Anomalous Proximity Effect in Triplet Superconductor Junctions

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2005　12/15 「スーパークリーン物質で実現する新しい量子相の物理」

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- T. Yokoyama Nagoya University

Contents of this talk

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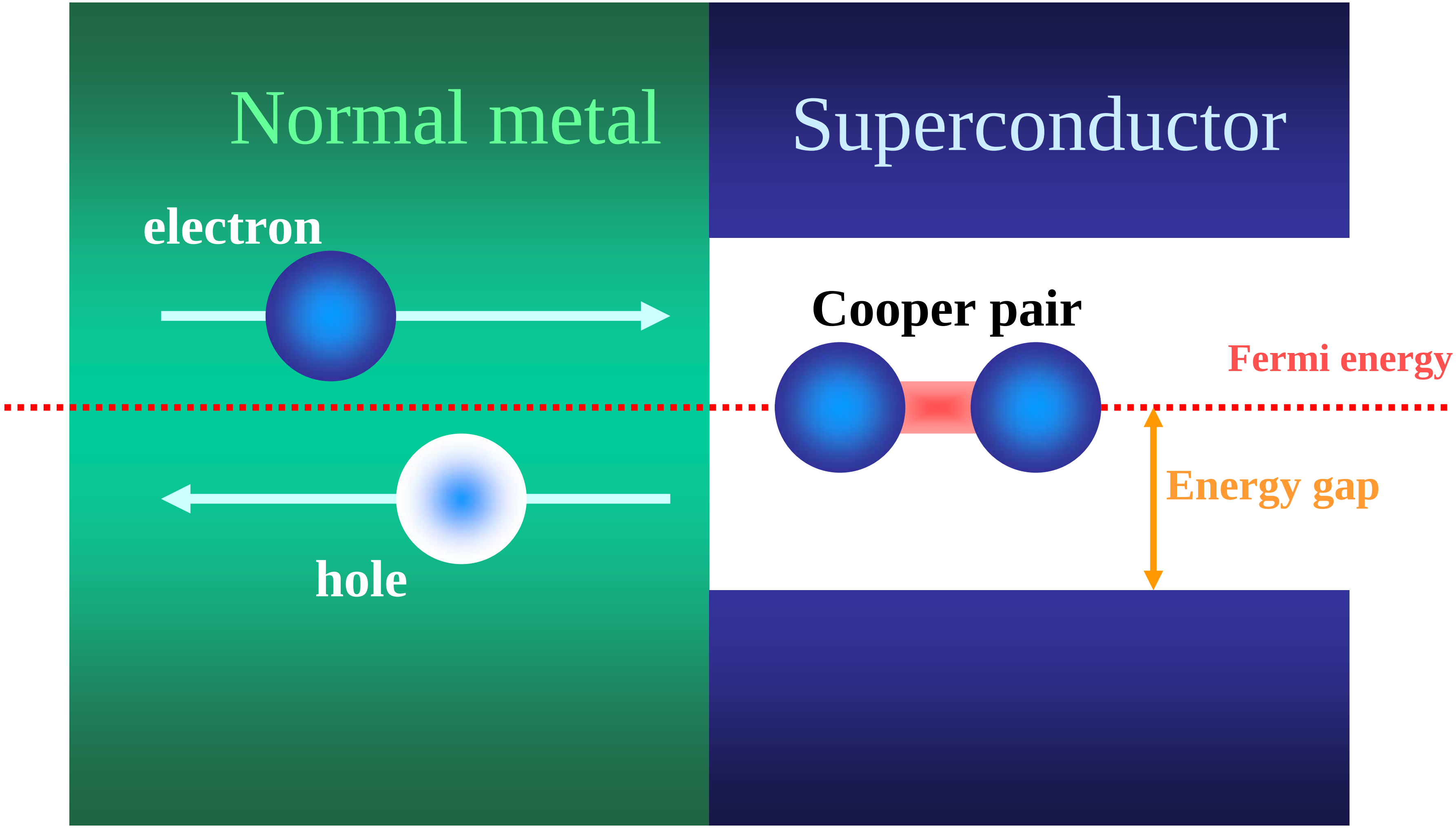
(2)Proximity effect in singlet superconductor junctions **[PRB 69 144519 (2004), PRL 90 167003(2003)]**

(3)Proximity effect in triplet superconductor junctions **[PRB 70, 012507 (2004), PRB71 024506(2005)]**

(4)Future Problems

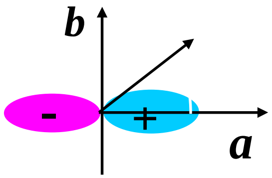
Andreev reflection



1964 Andreev

Tunneling spectroscopy of Unconventional superconductors

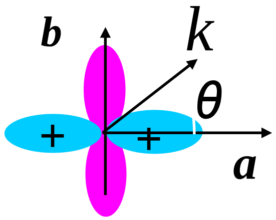
p_x- wave



$\Delta(\theta) = \Delta_0 \cos\theta$

Triplet superconductor

$d_{x^2-y^2}$-wave

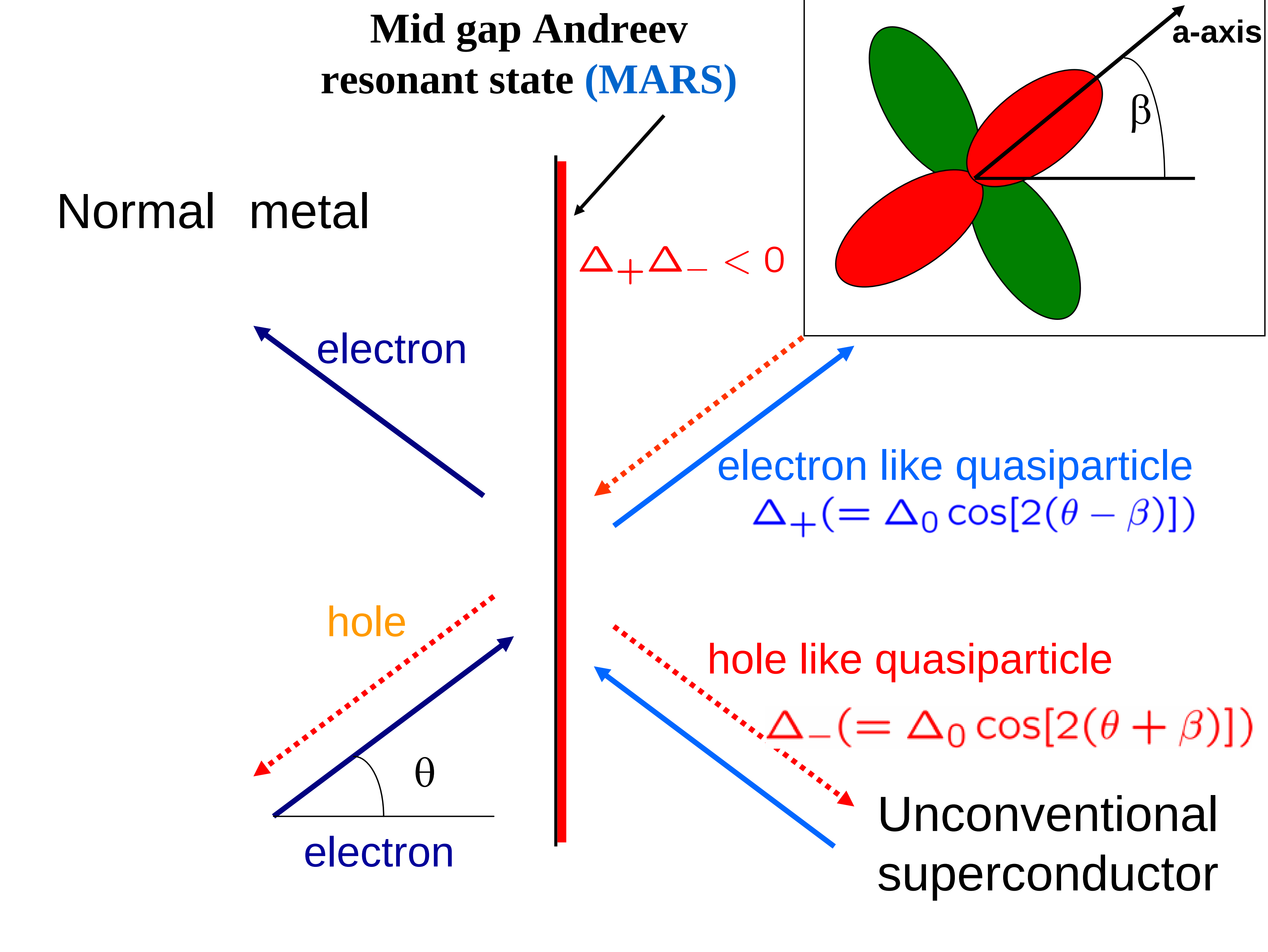


$\Delta(\theta) = \Delta_0 \cos 2\theta$

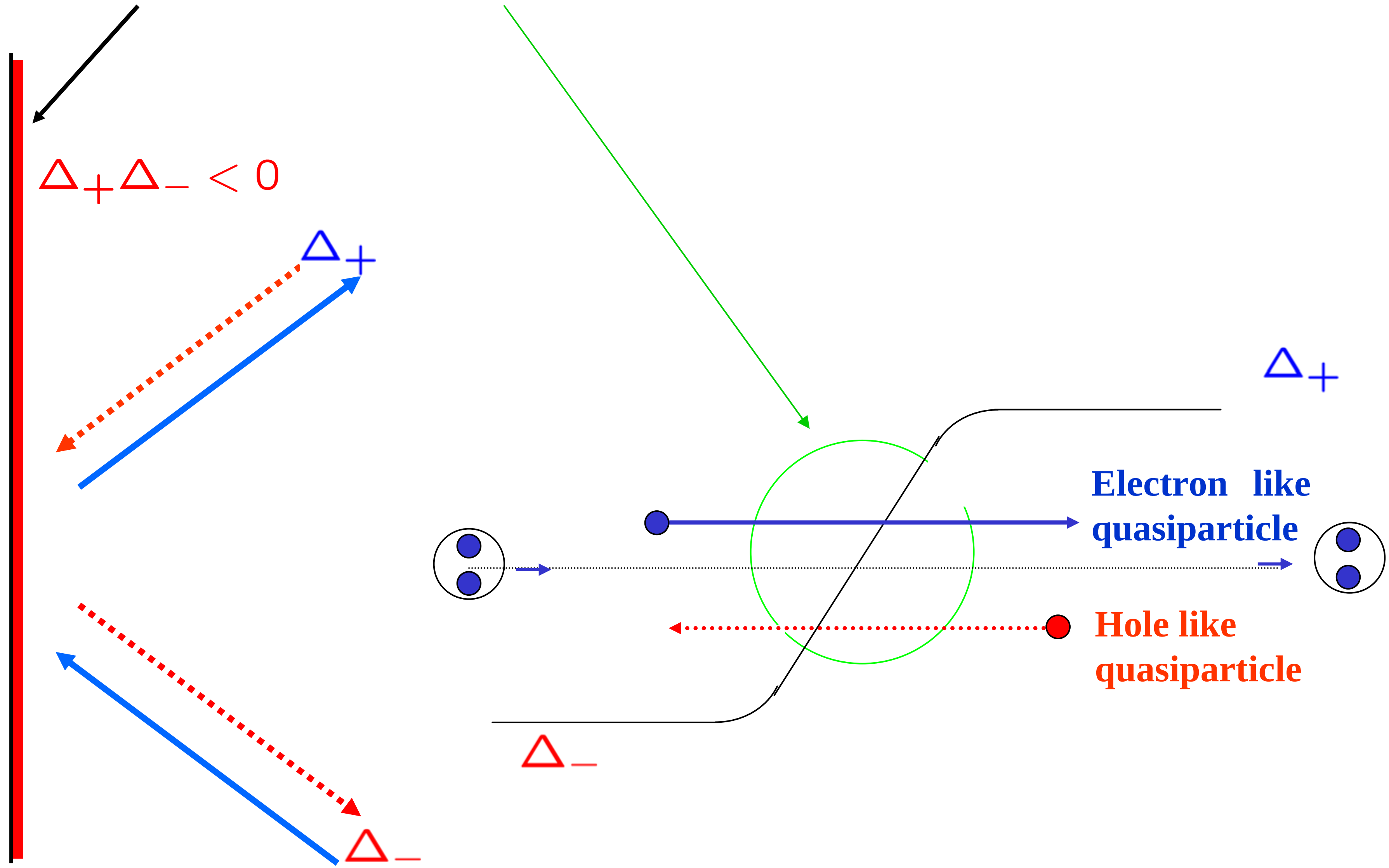
Singlet unconventional superconductor

Quasiparticles feel **different sign of the pair potential** depending on their motions.

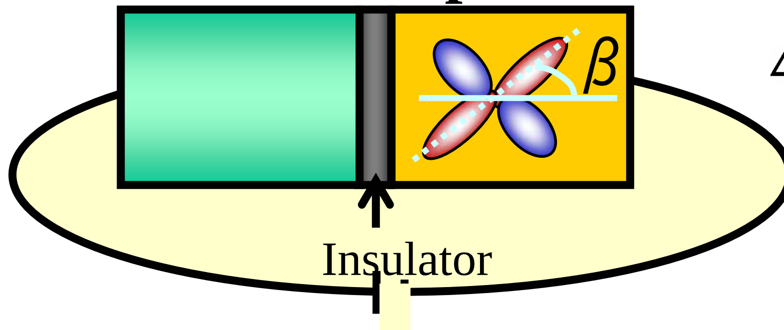
What is expected in unconventional superconductor junctions?


Mid gap Andreev
resonant state (MARS)
a-axis
β
Normal metal
$\Delta_+\Delta_- < 0$
electron
electron like quasiparticle
$\Delta_+ (= \Delta_0 \cos[2(\theta - \beta)])$
hole
hole like quasiparticle
$\Delta_- (= \Delta_0 \cos[2(\theta + \beta)])$
θ
electron
Unconventional
superconductor

Mid gap Andreev resonant state (MARS)



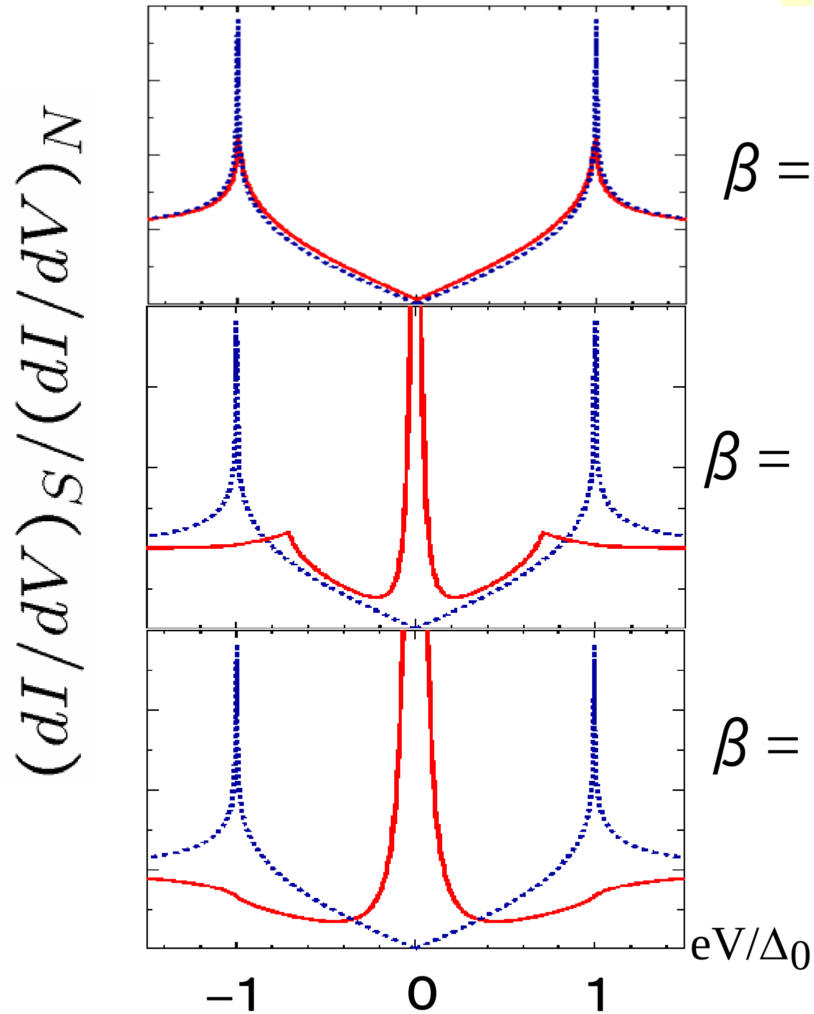
Tunneling conductance in d-wave superconductor junction (ballistic)



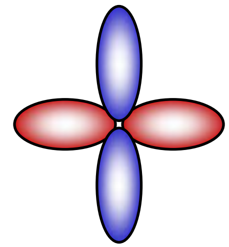
$\Delta_{\pm} = \Delta_0 \cos[2(\theta \mp \beta)]$

Bruder (1990)
Blonder Tinkham Klapwijk (1982)

Blue dotted line: Bulk d-wave DOS



$\beta = 0$

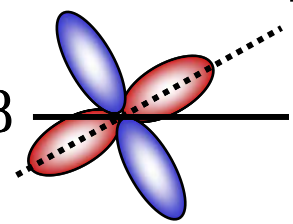


Tanaka Kashiwaya (1995)
Phys Rev Lett 74 3451 (1995)

ZBCP

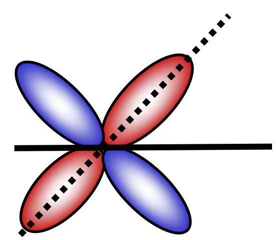
Zero bias conductance peak

$\beta = \pi/8$



Mid gap Andreev resonant state

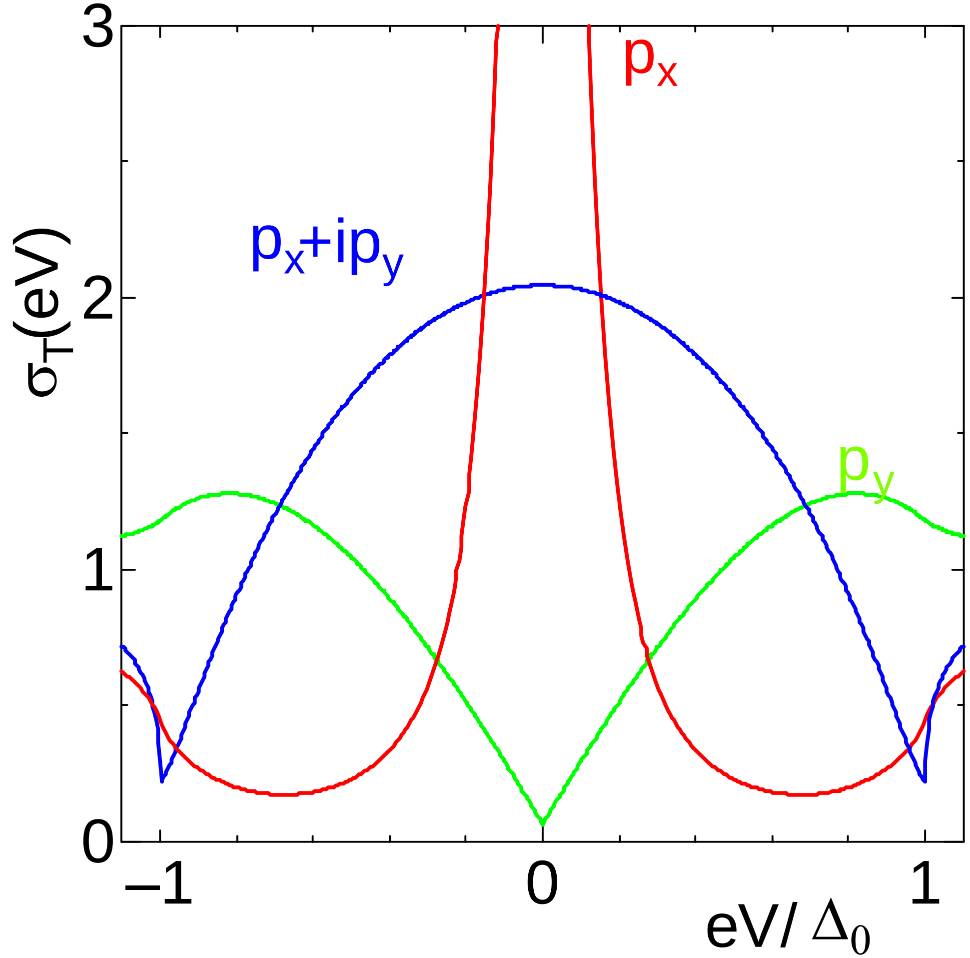
$\beta = \pi/4$

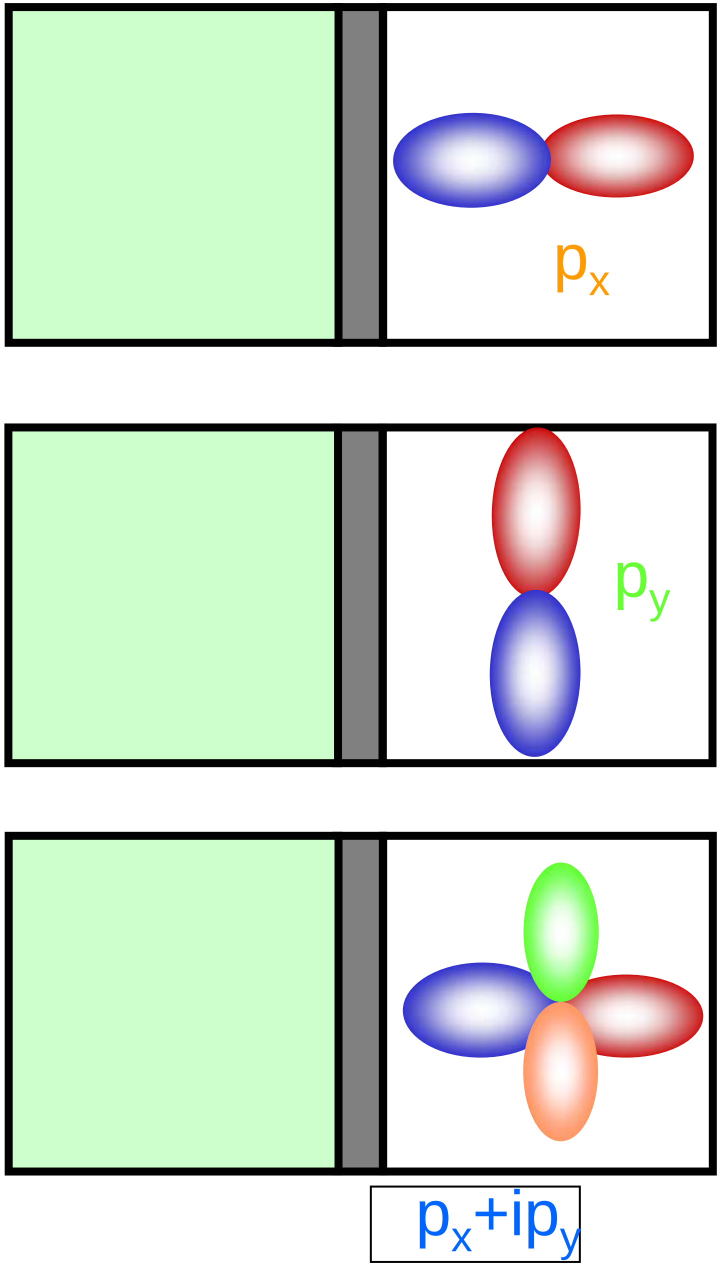


Surface bound state
Hu (1994)
Buchholtz (1981)
Hara Nagai(1986)
Matsumoto Shiba(1995)

Normal metal /triplet junctions

Phys. Rev. B. 56, 7847 (1997)
J. Phys. Soc. Jpn. 71, 2102 (2002)
J. Phys. Soc. Jpn. 67, 3224 (1998)

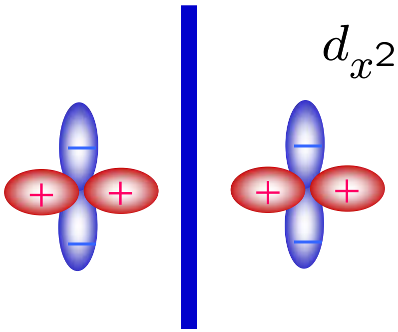




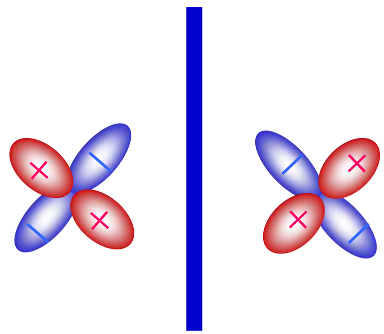
$$\Delta_{\uparrow\downarrow}(\theta) = \Delta_0 \exp(i\theta)$$

Condition of the formation of mid gap Andreev resonant state(MARS)

Inversion at the plane parallel to the interface



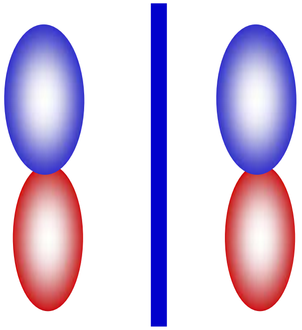
$d_{x^2-y^2}$



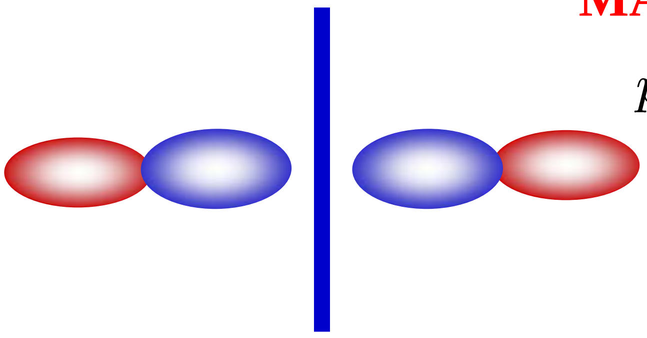
d_{xy}

Symmetric
No MARS

Anti-Symmetric
MARS

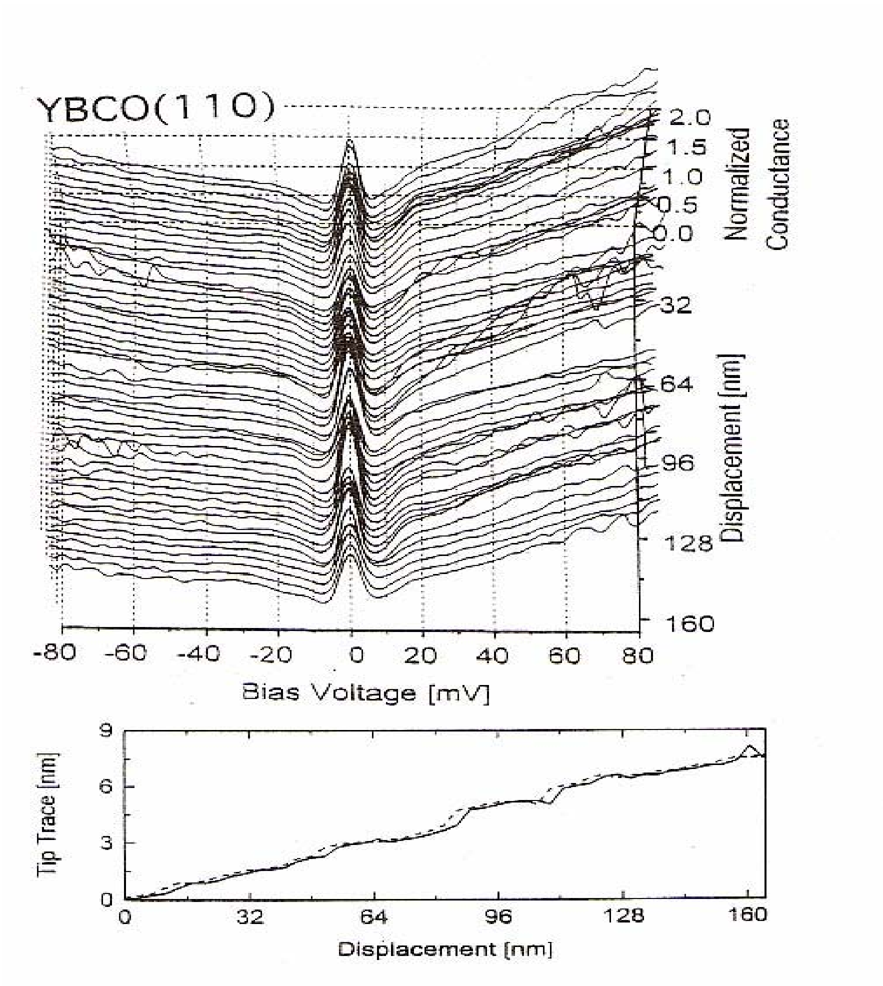


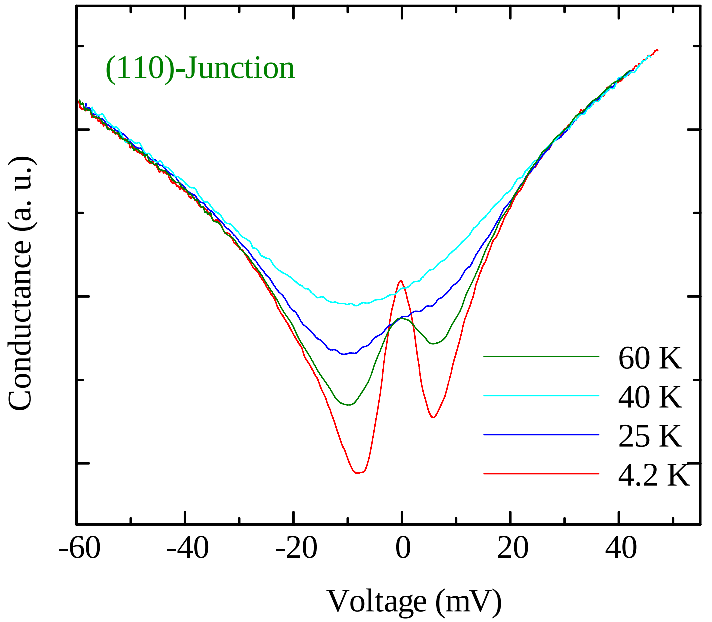
p_y

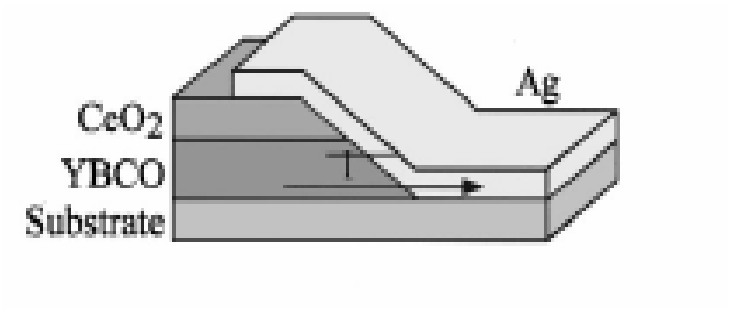


p_x

Zero bias conductance peak (by MARS) observed in cuprate







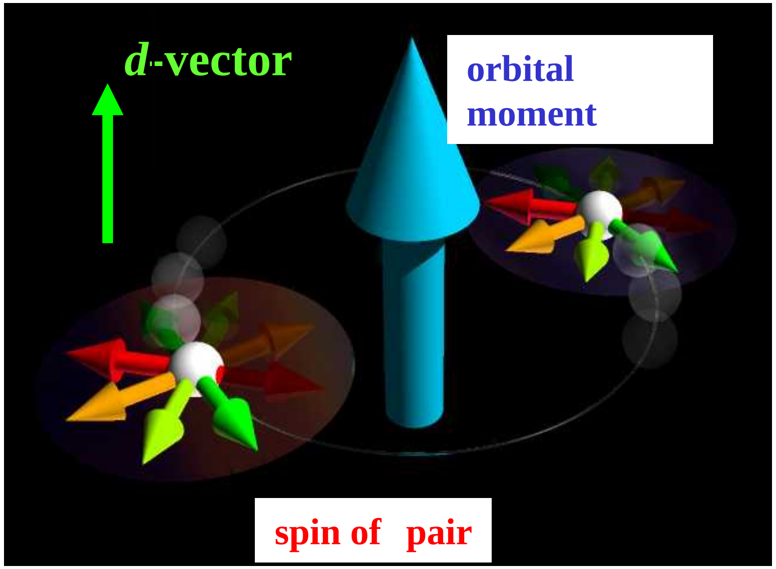
S. Kashiwaya and Y. Tanaka
Rep. Prog. Phys. (2000)

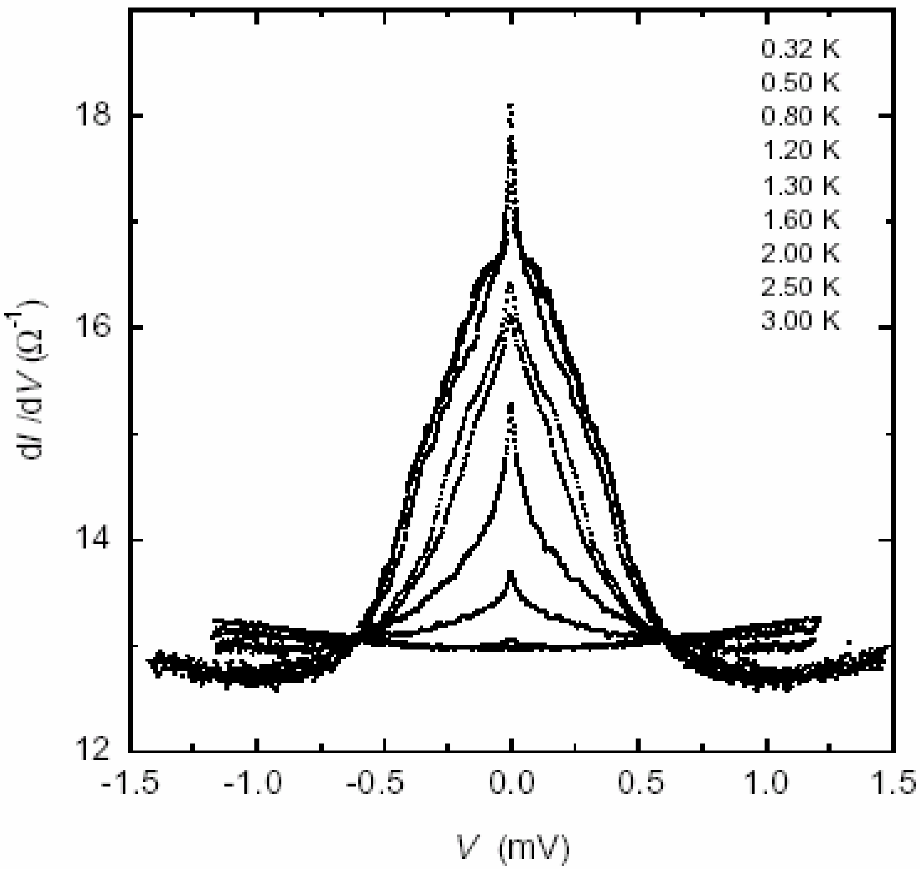
Iguchi Wang et al. –
Phys. Rev. B60, 4272 (1999)

MARS observed in triplet superconductor Sr_2RuO_4

Y. Maeno, G. Bednorz et al.
Nature 372 532 (1994)

(p-wave chiral)





Mao, Nelson, Jin, Liu and Maeno Phys. Rev. Lett. 87, 037003 (2001)

Kawamura, Yaguchi, Kikugawa Maeno Takayanagi
J. Phys. Soc. Jpn. 74 531 (2005)

Superconducting Materials where MARS is observed

$YBa_2CuO_{7-\delta}$ (Geerk, Kashiwaya, Iguchi, Greene, Yeh, Wei…)

$Bi_2Sr_2CaCu_2O_y$ (Ng, Suzuki, Greene….)

$La_{2-x}Sr_xCuO_4$ (Iguchi)

$La_{2-x}Ce_xCuO_4$ (Cheska)

$Pr_{2-x}Ce_xCuO_4$ (R.L.Greene)

Sr_2RuO_4 (Mao, Meno, Kawamura,Lube)

κ-$(BEDT\text{-}TTF)_2X$, $X=Cu[N(CN)_2]Br$ (Ichimura)

UBe_{13} (Ott)

$CeCoIn_5$ (Wei)

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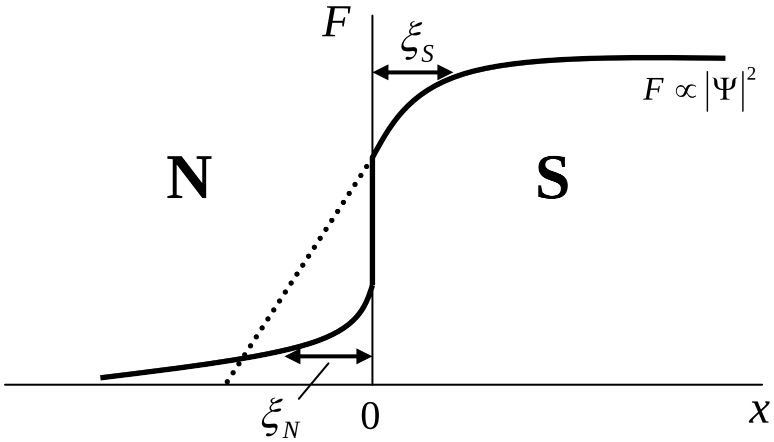
(4)Future Problems

Proximity effect and total resistance of the junction

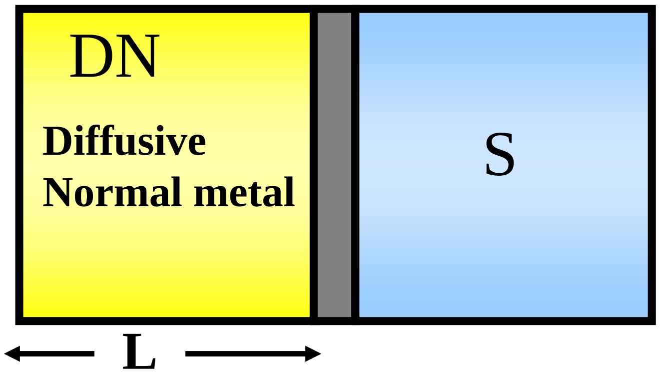
Pair amplitude $F = \left\langle \Psi_{\uparrow} \Psi_{\downarrow} \right\rangle$

Normal metal $F \propto \exp\left(-\frac{|x|}{\xi_N} \right)$



Proximity effect has an crucial influence on the charge transport in diffusive normal metal / s-wave conventional superconductor junction （DN / S junction）

insulator



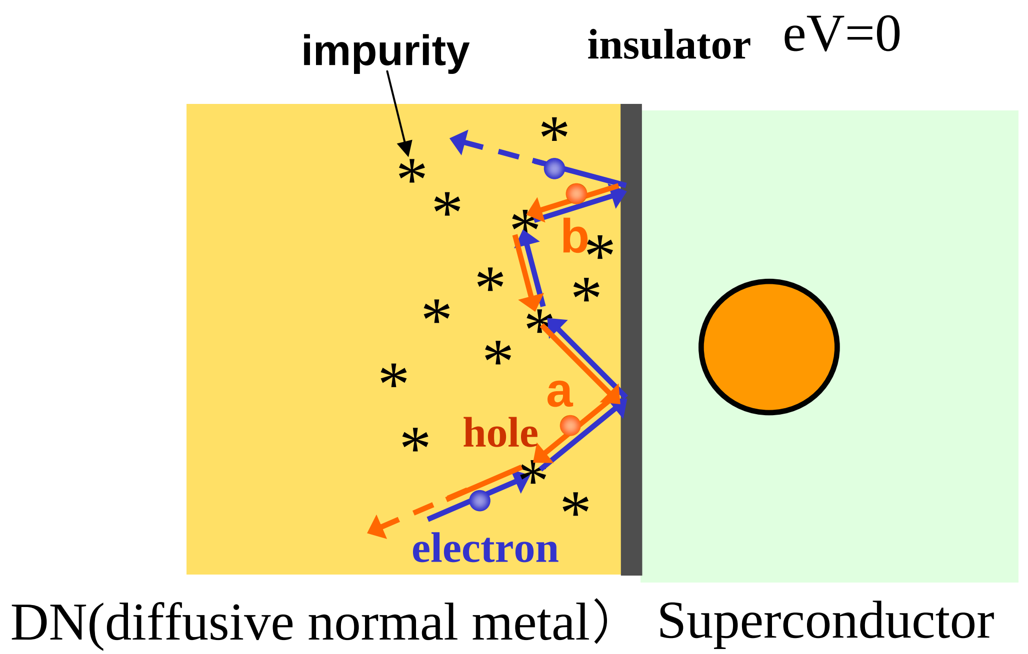
ξ : **localization length**

l : **mean free path**

$l \ll L \ll \xi$

Retro reflectivity of the Andreev reflection in DN

Beenakker: Rev. Mod. Phys. (97)

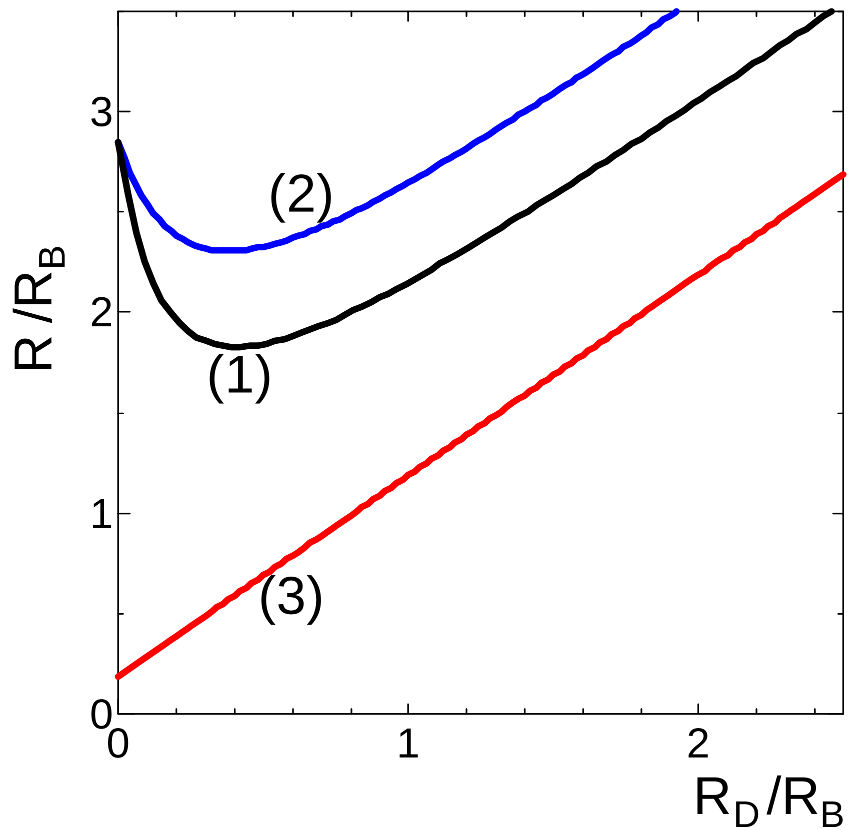


Van Wees *et al*.(1992)

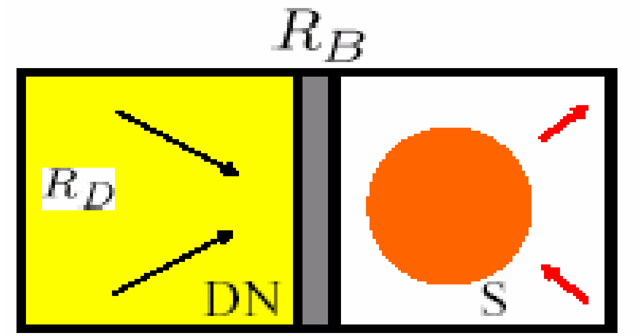
Proximity effect is enhanced by the Andreev reflection

It is effective to use quasiclassical Green's function to describe charge transport.

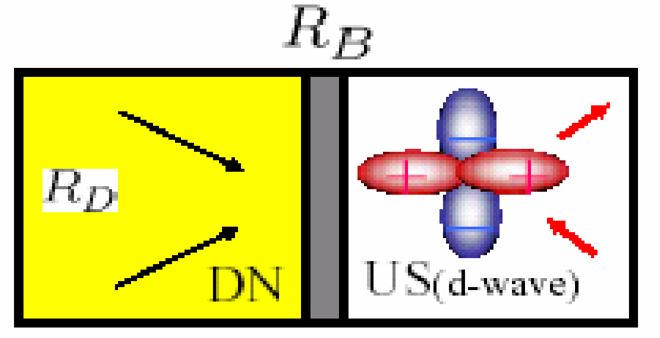
Zero voltage total resistance



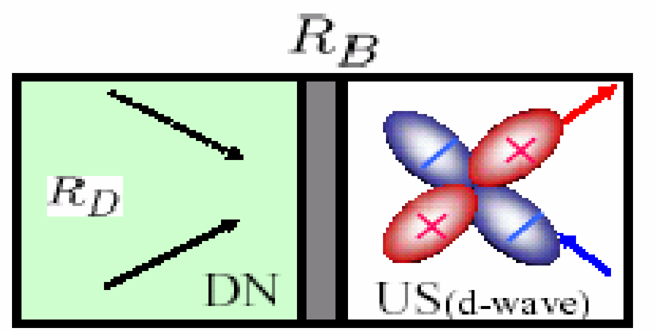
(1)



(2)



(3)



$\theta(x) = 0$

(1) Proximity no MARS (reentrance)

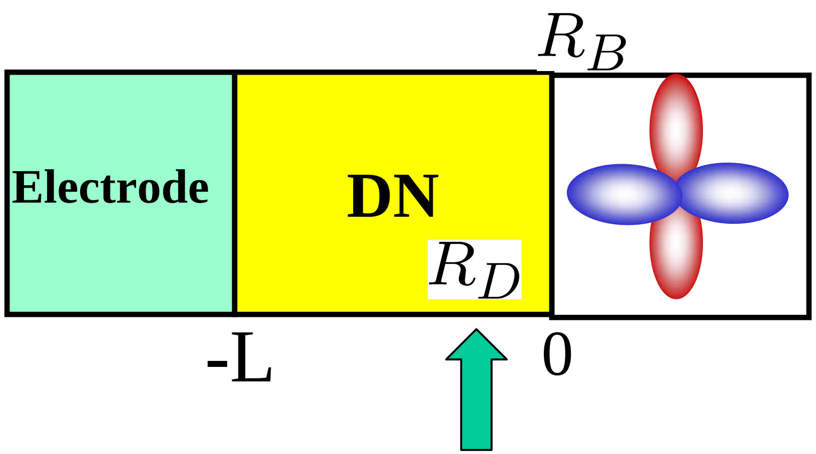
(2) Proximity no MARS (reentrance)

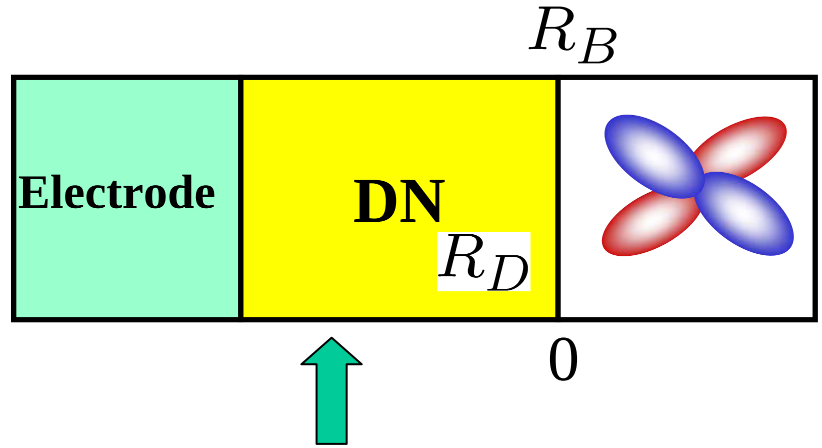
(3) No Proximity MARS (Ohm's rule)

R_0; Sharvin resistance

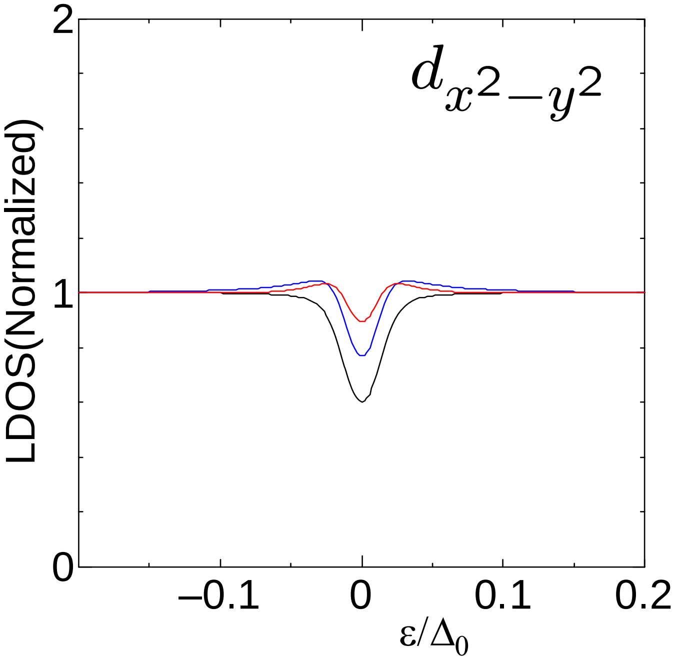
$$R_B = 2R_0 / \int_{-\pi/2}^{\pi/2} T(\phi) \cos\phi d\phi$$

Local density of states in DN (d-wave)





Z=10



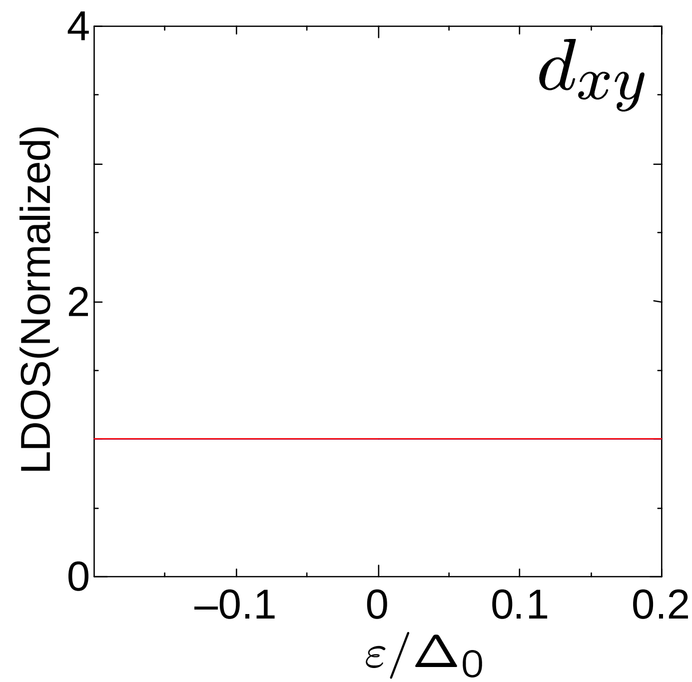
Energy gap due to proximity effect

$L/\xi = 18$

$E_{th}/\Delta_0 = 0.01$

$\xi = \sqrt{D/(2\pi T_C)}$

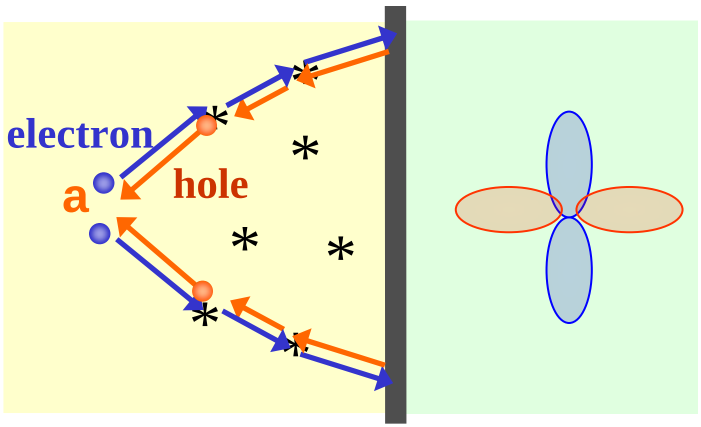
x=0
x= –L/4
x= –L/2

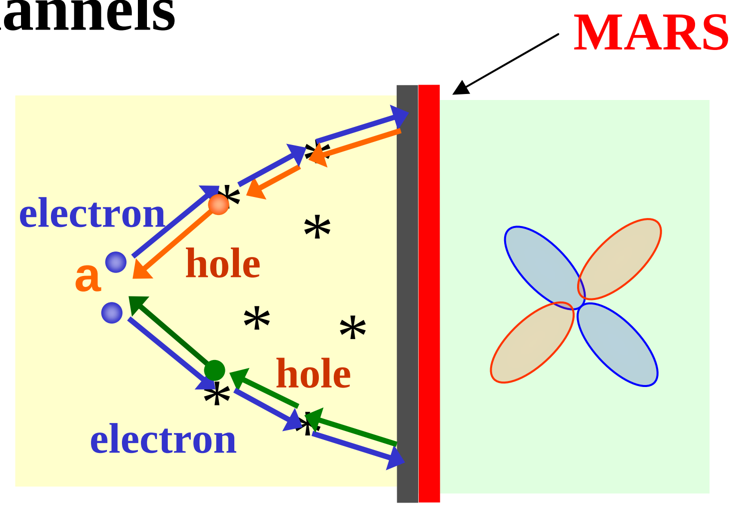


No proximity effect

Condition for the proximity effect

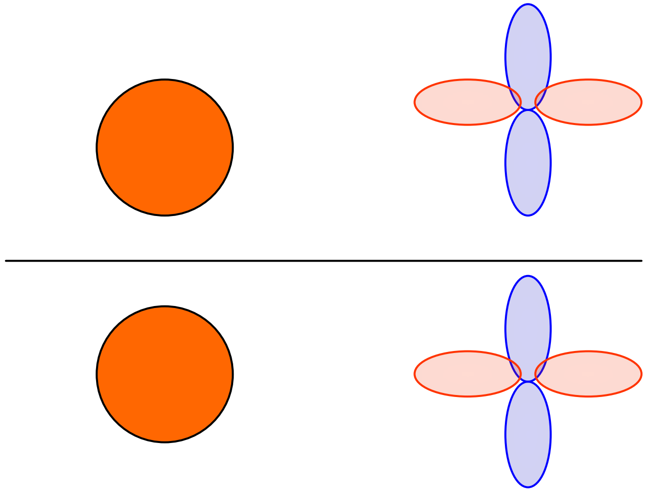
Averaging from many channels



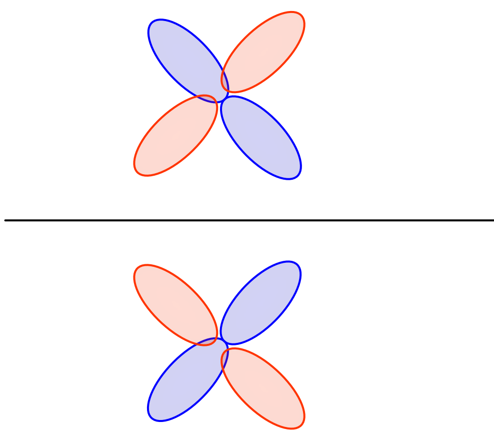


$d_{x^2-y^2}$ **Finite proximity**

proximity effect is absent



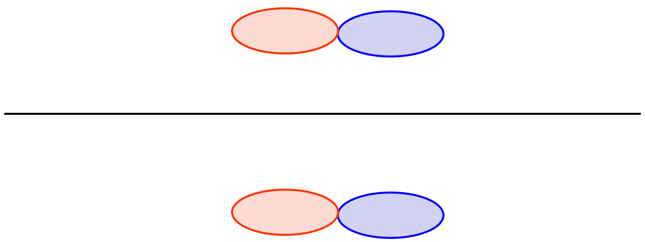
Inversion symmetry at the plane perpendicular to the interface



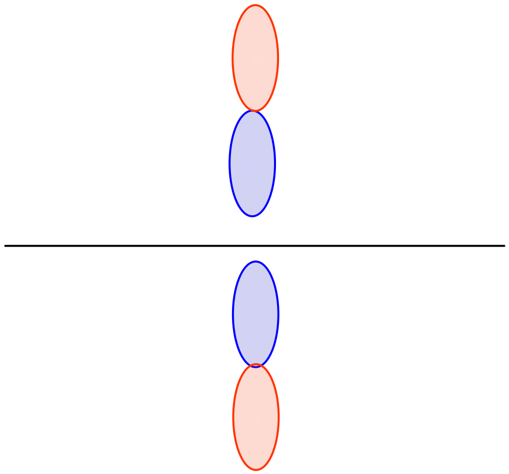
Symmetric

Anti symmetric

Condition for the proximity effect



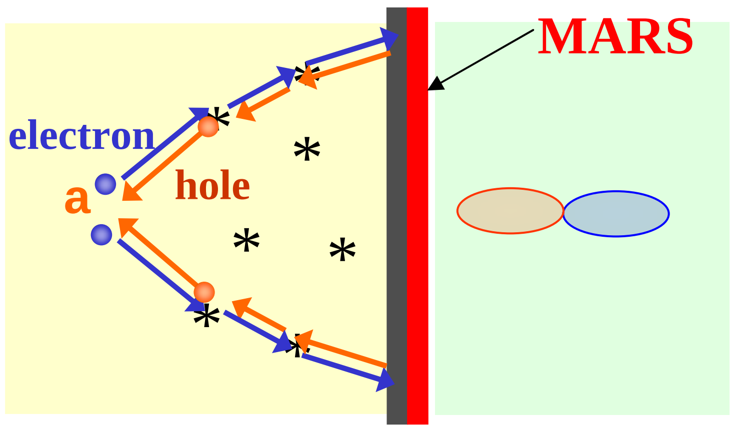
Inversion symmetry at the plane perpendicular to the interface

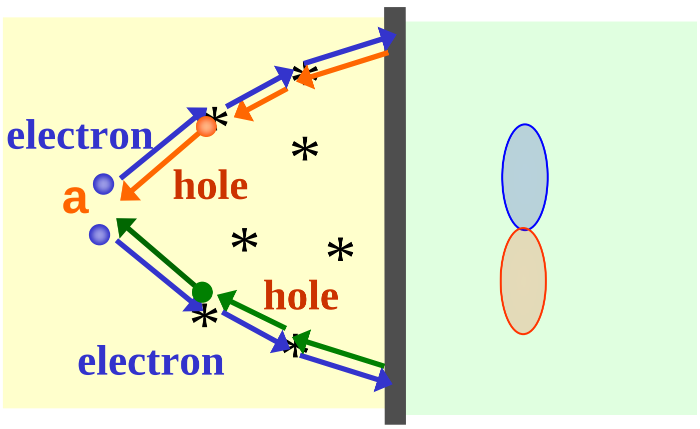


p_x **Symmetric**

p_y Anti symmetric

Averaging from many channels





Finite proximity

proximity effect is absent

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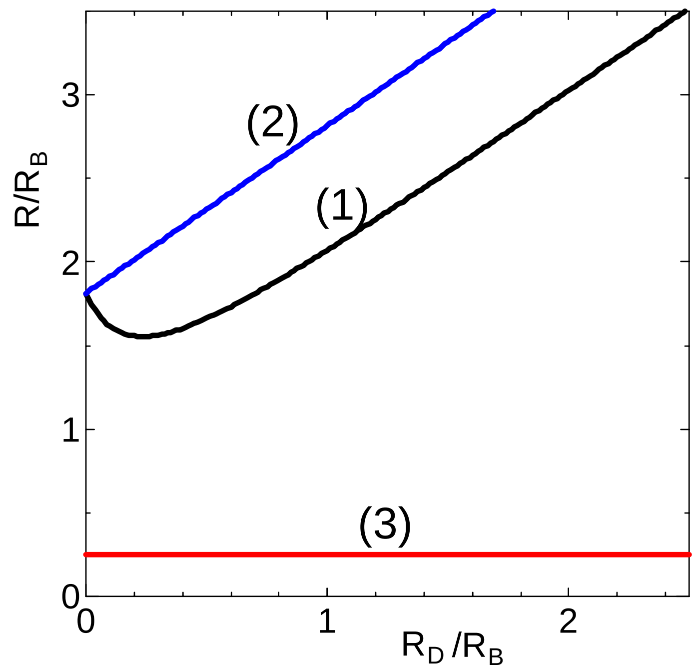
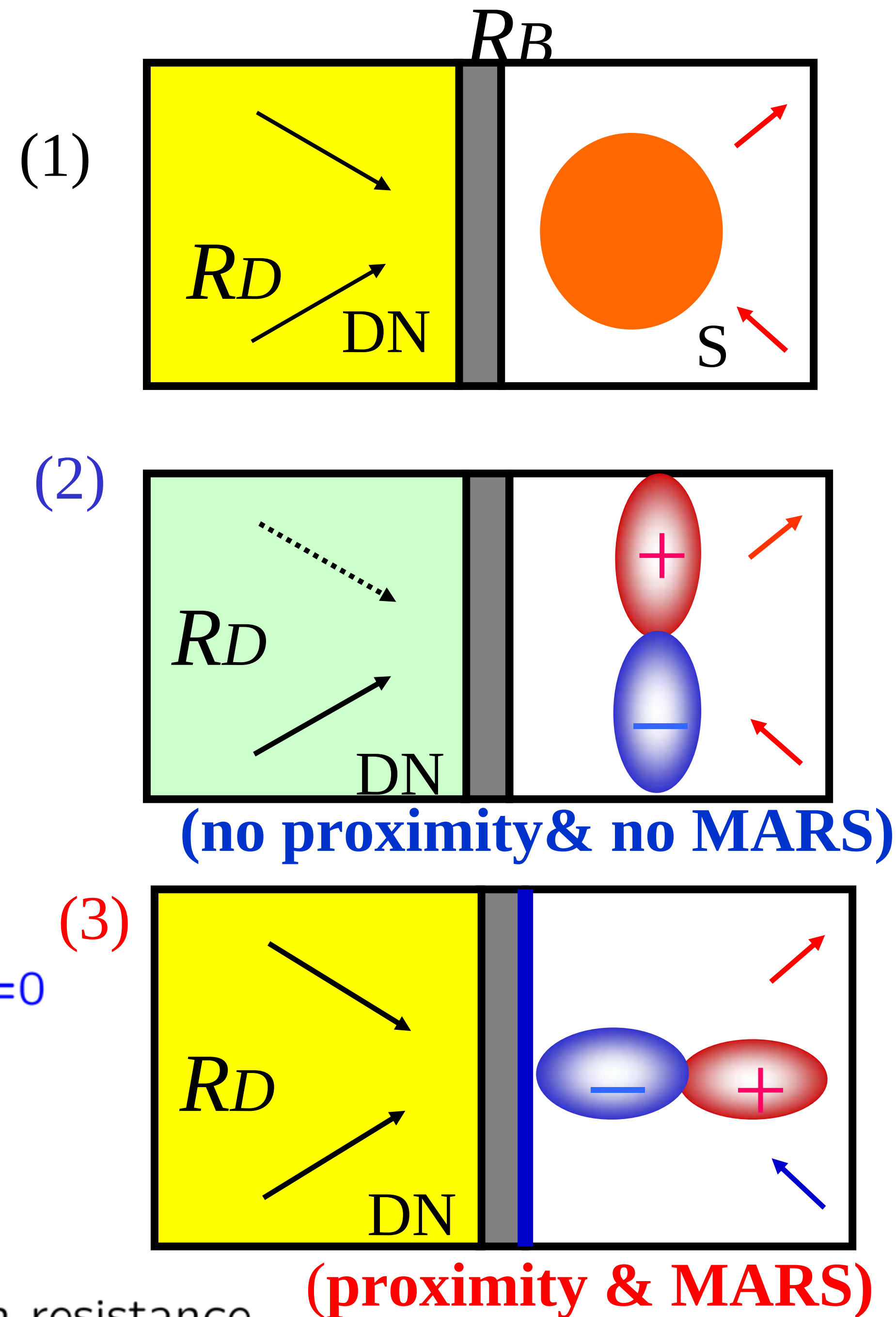
(4)Future Problems

Total resistance (eV=0)





R_D Resistance in DN

R_B Resistance at the interface

(2) p_y-wave $\quad R = R_D + R_{R_D=0}$

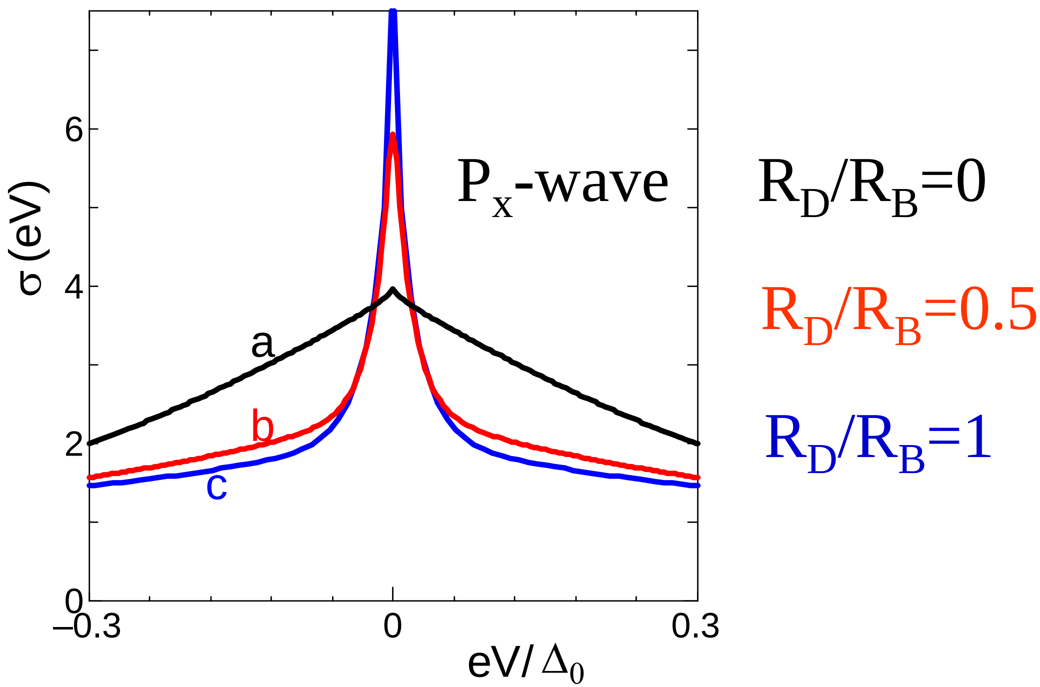
(3) p_x-wave

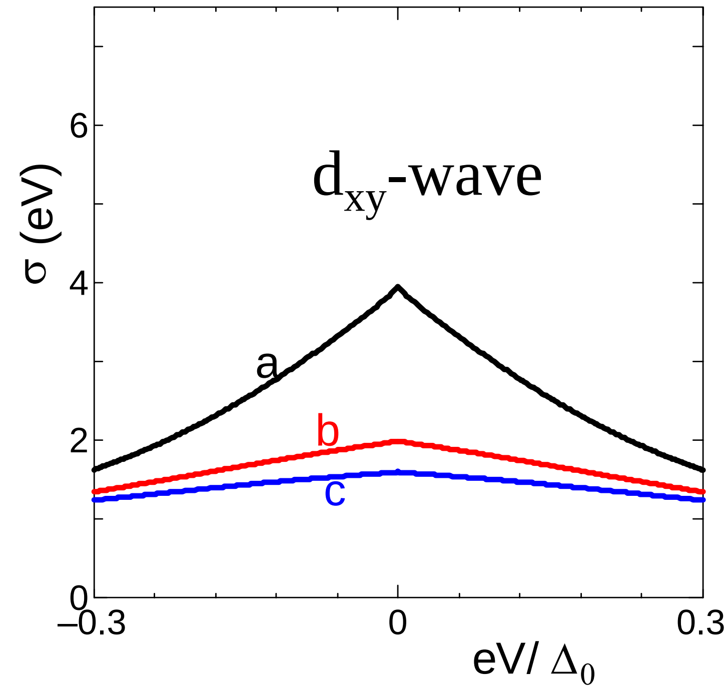
R is independent of R_D!!

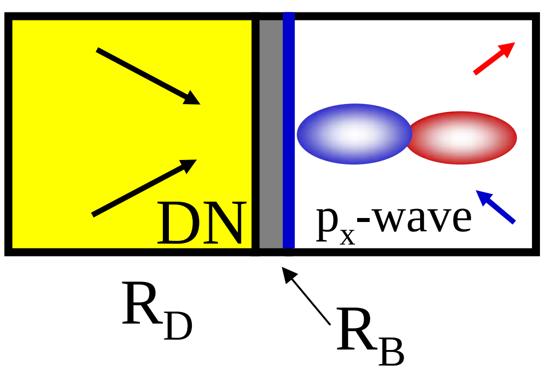
$$R = R_0/2$$

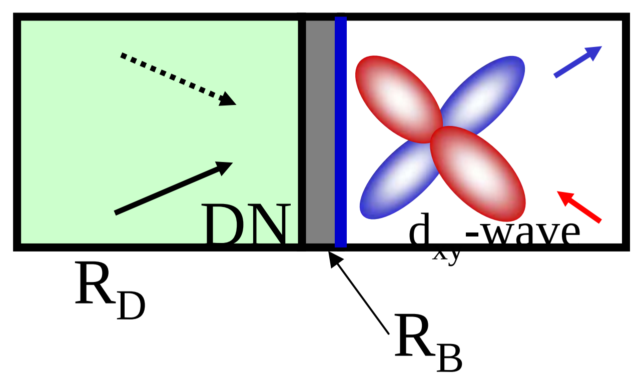
$R_B = 2R_0 / \int_{-\pi/2}^{\pi/2} T(\phi)\cos\phi d\phi$ $\quad R_0$; Sharvin resistance

Normalized tunneling conductance









ZBCP by MARS R_D/R_B is small

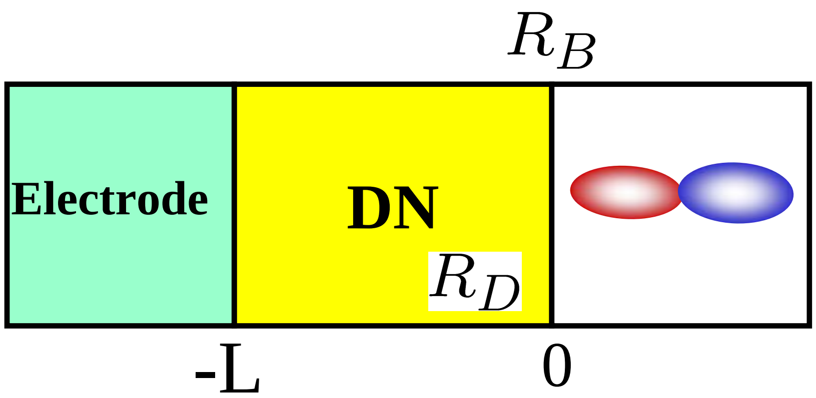
ZBCP by proximity effect

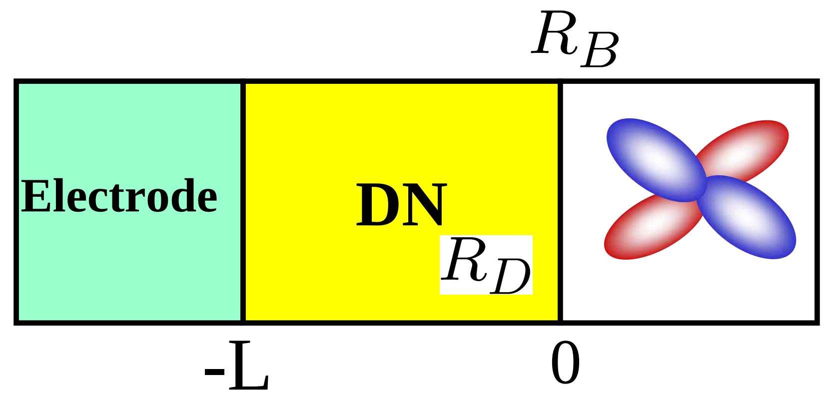
R_D/R_B is large **Giant ZBCP**

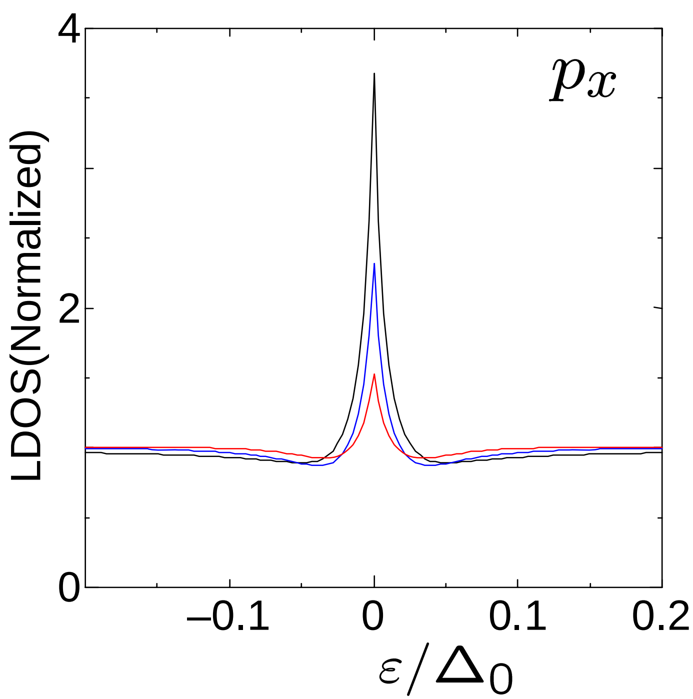
ZBCP only by MARS

No proximity effect

Local density of states in DN







Z=1.5

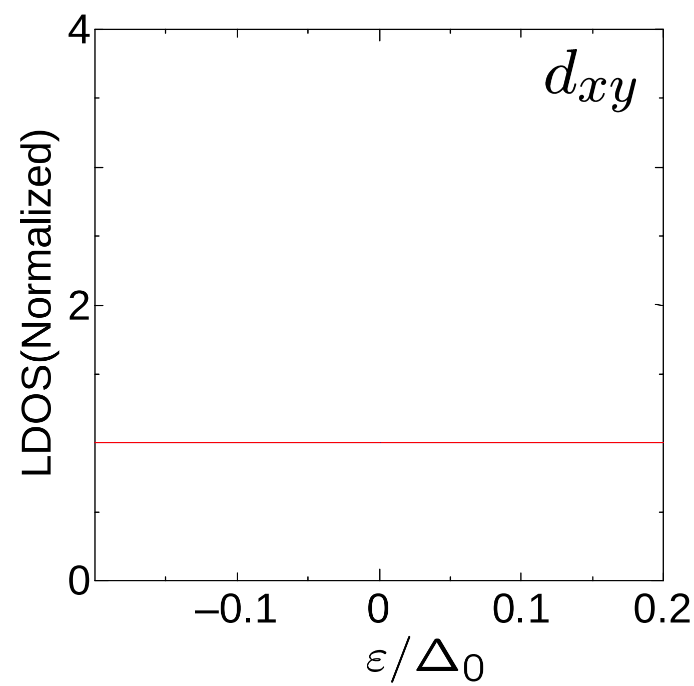
$R_D/R_B = 0.5$

$E_{th}/\Delta_0 = 0.02$

$L/\xi = 13$

$\xi = \sqrt{D/(2\pi T_C)}$

x=0
x=–L/4
x=–L/2



Zero energy peak (ZEP) is expected only for triplet junctions!!

LDOS at $\epsilon = 0$ $\rho(x)$ $\qquad \rho(x) = \cosh[\frac{2R_D(x+L)}{LR_0}]$

Unusual energy dependence of pair amplitude

- Triplet junctions

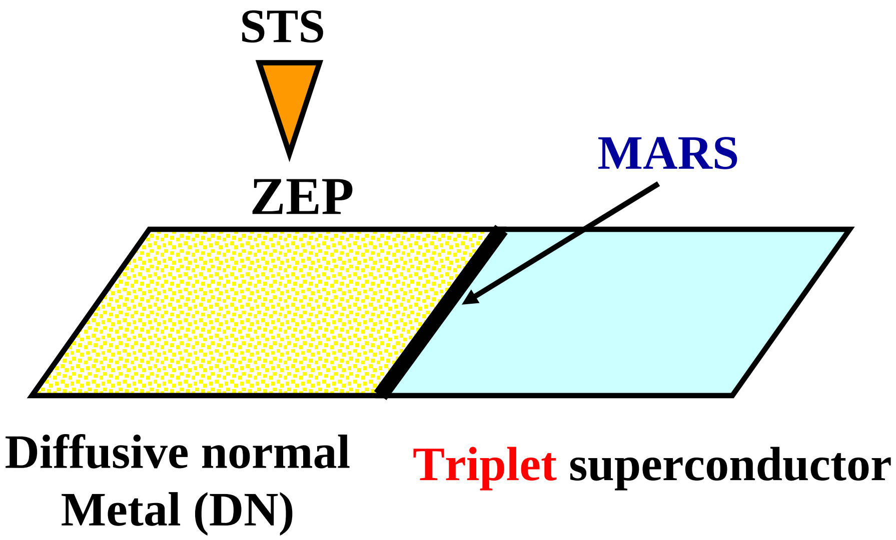
$$f_N(\varepsilon) = -f_N^*(-\varepsilon)$$

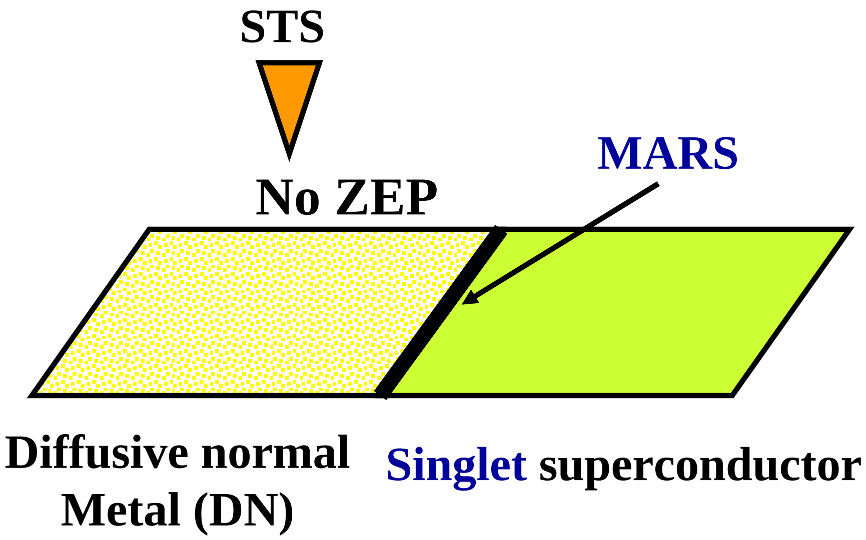
- Singlet junctions

$$f_N(\varepsilon) = f_N^*(-\varepsilon)$$

New idea to detect triplet superconductor

MARS (Mid gap Andreev resonance state) can penetrate into DN by proximity effect only for triplet superconductor junctions





LDOS in DN has a zero energy peak!!

LDOS in DN does not have a zero energy peak!!

Conclusions

Charge transport in DN/unconventional superconductor junctions

1. **Singlet superconductor junctions (Example d-wave)**
   MARS (Andreev resonant state) competes with proximity effect
   MARS can not penetrate into DN

2. **Triplet superconductor junctions (Example p-wave)**
   MARS can coexist with proximity effect
   Total resistance of the junction is drastically reduced!!
   MARS can penetrate into DN
   Enhanced proximity effect is sensitive to applied magnetic field

Future plans

(1)To clarify anomalous proximity effect

(Meissner effect, unusual energy dependence of pair amplitude) **[Phys. Rev. B 71, 094513(2005)]**

(2)Josephson effect

(3)Ferromagnet junction and spin current

(4)Noise and full current statistics

(1)Sr_2RuO_4-Ru, Sr_2RuO_4-$Sr_3Ru_2O_7$

(2)3K Phase

(3)STM experiments of Sr_2RuO_4