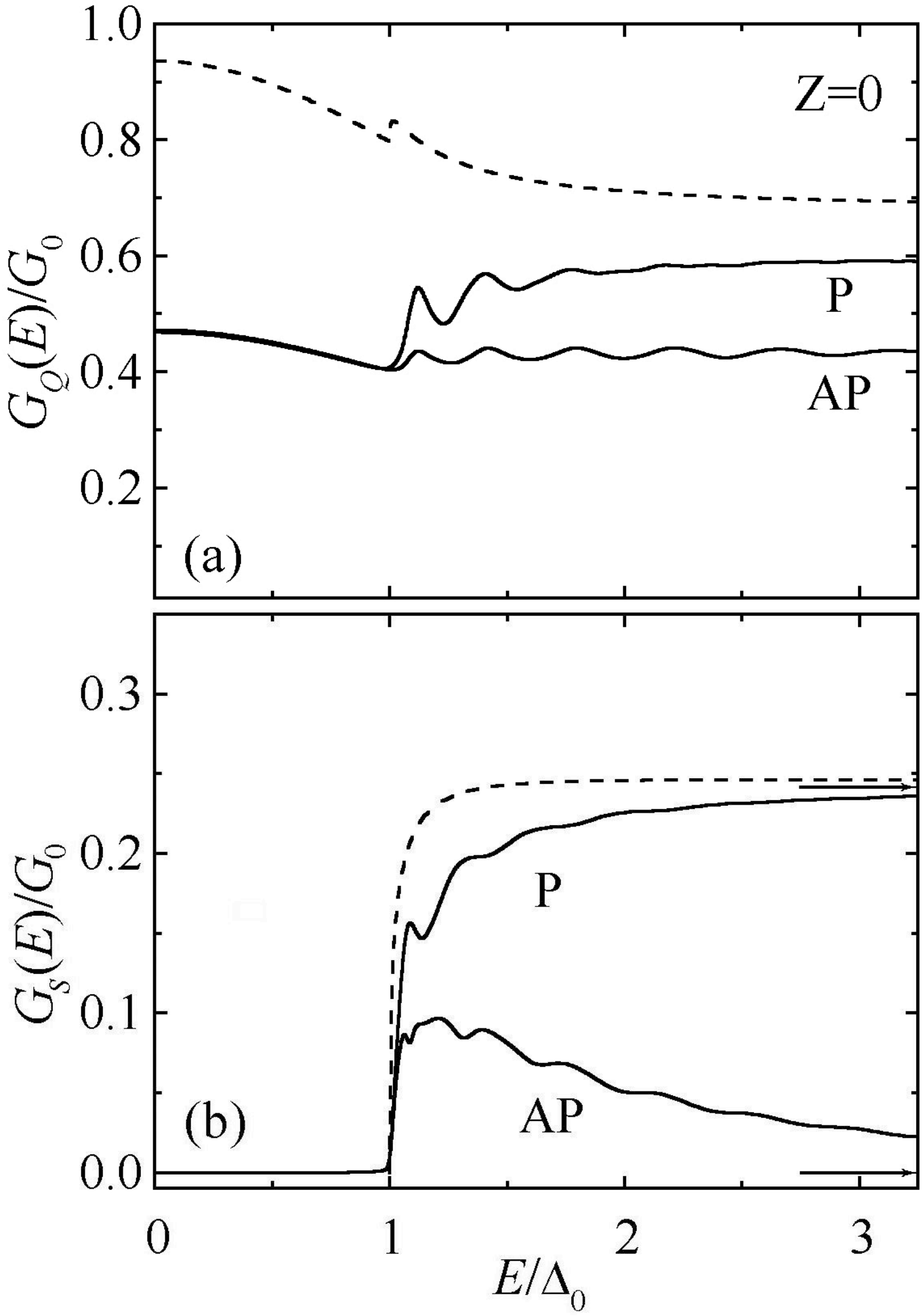
FSF short transparent junctions

$$Z = 0, \quad X = 0.5$$

$$dk_F^{(S)} = 10^3 \quad [d/\xi_0 \approx 1]$$

$$\kappa = 1\ , \ \ \Delta/E_F^{(S)} = 10^{-3}$$

M. Božović and Z. Radović, Phys. Rev. B **66**, 134524 (2002); 71, 229901(E) (2005).



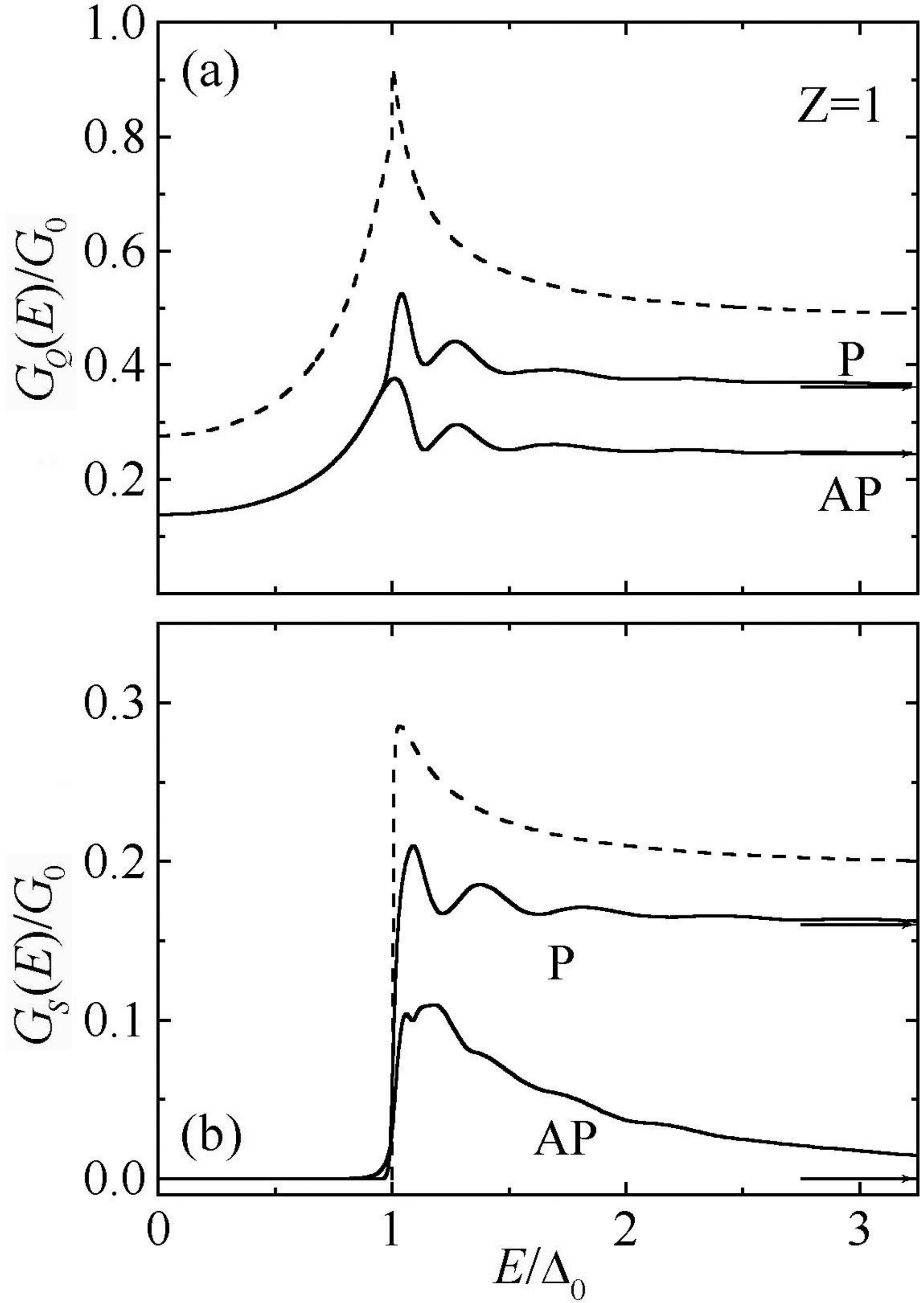
FSF
long transparent junction

$$Z = 0, \quad X = 0.5$$

$$dk_F^{(S)} = 10^4 \quad [d/\xi_0 \approx 10]$$

$$\kappa = 1 \; , \; \Delta/E_F^{(S)} = 10^{-3}$$

M. Božović and Z. Radović,
Phys. Rev. B **66**, 134524 (2002);
71, 229901(E) (2005).



FSF
long finite-transparency junction

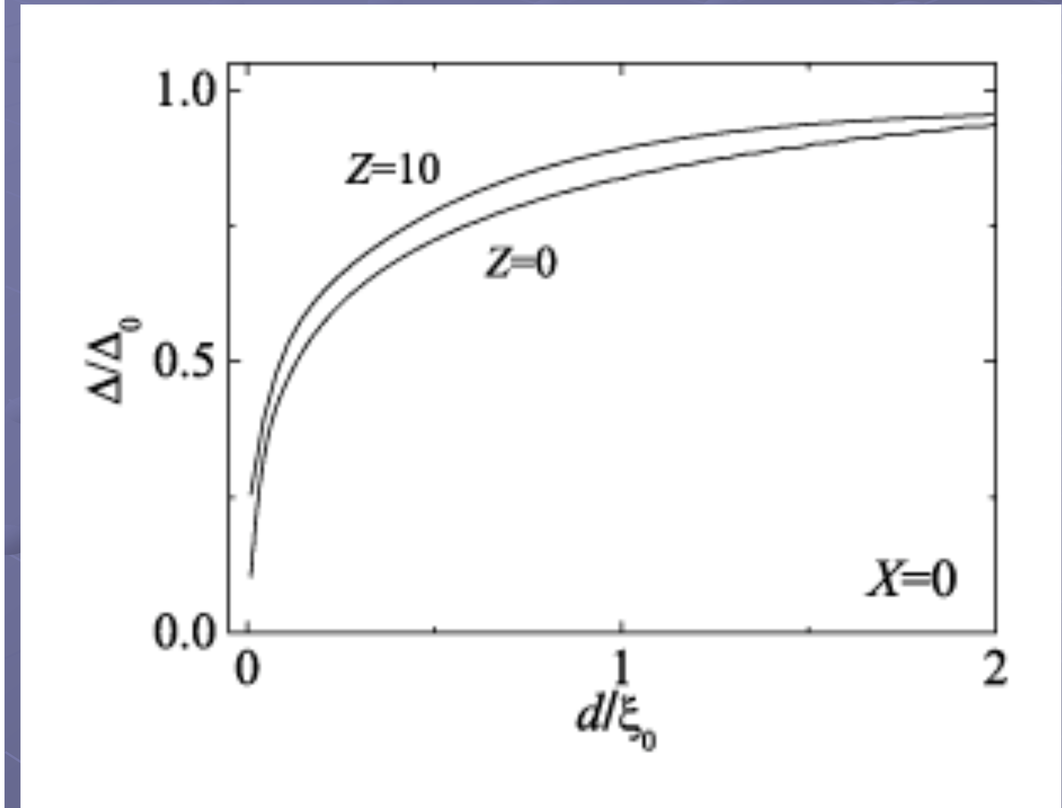
$$Z = 1, \quad X = 0.5$$

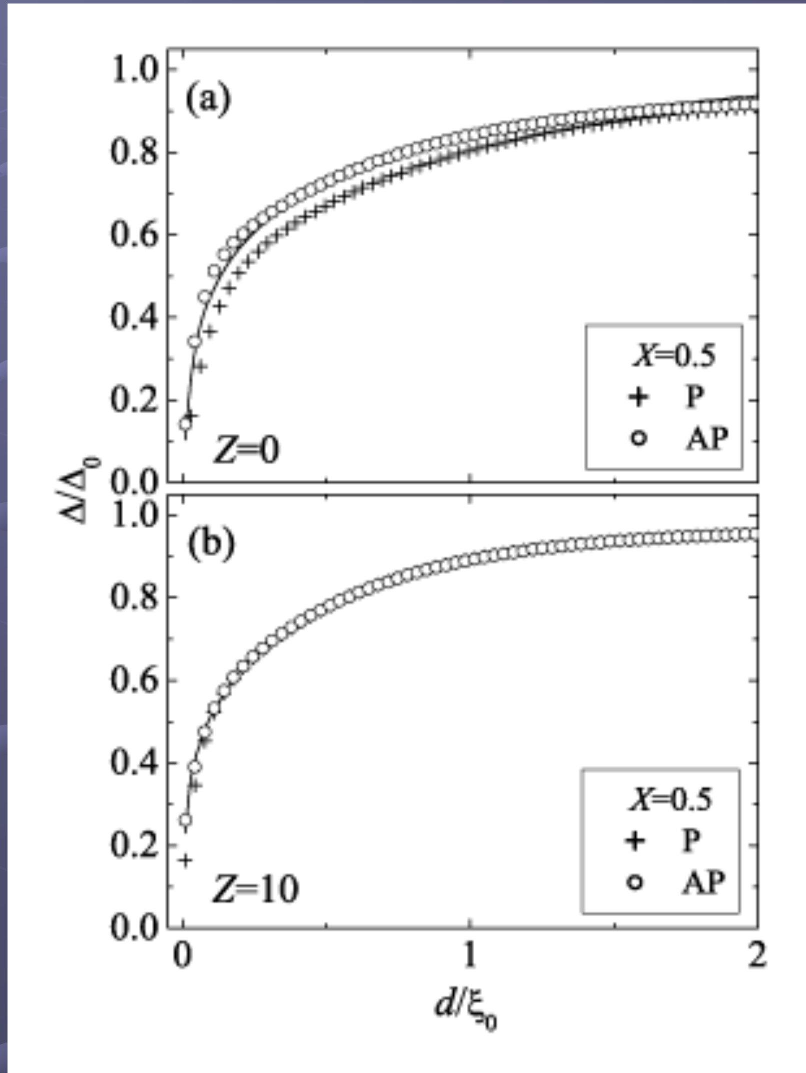
$$dk_F^{(S)} = 10^4 \quad [d/\xi_0 \approx 10]$$

$$\kappa = 1 \ , \ \Delta/E_F^{(S)} = 10^{-3}$$

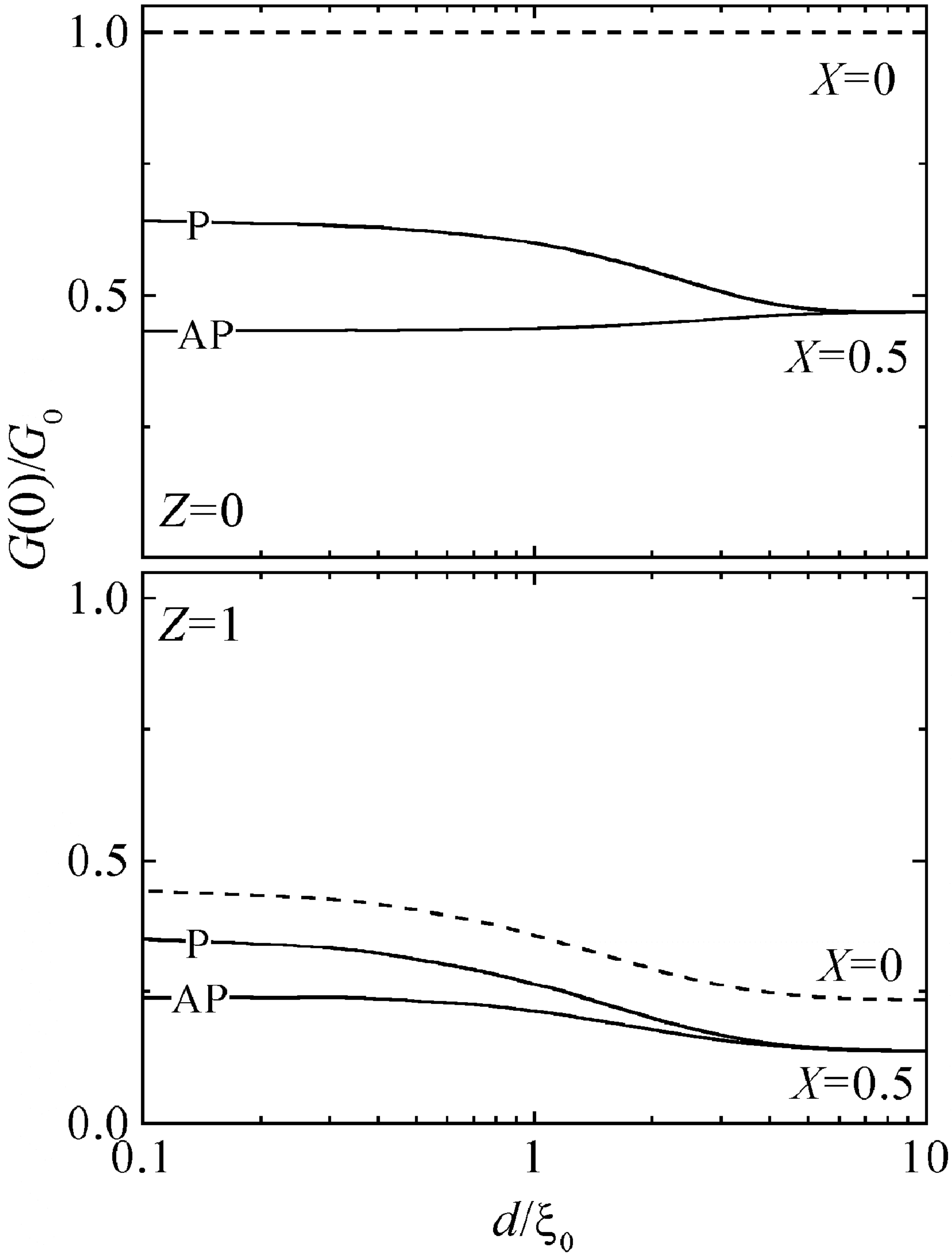
M. Božović and Z. Radović,
Phys. Rev. B **66**, 134524 (2002);
71, 229901(E) (2005).

NSN and FSF junctions: self-consistent pair potential



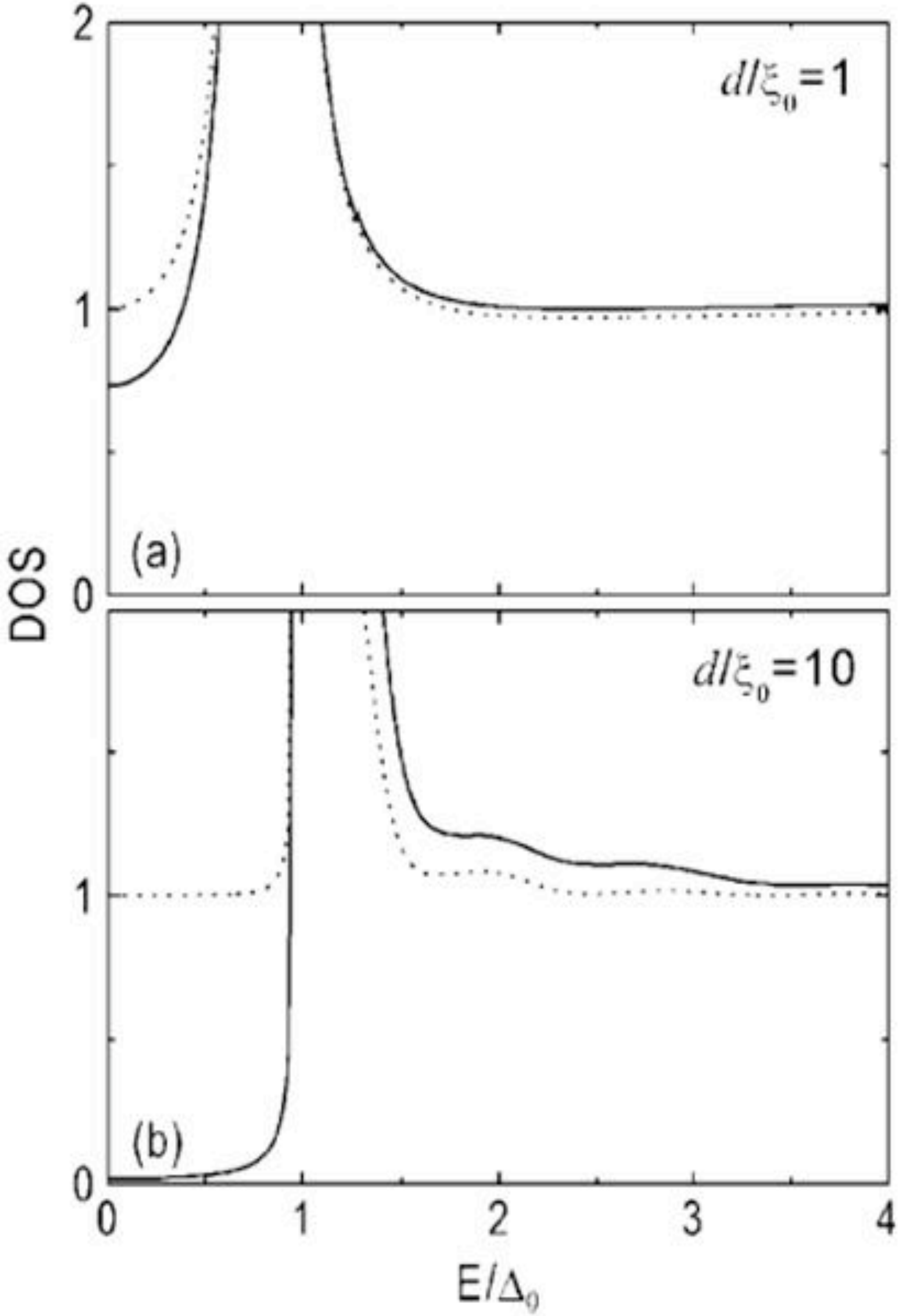


M. Božović and Z. Radović,
Europhys. Lett. **70**, 513 (2005).



NSN and FSF junctions: zero-bias conductance

M. Božović and Z. Radović, Europhys. Lett. **70**, 513 (2005).

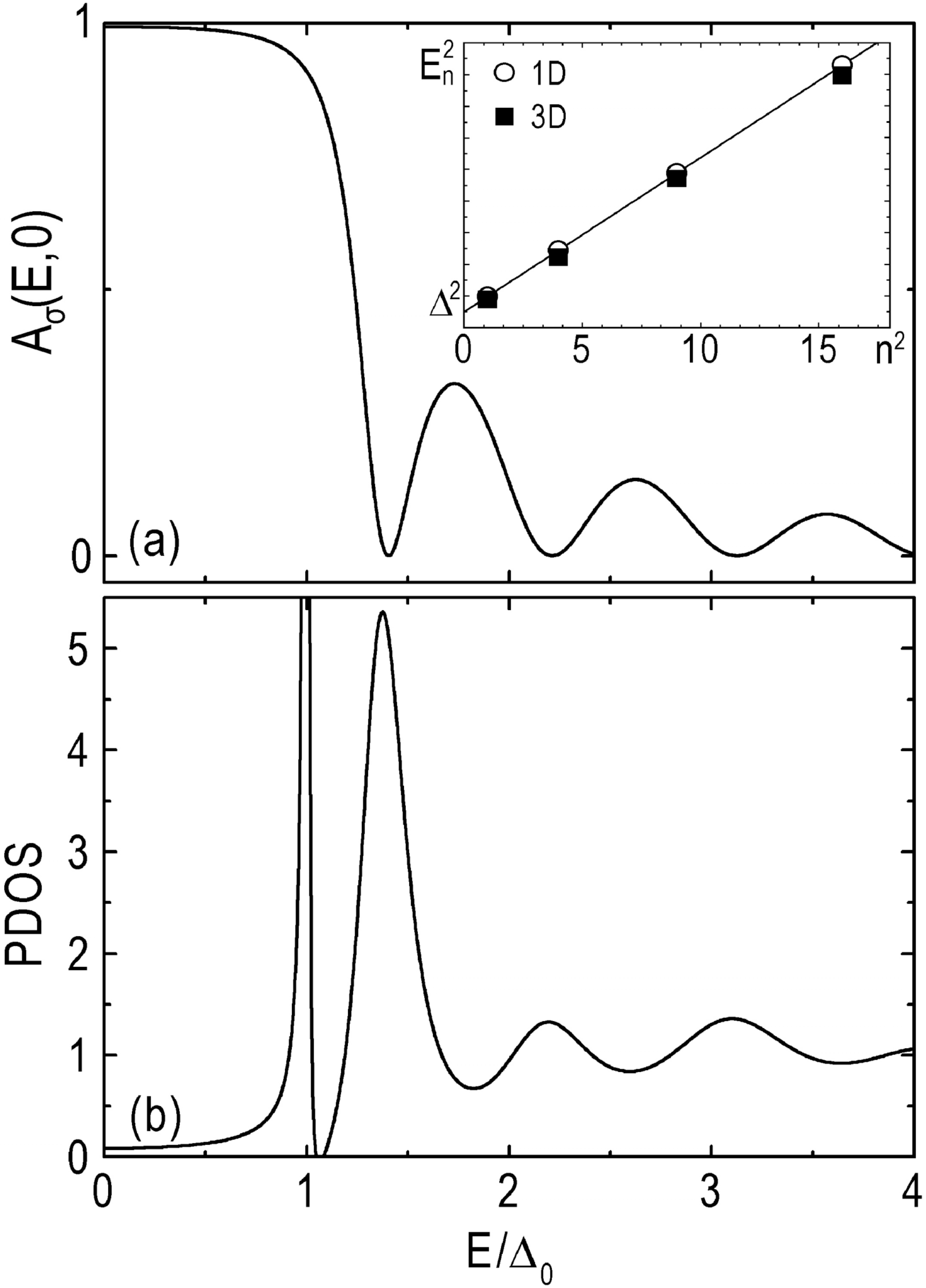


NSN transparent junctions: local density of states in S

solid curves: center of S layer
dotted curves: S-N interface

$$\Delta/E_F = 10^{-3}$$

M. Božović, Z. Pajović, and Z. Radović, Physica C **391**, 309 (2003).



NSN long transparent 1D junction

$Z = 0, \quad X = 0$

$\theta = 0$

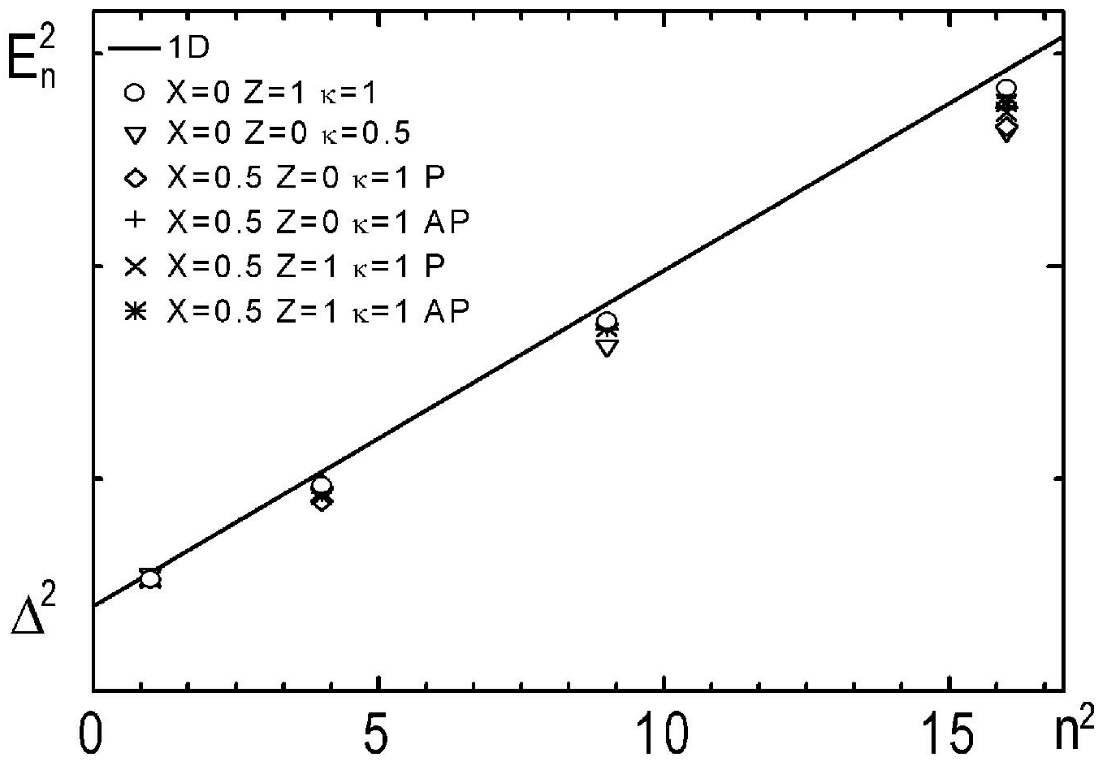
$d/\xi_0 \approx 10$

$\kappa = 1\ , \ \ \Delta/E_F^{(S)} = 10^{-3}$

M. Božović, Z. Pajović, and Z. Radović, Physica C **391**, 309 (2003).

How to infer Δ and v_F in the superconductor?

Conductance minima satisfy: $$E_n^2 = \Delta^2 + \left(\frac{\pi\hbar v_F^{(S)}}{d}\right)^2 n^2$$

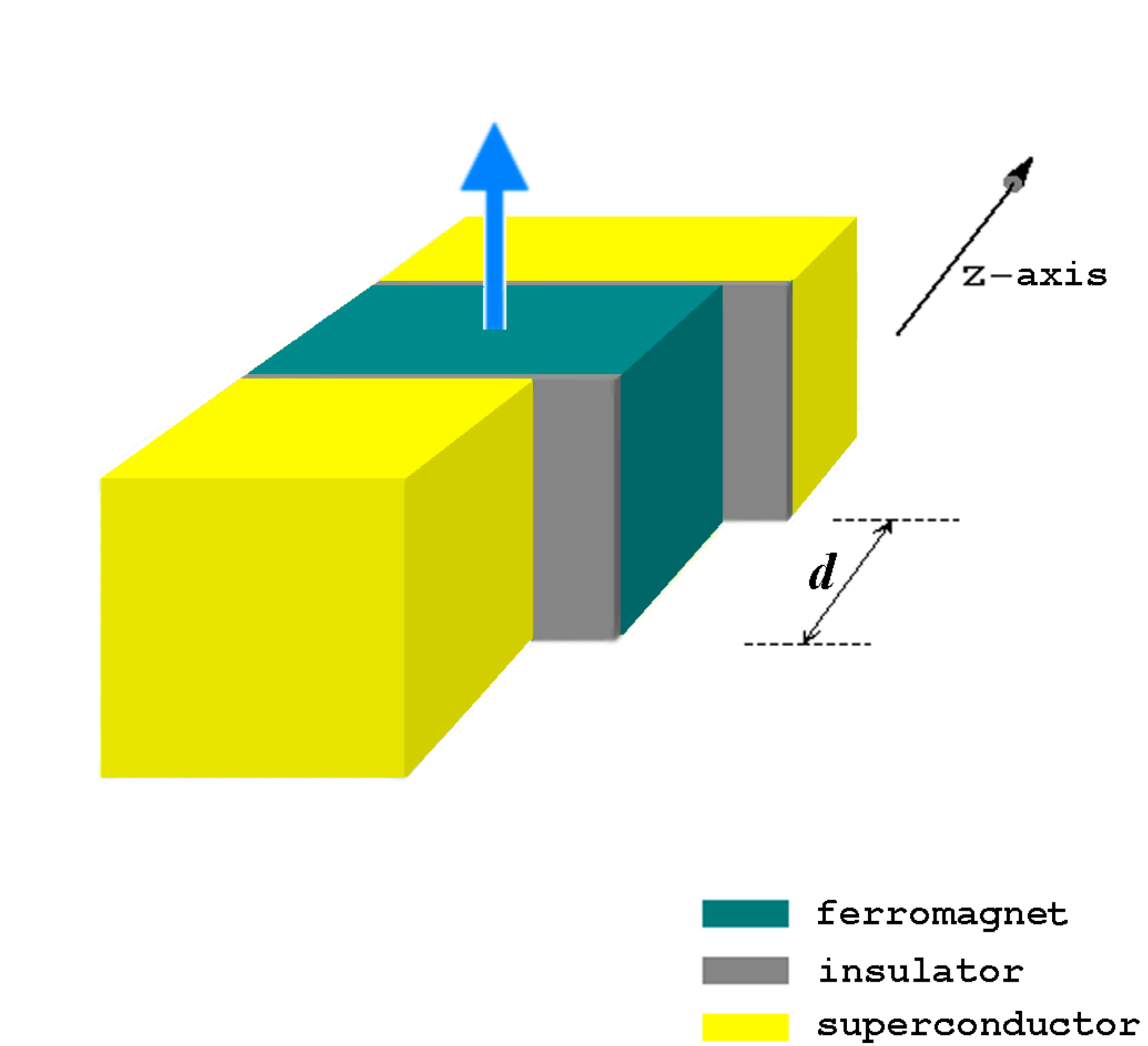


Ballistic spectroscopy

O. Nesher and G. Koren, Phys. Rev. B **60**, 9287 (1999).

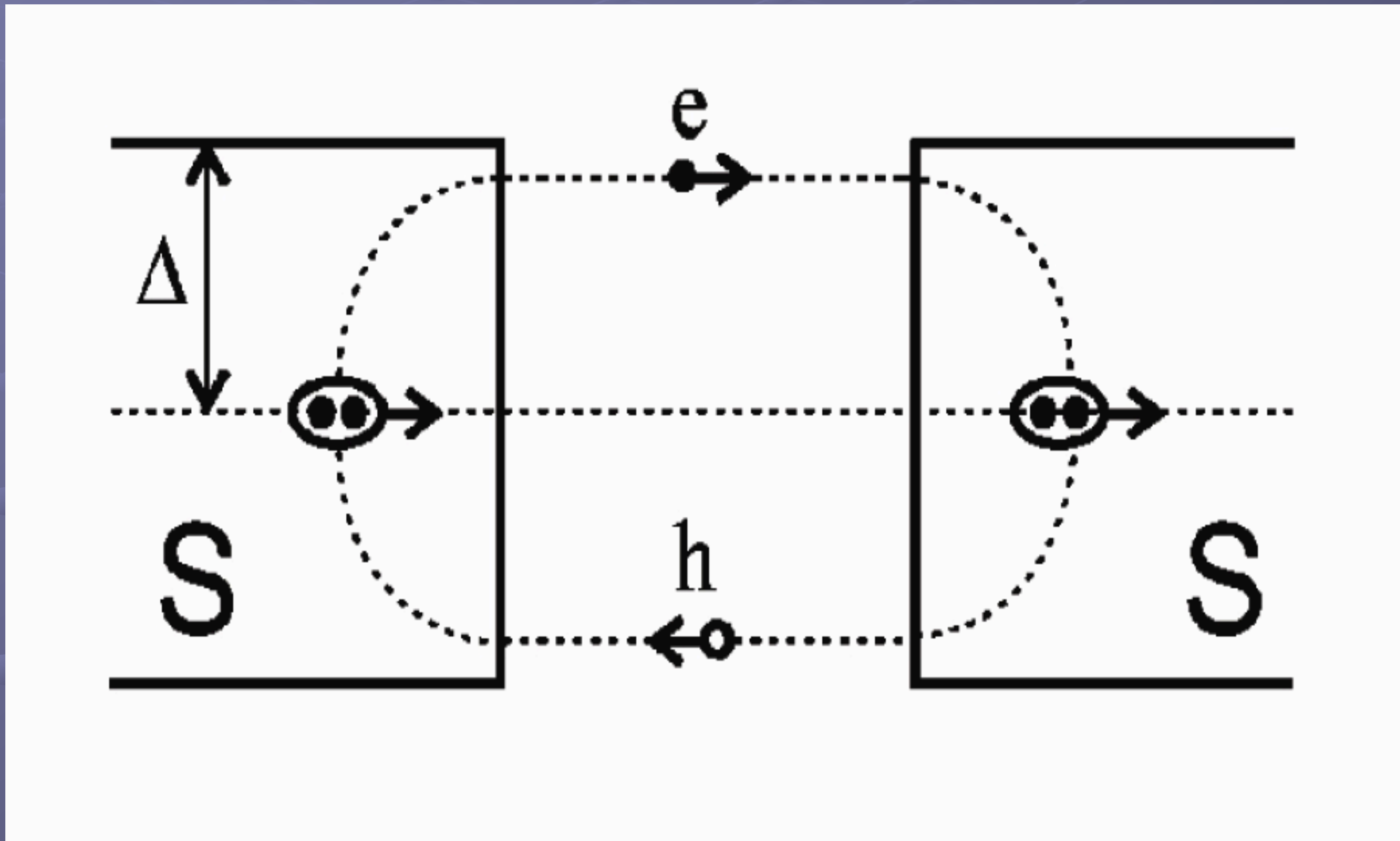
M. Božović and Z. Radović in *Supercond. and Rel. Ox.: Phys. and nanoeng. V, Proc. of SPIE, vol. 4811* (Seattle, 2002), p. 216.

The Model (SIFIS)

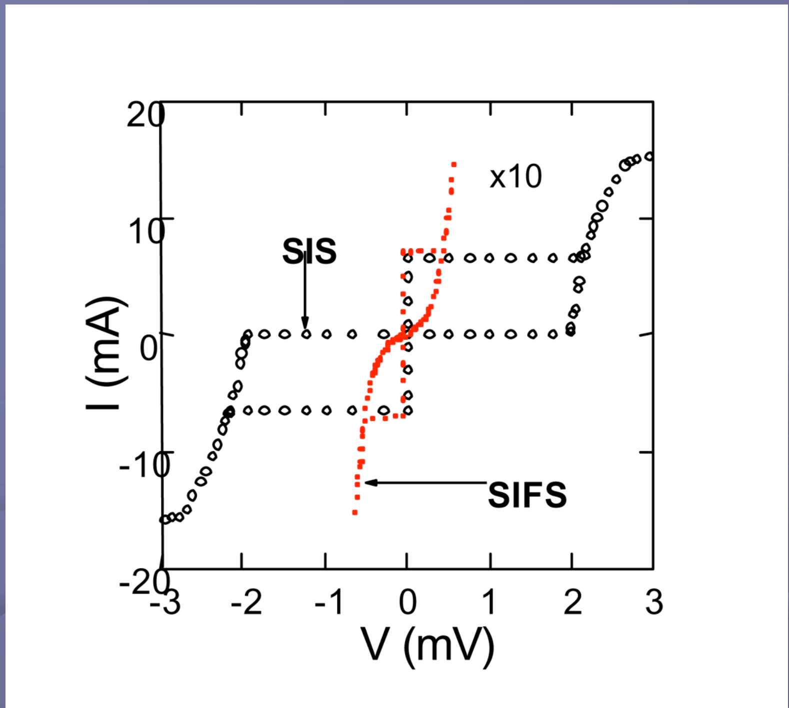


Andreev reflection

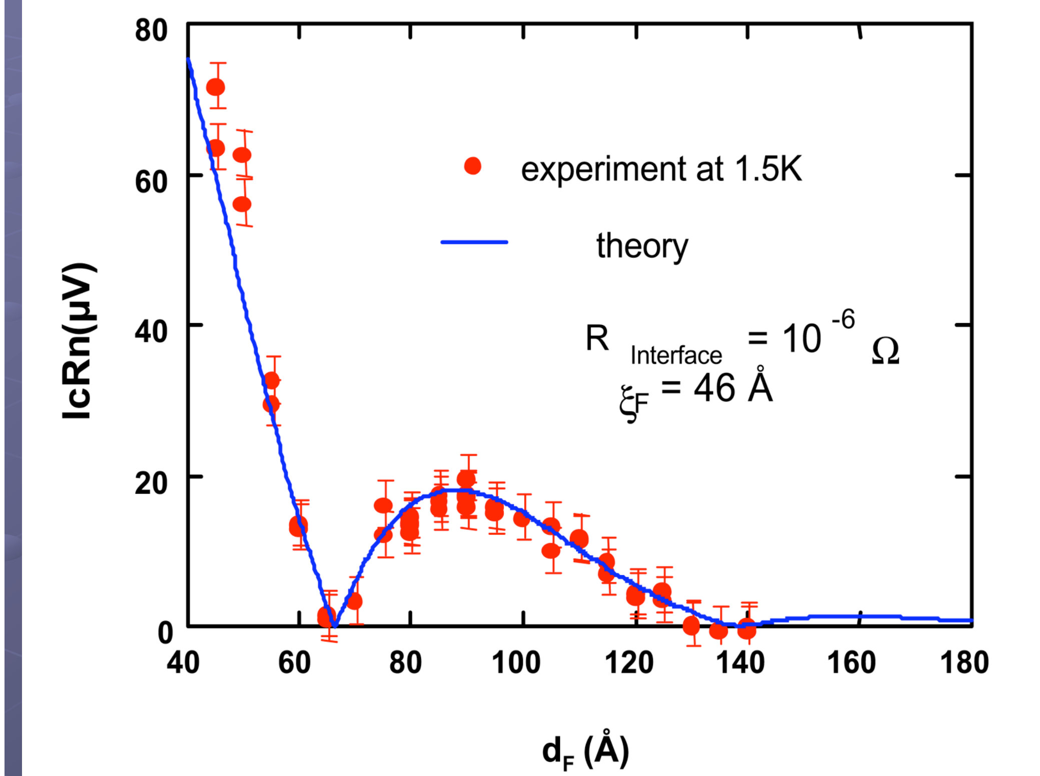
A. F. Andreev, Sov. Phys. JETP **19**, 1228 (1964).



SFS junctions (exp)



I-V characteristics



T. Kontos, M. Aprili, J. Lesueur, F. Genet, B. Stephanidis, and R. Boursier, Phys. Rev. Lett. **89**, 137007 (2002).

Zero and p states of the junction

L.N.Bulaevskii, V.V.Kuzii, and A.A.Sobyanin, JETP Lett. **25**, 290 (1977).

SIFIS: Bogoliubov – de Gennes equation

$$\begin{pmatrix} H_0(\mathbf{r}) - \rho_\sigma h(\mathbf{r}) & \Delta(\mathbf{r}) \\ \Delta^*(\mathbf{r}) & -H_0(\mathbf{r}) + \rho_{\bar{\sigma}} h(\mathbf{r}) \end{pmatrix} \Psi_\sigma(\mathbf{r}) = E\Psi_\sigma(\mathbf{r})$$

$$\Psi_\sigma(\mathbf{r}) \equiv \begin{pmatrix} u_\sigma(\mathbf{r}) \\ v_{\bar{\sigma}}(\mathbf{r}) \end{pmatrix} = \exp(i\mathbf{k}_\parallel \cdot \mathbf{r})\psi_\sigma(z)$$

Exchange energy $h(\mathbf{r})/E_F^{(F)} = X\Theta(z)\Theta(d-z)$ $\rho_{\uparrow,\downarrow} = \pm 1$

Stepwise pair potential $\Delta(\mathbf{r}) = \Delta[\Theta(-z) \pm \Theta(z-d)]$

Interface potential $\hat{W}[\delta(z) + \delta(d-z)]$ $Z = 2m\hat{W}/\hbar^2 k_F^{(S)}$

FWVM parameter $\kappa = k_F^{(F)}/k_F^{(S)}$ $T = 1/(1+Z^2)$

Generalization of the Furusaki-Tsukada formula (PRB **43**, 10164 (1991)) for SNS to the ballistic double-barrier planar SIFIS

$$I = \frac{\pi k_B T \Delta^2}{eR} \int_0^{\pi/2} d\theta \sin\theta \cos\theta \sum_{\omega_n} \frac{1}{2} \sum_{\sigma} \frac{\sin\phi}{\Gamma_n}$$

$$\Gamma_n = \Delta^2 \cos\phi + (K^2\Omega_n^2 + \omega_n^2)\cosh[\frac{2(\omega_n - i\rho_\sigma h)d}{\hbar v}] + 2K\omega_n\Omega_n \sinh[\frac{2(\omega_n - i\rho_\sigma h)d}{\hbar v}] - (K^2 - 1 - 2Z_\theta^2)\,\Omega_n^2 \cos(2qd) + 2Z_\theta(K^2 - 1 - Z_\theta^2)^{1/2}\Omega_n^2 \sin(2qd)$$

$$K = \tfrac{1}{2}(\tilde{q} + \tfrac{1+Z_\theta^2}{\tilde{q}}) \qquad \tilde{q} = \tfrac{k_N}{k_S} \qquad v_N = \tfrac{\hbar k_N}{m}$$

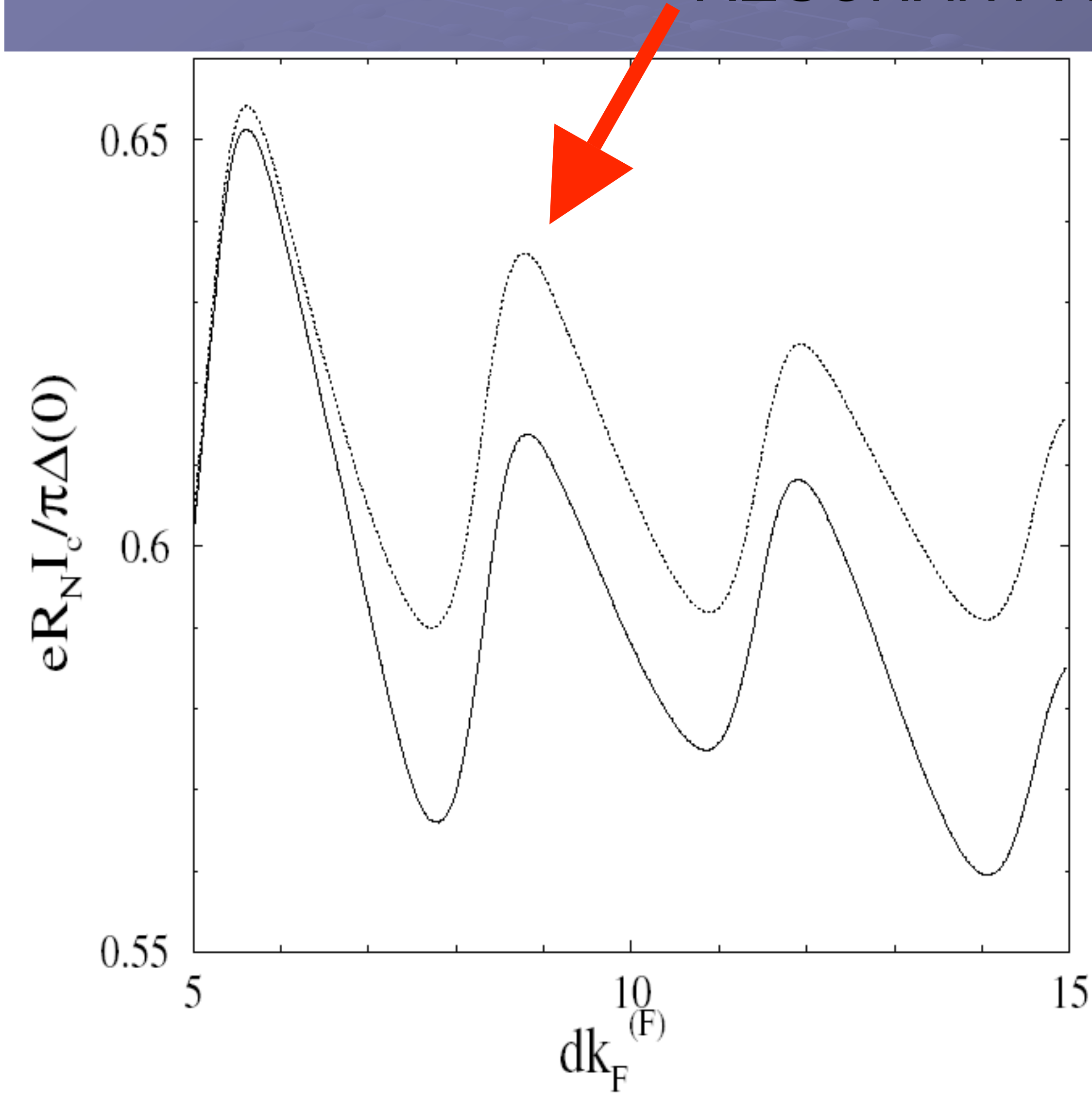
$$k_N = \sqrt{{k_F^{(N)}}^2 - \mathbf{k}_{||}^2} \qquad k_S = \sqrt{{k_F^{(S)}}^2 - \mathbf{k}_{||}^2} \qquad |\mathbf{k}_{||}| = k_F^{(S)} \sin\theta$$

$$Z_\theta = Z / \cos\theta$$

Z. Radović, N. Lazarides, and N. Flytzanis, Phys. Rev. B **68**, 014501 (2003).

SFS double junction: critical Josephson current $I_c(d)$

RESONANT AMPLIFICATION



$$T/T_C = 0.1$$

$$Z = 1$$

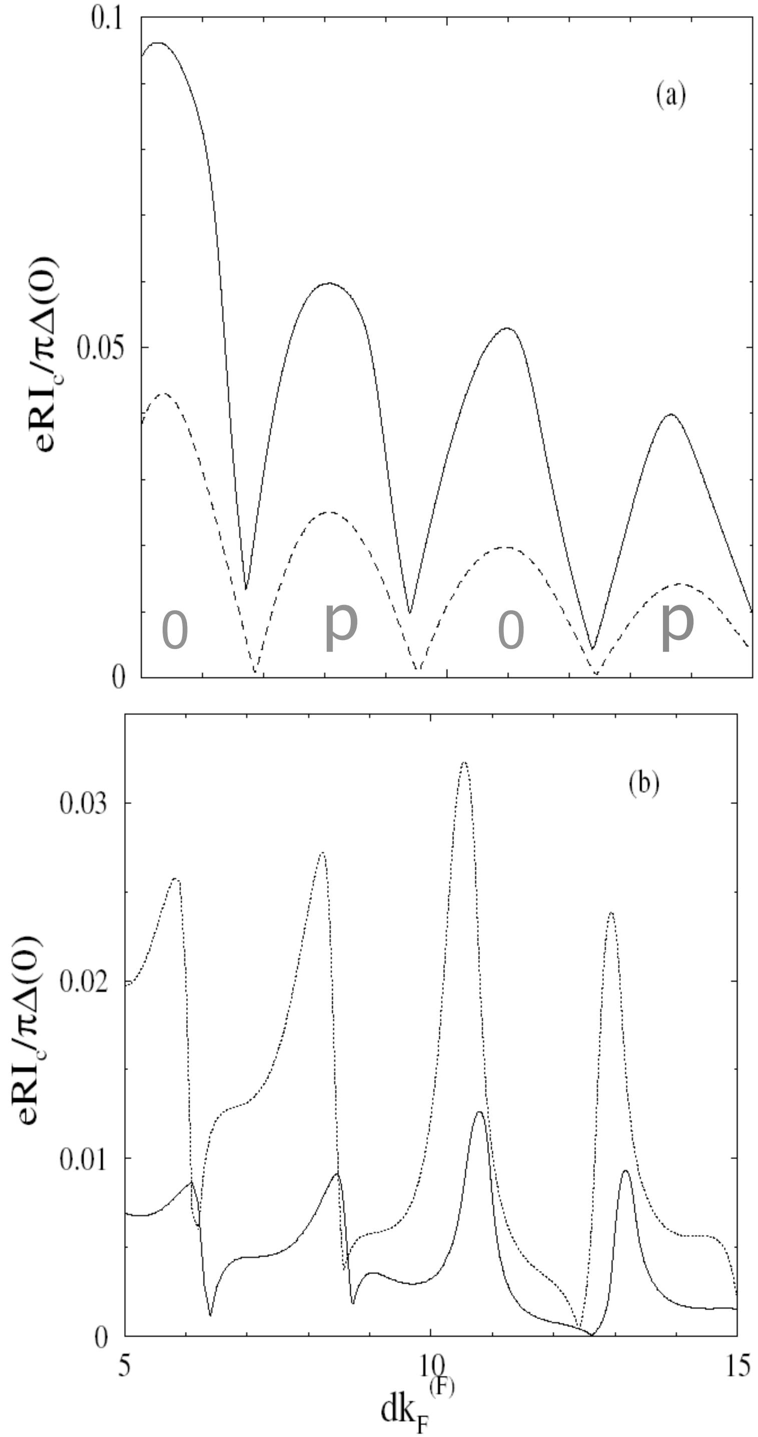
$$X = 0.01 \text{ (solid)}$$

$$X = 0 \text{ (dotted)}$$

$$\kappa = 1$$

$$\Delta/E_F^{(S)} = 10^{-3}$$

Z. Radović, N. Lazarides, and N. Flytzanis, Phys. Rev. B **68**, 014501 (2003).



Strong ferromagnet: $0 \leftrightarrow \pi$ transitions

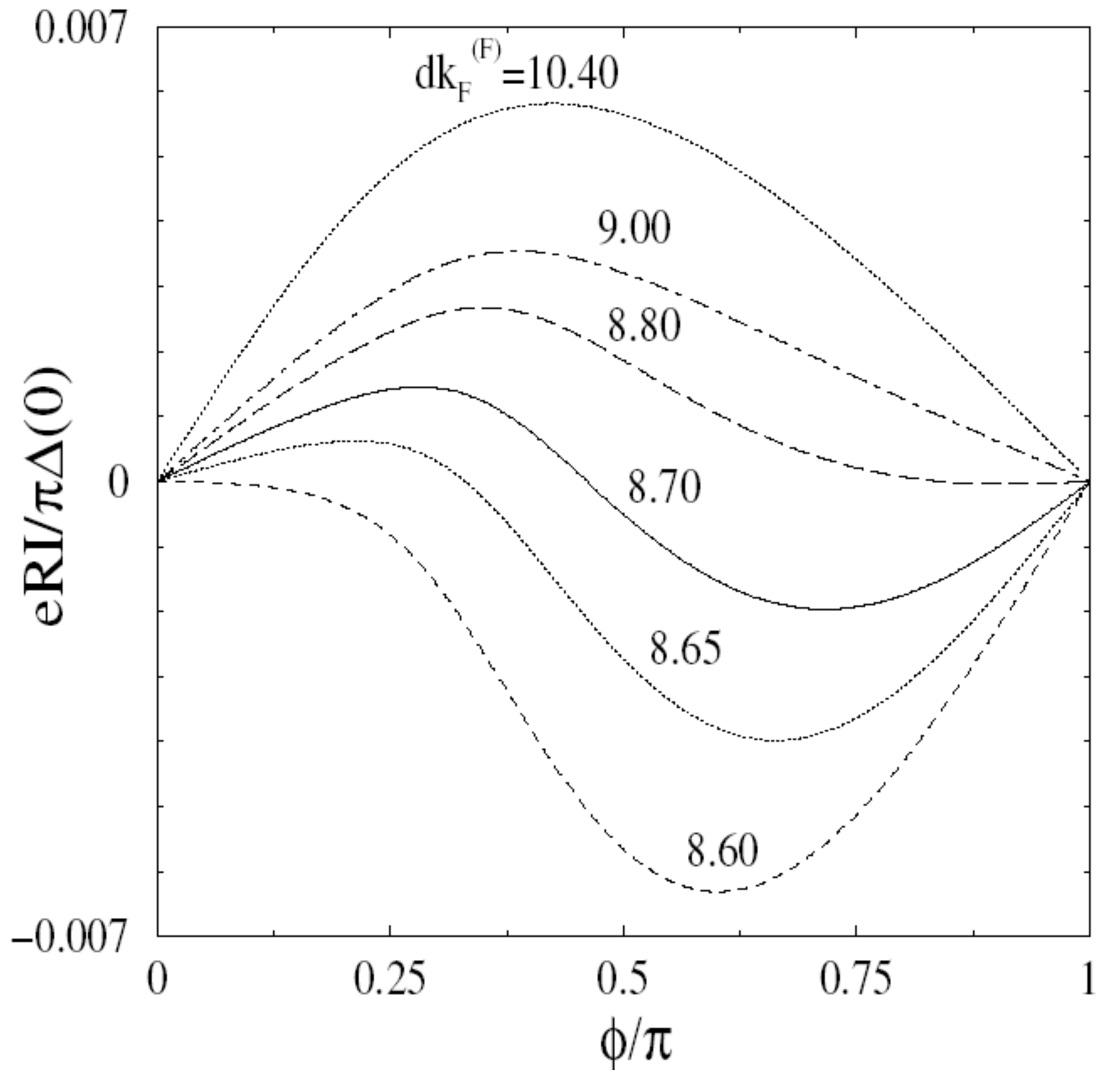
$$X = 0.9$$

$$\Delta / E_F^{(S)} = 10^{-3}$$

Top panel:	Bottom panel:
$Z = 0$	$Z = 1$
$\kappa = 1$	$T/T_C = 0.1$
$T/T_C = 0.1$ (solid)	$\kappa = 0.7$ (solid)
$T/T_C = 0.7$ (dotted)	$\kappa = 1$ (dotted)

Z. Radović, N. Lazarides, and N. Flytzanis, Phys. Rev. B **68**, 014501 (2003)

SFS double junction: the current-phase relation close to the 0-π transition



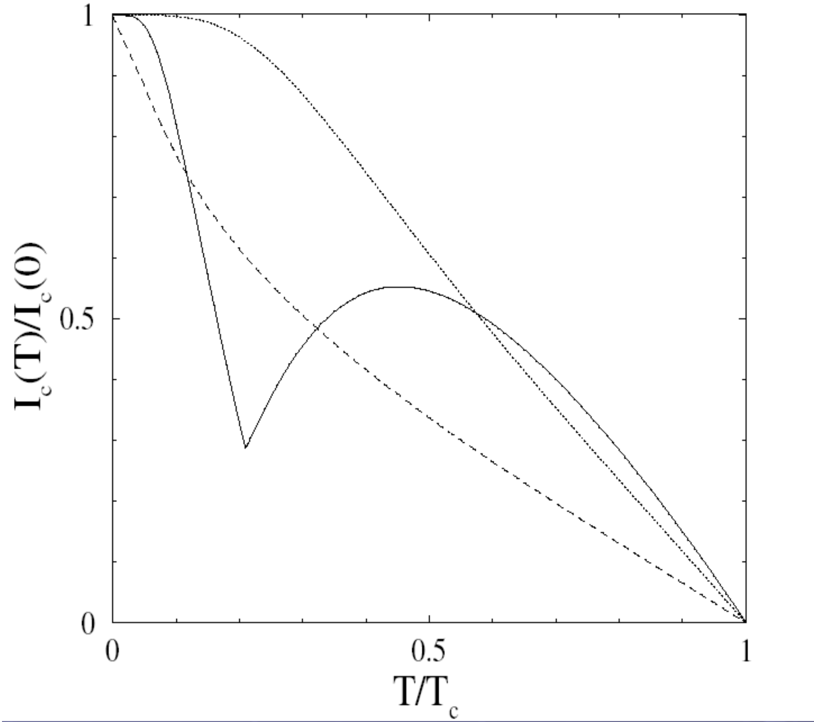
$$Z = 1$$

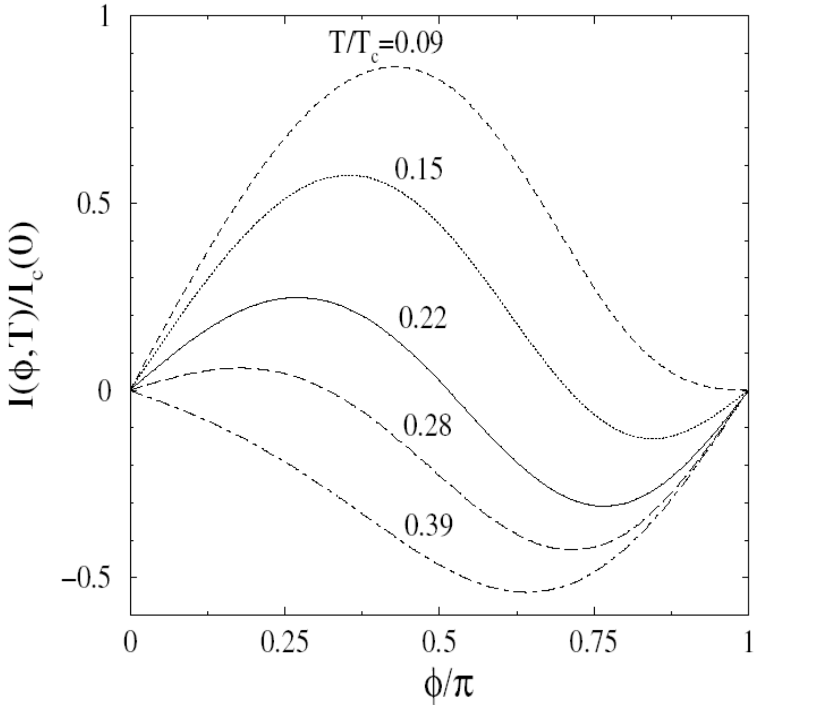
$$X = 0.9$$

$$\kappa = 0.7$$

$$\Delta / E_F^{(S)} = 10^{-3}$$

Z. Radović, N. Lazarides, and N. Flytzanis, Phys. Rev. B **68**, 014501 (2003).





Temperature-induced 0-π transition (theory)

finite transparency

strong ferromagnet

$Z = 1.2$ $X = 0.92$

$\kappa = 1$

$\Delta/E_F^{(S)} = 10^{-3}$

Top panel:

$dk_F^{(F)} = 17$ (dotted)

$dk_F^{(F)} = 17.23$ (solid)

$dk_F^{(F)} = 17.4$ (dashed)

Bottom panel:

$dk_F^{(F)} = 17.23$

Five values of T

Z. Radović, N. Lazarides, and N. Flytzanis, Phys. Rev. B **68**, 014501 (2003).

Temperature-induced 0-π transition (exp)

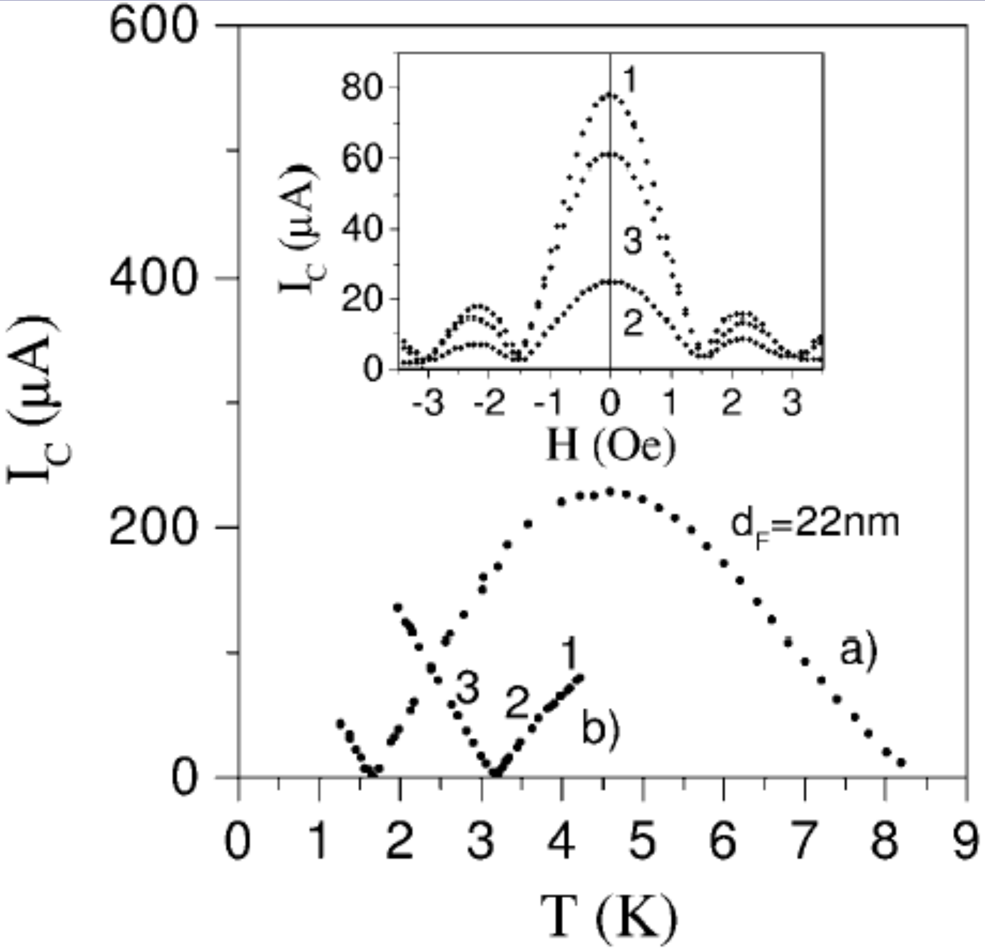
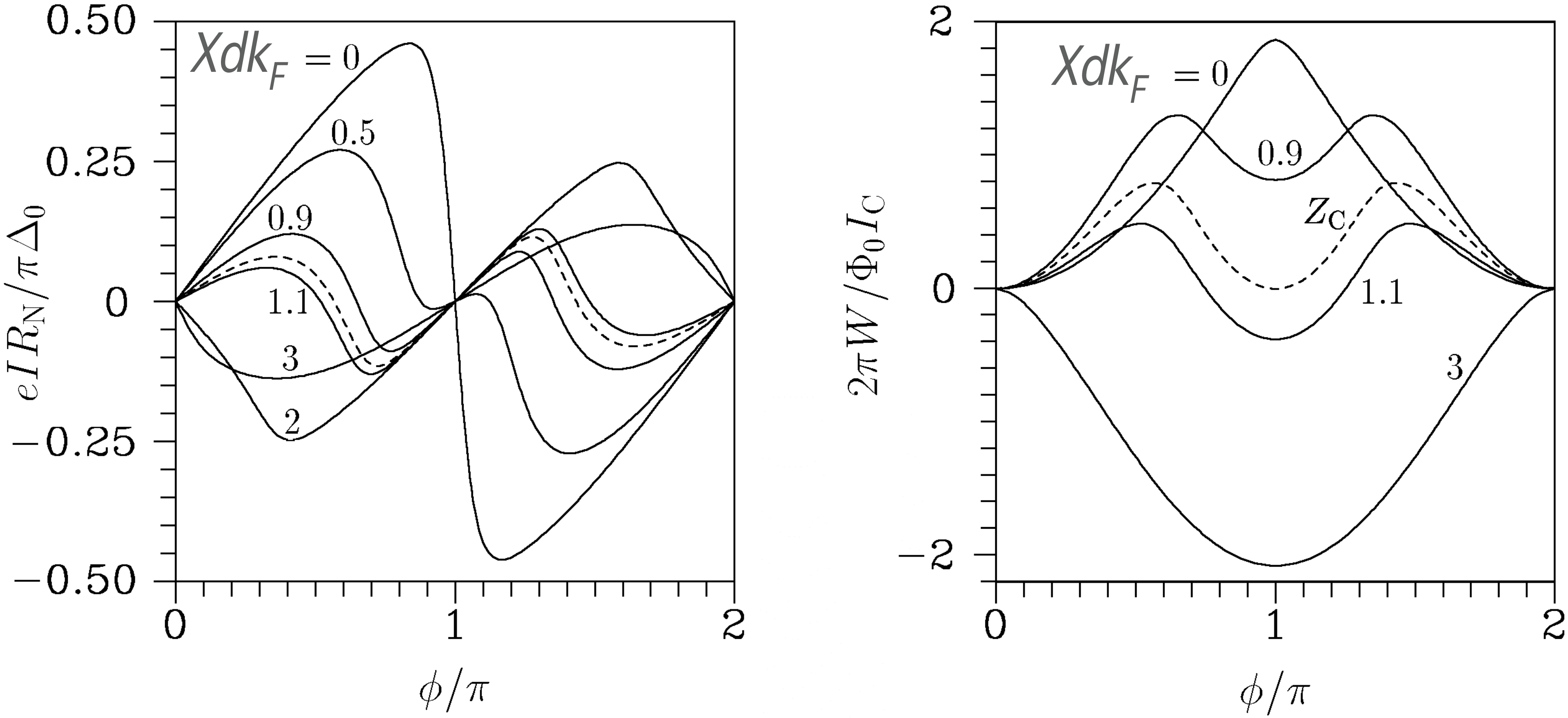


FIG. 3. Critical current I_c as a function of temperature T for two junctions with $Cu_{0.48}Ni_{0.52}$ and $d_F = 22$ nm [17]. Inset: I_c versus magnetic field H for the temperatures around the crossover to the π state as indicated on curve b: (1) $T = 4.19$ K, (2) $T = 3.45$ K, (3) $T = 2.61$ K.

V. V. Ryazanov *et al.*, Phys. Rev. Lett. **86**, 2427 (2001).

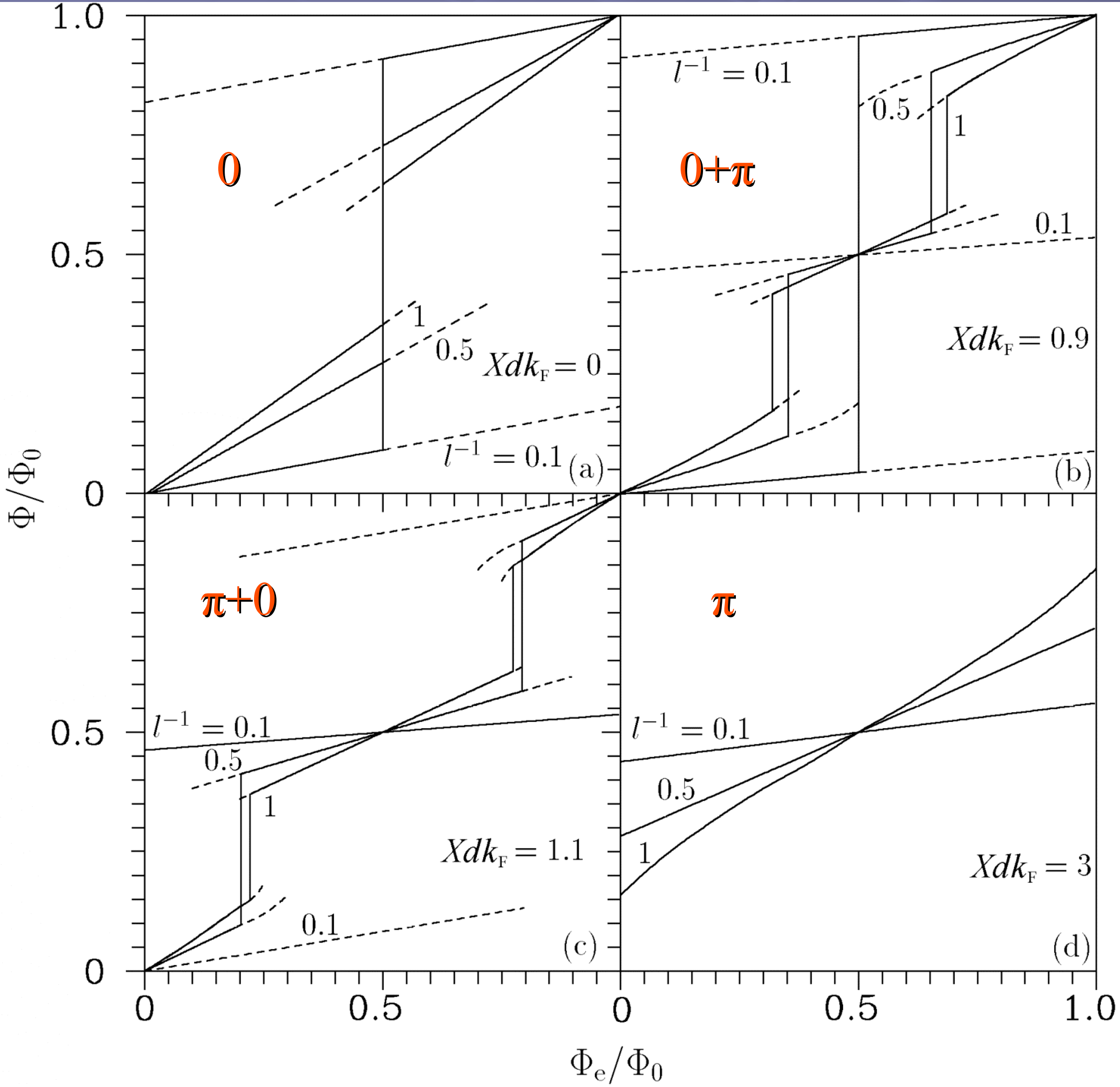
Coexistence of stable and metastable 0 and π states



Z. Radović, L. Dobrosavljević-Grujić, and B. Vujičić, Phys. Rev. B **63**, 214512 (2001).

Magnetic flux vs. external flux in SQUIDs

$$l = \frac{2\pi}{\Phi_0} L I_C$$



Effectively two times smaller flux quantum in 0+p SQUIDs

Z. Radović, L. Dobrosavljević-Grujić, and B. Vujičić, Phys. Rev. B **63**, 214512 (2001).

Experimental evidence of $\Phi_0 \rightarrow \Phi_0/2$

V. V. Ryazanov *et al.*, Microel. Eng., **69**, 341 (2003).

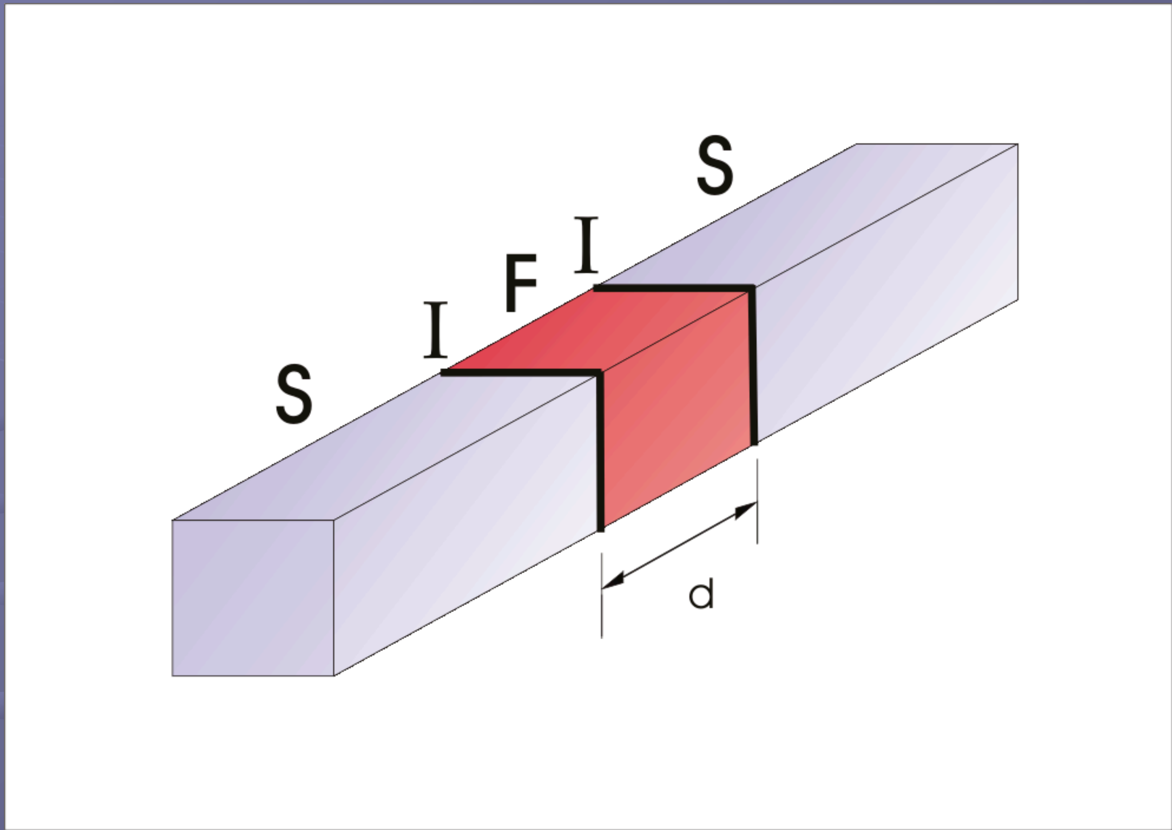
C. W. Schneider *et al.*, Europhys. Lett. **68,** 86 (2004).

H. Sellier *et al.*, Phys. Rev. Lett. **92,** 257005 (2004).

In the tunnel limit, for short one-channel junctions, the nature of the 0-π transition may be fully revealed.

I. Petković, Z. Radović, and N. Chtchelkatchev,
to be published (2005).

Short one–channel junction

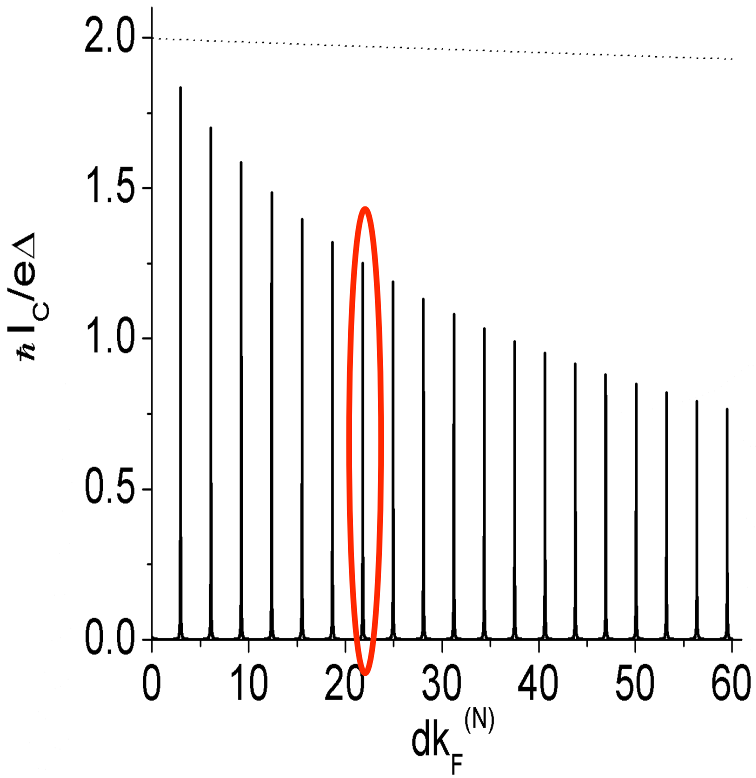


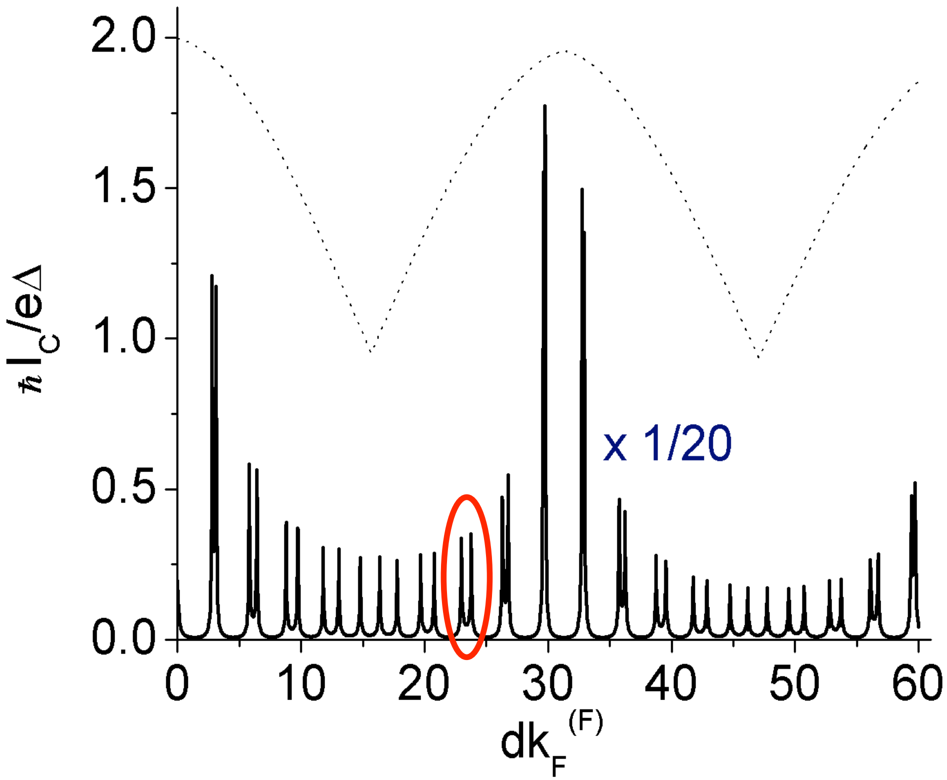
$$I(\phi) = \frac{2e}{\hbar} \sum_{n\sigma} f_{n\sigma}(T)\ \partial_\phi E_{n\sigma}(\phi)$$

$f_{n\sigma}(T)$ - Fermi distribution

# SINIS
X=0

# SIFIS
X=0.1





dotted curve	**Z=0**
thick curve	**Z=10**

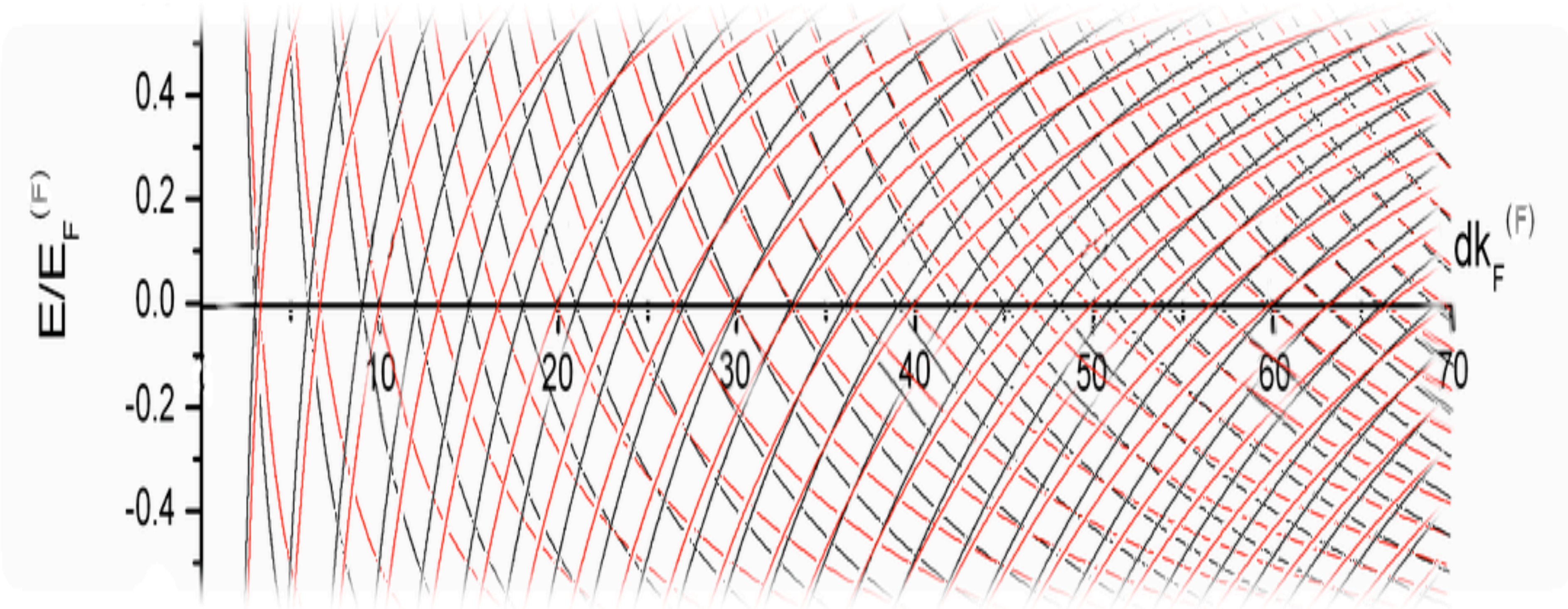
$T/T_C = 0.01$

$E_F^{(F)} = E_F^{(S)}$

$\Delta/E_F^{(S)} = 10^{-3}$

Bound states of an isolated ferromagnet

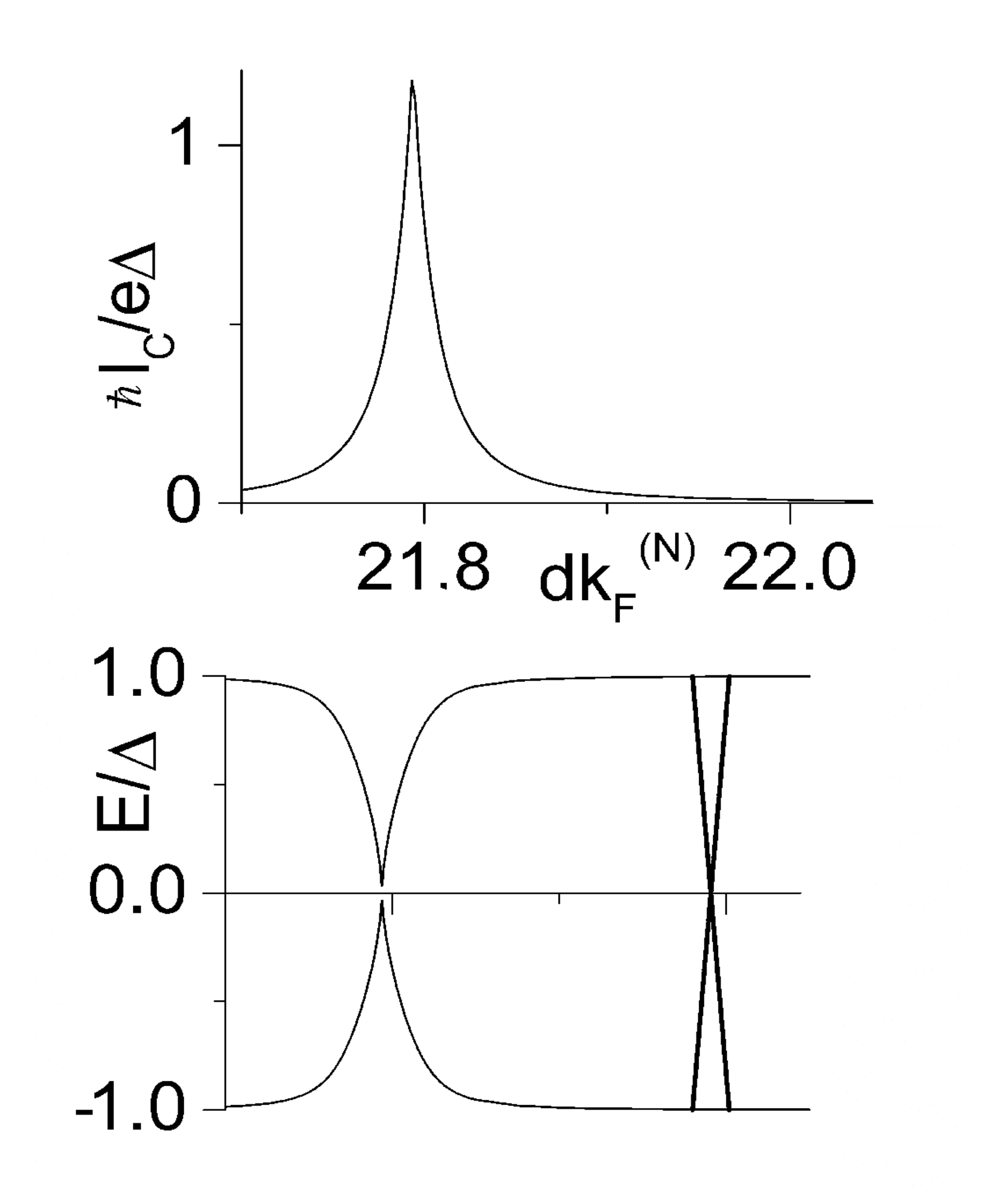
X=0.1



black lines: spin up
red lines: spin down

With increasing transparency, bs ⟶ quasi bs, broader and shifted towards lower energy.

Resonant tunneling amplifies the current



$$X = 0$$

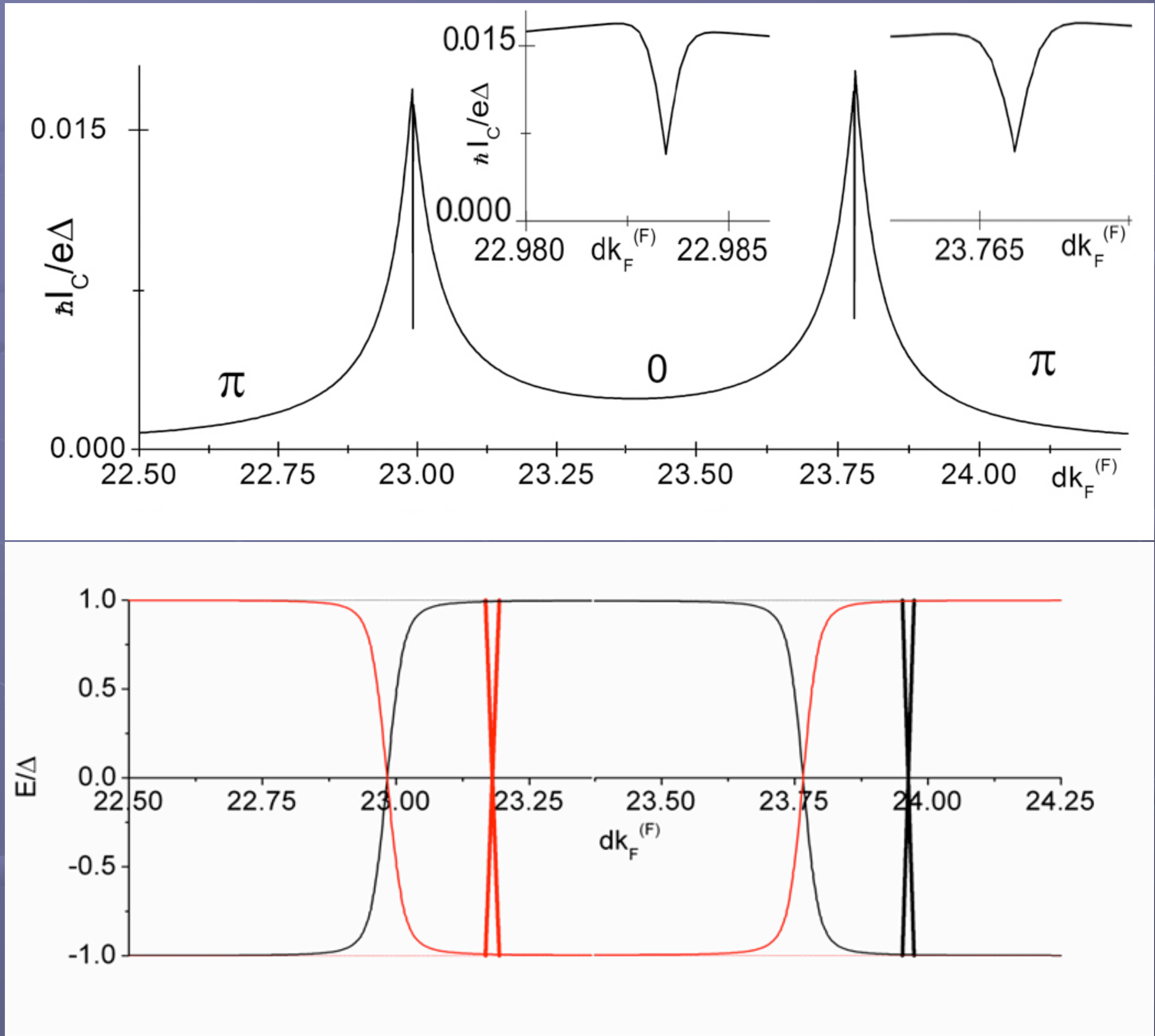
$$Z = 10$$

$$T/T_C = 0.01$$

$$E_F^{(F)} = E_F^{(S)}$$

$$\Delta/E_F^{(S)} = 10^{-3}$$

Resonant tunneling triggers 0-π transitions



$$X = 0.1$$

$$Z = 10$$

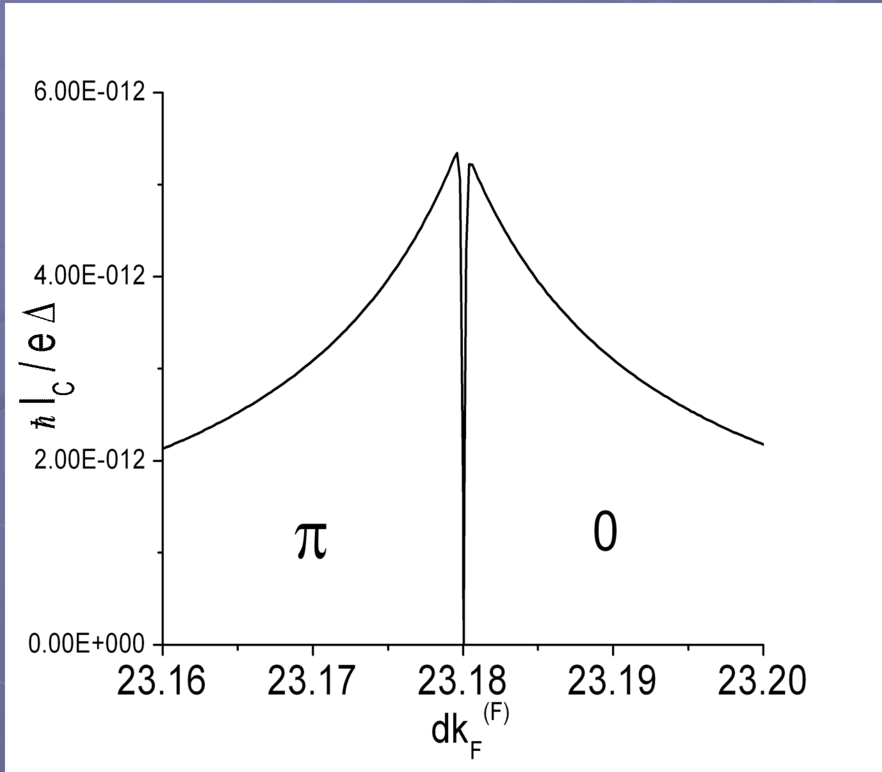
$$T/T_C = 0.01$$

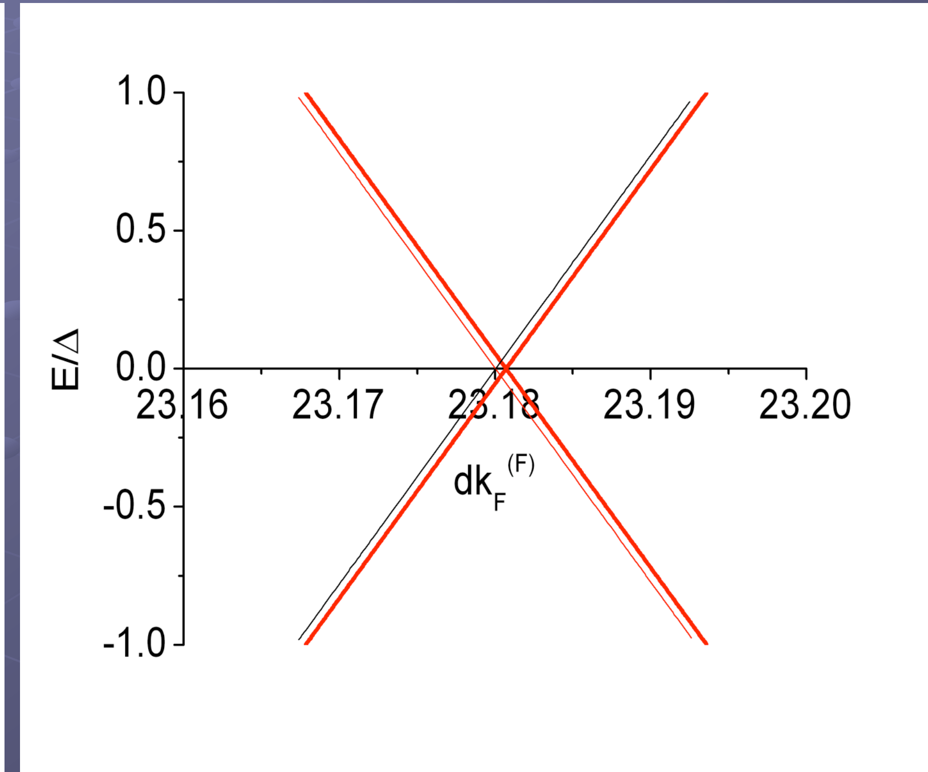
$$E_F^{(F)} = E_F^{(S)}$$

$$\Delta/E_F^{(S)} = 10^{-3}$$

black lines: spin up
red lines: spin down

Tunnel limit
Z=3000



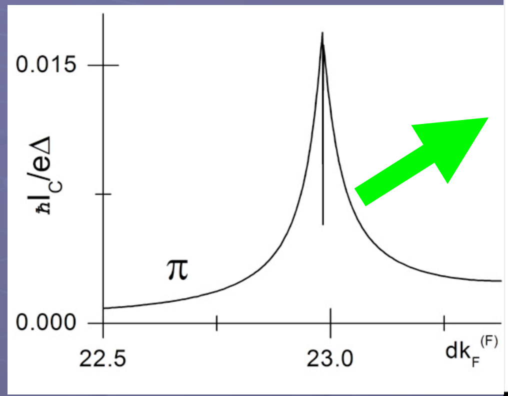


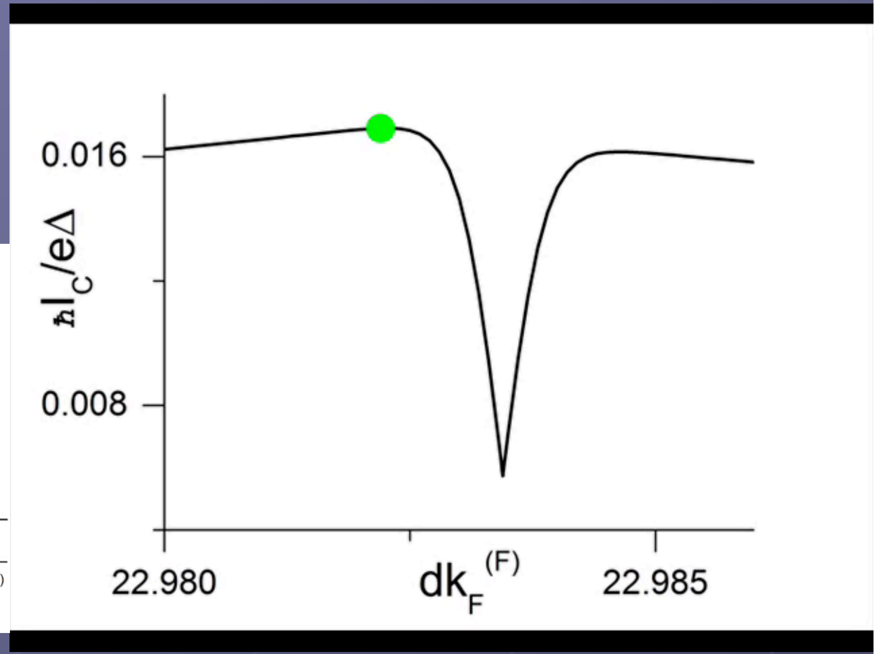
thick lines: bound states
thin lines: Andreev states
black lines: spin up
red lines: spin down

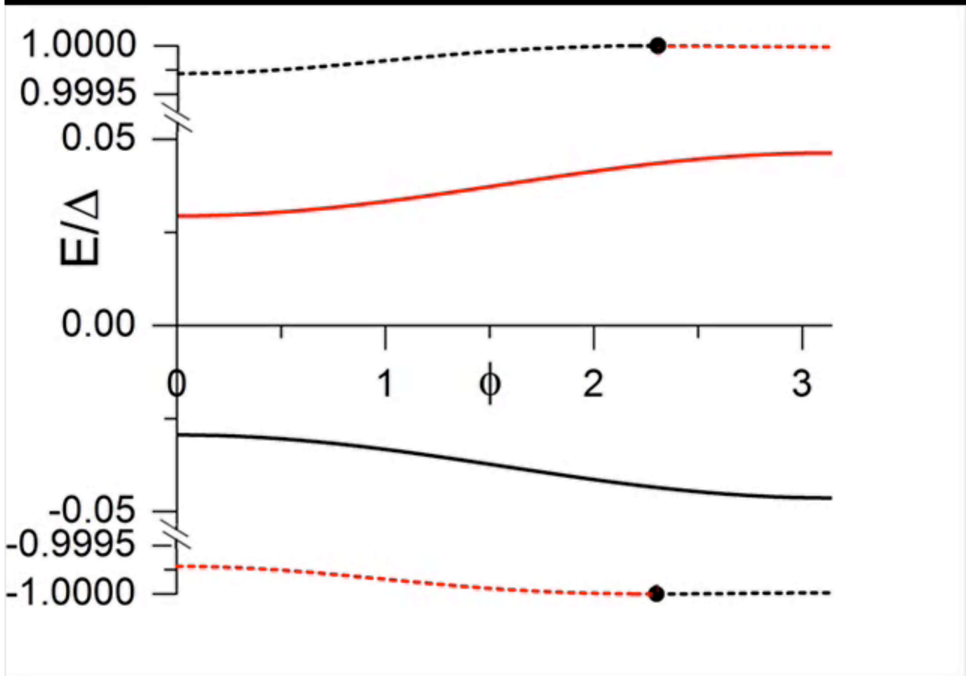
Andreev states and Josephson current components in the 0-π transition

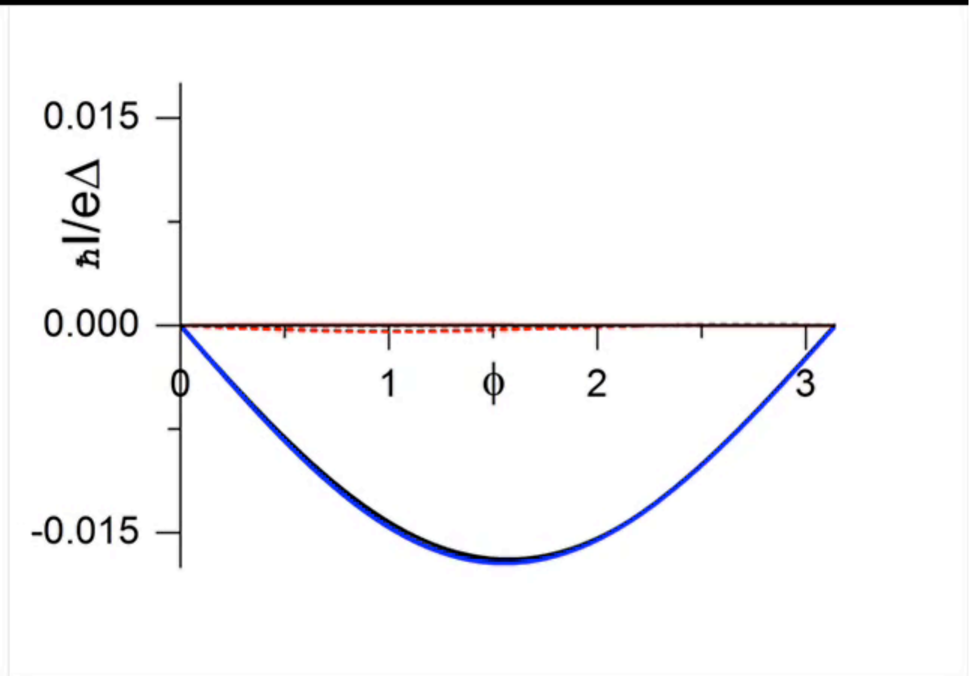
$$X = 0.1$$

$$Z = 10$$

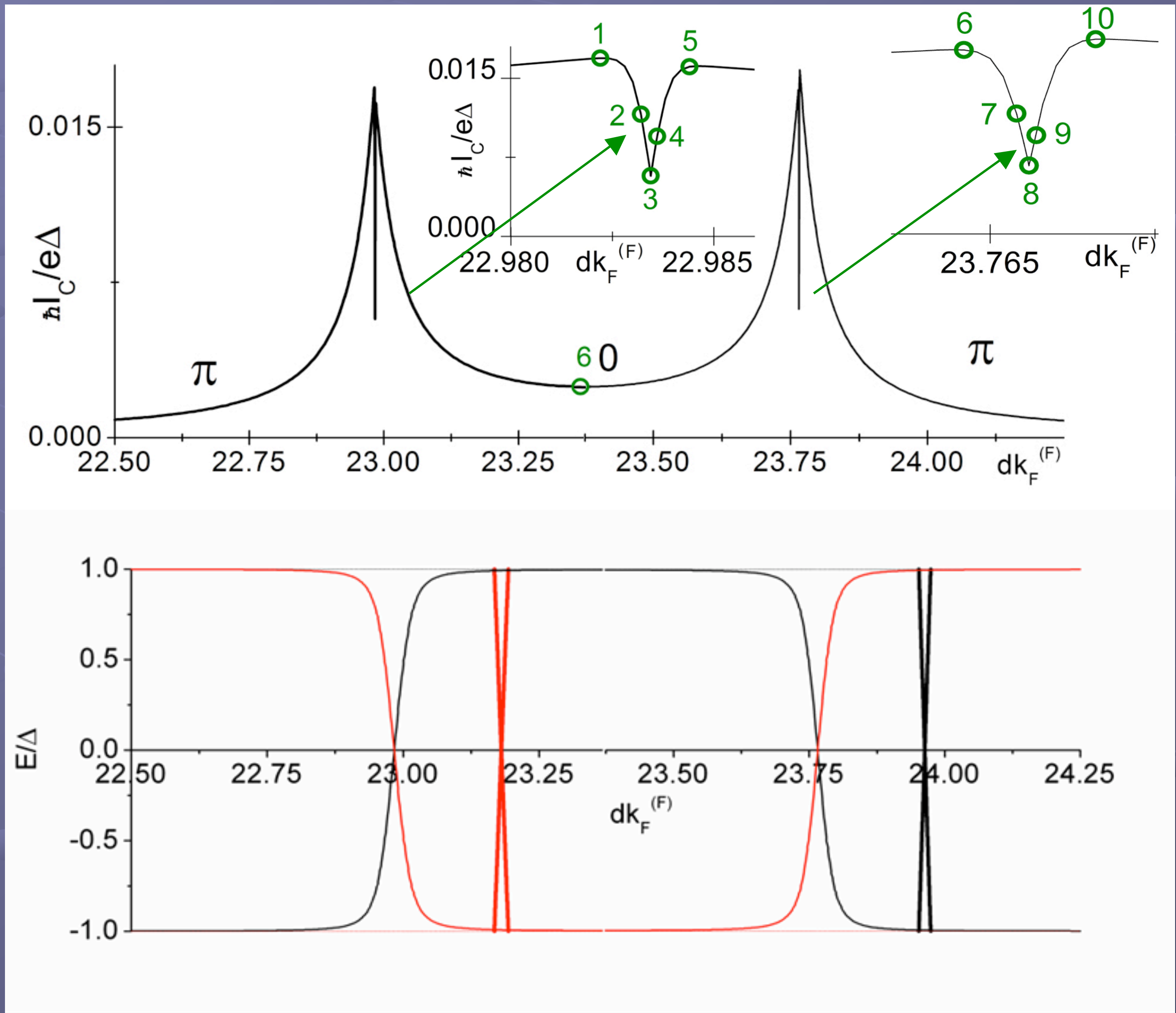








Resonant tunneling triggers 0-π transitions



$$X = 0.1$$

$$Z = 10$$

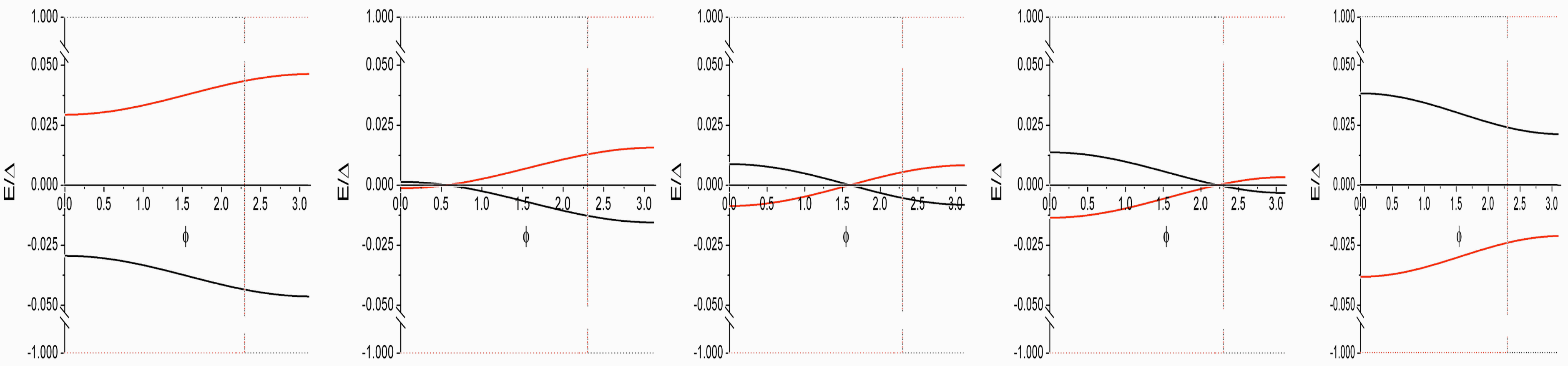
$$T/T_C = 0.01$$

$$E_F^{(F)} = E_F^{(S)}$$

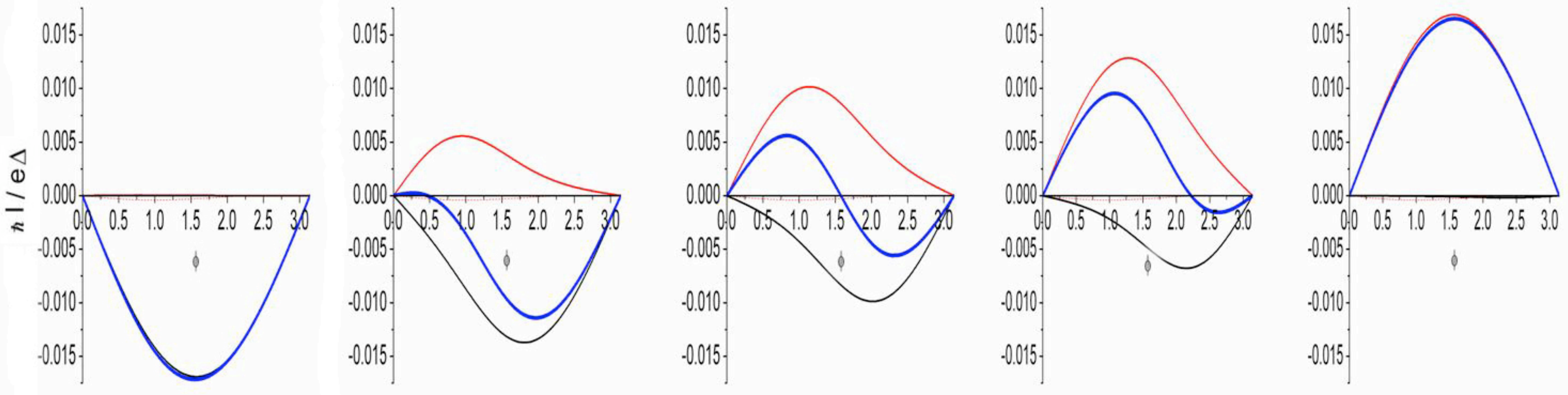
$$\Delta/E_F^{(S)} = 10^{-3}$$

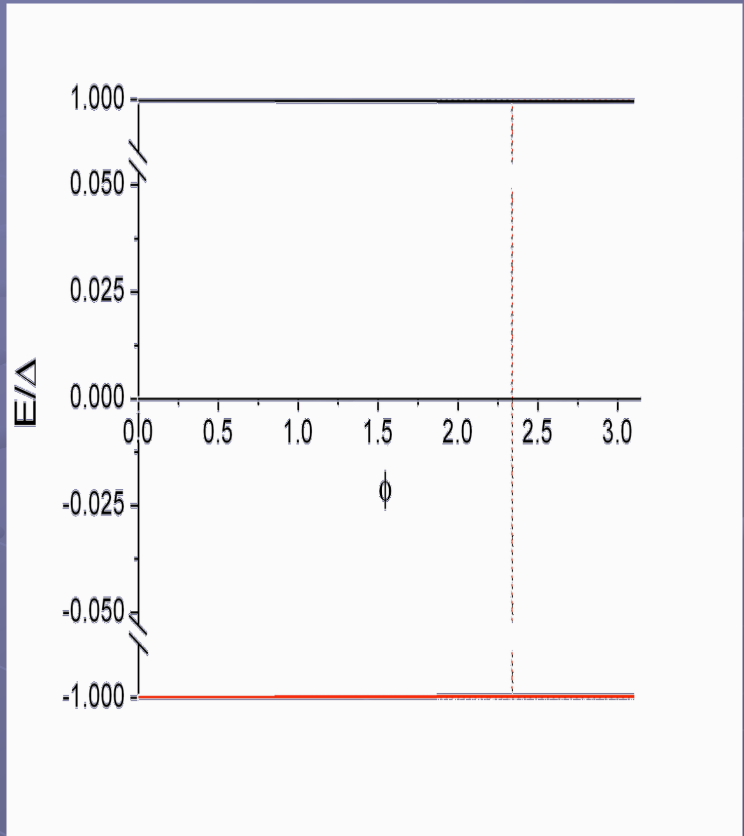
black lines: spin up

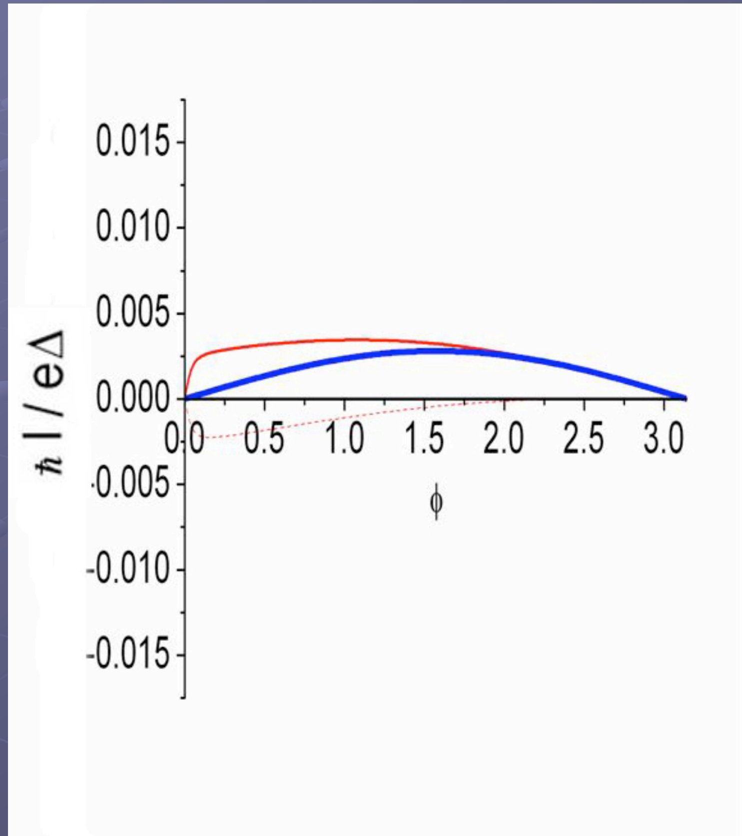
red lines: spin down

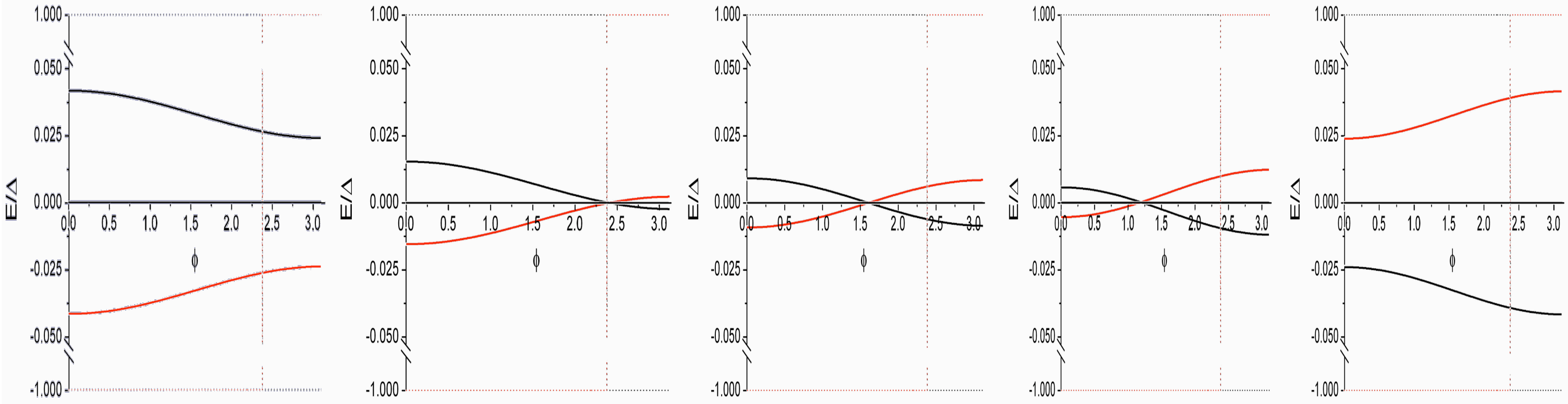

E/Δ
1.000
0.050
0.025
0.000
-0.025
-0.050
-1.000
0.0 0.5 1.0 1.5 2.0 2.5 3.0
ϕ

1 2 3 4 5


ħ I / eΔ
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
0.0 0.5 1.0 1.5 2.0 2.5 3.0
ϕ

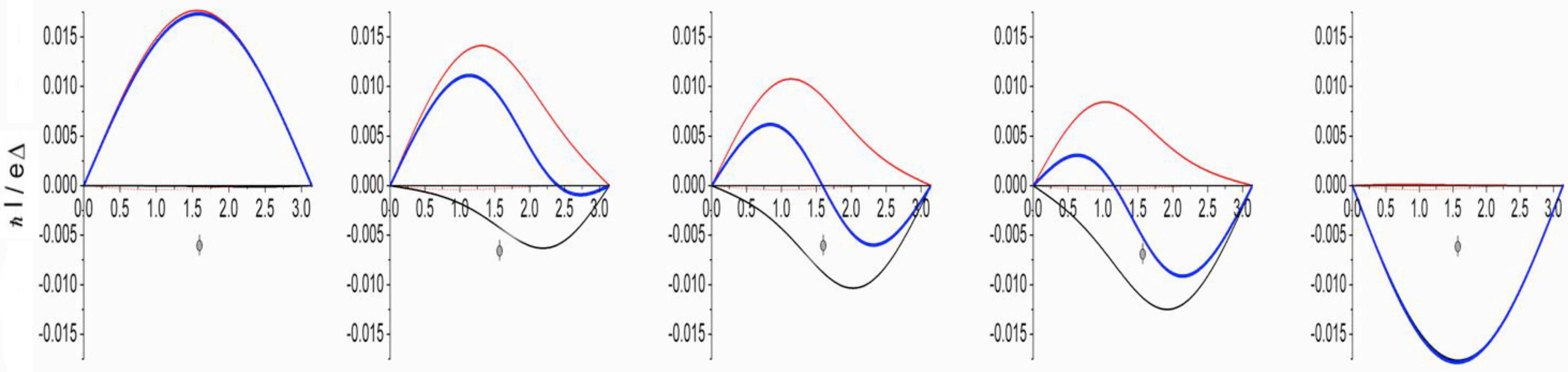

1.000
0.050
0.025
0.000
-0.025
-0.050
-1.000
E/Δ
0.0
0.5
1.0
1.5
2.0
2.5
3.0
ϕ


0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
ℏ I / eΔ
0.0
0.5
1.0
1.5
2.0
2.5
3.0
ϕ



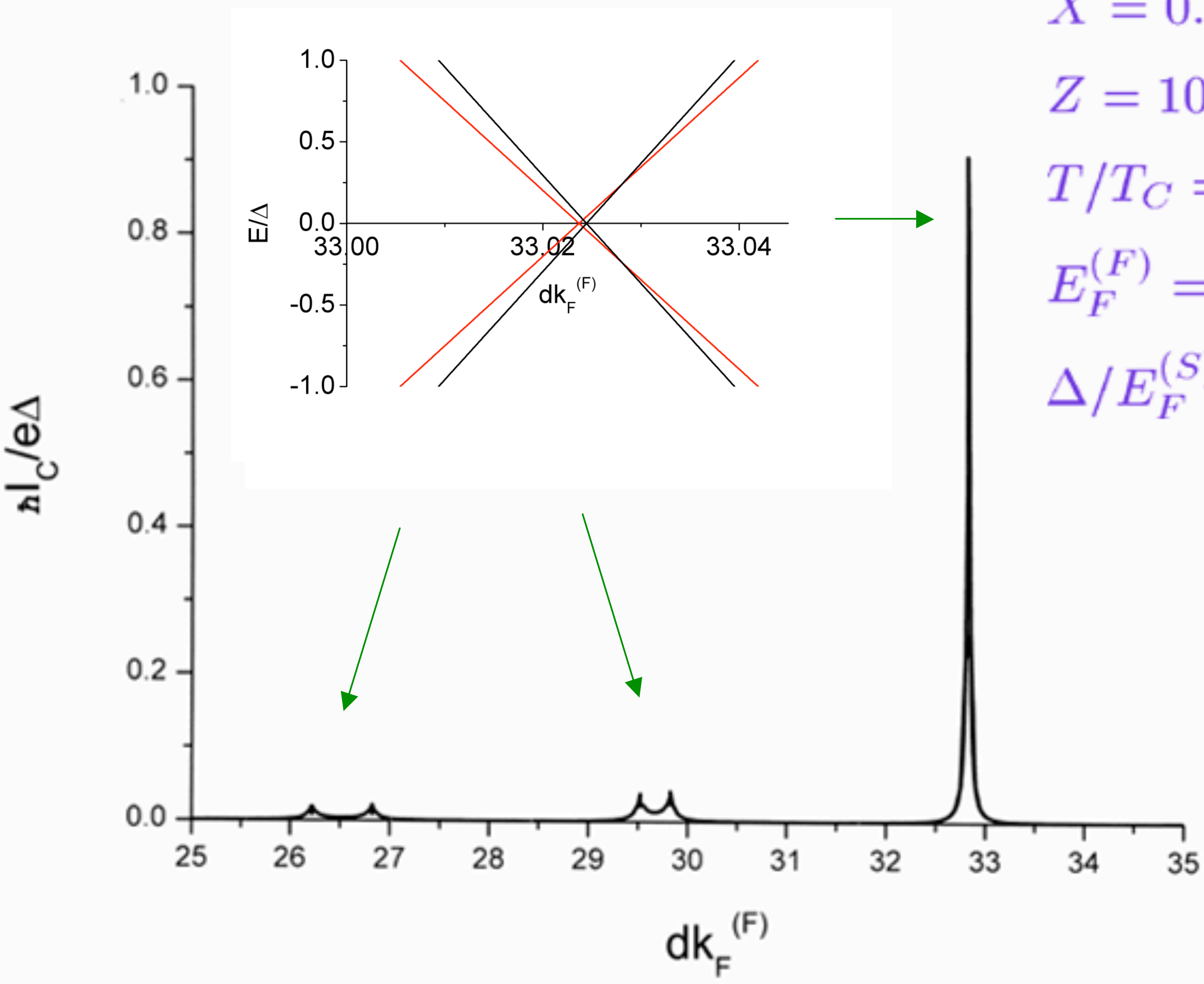
E/Δ
φ
1.000
0.050
0.025
0.000
-0.025
-0.050
-1.000
0.0 0.5 1.0 1.5 2.0 2.5 3.0

7 8 9 10 11



ħ I / eΔ
φ
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
0.0 0.5 1.0 1.5 2.0 2.5 3.0

Spin unpolarized quasibound states – no dip, no 0 - π transition !



$X = 0.095$

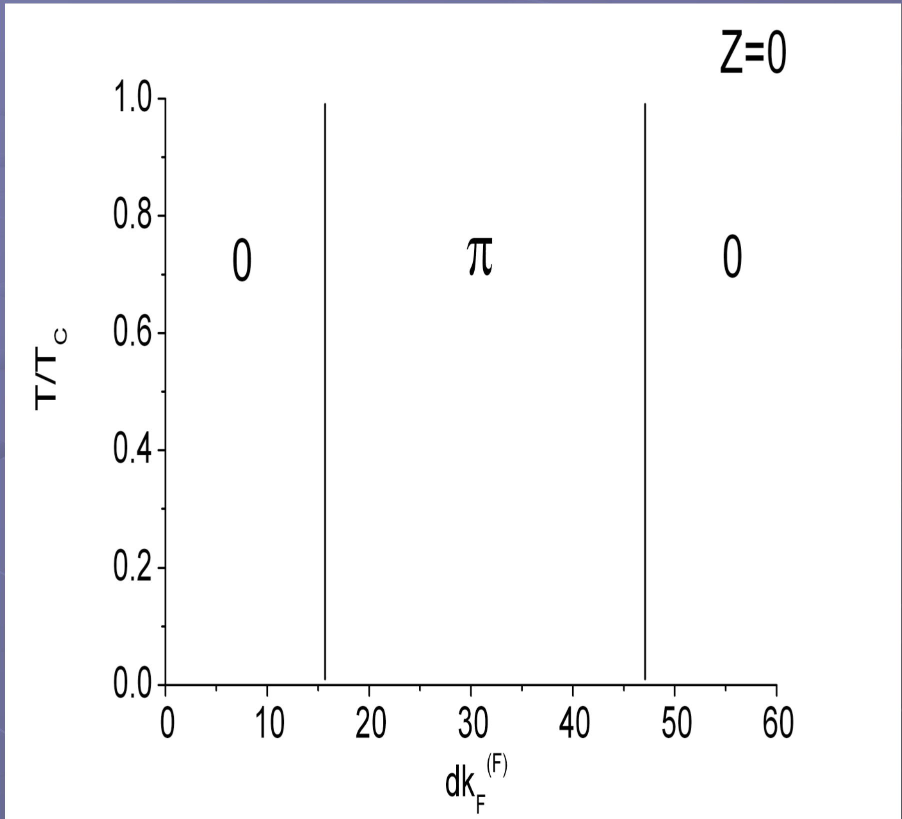
$Z = 10$

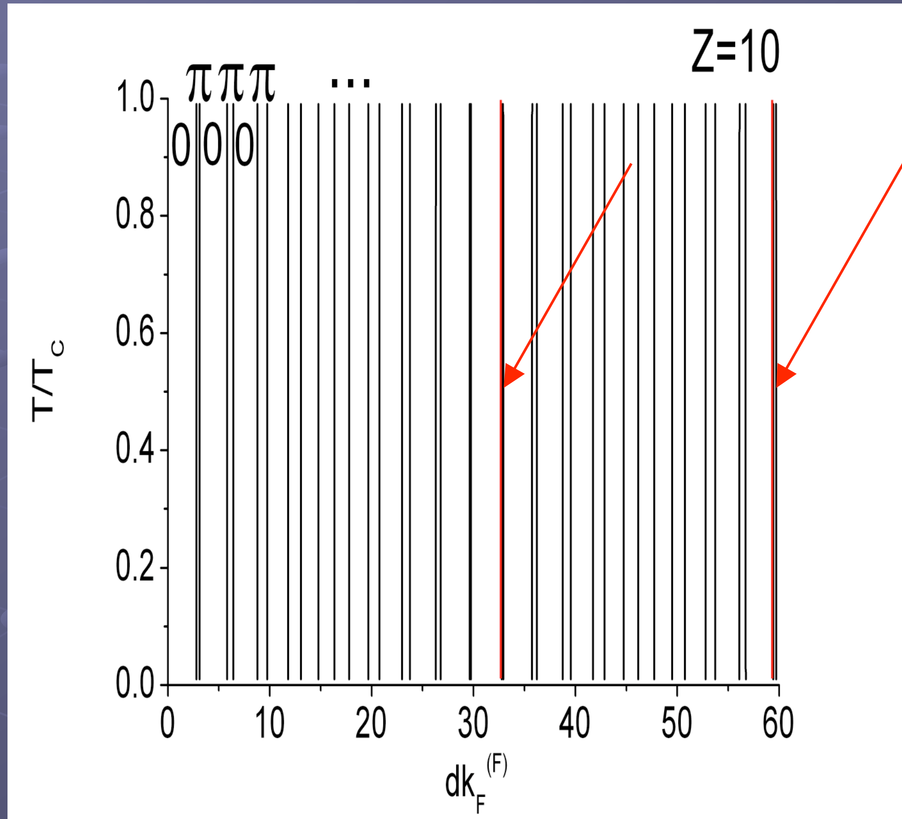
$T/T_C = 0.01$

$E_F^{(F)} = E_F^{(S)}$

$\Delta/E_F^{(S)} = 10^{-3}$

Phase diagram – one channel



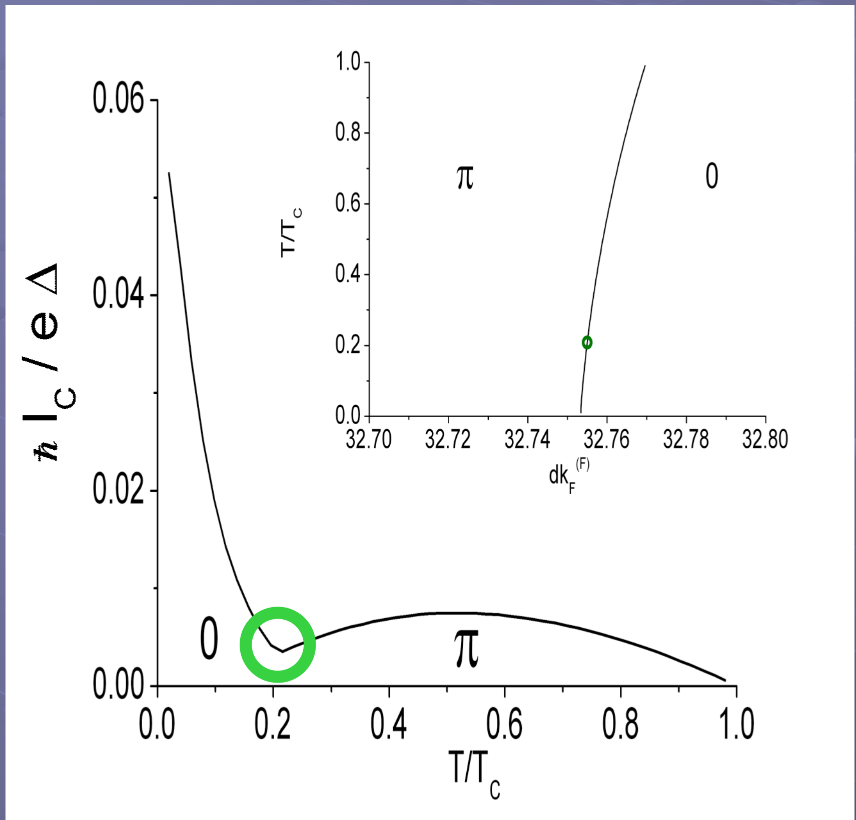


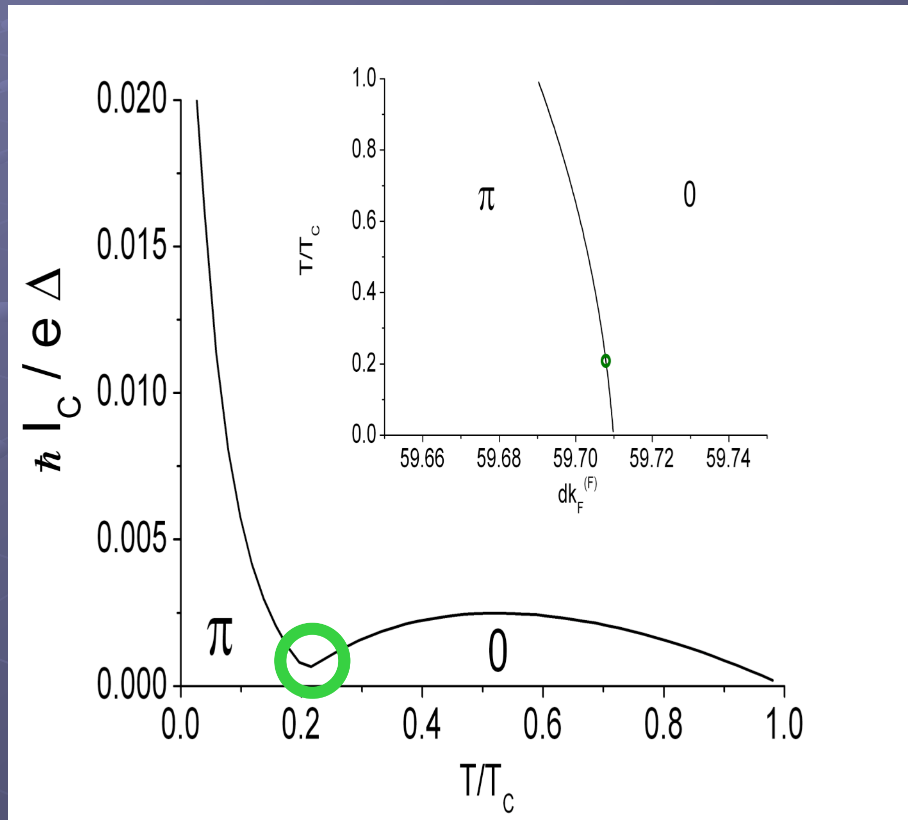
$X = 0.1$

$E_F^{(F)} = E_F^{(S)}$

$\Delta / E_F^{(S)} = 10^{-3}$

Temperature-induced 0-π transitions

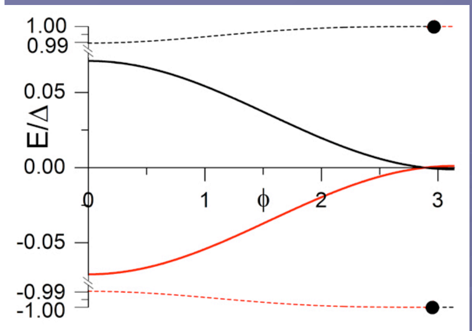




$$dk_F^{(F)} = 32.766$$

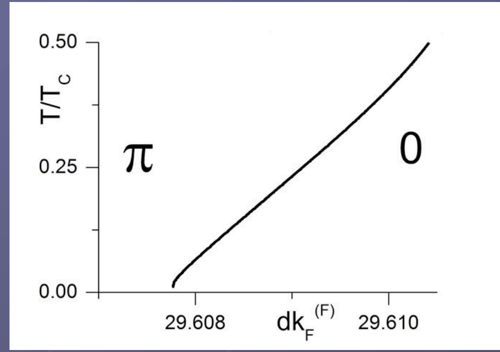
$$dk_F^{(F)} = 59.708$$

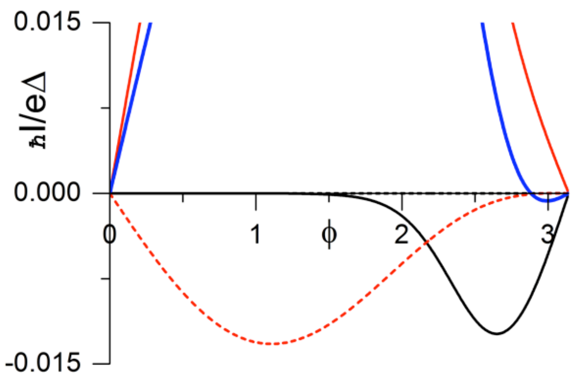
Temperature-induced 0-π transitions

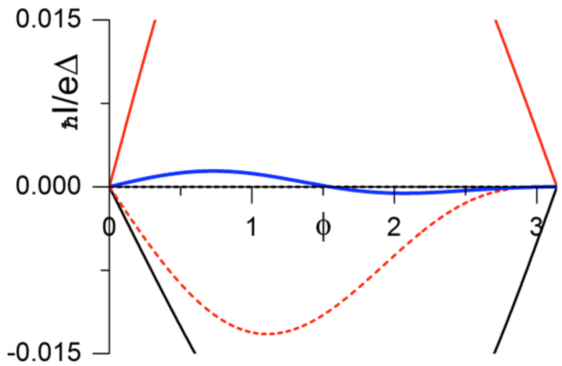


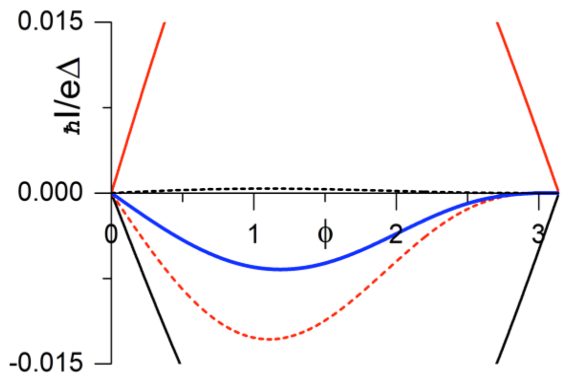
$$X = 0.1$$

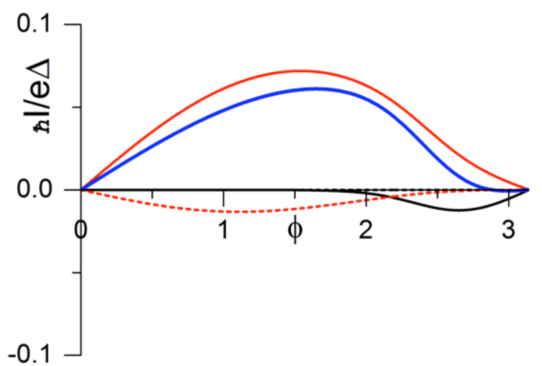
$$Z = 10$$

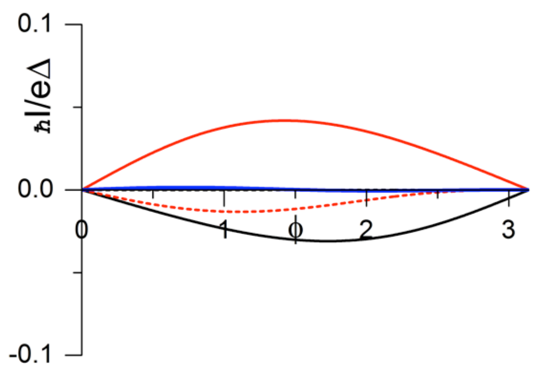


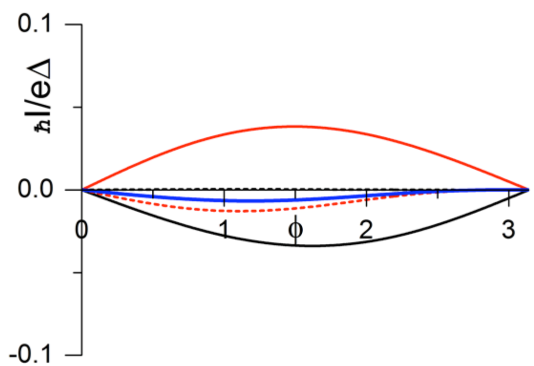






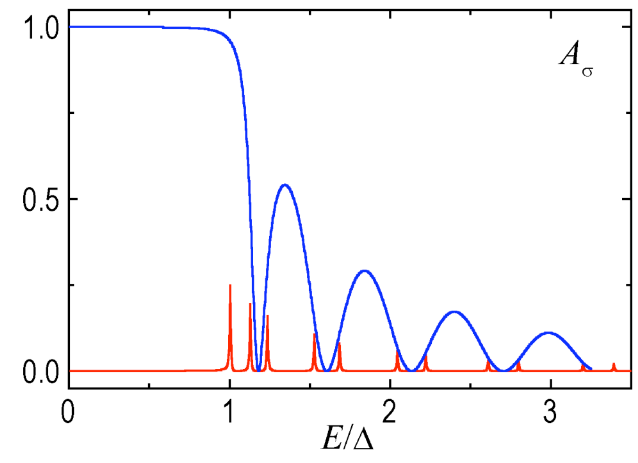






Conclusion

- Features of finite size and coherency in clean FISIF:
  - Subgap transport of electrons
    (reduction of the excess current in thin S film)
  - Oscillations of differential conductances
    (vanishing of the Andreev reflection at geometrical resonances)
  - Conductance channels:
    1. Quasiparticle transport through resonances in <u>metallic junctions</u>
    2. Supercurrent through bound states in <u>tunnel junctions</u>



Conclusion

- Spin polarization of the current without excess spin accumulation in S, i.e. without destruction of superconductivity,

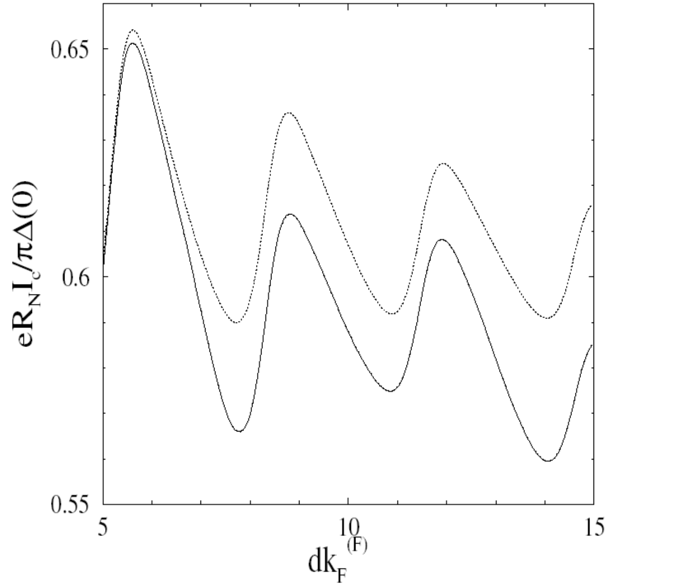
  non-trivial even in the AP alignment.

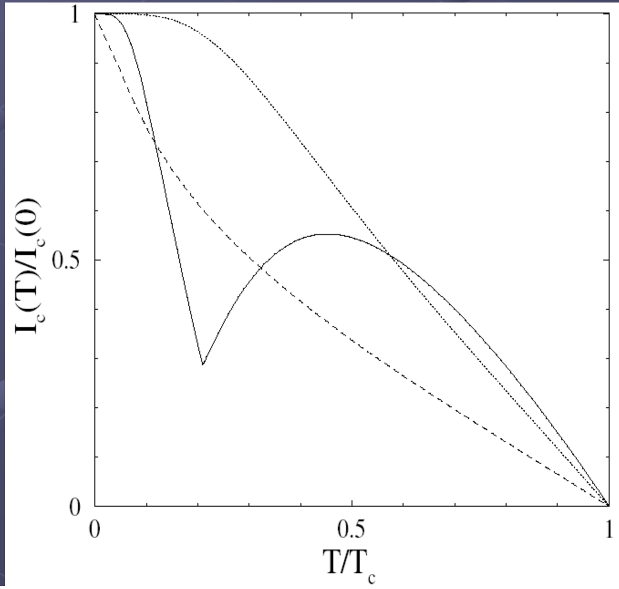
- Reliable ballistic spectroscopy

  of quasiparticle excitations in superconductors – measurements of Δ and v_F.

Conclusion

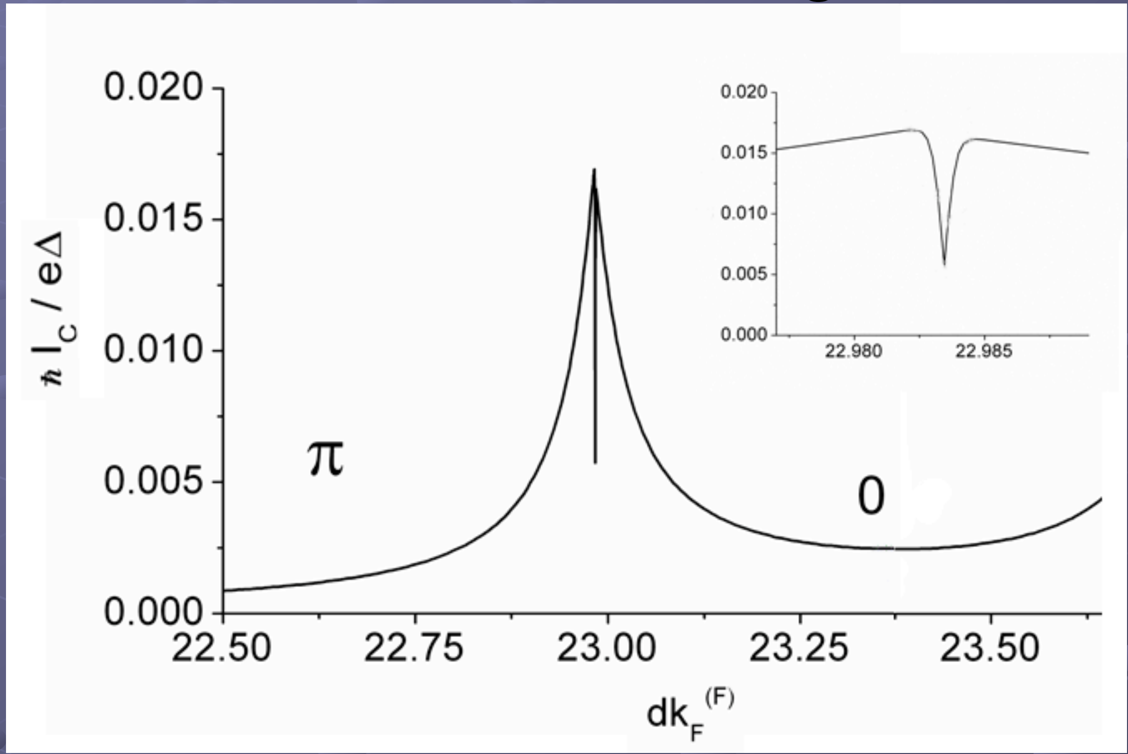
- Features of finite size and coherency in clean SIFIS:
  - Geometrical oscillations of the maximum Josephson current
  - Oscillations related to the crossovers between 0 and π states
  - Temperature-induced 0- π transitions - region of coexisting 0 and π states is considerably large.





Conclusion

- In the tunnel limit, 0-π transitions are triggered by spin-split quasi bound states crossing the Fermi surface



- Possible application: π SQUID which operates as a 0 SQUID with effectively 2x (or 4x) smaller flux quantum - improved accuracy