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スーパークリーン 箱根

Surface Impedance in Spin-triplet Superconducting Proximity Structures

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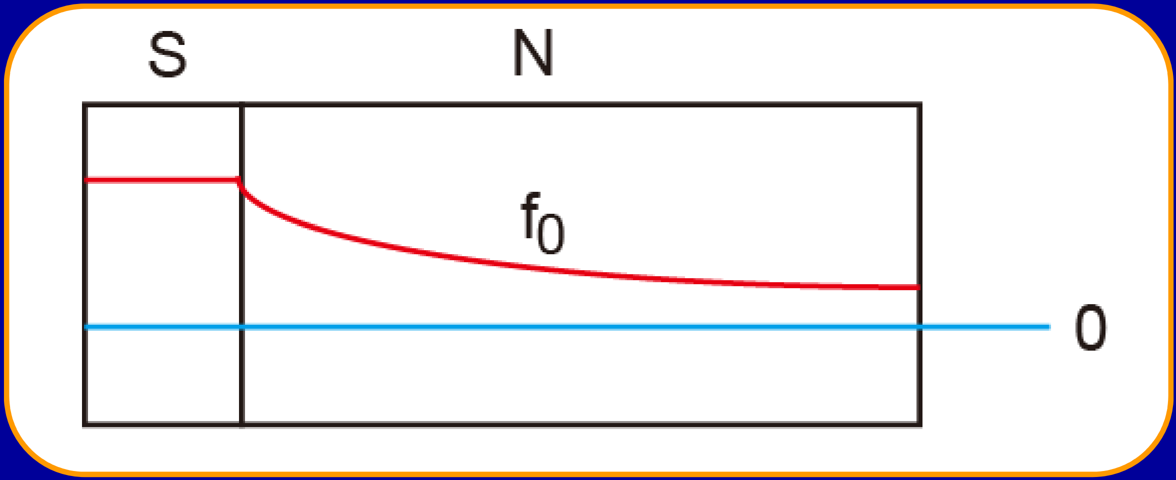
Introduction

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

Phenomenological theory

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

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

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

A simple relation

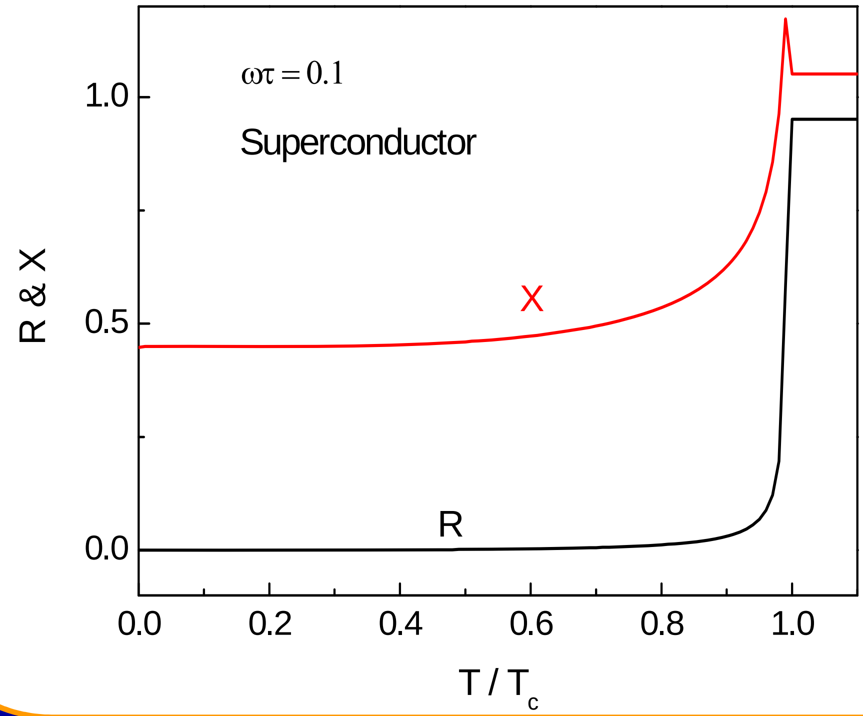
$T < T_c$ $\quad R < X$

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

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

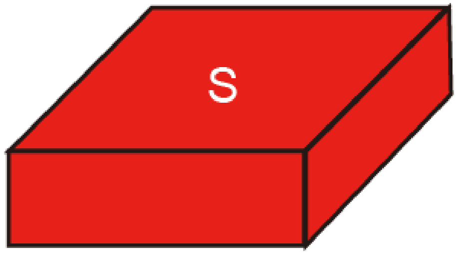
$$n = n_n + n_s$$

Theoretical Results



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

$$n_n = n - n_s$$

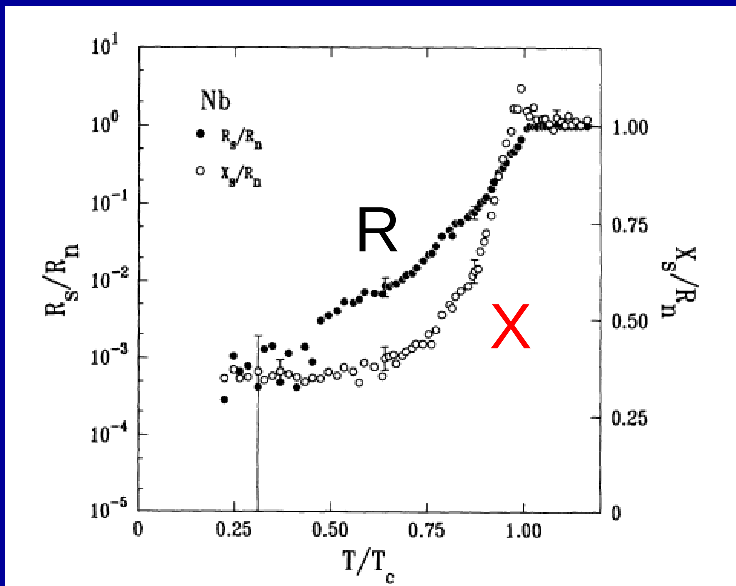


A simple relation

$T < T_c \qquad R < X$

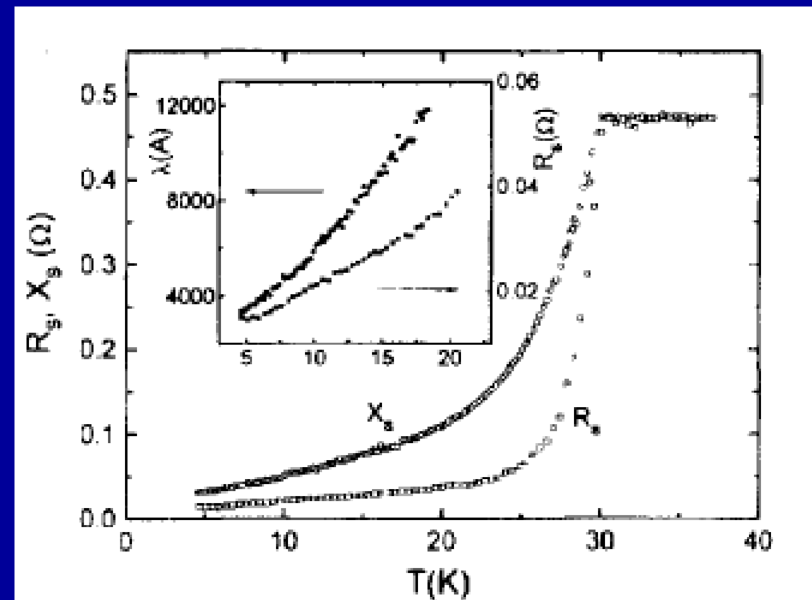
Experimental results

Nb

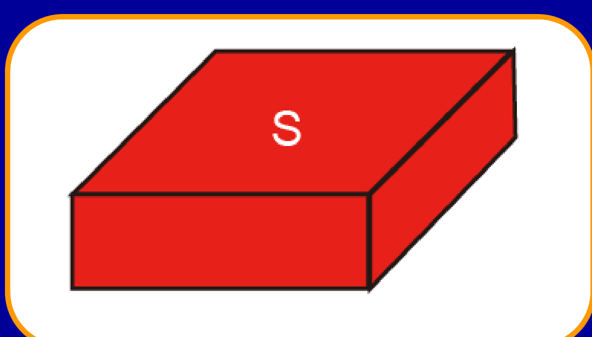


Klein, Nicol, Holczer, Gruner,
PRB 50, 6307(94)

YBCO

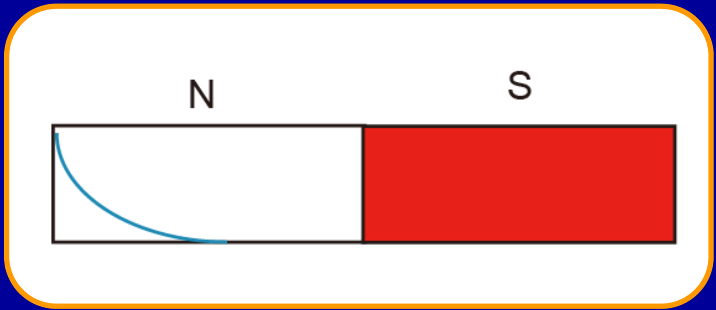


Trunin, Zhukov, Emel'chenko, Naumenko
JETP Lett, 64, 832 (97)



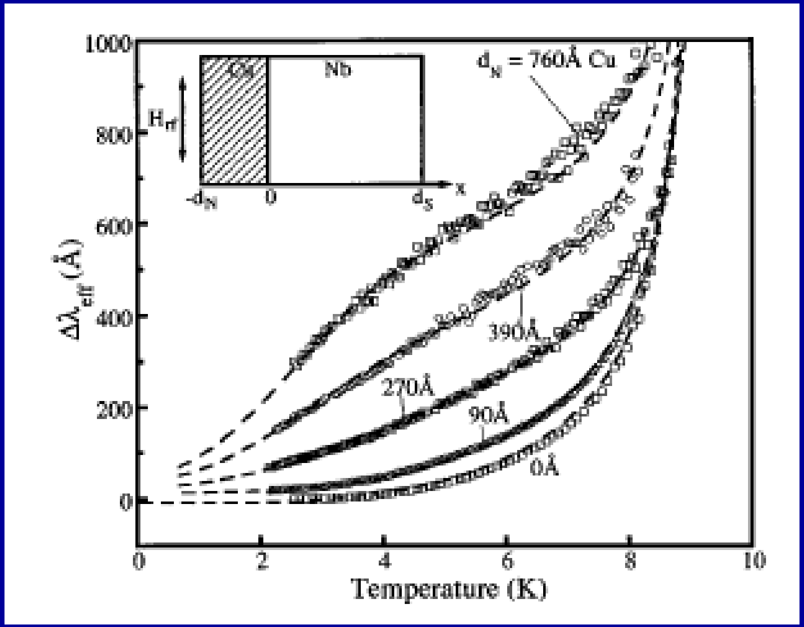
$$R < X$$

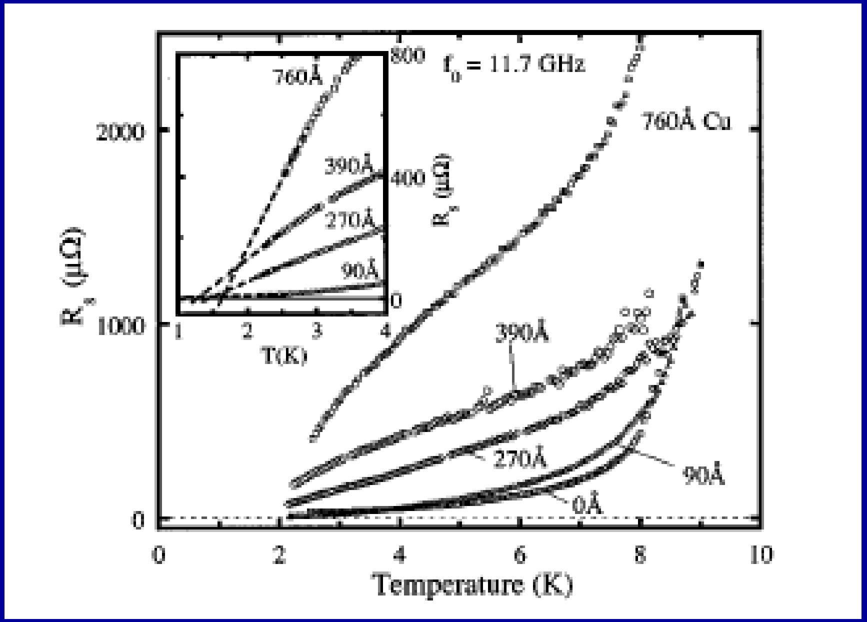
Normal proximity effect



$R < X$?

Maybe!

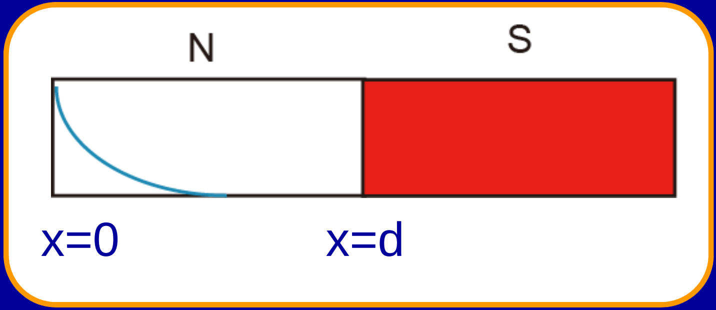




Pambianchi, Chen, Anlage, PRB 54, 3508(96)

Proximity structures

Strategy



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 $d < x$

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

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

Maxwell's Eqs.

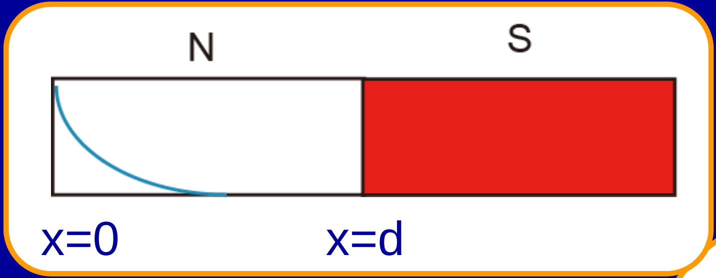
$$E = \frac{\partial_x H}{\sigma}$$

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

Continuity of electromagnetic field

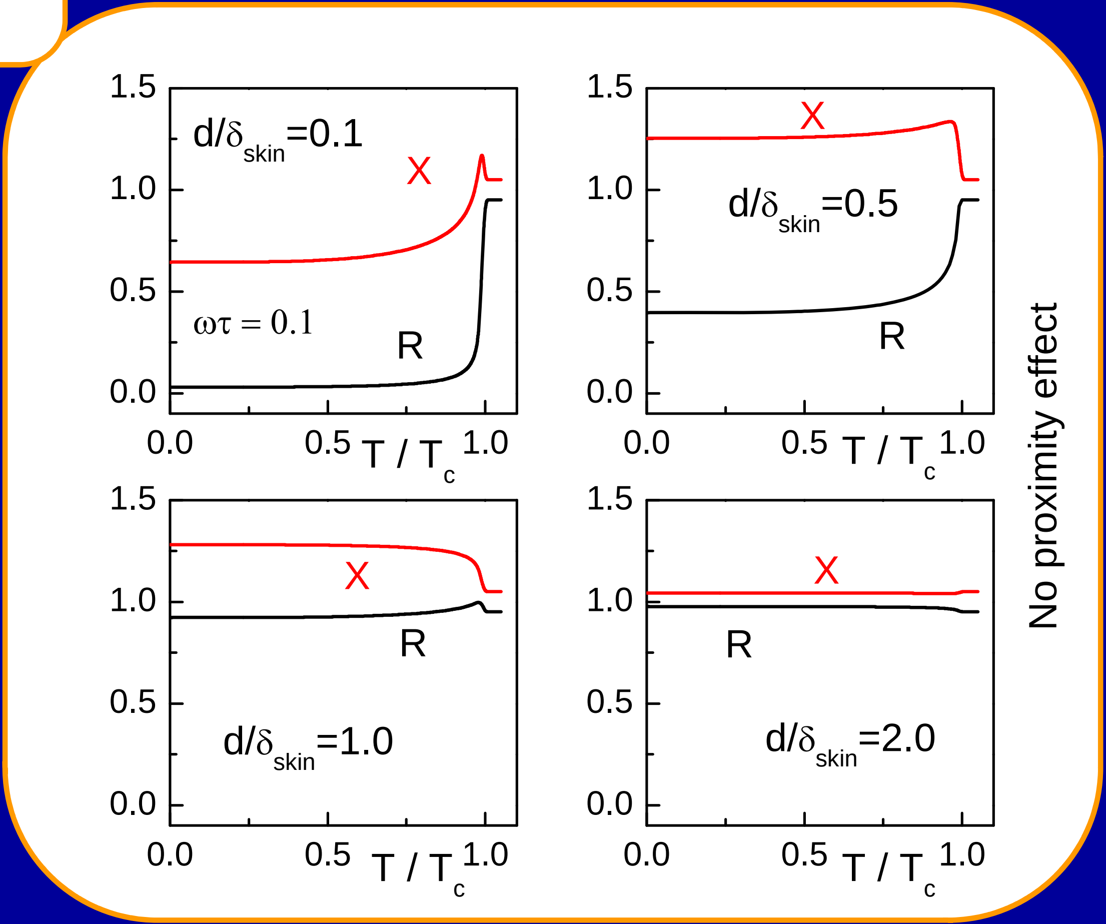
$$Z_{NS} = Z_N \frac{Z_S \cos(k_n d) + i Z_N \sin(k_n d)}{Z_N \cos(k_n d) + i Z_S \sin(k_n d)}$$

I : zero proximity effect

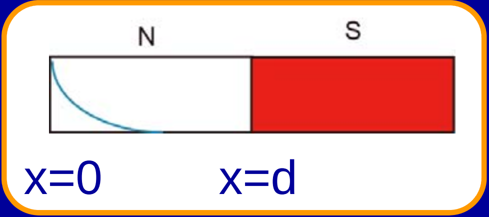


$n_s = 0$ in N

$R < X$



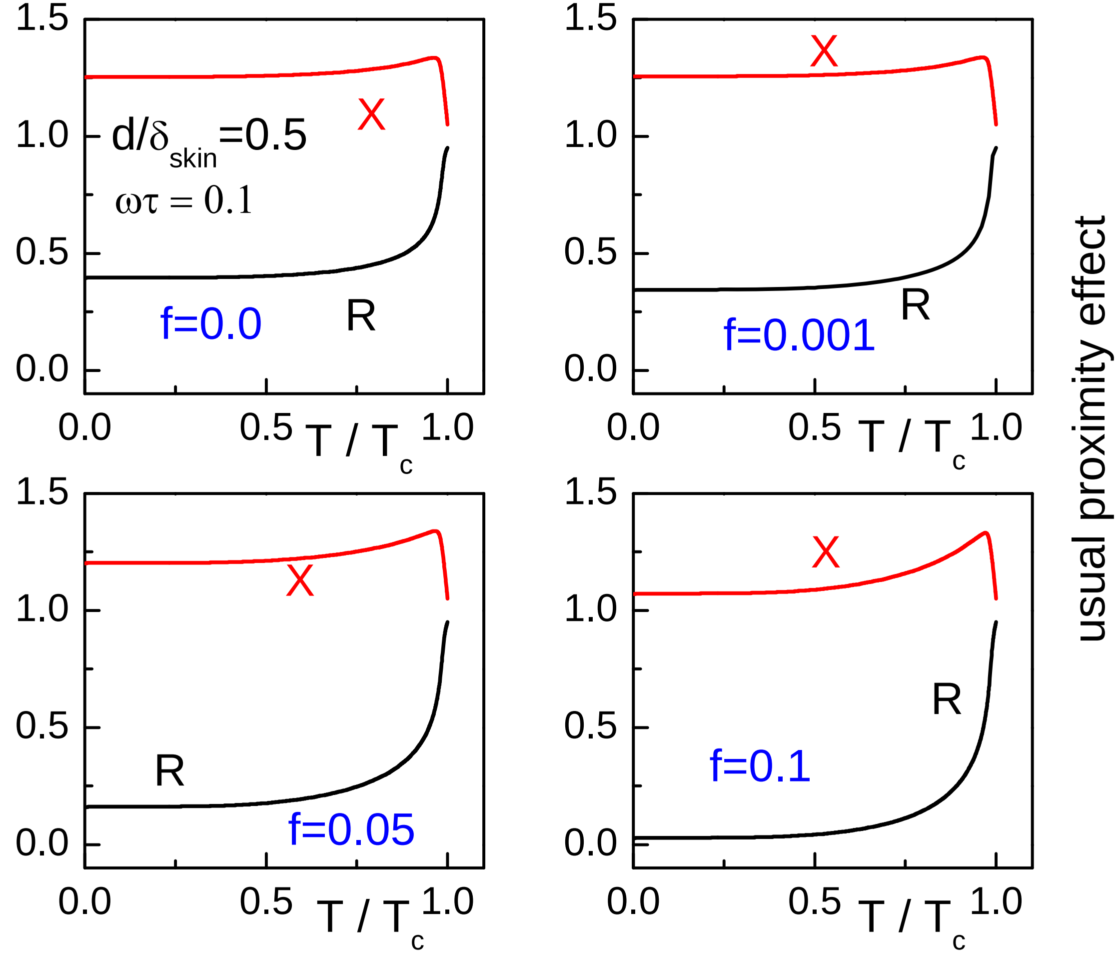
II : usual proximity effect



f: strength of proximity effect

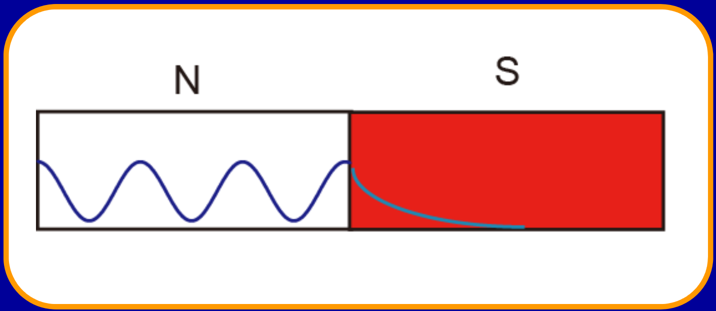
$$n_s = f\, n \frac{\Delta(T)}{\Delta(0)}$$

$$R < X$$



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

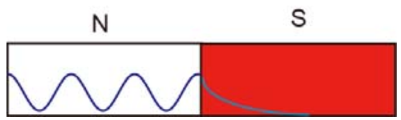
$$\sigma_1 = \frac{n_n e^2 \tau}{m}$$

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

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

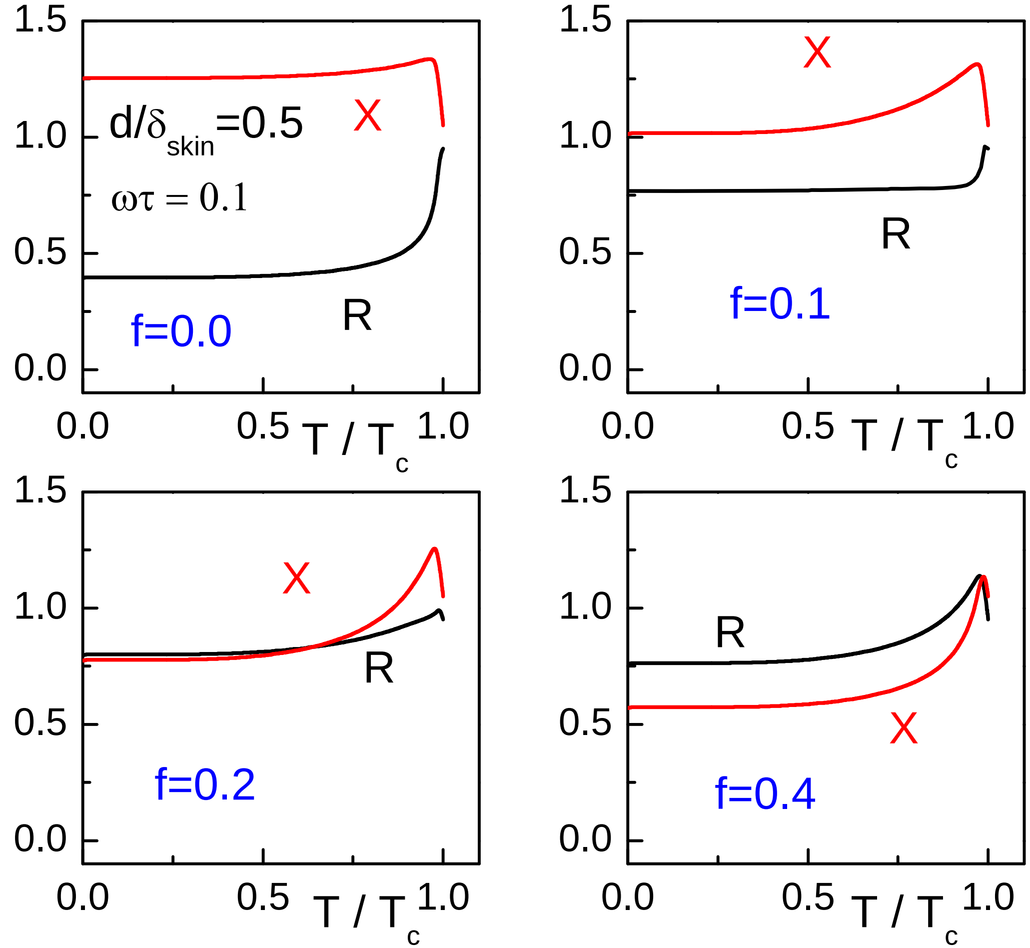
negative density

III : anomalous proximity effect



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

$$R > X$$



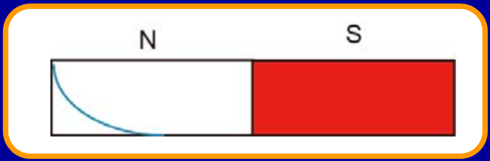
Summary

surface impedance in NS proximity structures

$$Z = R + iX$$

A phenomenological theory indicates

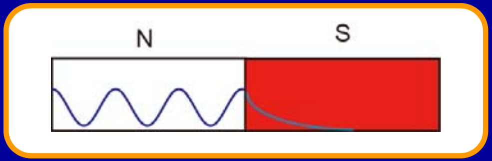
spin-singlet



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)