Surface Impedance in Spin-triplet Superconducting Proximity Structures

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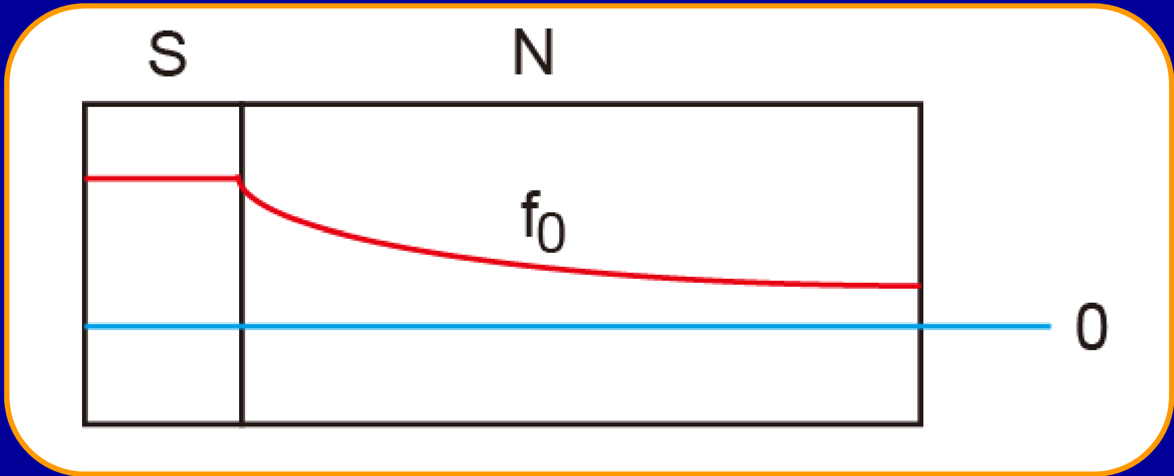
Introduction

Proximity effect



$$f_0 \approx e^{-x/\xi_T}$$

$$\xi_T = \sqrt{\frac{D_0}{4\pi T}}$$

Tunneling spectra of NS
Josephson current in SNS

What happen on N attached to spin-triplet superfluids?

Surface Impedance

Response to electromagnetic field

$$Z = \frac{4\pi}{c}\frac{E}{H} = R + iX$$

reflects various properties of quasiparticle states

R: surface resistance
loss of microwave power due to normal carrier

X: reactance
response of superconducting carriers

Usual electromagnetic property

London's Eq.

$$\boldsymbol{J} = -\frac{c}{4\pi\lambda^2}\boldsymbol{A}$$

$$\lambda^2 = \frac{mc^2}{4\pi n_s e^2}$$

Together with a Maxwell's Eq.

$$\nabla \times \boldsymbol{H} = \frac{4\pi}{c}\boldsymbol{J}$$ (static case)

$$\nabla \times \nabla \times \boldsymbol{H} = -\frac{1}{\lambda^2}\boldsymbol{H} \quad (\boldsymbol{H} = \nabla \times \boldsymbol{A})$$

$$\left(\nabla^2 - \frac{1}{\lambda^2}\right)\boldsymbol{H} = 0$$

Magnetic field usually decays in superconductor.

Unusual electromagnetic property

Expression of λ in linear response theory

$$\boldsymbol{J} = -\frac{c}{4\pi\lambda^2}\boldsymbol{A} \quad \lambda(x)^{-2} = \frac{K}{\xi_N^2(T_c)}\frac{T}{T_c}\sum_{\omega_n>0} F_{\omega_n}^2(x)$$

Belzig, Bruder, Schon, PRB 53, 5727(96)

F: anomalous part of Usadel Green function

even-freq. proximity
F is real number

$$\lambda^2 > 0$$

$$\left(\nabla^2 - \frac{1}{\lambda^2}\right)\boldsymbol{H} = 0$$

decay of H

odd-freq. proximity
F is pure imaginary

$$\lambda^2 < 0$$

$$\left(\nabla^2 + \frac{1}{|\lambda^2|}\right)\boldsymbol{H} = 0$$

oscillations of H

Phenomenological theory

$$\boldsymbol{j} = \boldsymbol{j}_n + \boldsymbol{j}_s = (\sigma_1 - i\sigma_2)\boldsymbol{E} \qquad \omega \sim 10\mathrm{GHz}$$

$$\sigma_1 = \sigma_0 \frac{n_n}{n}$$

for $\omega\tau \ll 1$

$$\sigma_2 = \sigma_0 \omega\tau \frac{n_n}{n} + \frac{c^2}{4\pi\lambda_L^2\omega}$$

$$R + iX = \left[\frac{4\pi i\omega}{c^2(\sigma_1 - i\sigma_2)}\right]^{1/2}$$

$$\sigma_0 = \frac{ne^2\tau}{m}$$

Drude conductivity
in normal state

$$\frac{c^2}{4\pi\lambda_L^2\omega} = \sigma_0 \frac{n_s}{n}\frac{1}{\omega\tau}$$

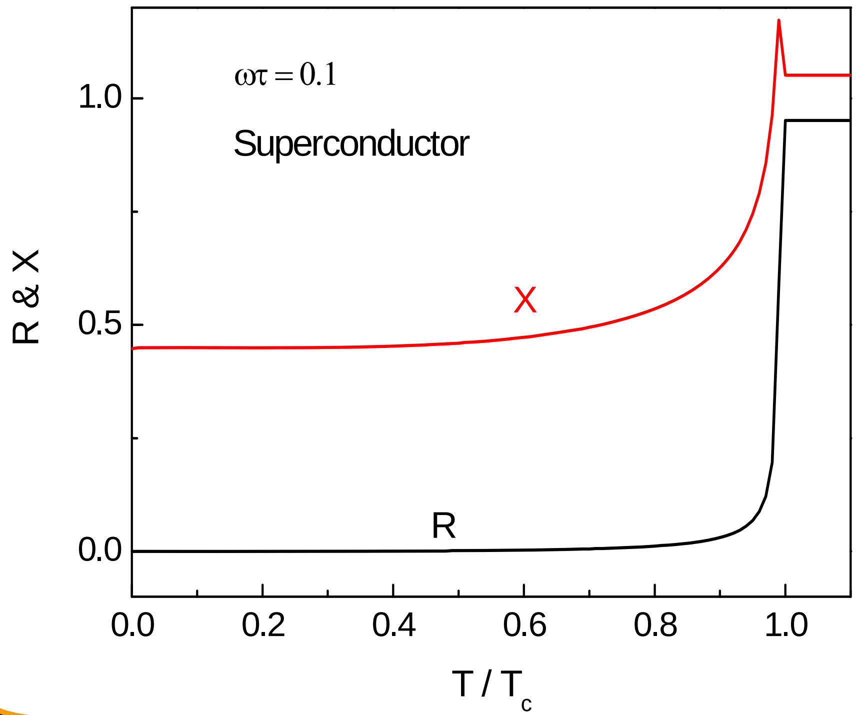
$$n = n_n + n_s$$

A simple relation

$T < T_c \qquad R < X$

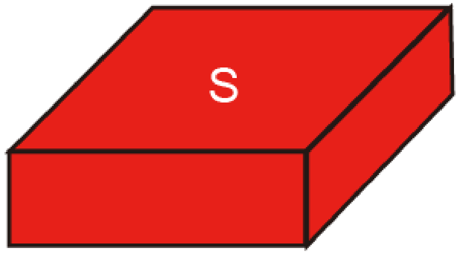
$T \geq T_c \qquad R \approx X$

Theoretical Results



$$n_s = n \frac{\Delta(T)}{\Delta(0)}$$

$$n_n = n - n_s$$

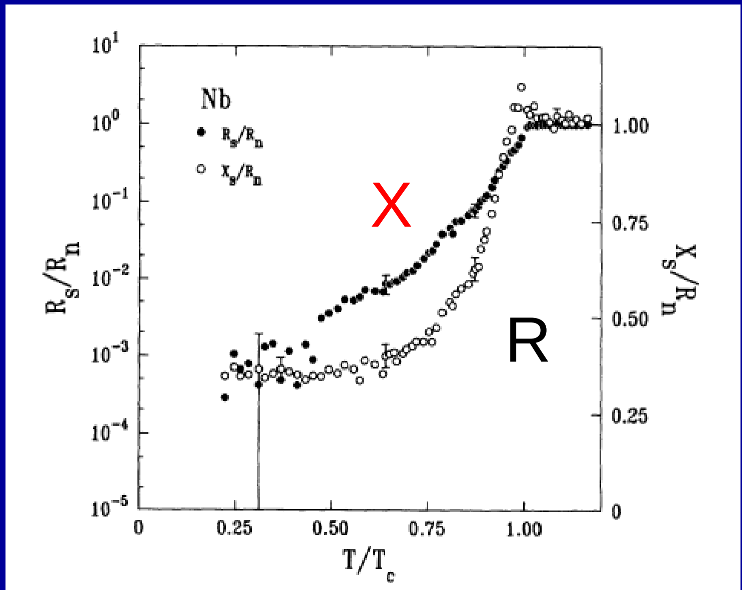


A simple relation

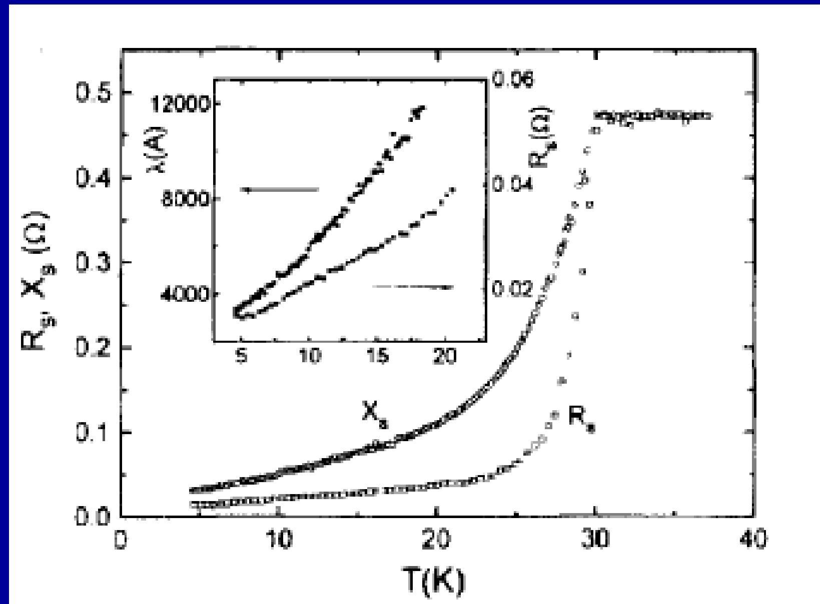
$T < T_c \qquad R < X$

Experimental results

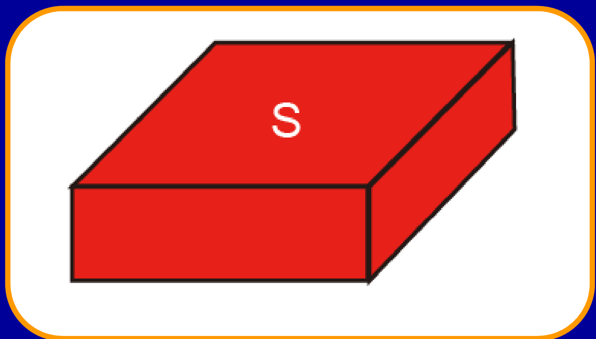
Nb | **YBCO**



Klein, Nicol, Holczer, Gruner,
PRB 50, 6307(94)

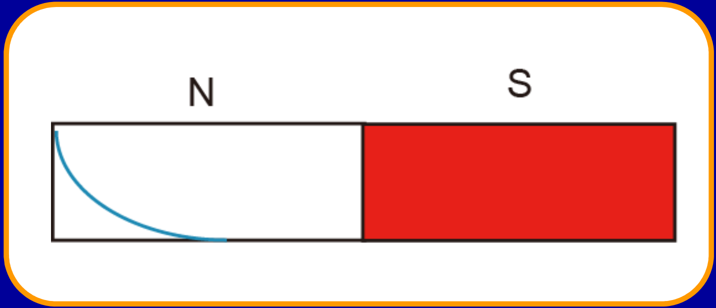


Trunin, Zhukov, Emel'chenko, Naumenko
JETP Lett, 64, 832 (97)

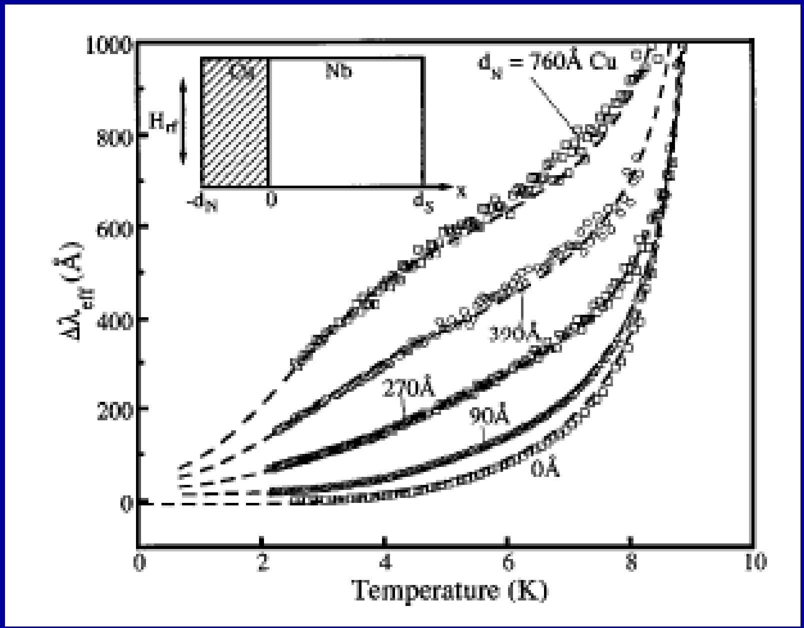


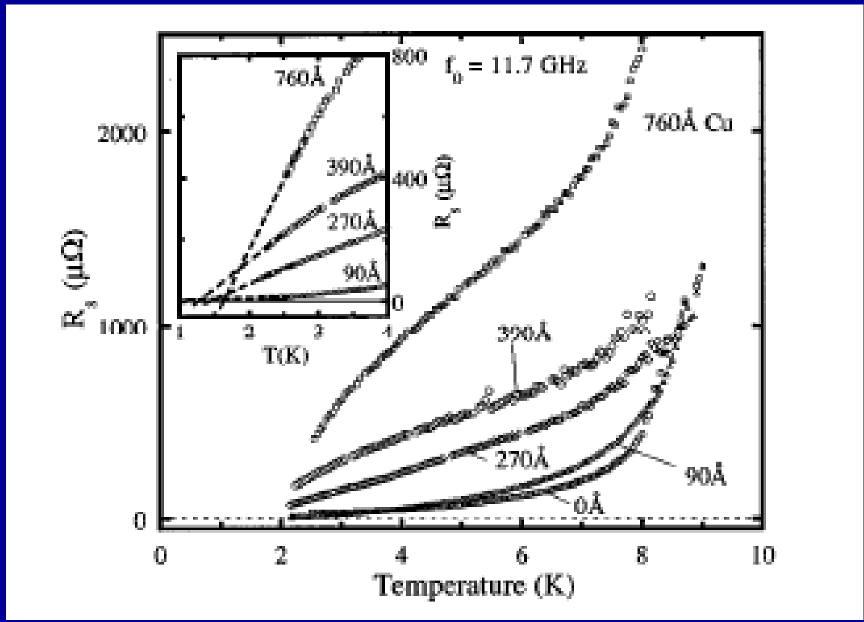
$$R < X$$

Normal proximity effect



$$R < X$$

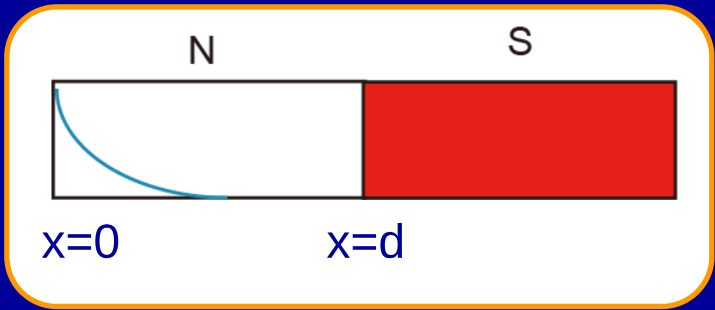




Pambianchi, Chen, Anlage, PRB 54, 3508(96)

Proximity structures

Strategy



Maxwell's Eqs.

$$E = \frac{\partial_x H}{\sigma}$$

$$H = -i\frac{c}{\omega}\partial_x E$$

For $0 < x < d$

$$\boldsymbol{H} = \boldsymbol{y}(H_1 e^{ik_n x} + H_2 e^{-ik_n x})e^{i\omega t}$$

$$\boldsymbol{E} = \boldsymbol{z}(E_1 e^{ik_n x} + E_2 e^{-ik_n x})e^{i\omega t}$$

For $d < x$

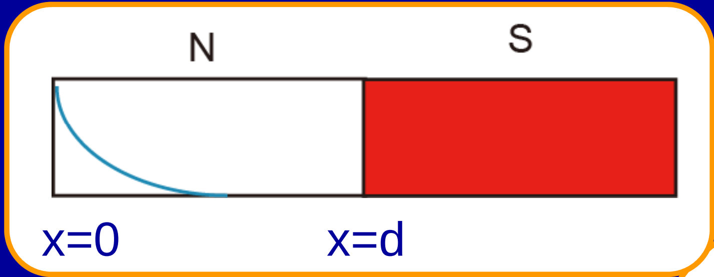
$$\boldsymbol{H} = \boldsymbol{y} H_s e^{-ik_s x} e^{i\omega t}$$

$$\boldsymbol{E} = \boldsymbol{z} E_s e^{-ik_s x} e^{i\omega t}$$

Continuity of electromagnetic field

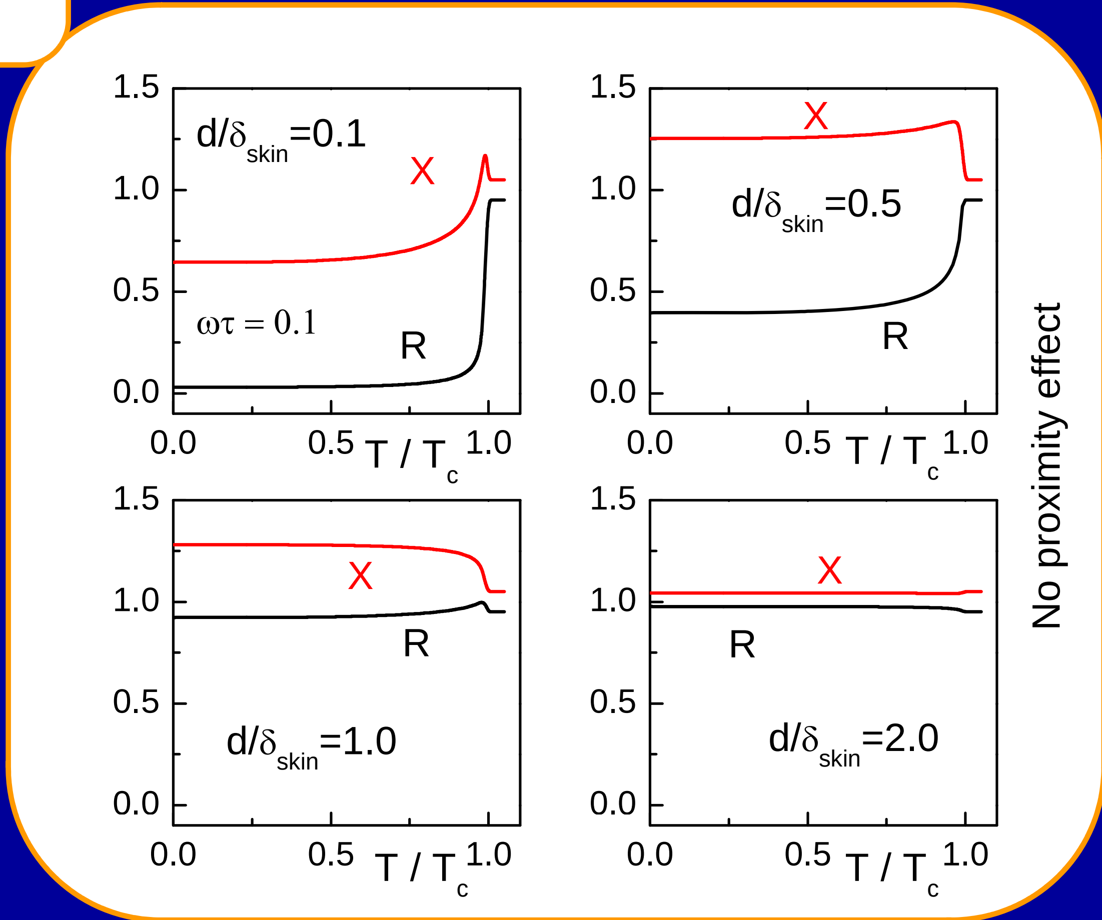
$$Z_{NS} = Z_N \frac{Z_S \cos(k_n d) + iZ_N \sin(k_n d)}{Z_N \cos(k_n d) + iZ_S \sin(k_n d)}$$

I : zero proximity effect



$n_s = 0$ in N

$R < X$

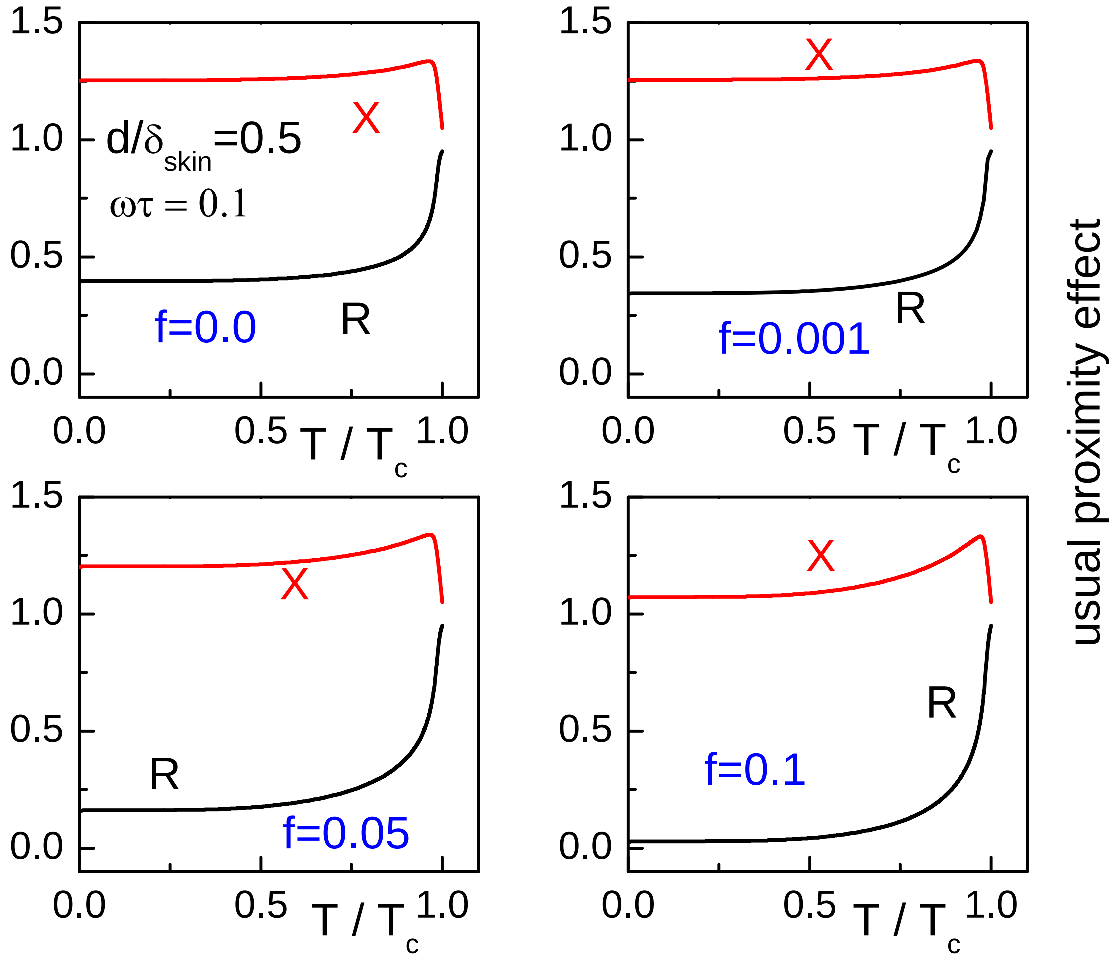


II : usual proximity effect

f: strength of proximity effect

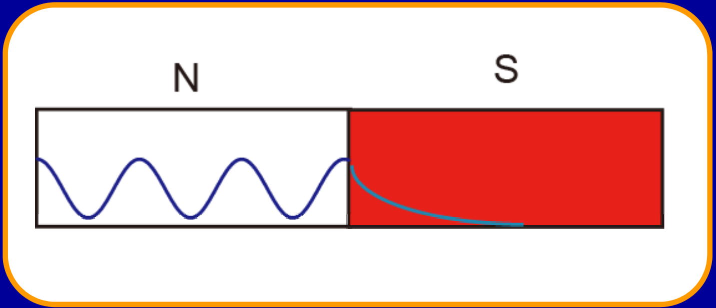
$$n_s = f\, n \frac{\Delta(T)}{\Delta(0)}$$

$$R < X$$



Anomalous proximity effect

Spin-triplet p-wave



Tanaka, Asano, Golubov, Kashiwaya,
PRB 72, 140503R (05);
PRB 73, 059901 (E) (06).

$\lambda^2 < 0$ due to odd-frequency

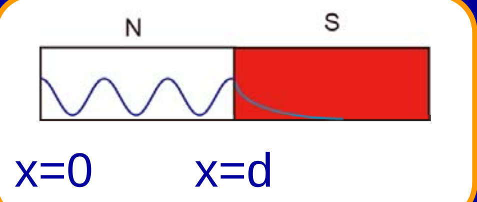
$$\sigma_1 = \frac{n_n e^2 \tau}{m}$$

$$\sigma_2 = \frac{n_n e^2 \tau}{m} \omega\tau + \frac{c^2}{4\pi\lambda_L^2 \omega}$$

$$\frac{c^2}{4\pi\lambda_L^2 \omega} = \sigma_0 \frac{n_s}{n} \frac{1}{\omega\tau}$$

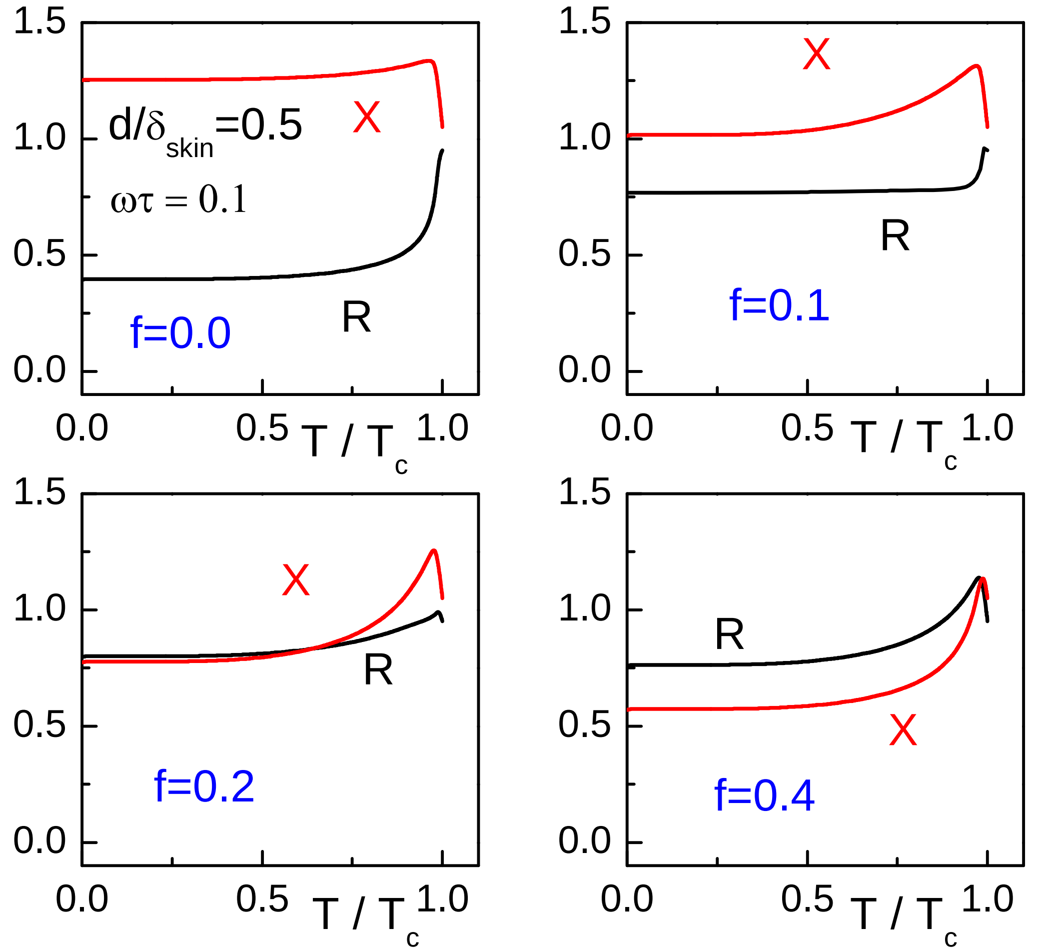
negative density

III : anomalous proximity effect



$$n_s = -f\,n\frac{\Delta(T)}{\Delta(0)}$$

$$\boxed{R > X}$$



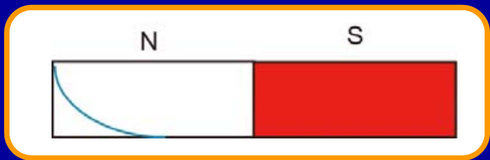
Summary

surface impedance in NS proximity structures

$$Z = R + iX$$

A phenomenological theory indicates

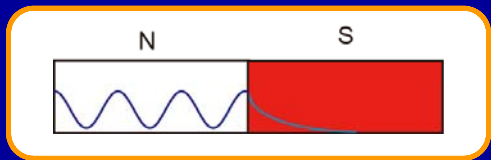
spin-singlet



even freq. pairs

$$R < X$$

spin-triplet



odd freq. pairs

$$R > X$$: unusual relation

Beyond the phenomenological theory….

Mattice & Bardeen, Phys. Rev. 111, 412(1958)
Nam, Phys. Rev. 156, 470(67); 156, 487(1967)
Abrikosov, Gor'kov, Dzyaloshinskii, Text (1962)
Trunin and Golubov, (2003)

Unusual Impedance

$$\sigma_1 = \frac{n_n e^2 \tau}{m}$$

$$\sigma_2 = \frac{n_s e^2}{m\omega} = \frac{1}{\mu_0 \omega \lambda^2}$$

$$R + iX = \left[\frac{i\omega\mu_0}{\sigma_1 - i\sigma_2} \right]^{1/2}$$

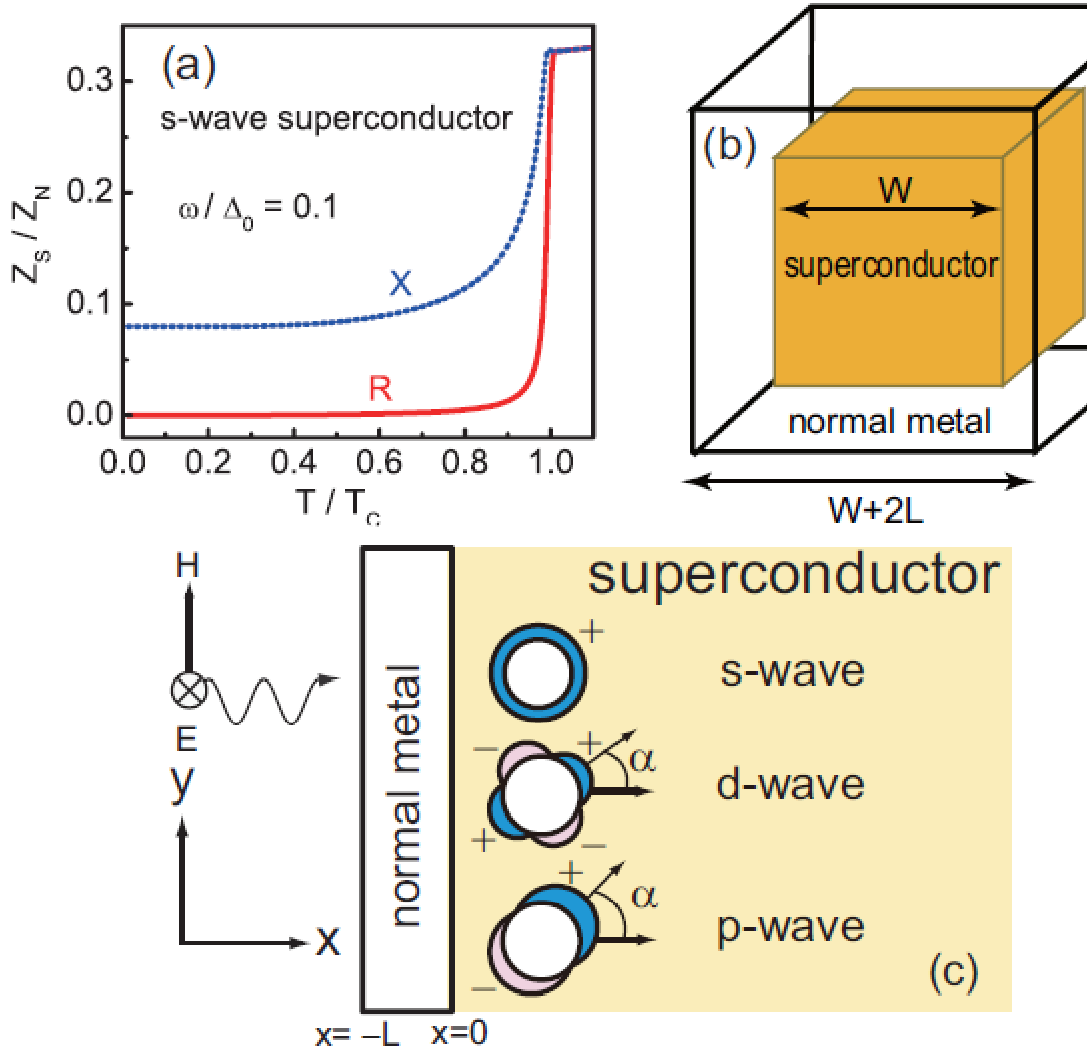
In singlet proximity structures(even freq. pair)

$\lambda^2 > 0$ $\qquad$ $R < X$

In triplet proximity structures(odd freq. pair)

$\lambda^2 < 0$ $\quad \sigma_2$ changes its sign!

$R > X$


(a)
s-wave superconductor
ω / Δ0 = 0.1
X
R
Zs / ZN
T / Tc
0.0
0.1
0.2
0.3
0.0
0.2
0.4
0.6
0.8
1.0
(b)
W
superconductor
normal metal
W+2L
superconductor
H
E
y
x
normal metal
s-wave
d-wave
p-wave
α
(c)
x= –L
x=0

Formalism :

$$\left.\frac{\partial \theta(x,\epsilon)}{\partial x}\right|_{x=0} = \frac{1}{L}\frac{R_D}{R_B}\frac{\langle F\rangle}{T_B},$$

$$\langle F\rangle = \int_{-\pi/2}^{\pi/2} d\gamma \frac{T_N \cos\gamma (f_s\cos\theta_0 - g_s \sin\theta_0)}{(2-T_N) + T_N(g_s\cos\theta_0 + f_s\sin\theta_0)},$$

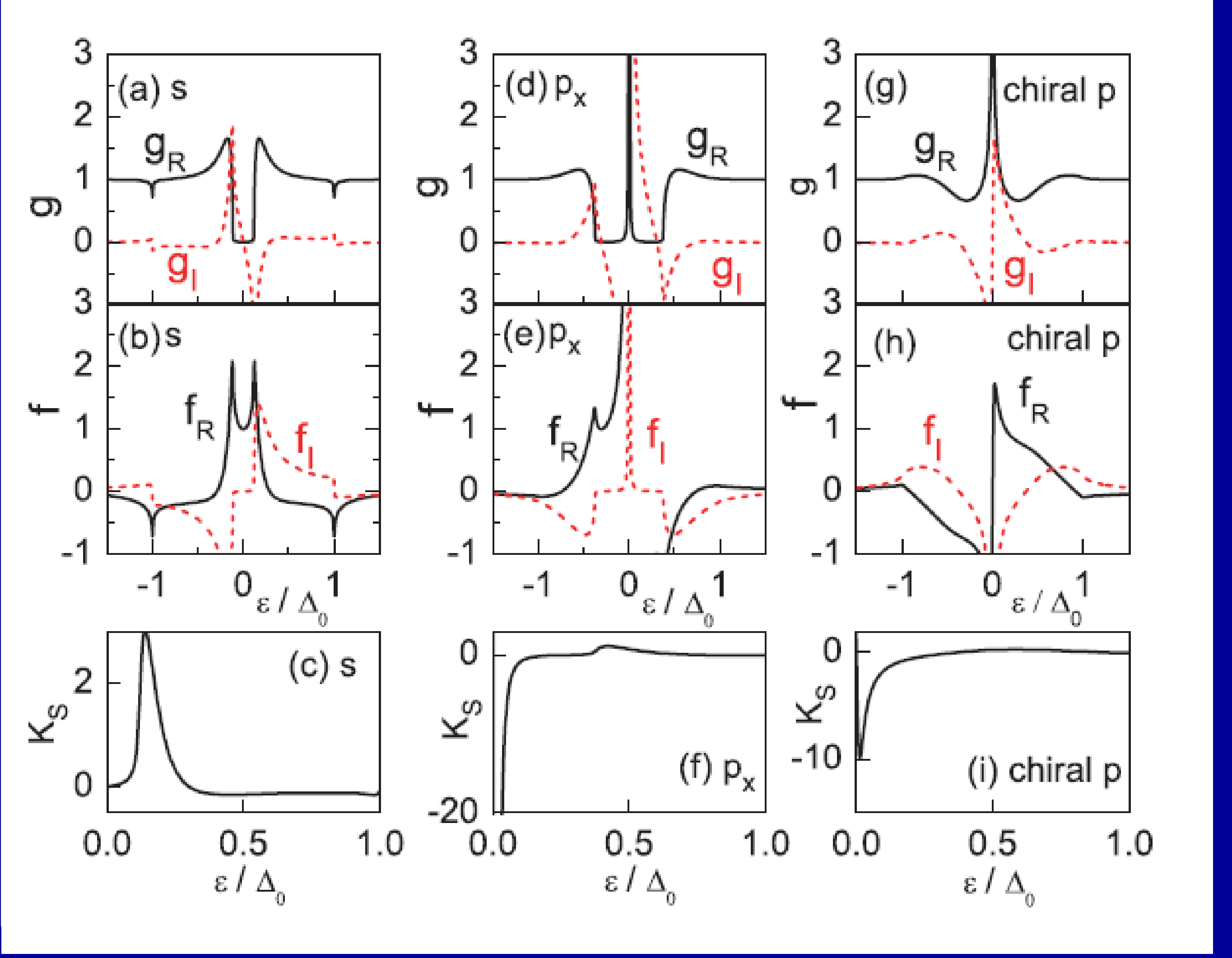
$$\begin{aligned}
\sigma_{\rm NS}(\omega) =& \sigma_1 + i\sigma_2,\\
\frac{\sigma_1}{\sigma_0} =& \frac{1}{2\omega}\int_{-\infty}^{\infty} d\epsilon\,[J(\epsilon+\omega) - J(\epsilon)]\,K_1,\\
\frac{\sigma_2}{\sigma_0} =& \frac{1}{2\omega}\int_{-\infty}^{\infty} d\epsilon\,[J(\epsilon+\omega)K_2 + J(\epsilon)K_3]\,,\\
K_1 =& f_I(\epsilon)f_I(\epsilon+\omega) + g_R(\epsilon)g_R(\epsilon+\omega),\\
K_2 =& f_R(\epsilon)f_I(\epsilon+\omega) - g_I(\epsilon)g_R(\epsilon+\omega),\\
K_3 =& f_R(\epsilon+\omega)f_I(\epsilon) - g_I(\epsilon+\omega)g_R(\epsilon),
\end{aligned}$$

with $J(\epsilon) = \tanh(\epsilon/2T)$ and

$$\begin{aligned}
g_R(\epsilon) =& \mathrm{Re}\,[g(\epsilon)]\,, \quad g_I(\epsilon) = \mathrm{Im}\,[g(\epsilon)]\,,\\
f_R(\epsilon) =& \mathrm{Re}\,[f(\epsilon)]\,, \quad f_I(\epsilon) = \mathrm{Im}\,[f(\epsilon)]\,.
\end{aligned}$$

$$Z_{\rm NS}(\omega) = R - iX = -i\sqrt{\frac{2i\omega}{\Delta_0}\frac{\sigma_0}{\sigma_{\rm NS}(\omega)}}Z_{\rm N},$$

The results of calculations: Green functions



The results of calculations: impedance