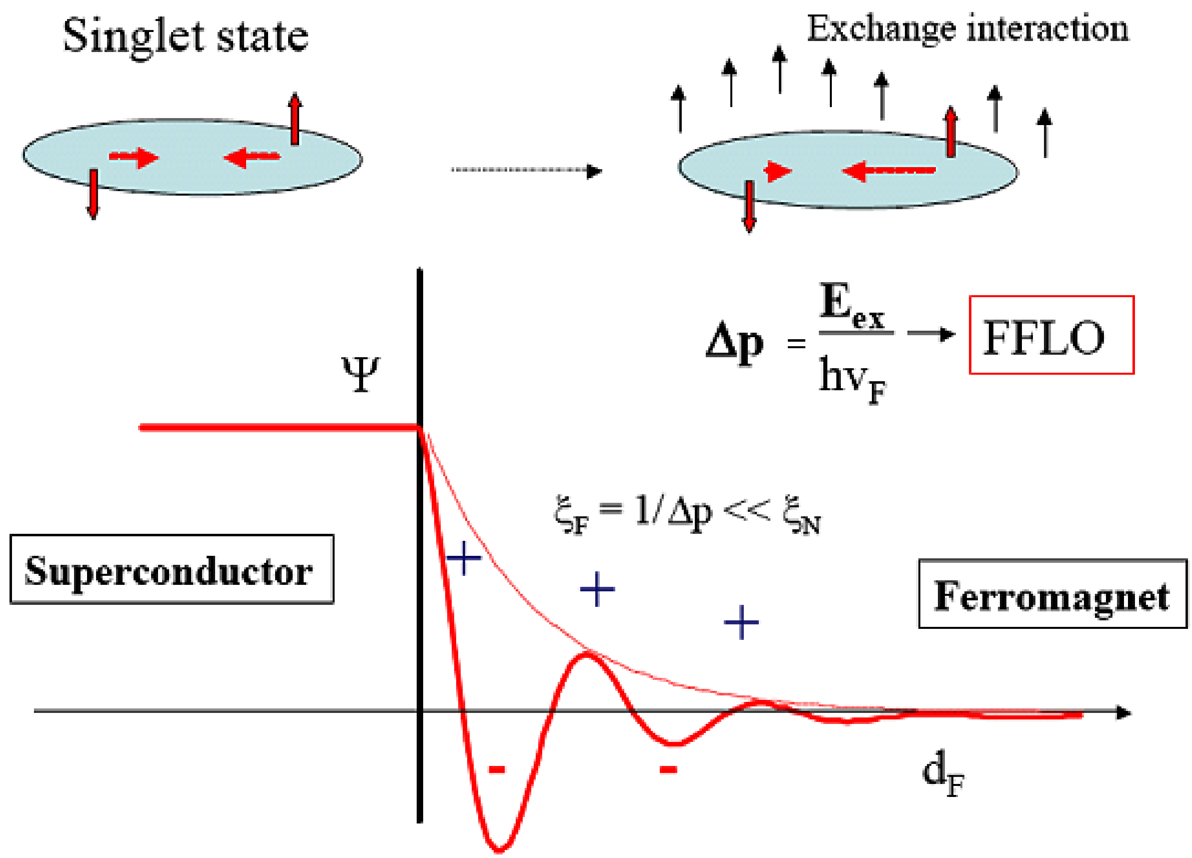
New results in theory of Ferromagnet/Superconductor hybrid nanostructures

Alexander Golubov

University of Twente, The Netherlands

In collaboration with
A.S. Vasenko (Grenoble, France)
S. Kawabata (AIST, Tsukuba, Japan)
M.Yu. Kupriyanov (MSU, Russia)
Y. Tanaka and D. Yoshizaki (Nagoya University, Japan)

Proximity effect in FS structures



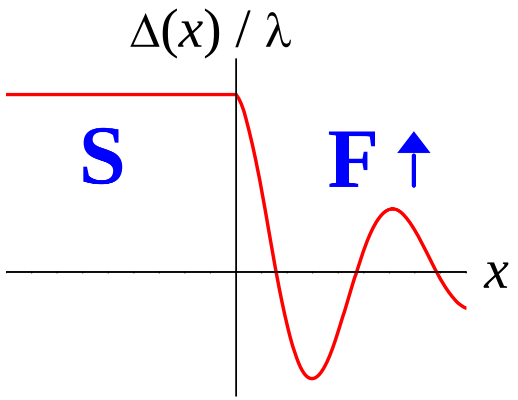
diffusive decay length

$$\xi_F = \sqrt{\frac{\hbar D_F}{E_{ex}}}$$

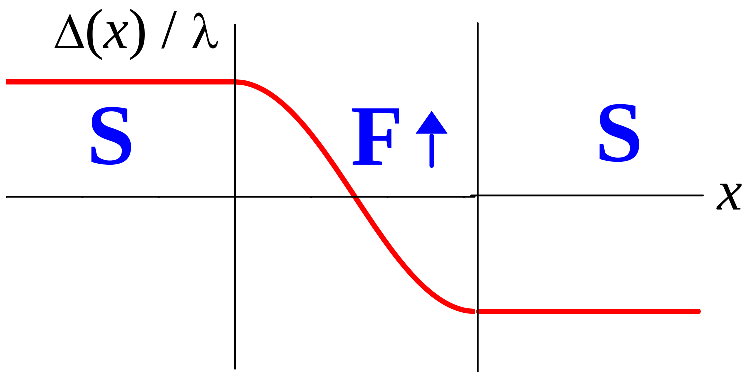
'0' and 'π' Josephson Junctions

$$0 \text{ junction}: \quad I = I_C \sin\varphi, \qquad I_C > 0$$

$$\pi \text{ junction}: \quad I = -I_C \sin\varphi = I_C \sin(\varphi + \pi)$$

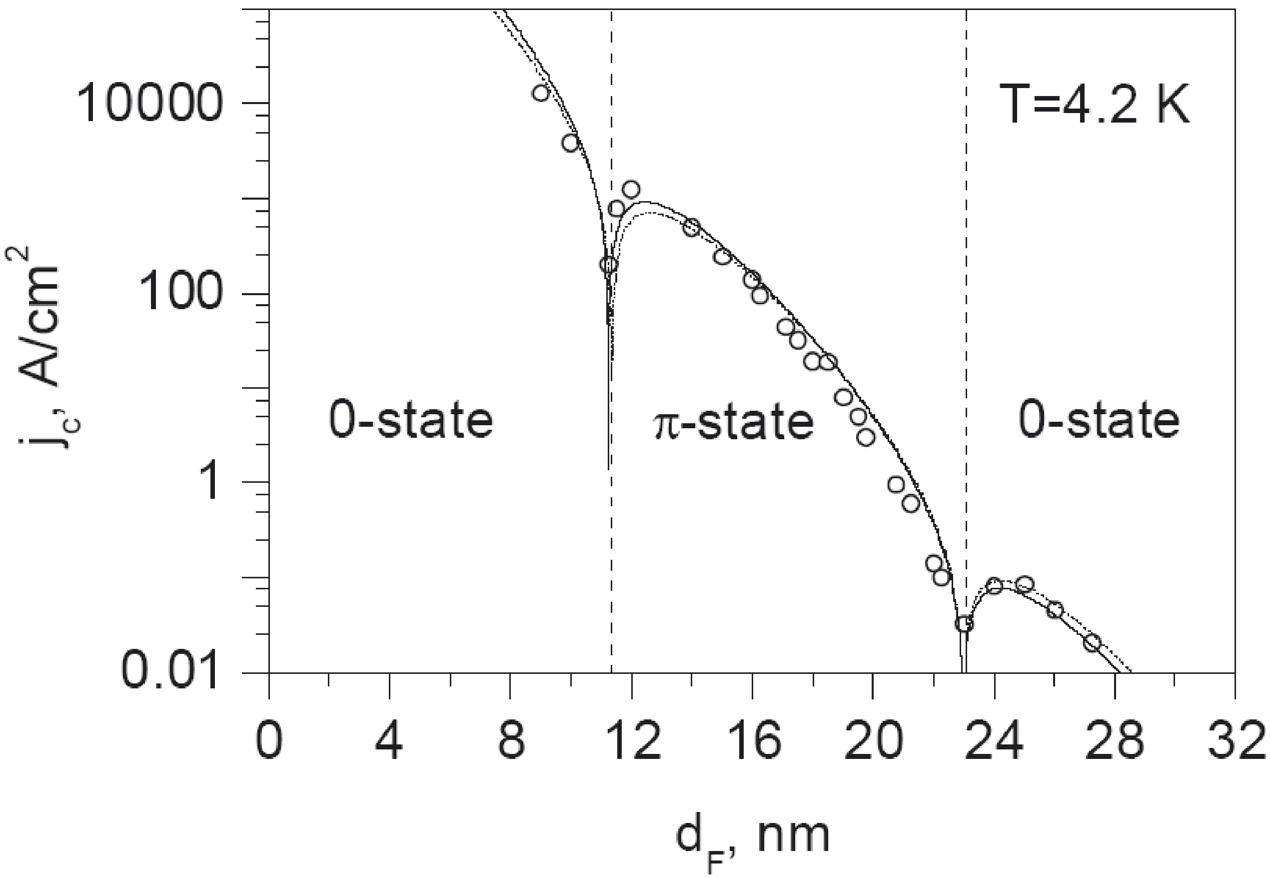


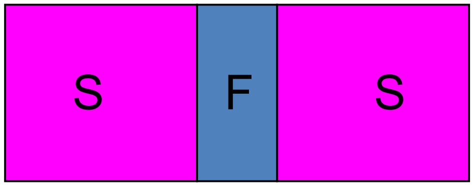
— spatial oscillations of the order parameter in the F layer



— thickness of F layer equals half wave-length of oscillations

SFS π-Junctions: experiment

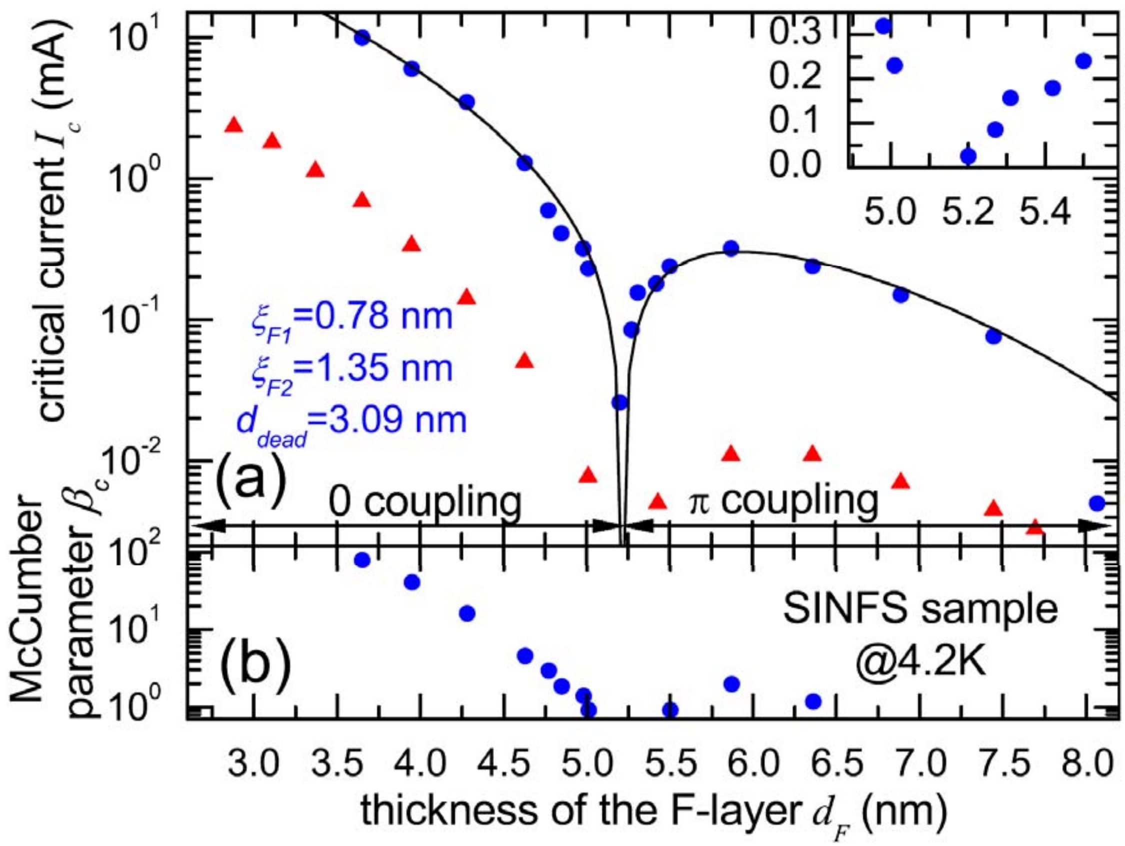


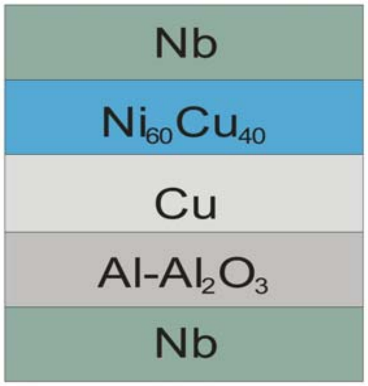


Oboznov et al., PRL, **96**, 197003 (2006)

SIFS π-Junctions: experiment

Weides et al., APL, **89**, 122511 (2006)





Critical current oscillations

A.S. Vasenko, S. Kawabata, A.A. Golubov, M.Yu. Kupriyanov, and M. Weides

PRB **77**, 134507 (2008); PRB **84**, 024524 (2011)

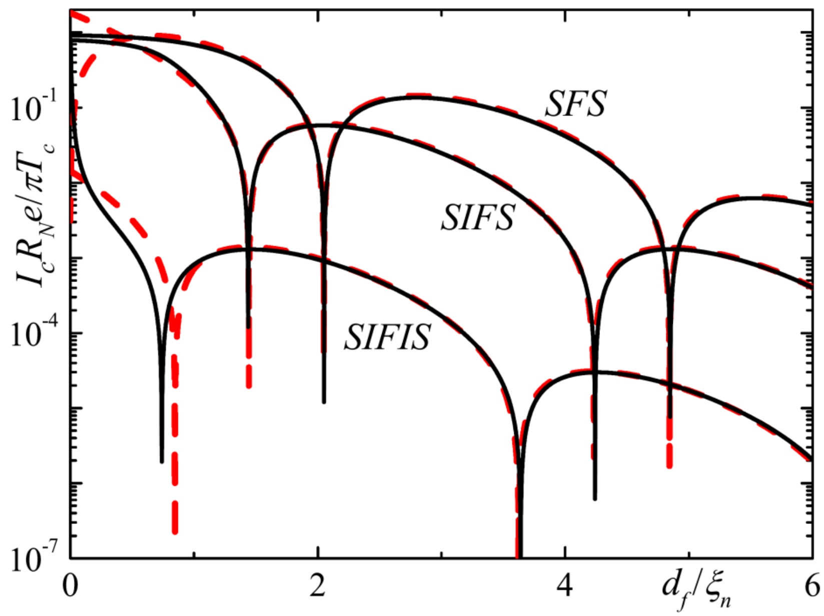


FIG. 2: (Color online) The F layer thickness dependence of the critical current for SFS ($\gamma_{B1,2} = 0$), SIFS ($\gamma_{B1} = 10^2$, $\gamma_{B2} = 0$) and SIFIS ($\gamma_{B1,2} = 10^2$) junctions in the absence of spin-flip scattering. Red dashed lines correspond to the modulus of the analytical results (31),(25) and (29) and black solid lines correspond to the result of the numerical calculation in Sec. IV, $h = 3\pi T_c$, $T = 0.5T_c$.

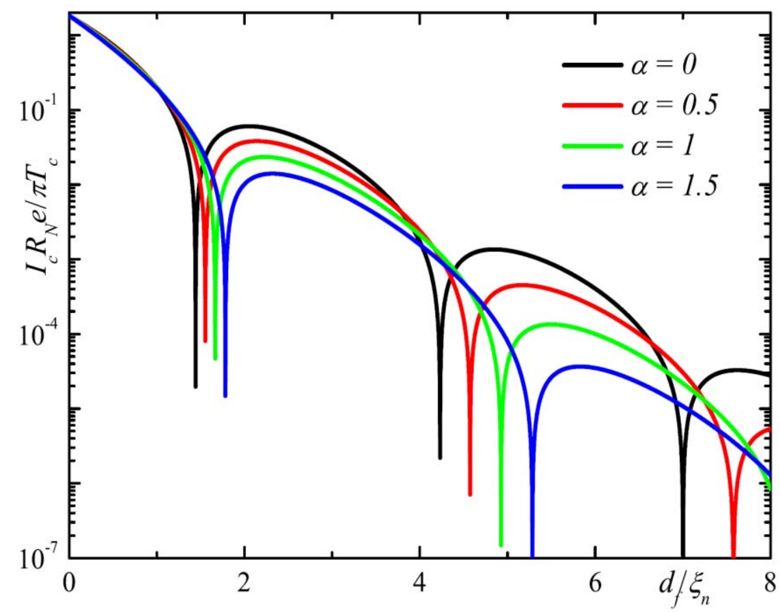


FIG. 3: (Color online) The F layer thickness dependence of the critical current in the SIFS junction [modulus of the Eq. (14)] for different values of $\alpha = 1/\pi T_c \tau_m$, $h = 3\pi T_c$, $T = 0.5T_c$.

Weides et al. experimental data fitting

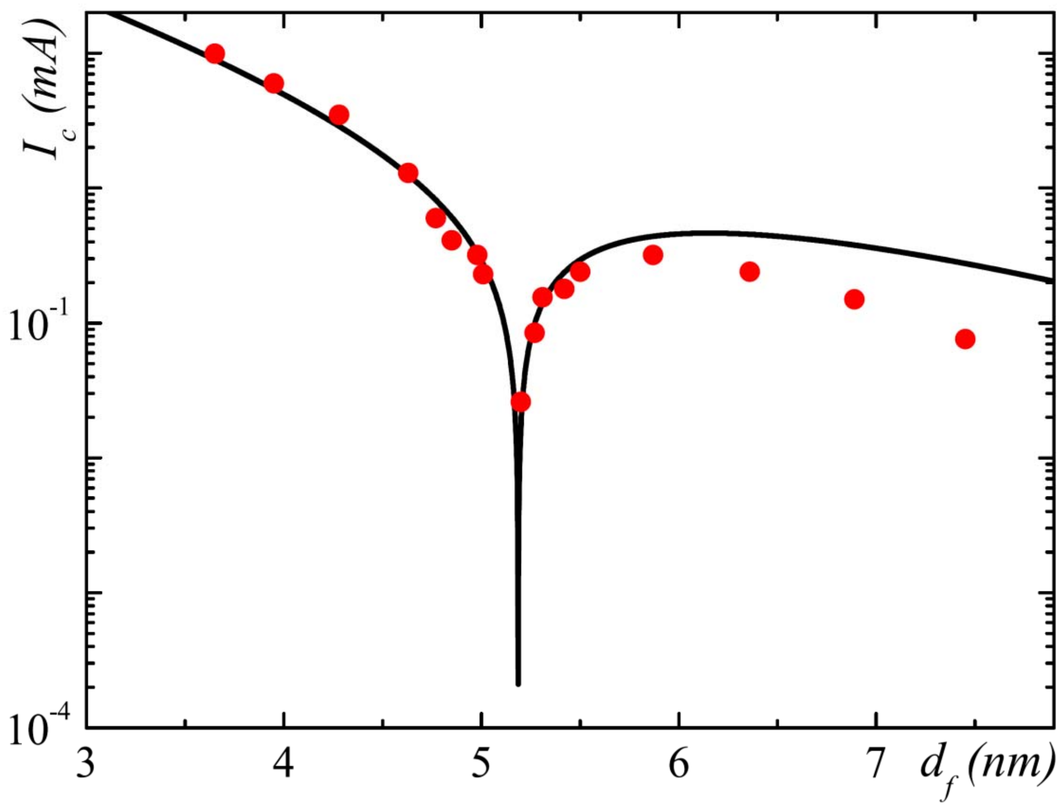
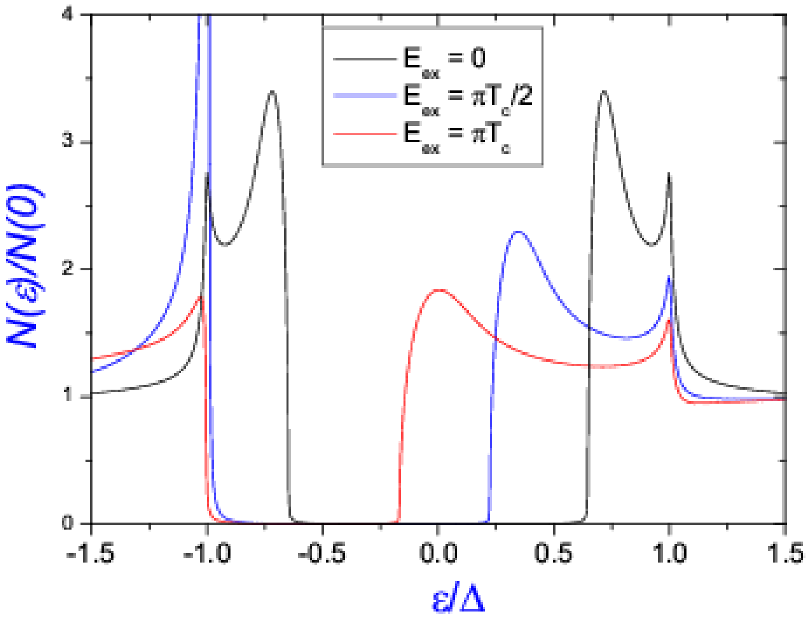
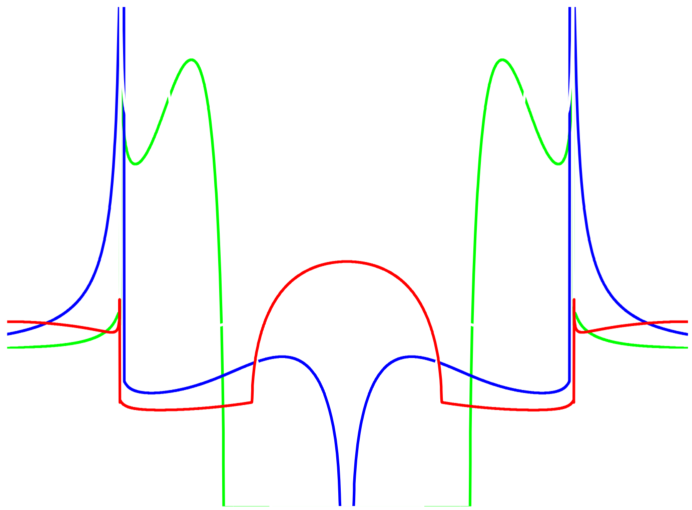


FIG. 5: (Color online) Fit to the experimental data from Ref. 14 for the critical current in a $Nb/Al_2O_3/Ni_{0.6}Cu_{0.4}/Nb$ junction. The fitting parameters are: $h/k_B = 950\ K$ and $1/\tau_m = 1.6\ h$.

DOS in SF junction: typical behavior





Spin-resolved DoS:
Zeeman shift of DoS peaks

Total DoS: the sum over both spin subbands.
Zero energy DoS oscillates as a function of exchange field

DOS oscillations at Fermi energy

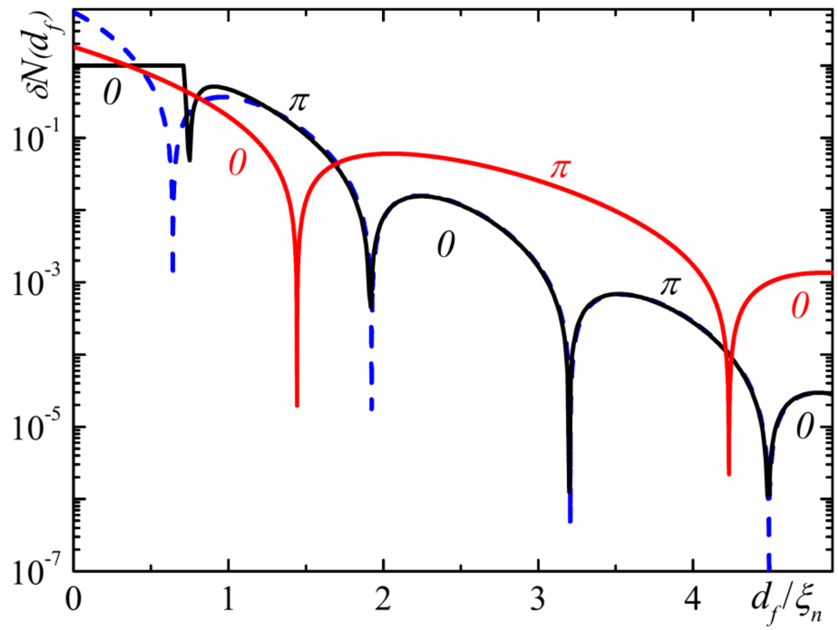
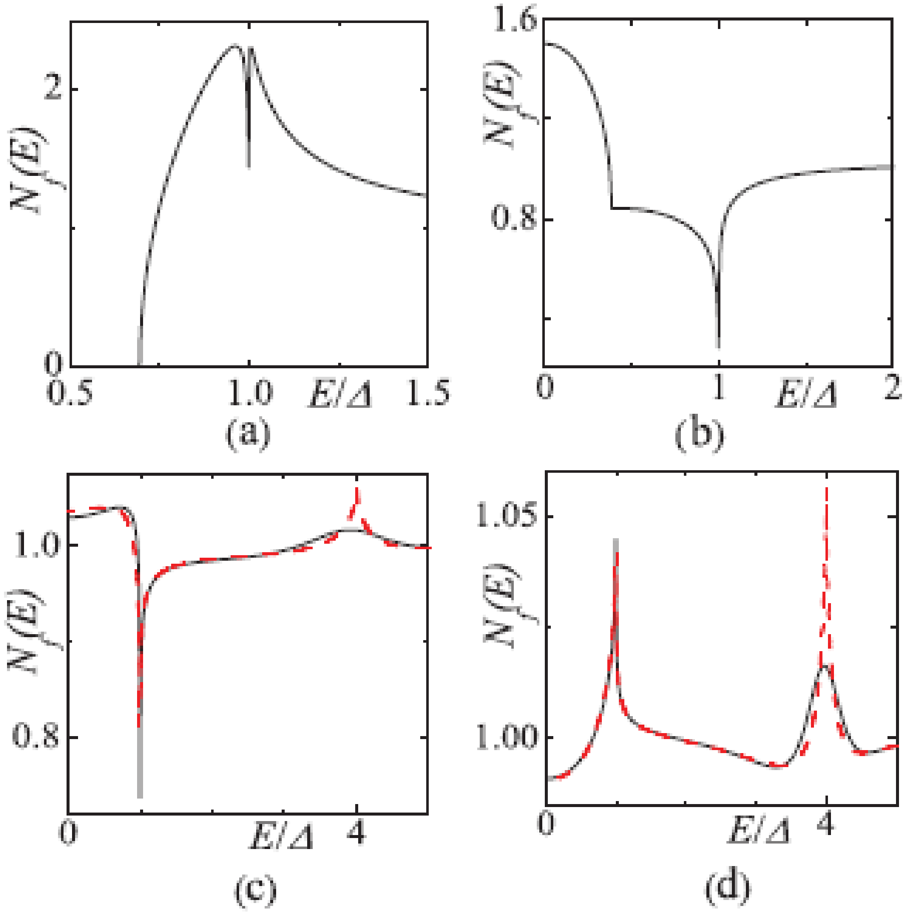


FIG. 8: (Color online) The F-layer dependence of the function $\delta N(d_f)$ in the absence of spin-flip scattering, $h = 3\pi T_C$, $T = 0.5T_c$. Black solid line is a result of the numerical calculation; blue dashed line is calculated with the use of Eq. (41). Red line shows normalized critical current for SIFS junction. Zero and π states defined from I_c are indicated by red color, while zero and π states defined from DOS are indicated by black color.

$$\delta N(d_f) = |1 - N_0|, \quad N_0 = N(E = 0)$$

$$\delta N(d_f) \approx \frac{32}{3+2\sqrt{2}} \left| \exp\left(-\frac{2d_f}{\xi_{f1}}\right) \cos\left(\frac{2d_f}{\xi_{f2}}\right) \right|$$

DOS in SF electrode of SIFS junctions



$$d_f = 0.5(a), 1(b), 2(c), 3(d)$$

$$N(E) = \left[N_\uparrow(E) + N_\downarrow(E)\right]/2,$$

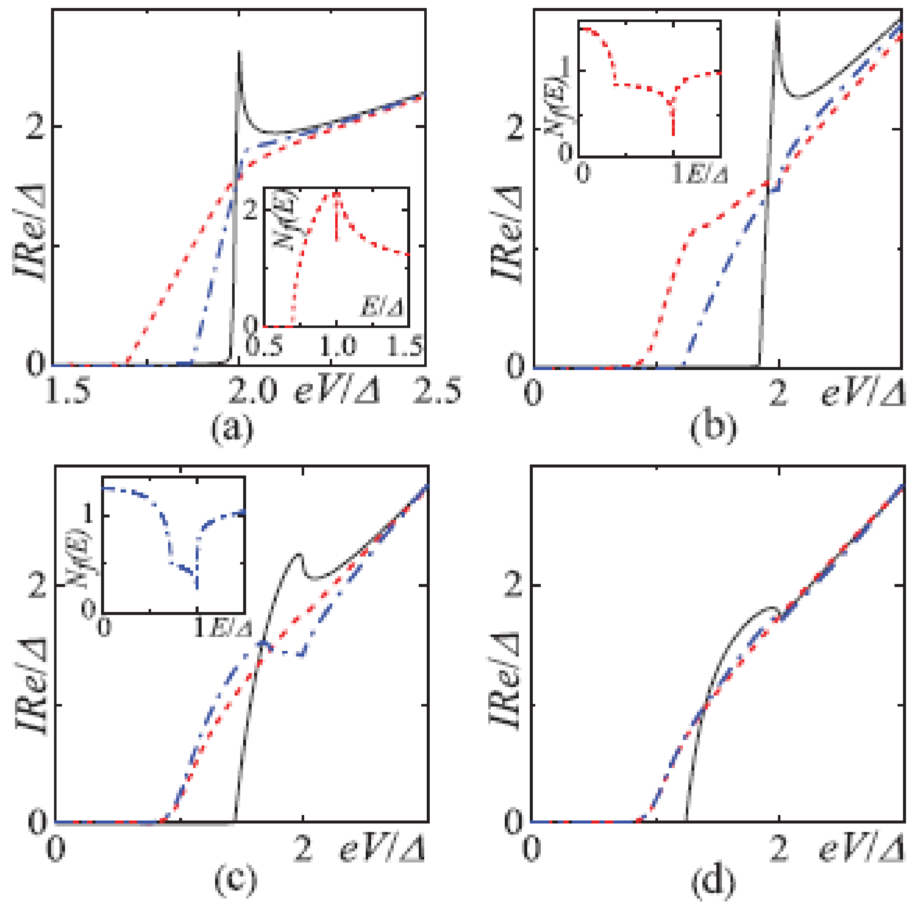
$$N_{\uparrow(\downarrow)}(E) = \mathrm{Re}\left[\cos\theta_{\uparrow(\downarrow)}(i\omega \to E + i0)\right]$$

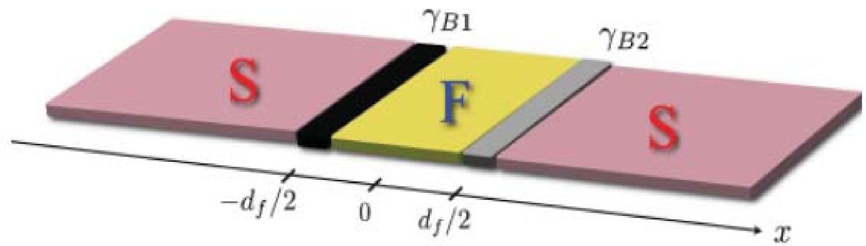
Peak at E=h occurs for large F-layer thicknesses, in accordance with the formula

$$N_f \approx 1 - \mathrm{Re}\sum_{\uparrow,\downarrow} \frac{16F^2(E)\exp\left(-p\frac{2d_f}{\xi_f}\right)}{(\sqrt{(1-\eta^2)F^2(E)+1}+1)^2}$$

Detailed discussion in the talk by Andrey Vasenko 23-OR-G8

I-V characteristics of SIFS junctions

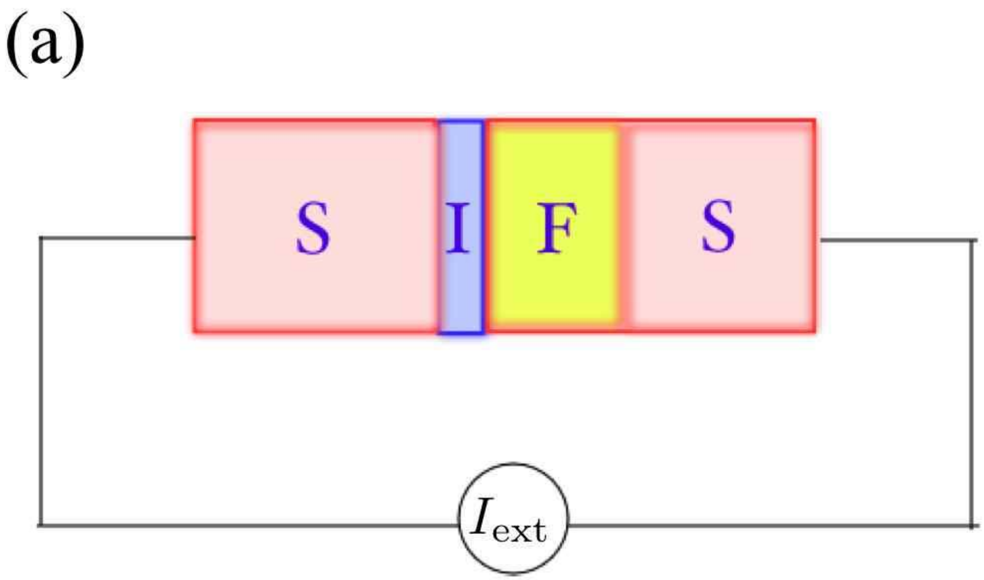




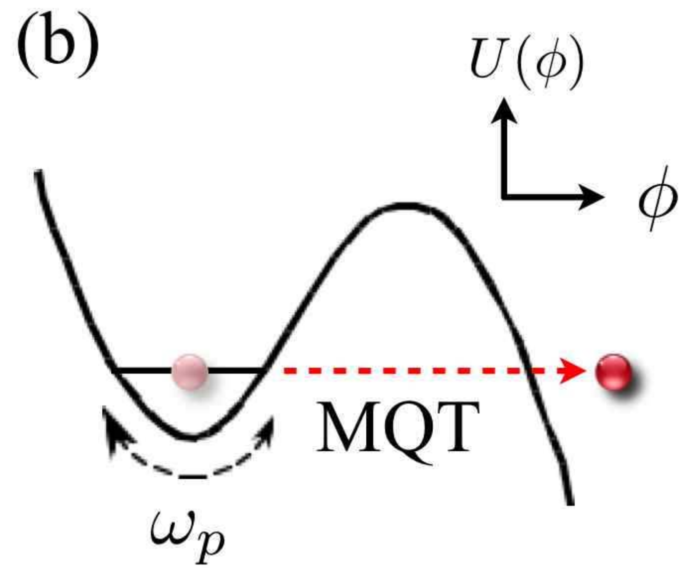
small quasipartice currrent at low bias => low dissipation

Detailed discussion in the talk by Andrey Vasenko 23-OR-G8

Macroscopic Quantum Tunneling in SIFS junctions

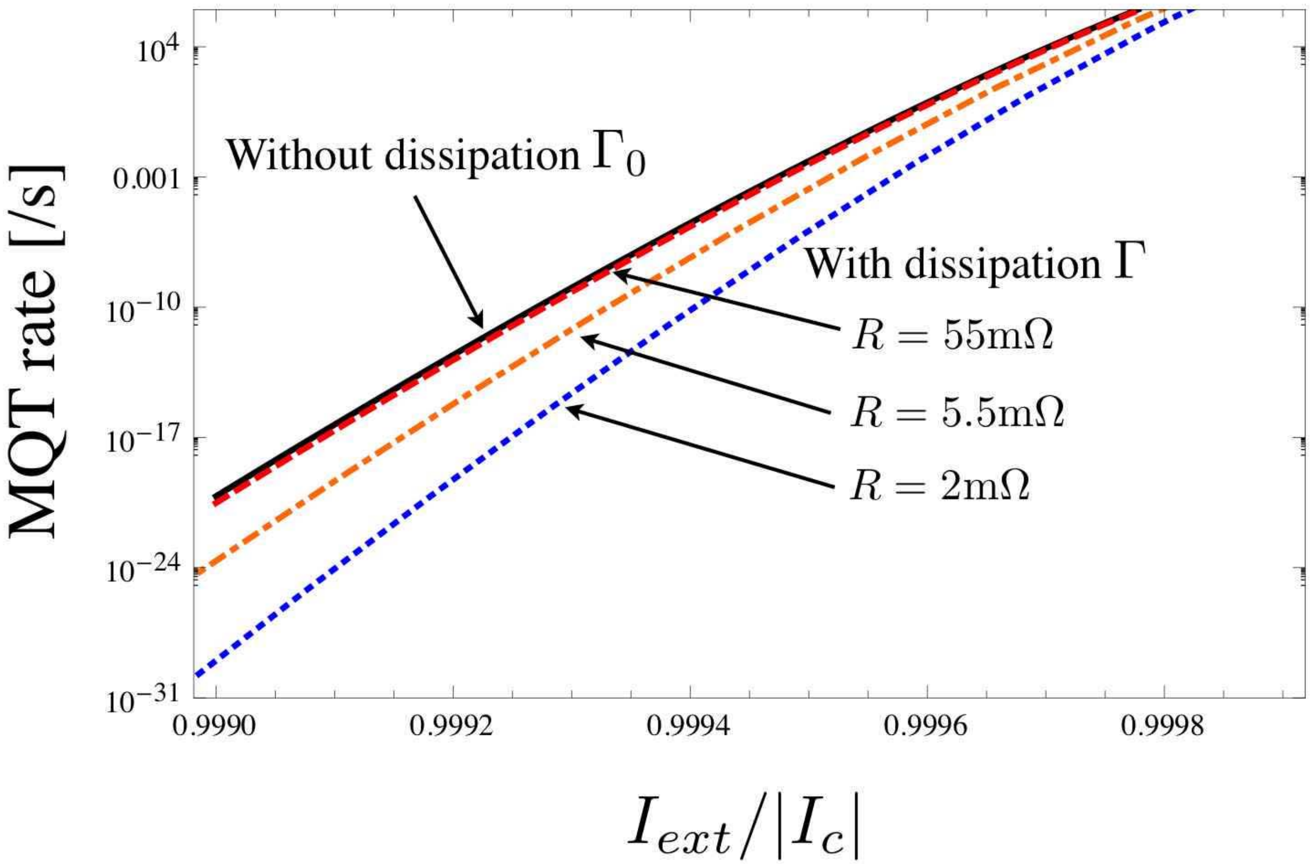


Current biased SIFS Josephson junction



Potential U(φ) vs the phase difference φ between two superconductors.
ωp is the Josephson plasma frequency of the junction

Macroscopic Quantum Tunneling in SIFS junctions



$RC \gg \hbar/\Delta$

↓

Corresponds to actual SIFS junctions

The MQT escape rate for a current-biased SIFS junction
Parameters: *C = 800 pF, = 1.3 meV, and |Ic| = 500 µA*

Summary Part I

We have performed theoretical study of critical current, DOS oscillations and I-V curves in SIFS tunnel Josephson junctions

Experimental data for critical current and 0-π transition agree well with theory and junction parameters can be determined

We show that SIFS junctions are promising for application in quantum circuits

Symmetry of the pair amplitude

Two electron's function ＝(Orbital) × (Spin) × (Time)

$$F(k,R,s_1,s_2,t)=\Phi(k,R)\chi(s_1,s_2)\psi(t)$$

(**Fermi-Dirac statistics**)

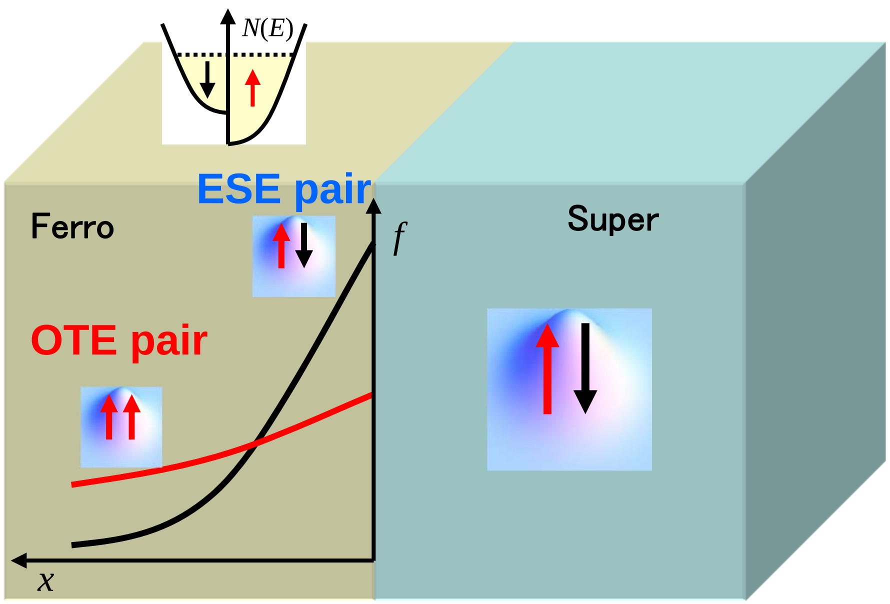
k	momentum
R	coordinate
s_1, s_2	Spin
t	Time

Orbital	Spin	Time	
even	singlet	even	Even frequency Cooper pair: BCS Superconductor, Cuprate Superconductor
odd	triplet	even	Even frequency Cooper pair: **3He** Sr_2RuO_4
even	triplet	odd	Odd frequency Cooper pair
odd	singlet	odd	Odd frequency Cooper pair

Background

Superconductor/Ferromagnet (S-F) junction

Interplay between Cooper pairs with spin-singlet in S and spin-aligned carriers in F



F. S. Bergeret, A. F. Volkov, and K. B. Efetov, PRL **86**, 4096 (2001)

Possible symmetry of the pairing in F (consistent with Pauli's principle)

In the F region, only the *s*-wave even-parity pairing state is allowed due to isotropization by impurity scattering.

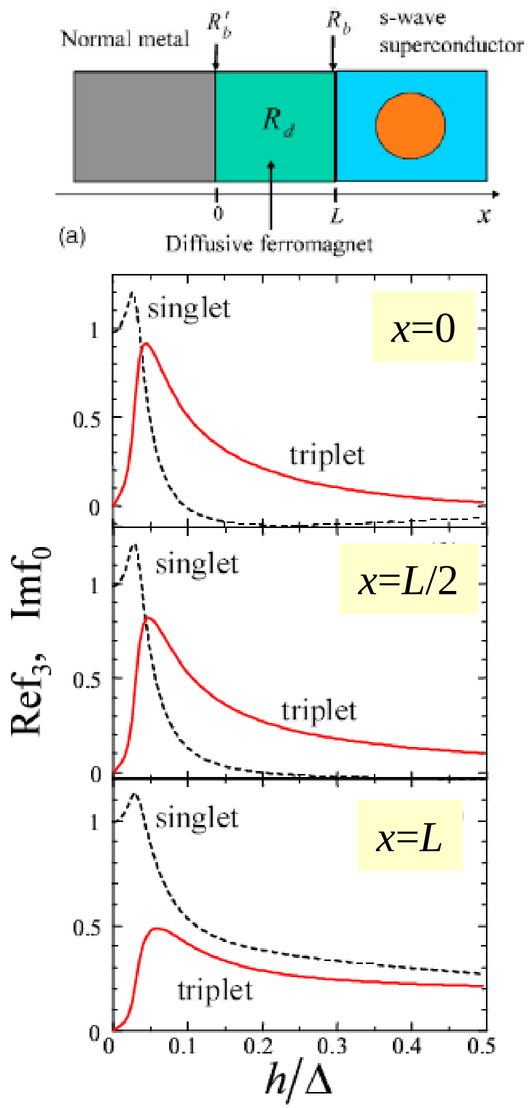
Even frequency spin-singlet s-wave even-parity (ESE) pair

+

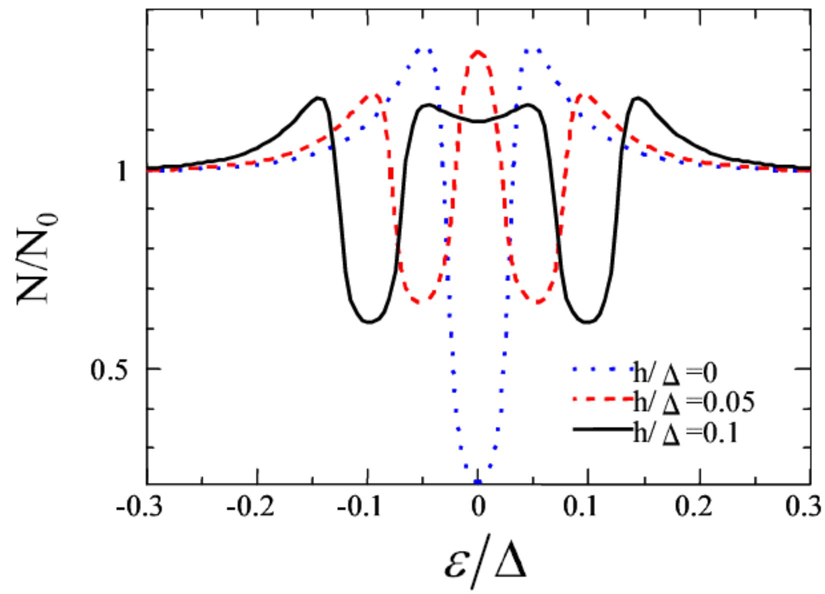
Odd frequency spin-triplet s-wave even-parity (OTE) pair

Odd frequency Cooper pair is induced in ferromagnet

S-F junction (theoretical prediction)



T. Yokoyama, Y. Tanaka, A.A. Golubov, PRB **75**, 134510 (2007)



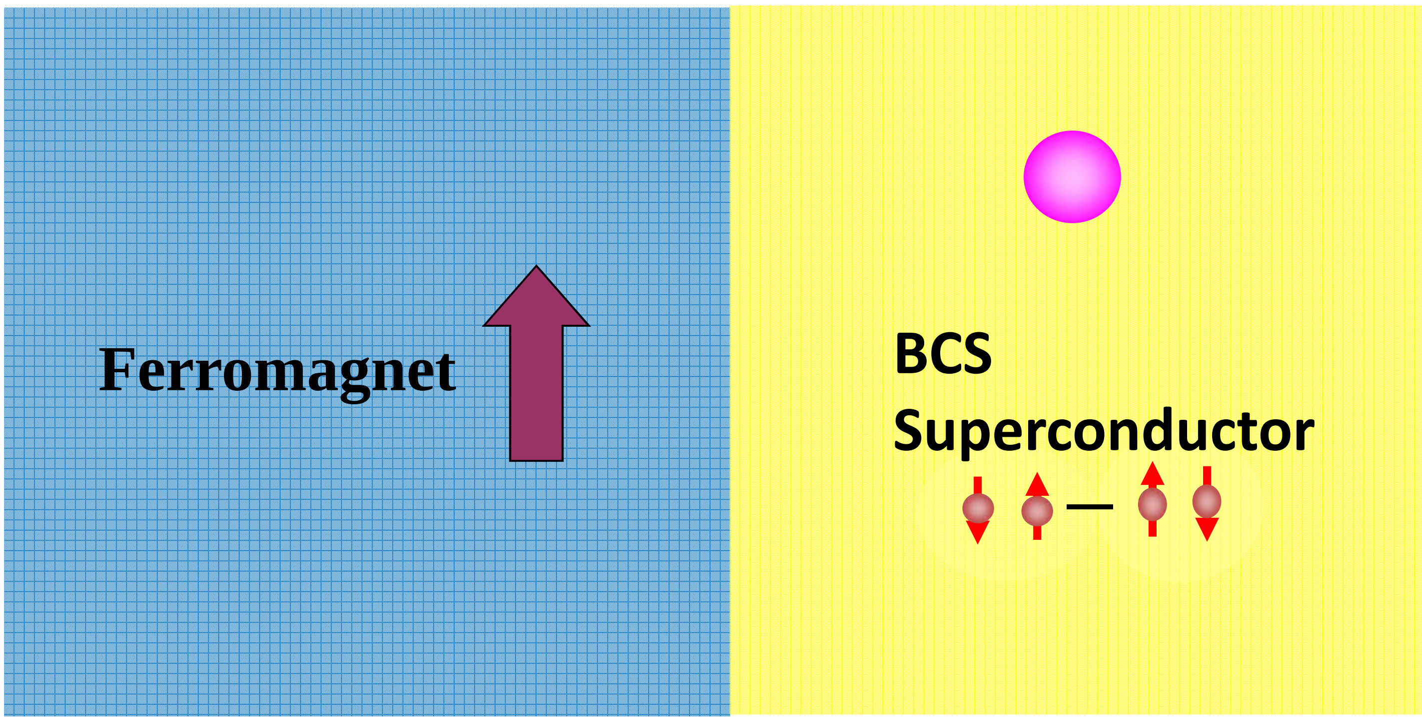
Normalized LDOS as a function of ε for R_d/R_b=1 with various h/Δ

The pair amplitudes f_3 (ESE) and f_0 (OTE) as a function of h in the F for ε=0

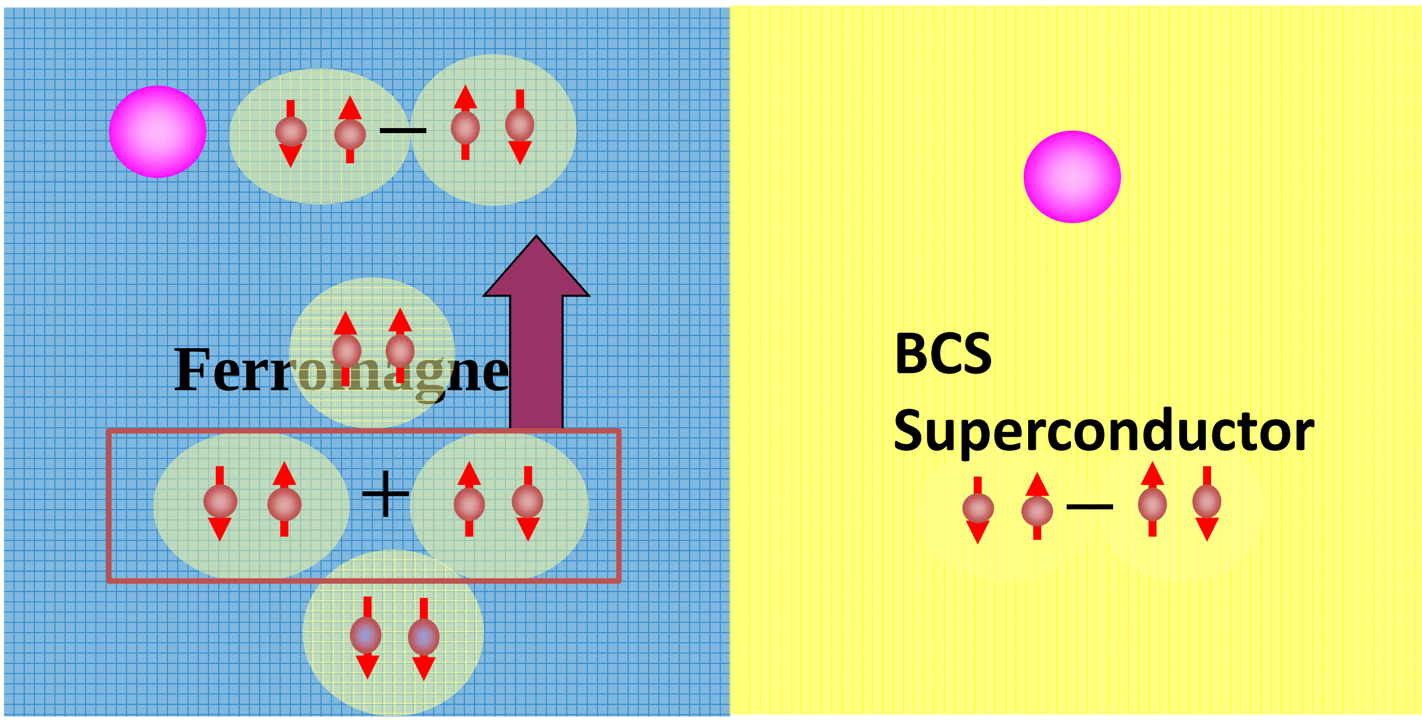
- When the OTE state dominates the ESE state in the F, the resulting LDOS has a zero-energy peak (ZEP).
- The amplitude of the OTE pair wave function near the N/F interface is enhanced at zero energy.

The observation of ZEP is the evidence that odd-frequency pair exists in F

Odd frequency Cooper pair (F/S junction)



Odd frequency Cooper pair (F/S junction)



2001 .*Bergeret .et.al*

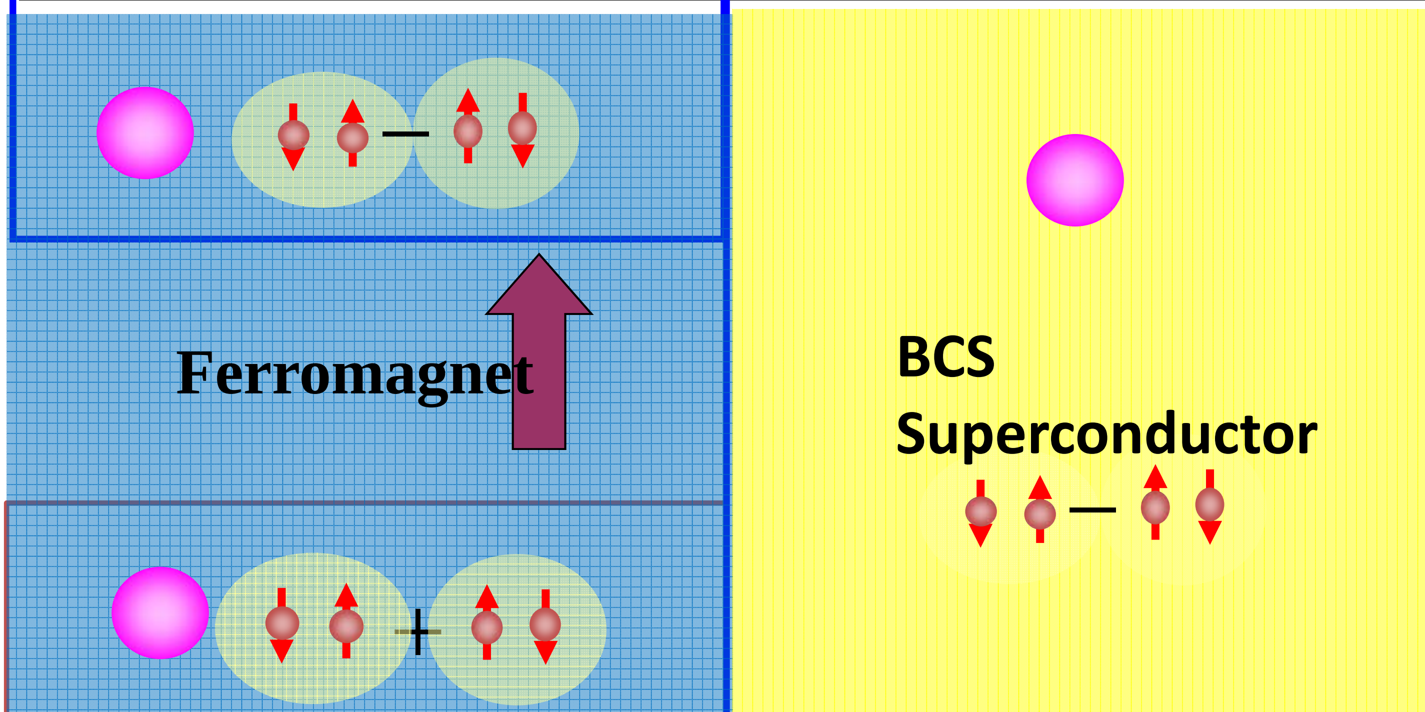
2001 .*Kadigrobov .et.al*

Odd frequency Cooper pair (F/S junction)

Even frequency Cooper pair

Orbital	Spin	Time
even	odd	even

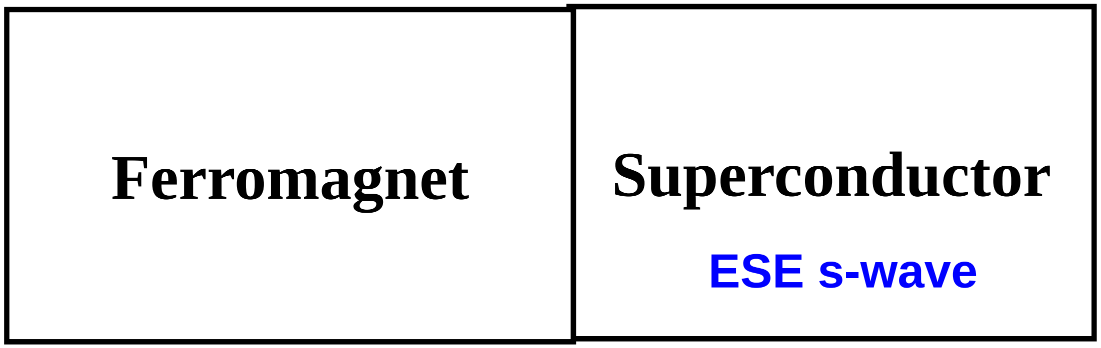
Orbital	Spin	Time
even	odd	even



Orbital	Spin	Time
even	even	odd

Odd frequency Cooper pair

Ferromagnet (metal)/superconductor junctions

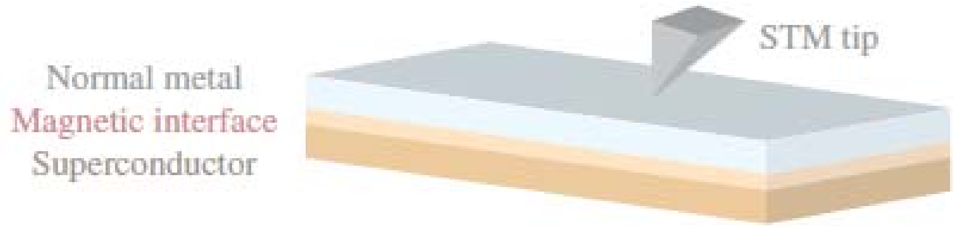


All four kinds of pairing is possible in ferromagnet (Eschrig, 2007)

(1) **Generation of OSO pairing by broken inversion (translational) symmetry**
(2) **Generation of OTE pairing by broken spin rotational symmetry**
(3) **Generation of ETO pairing both in the presence of broken inversion (translational) symmetry and broken spin rotational symmetry**

ESE : Even-frequency spin-Singlet Even-parity
ETO : Even-frequency spin-Triplet Odd-parity
OSO : Odd-frequency spin-Singlet Odd-parity
OTE : Odd-frequency spin-Triplet Even-parity

Induced odd-frequency pairing by magnetic interface



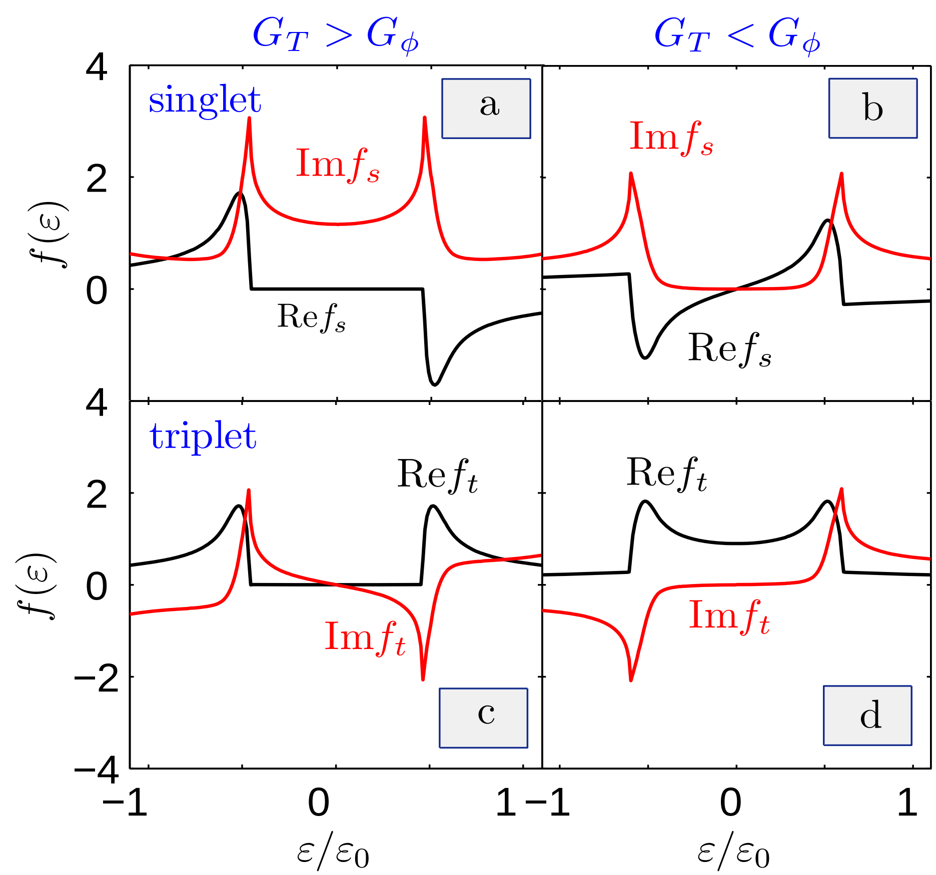
Odd-frequency pairing is induced by **interfacial spin-dependent phase shift**

G_T Interface conductance

G_ϕ Mixing conductance

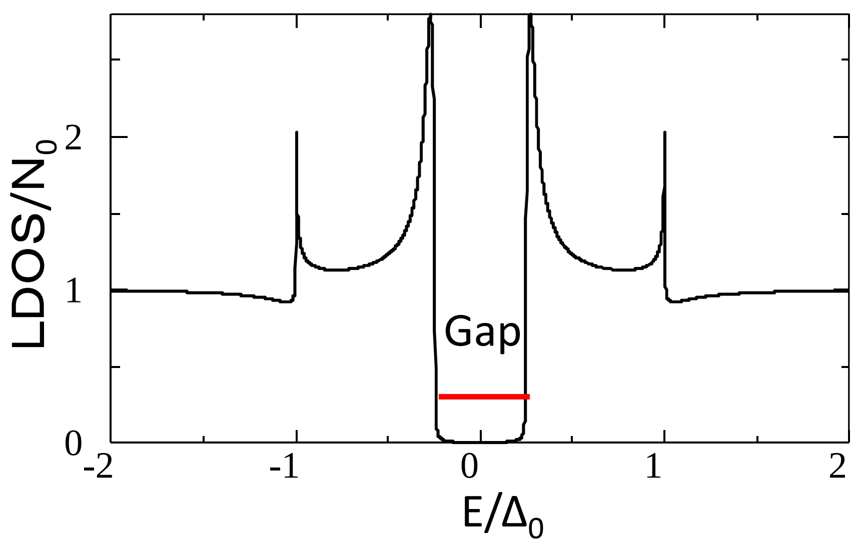
W. Belzig et al. (2002)

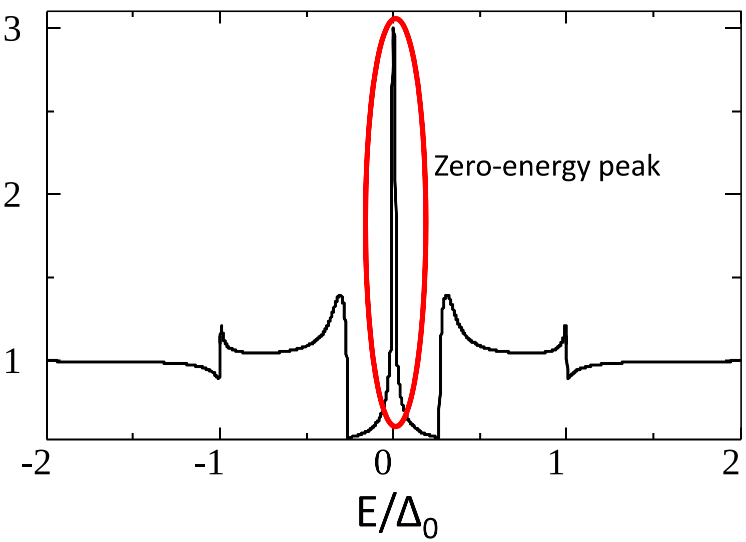
A. Brataas et al. (2000)



J. Linder, T. Yokoyama, A. Sudbo, and M. Eschrig, PRL 102, 107008 (2009)

LDOS

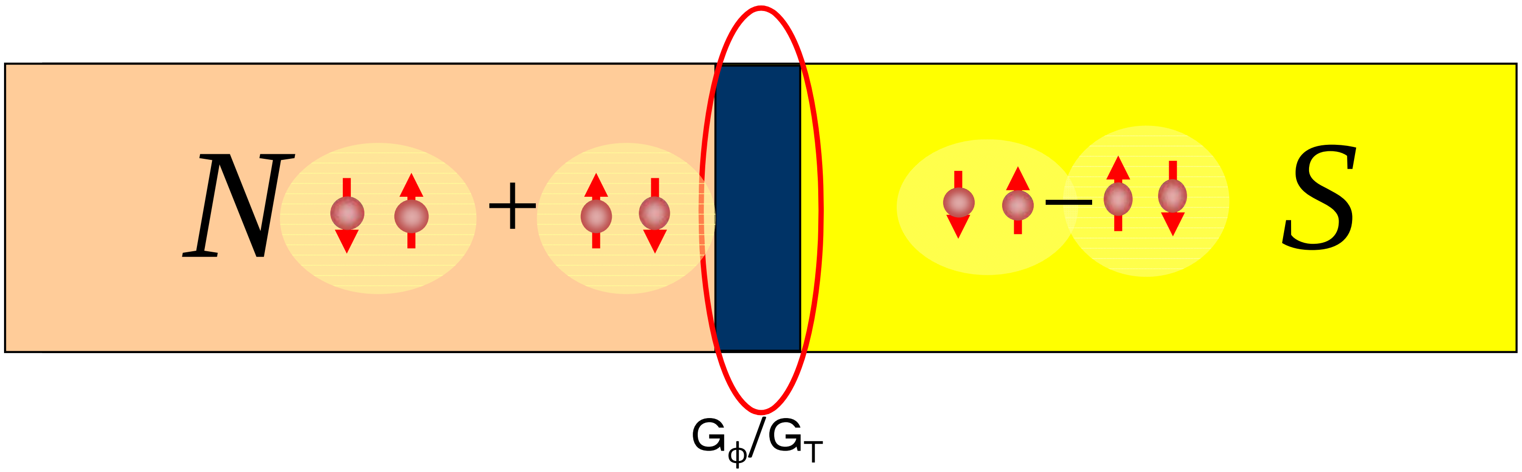




Minigap
s-wave singlet
(Even frequency)

Zero-energy peak
s-wave triplet
(Odd frequency)

Odd frequency Cooper pair
by spin-active interfaces



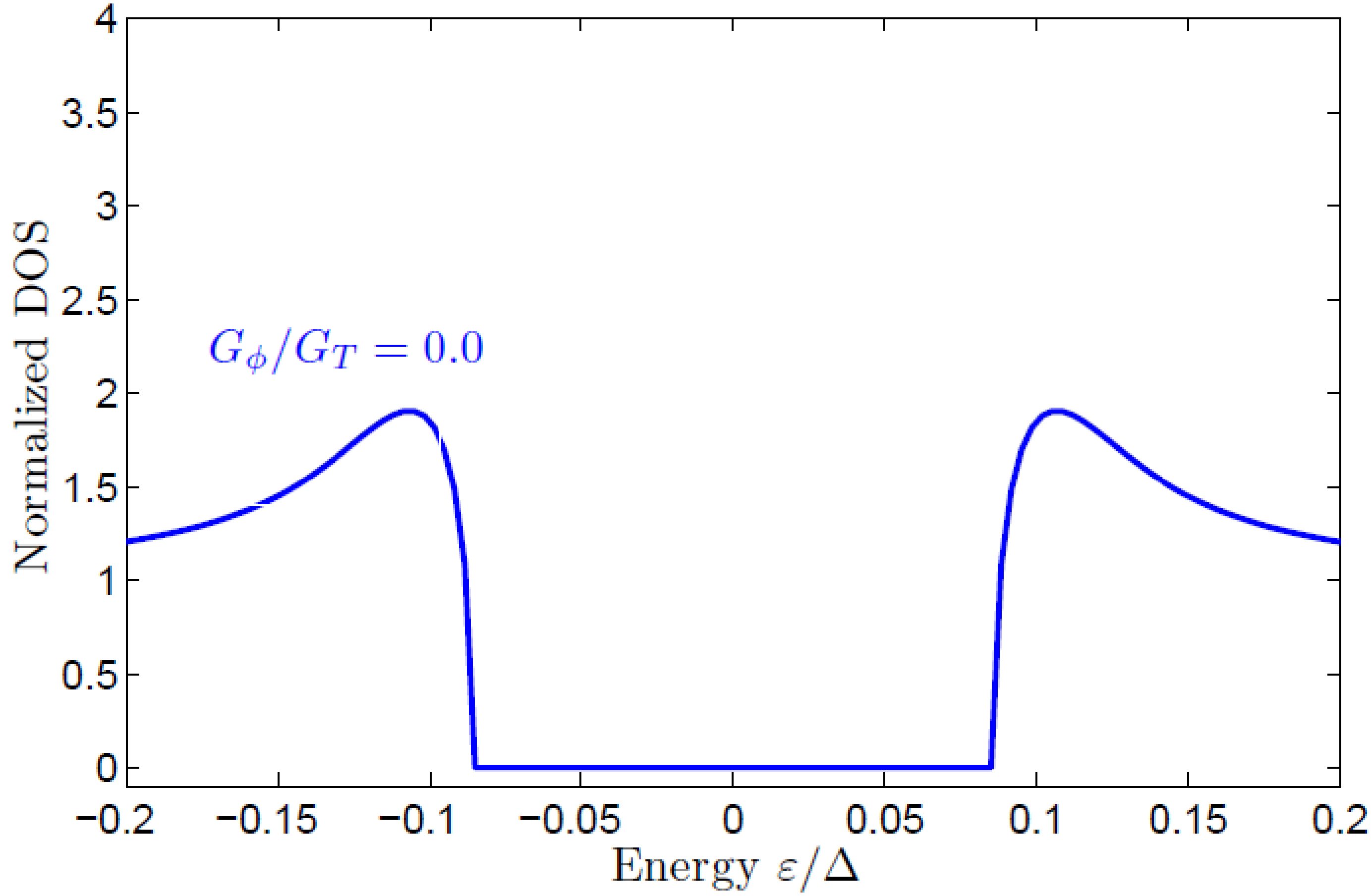
G_T : Normal-state tunnel conductance

G_ϕ : Spin-dependent phase-shifts occuring at the interface

by spin-active interfaces

J. Linder, T. Yokoyama, A. Sudbo, and M. Eschrig, PRL 102, 107008 (2009)

Change of DOS
by spin-active interfaces



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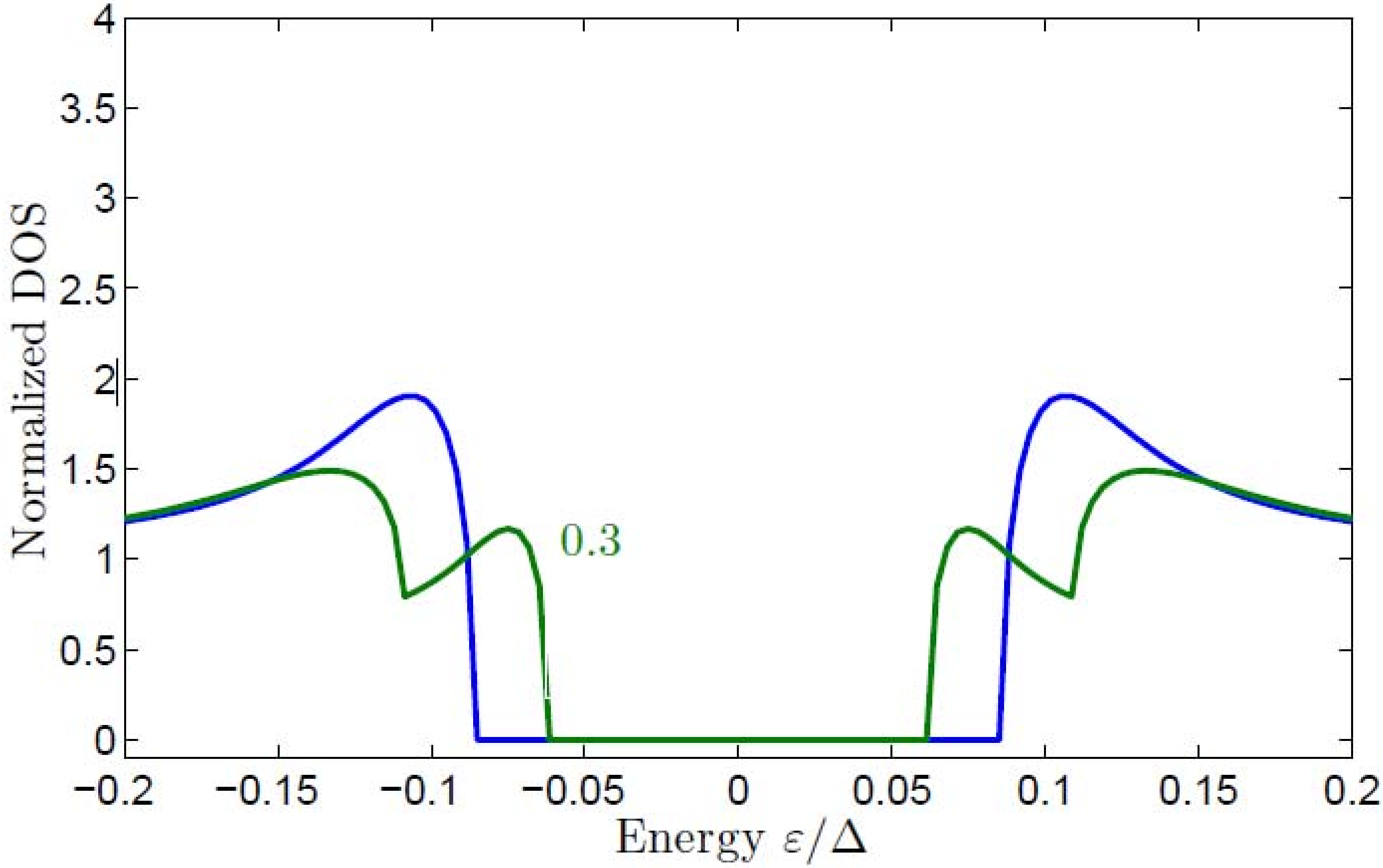

J. Linder, T. Yokoyama, A. Sudbo, and M. Eschrig, PRL 102, 107008 (2009)

Change of DOS
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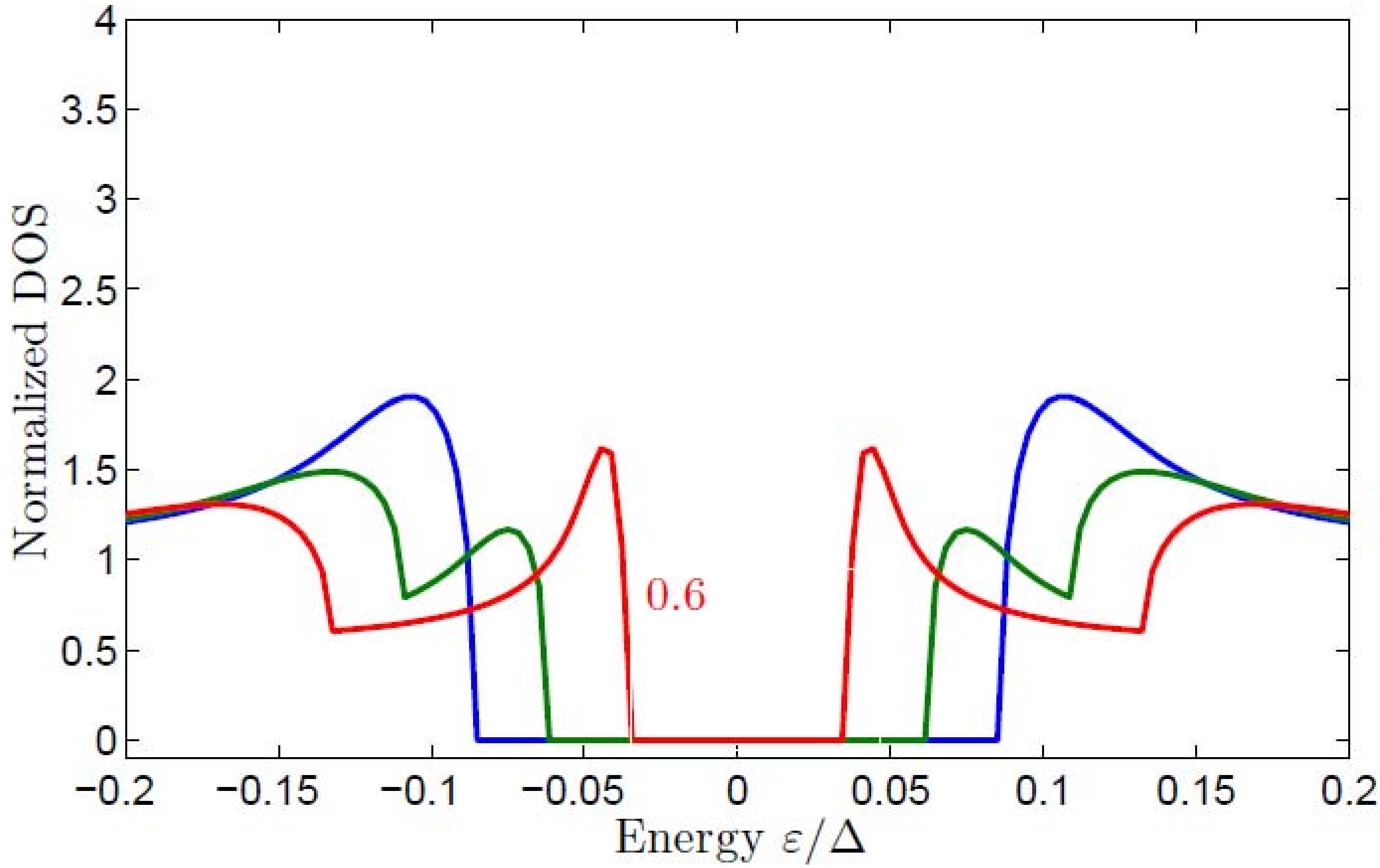
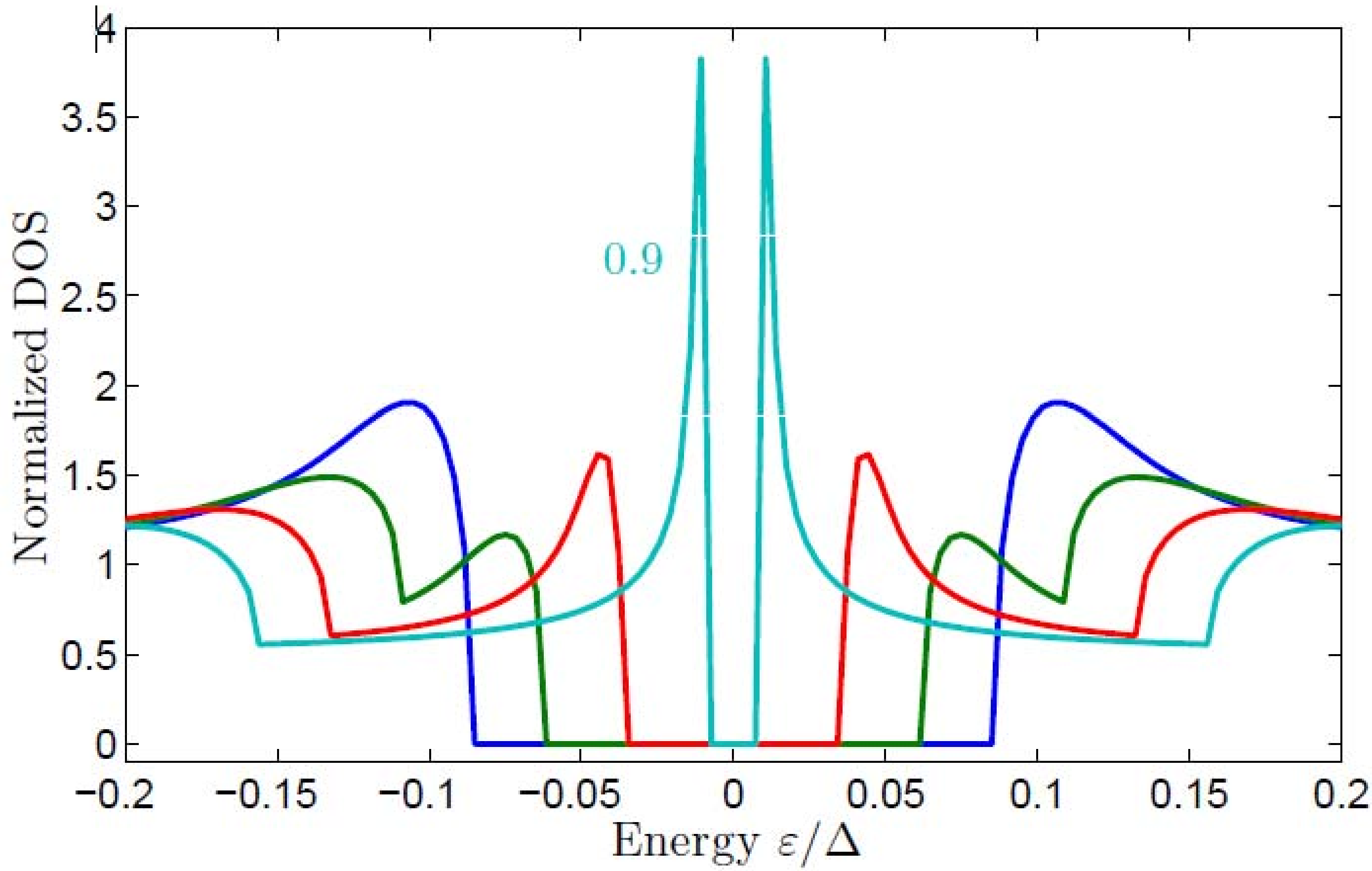


J. Linder, T. Yokoyama, A. Sudbo, and M. Eschrig, PRL 102, 107008 (2009)

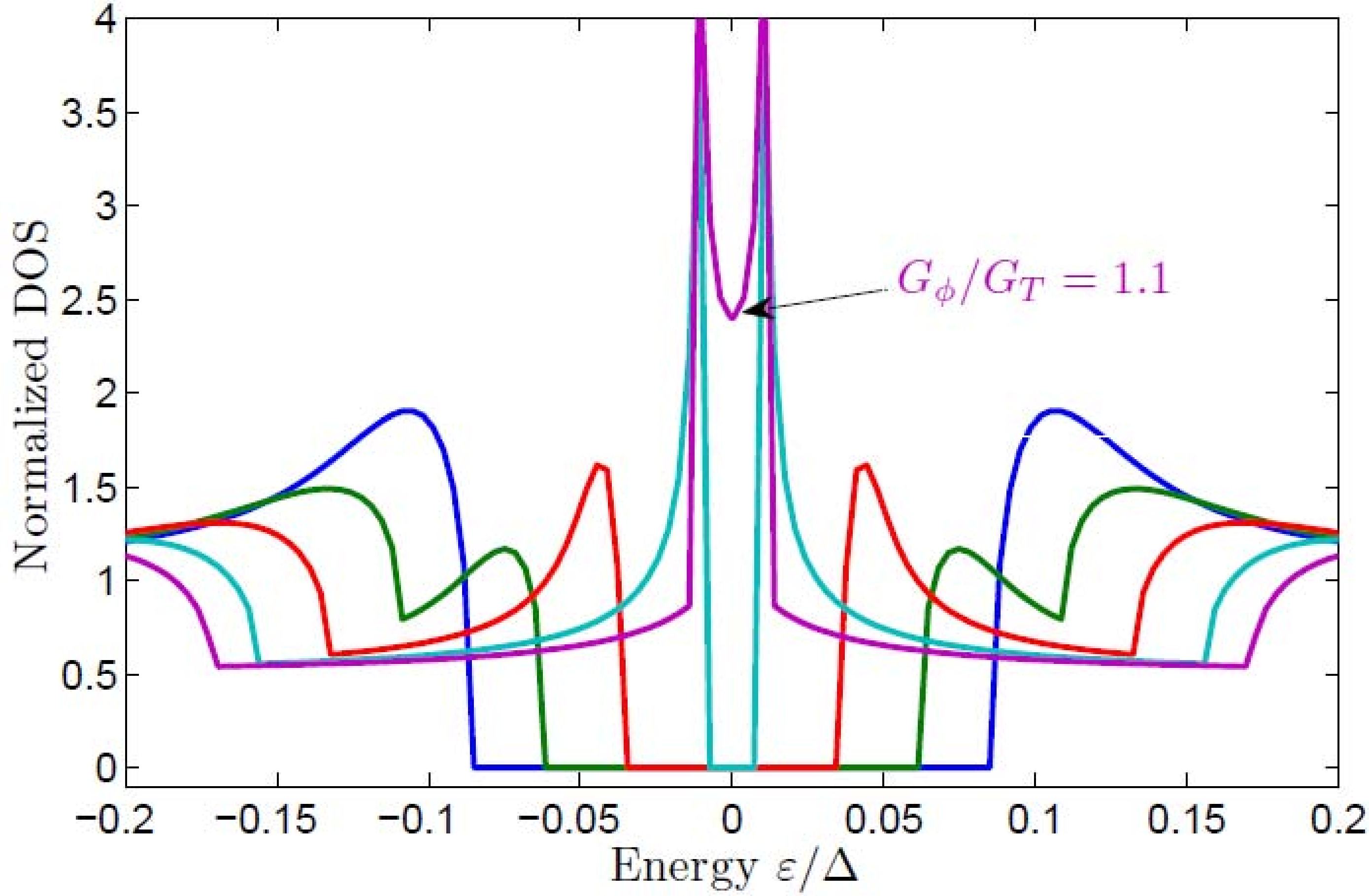
Change of DOS

by spin-active interfaces



J. Linder, T. Yokoyama, A. Sudbo, and M. Eschrig, PRL 102, 107008 (2009)

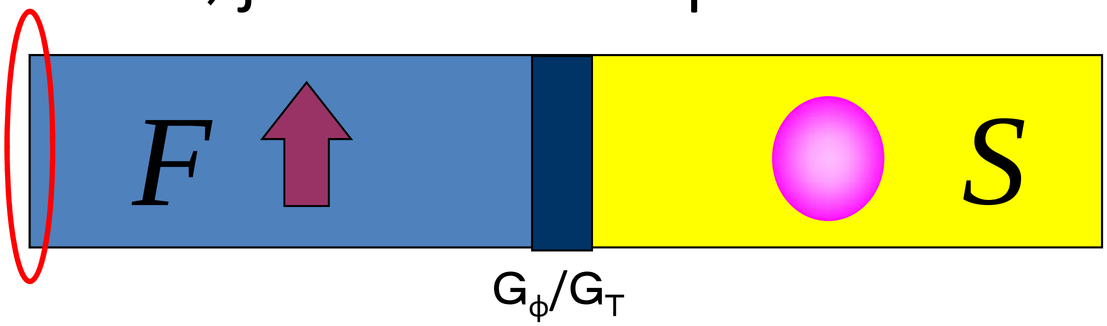
Change of DOS
by spin-active interfaces



J. Linder, T. Yokoyama, A. Sudbo, and M. Eschrig, PRL 102, 107008 (2009)

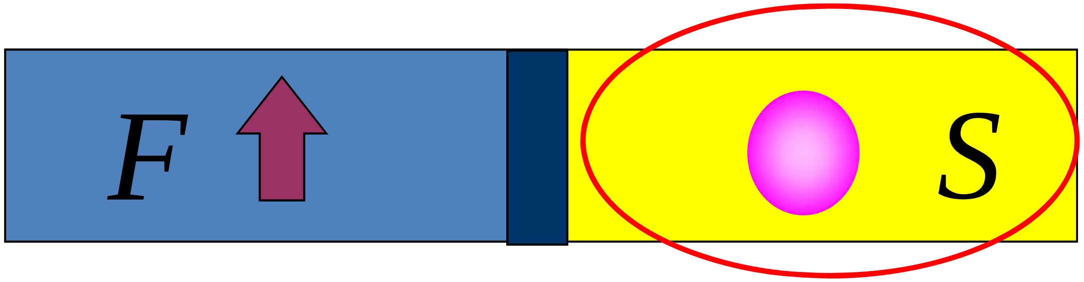
Model

F/S (s-wave) junction with spin-active interfaces



We study a change of the DOS (LDOS) both in the presence the exchange field from Ferromagnet and spin-active interface

Method



Δ: pair potential

The Usadel equation in S (x>d)

$$\theta_S'' + iE\sin\theta_S + \Delta\cos\theta_S = 0$$

Generalized boundary condition at the FS interface

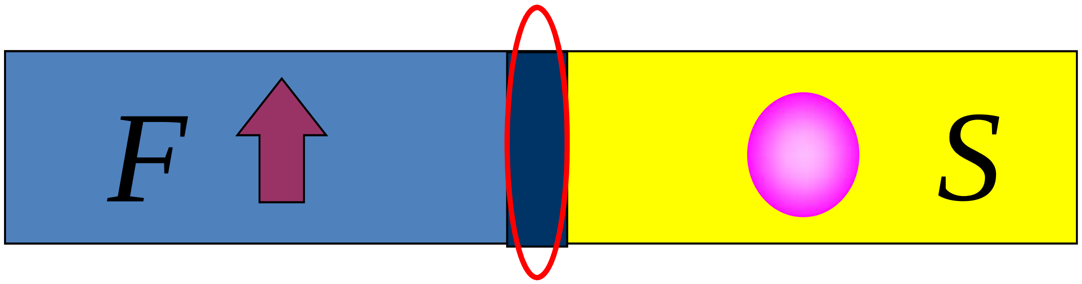
$$\theta_F' = -\frac{1}{\gamma_B}\sin(\theta_F - \theta_S) - i\gamma_\phi\sigma\sin\theta_F$$

F-layer with thickness d locates from x=0 to x=d

The Usadel equation in F

$$\theta_F'' + i(E + \sigma h)\sin\theta_F = 0$$

Method



γ_B : **Normal state interface resistance**

γ_φ : **Spin dependence of interfacial phase shifts**

G_T : **Normal-state tunnel condectance**

G_ϕ : **Spin-dependent phase shifts at the interface**

$$G_\phi / G_T = \gamma_\varphi \gamma_B$$

The Usadel equation in S (x>d)

$$\theta_S'' + iE\sin\theta_S + \Delta\cos\theta_S = 0$$

Generalized boundary condition at the FS interface

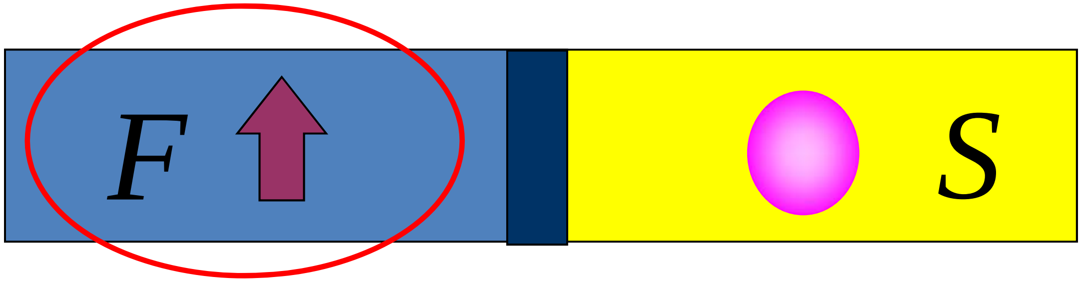
$$\theta_F' = -\frac{1}{\gamma_B}\sin(\theta_F - \theta_S) - i\gamma_\phi \sigma \sin\theta_F$$

F-layer of thickness d occupies the range from x=0 to x=d

The Usadel equation in F

$$\theta_F'' + i(E + \sigma h)\sin\theta_F = 0$$

Method



h : exchange field

The Usadel equation in S (x>d)

$$\theta_S'' + iE\sin\theta_S + \Delta\cos\theta_S = 0$$

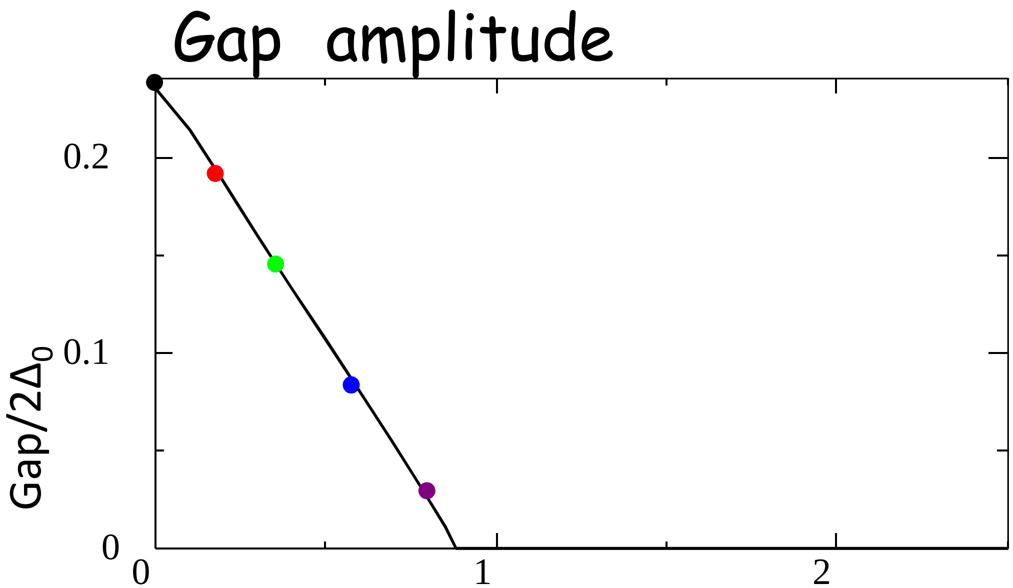
Generalized boundary condition at the FS interface

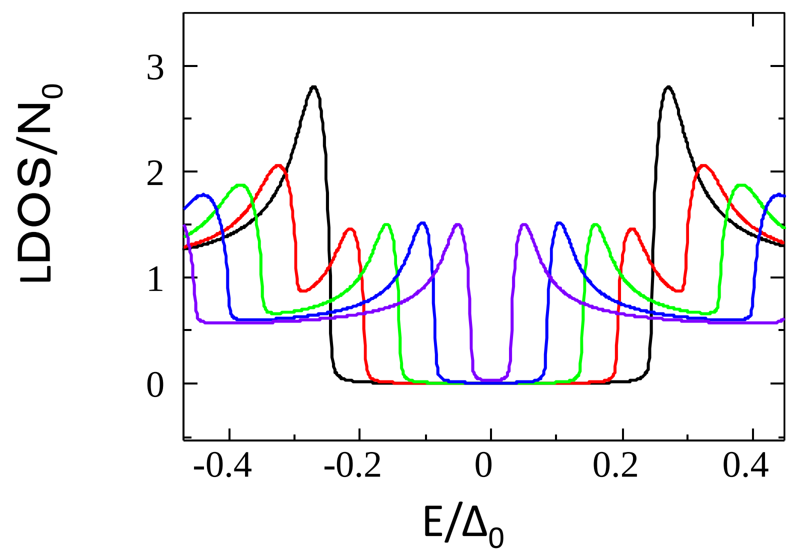
$$\theta_F' = -\frac{1}{\gamma_B}\sin(\theta_F - \theta_S) - i\gamma_\phi \sigma \sin\theta_F$$

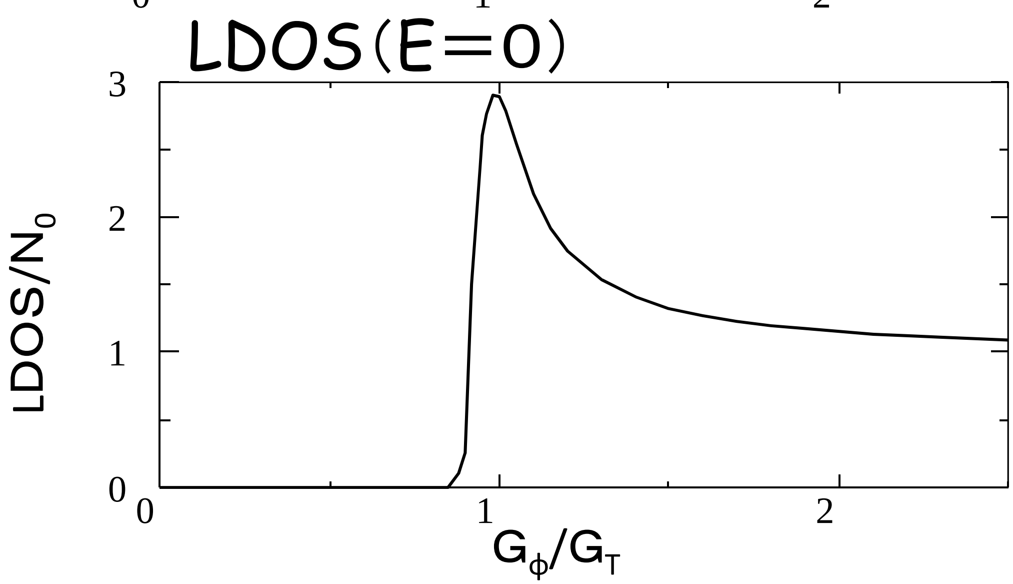
F-layer of thickness d occupies the range from x=0 to x=d
The Usadel equation in F

$$\theta_F'' + i(E + \sigma h)\sin\theta_F = 0$$

The relation between G_φ/G_T and DOS

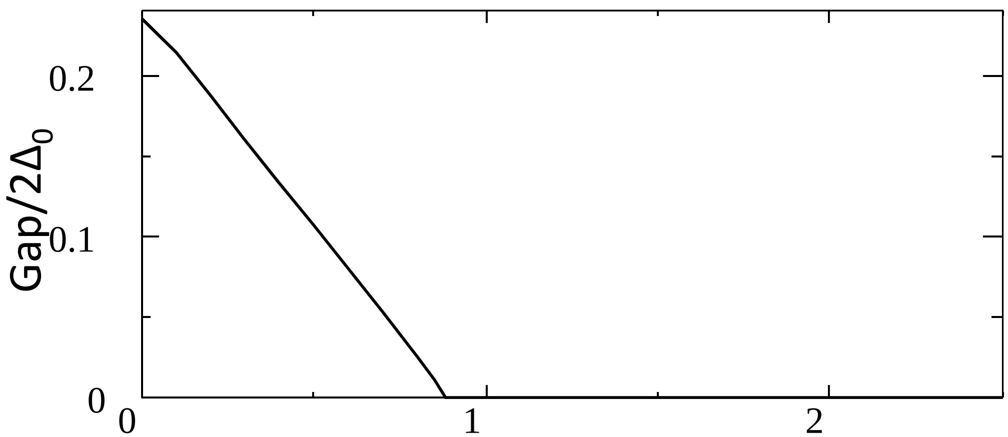




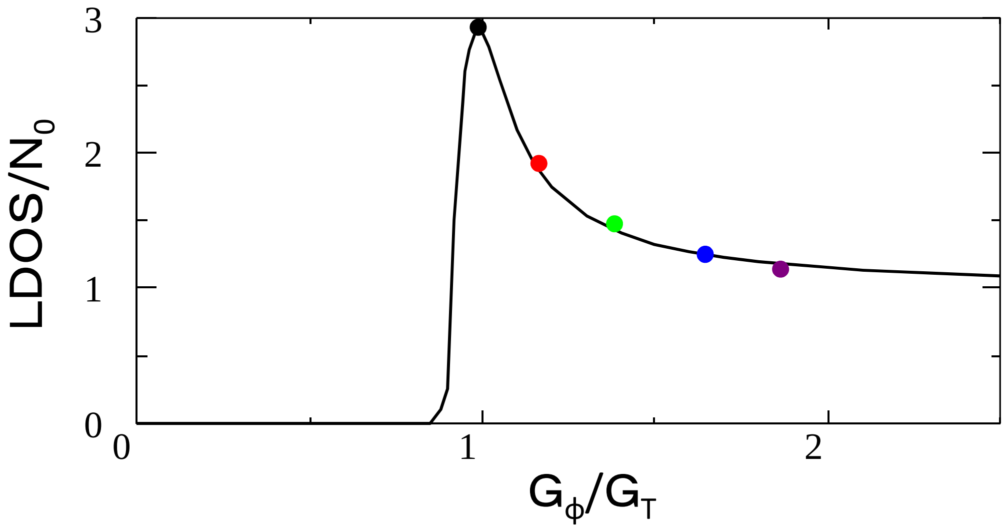


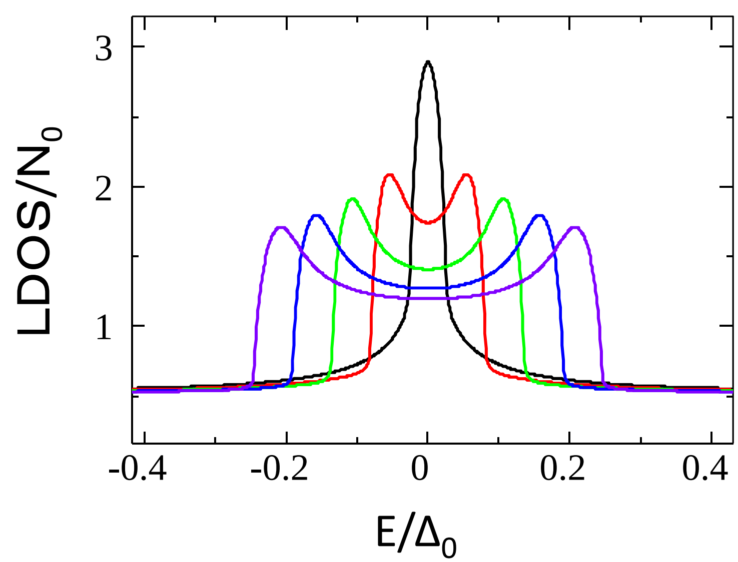
The relation between G_{φ}/G_T and DOS

Gap amplitude

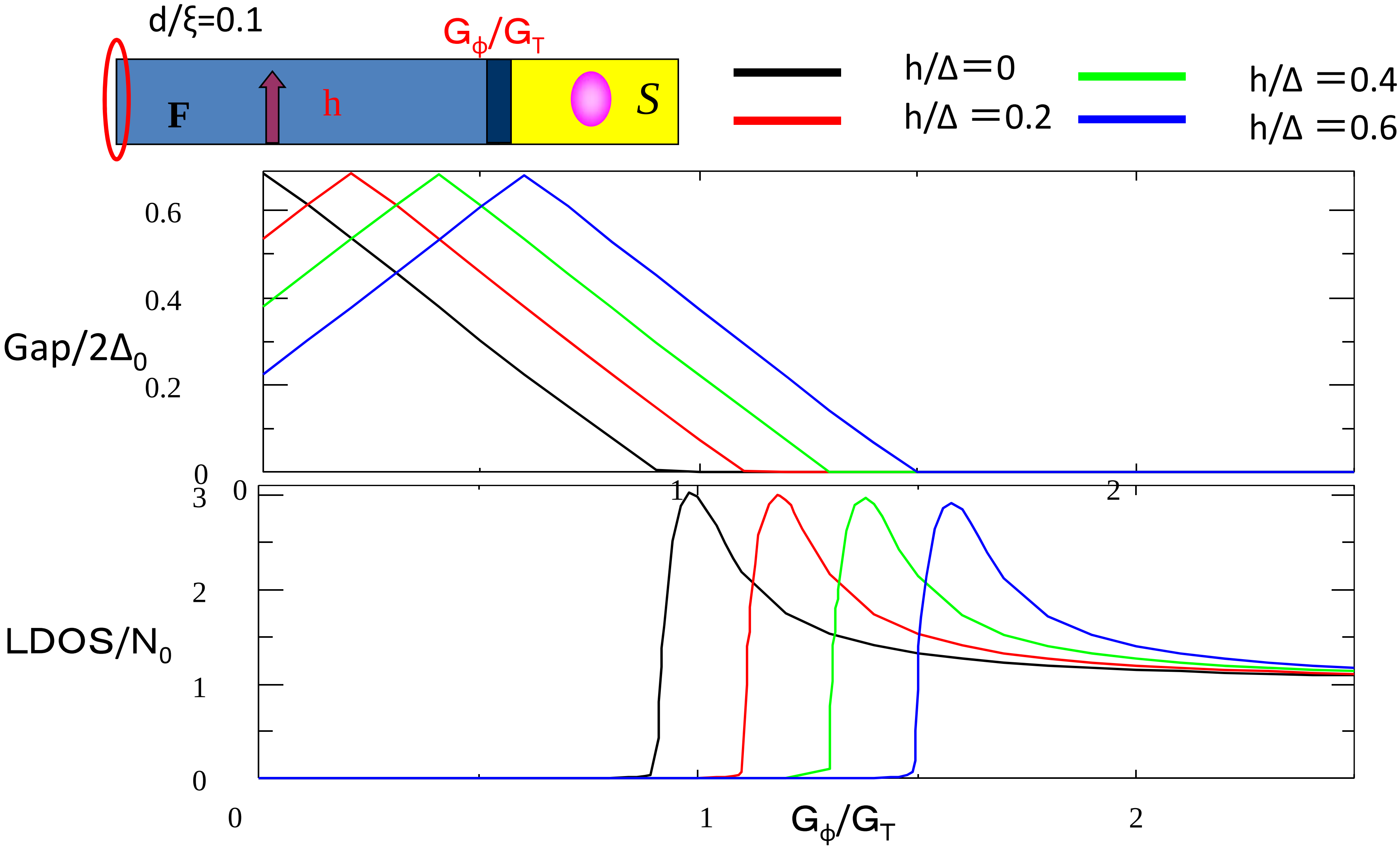


LDOS(E=0)



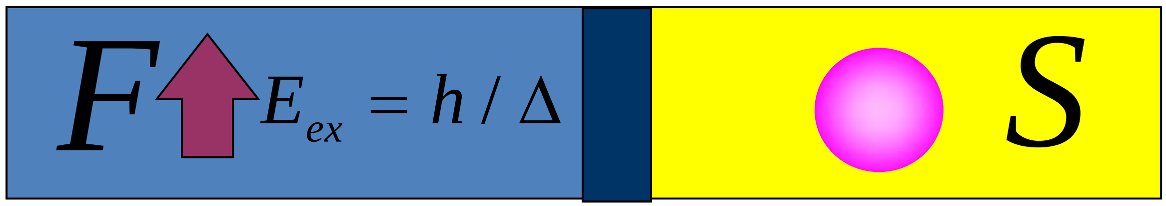


Change of DOS by h and G_φ/G_T (d/ξ＝0.1)



Crossover point from minigap to zero-energy peak

$d_0 = d/\xi$ $\quad$ γ_B : **Normal state interface resistance**



G_φ / G_T

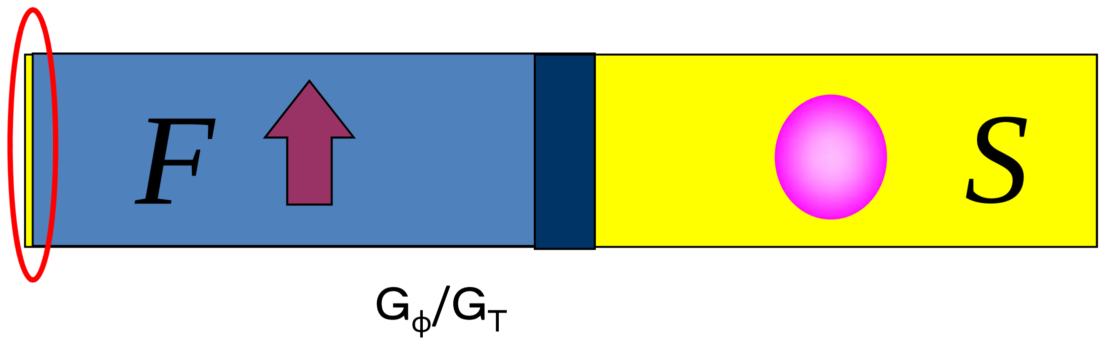
d/ξ<<1 :

$$LDOS(E=0) = \mathrm{Re}\left(\frac{\left| E_{ex}\gamma_B d_0 - G_\phi / G_T \right|}{\sqrt{(E_{ex}\gamma_B d_0 - G_\phi / G_T)^2 - 1}} \right)$$

Crosover point from minigap to zero-energy peak

$$\left| E_{ex}\gamma_B d_0 - G_\phi / G_T \right| \geq 1$$

Summary Part II



- Ferromagnet effect and spin-active interfaces effect

- Ferromagnet effect spin-active interfaces effect ⇒ Spin triplet Odd frequency cooper pair ⇒ LDOS ZEP

- d/ξ<<1 :
  Crossover point from minigap to zero-energy peak (E=0)

$$\left| E_{ex}\gamma_B d - G_\phi / G_T \right| \geq 1$$