Spintronics:
Physics and applications (II)

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IPM, 15 TiR 1387

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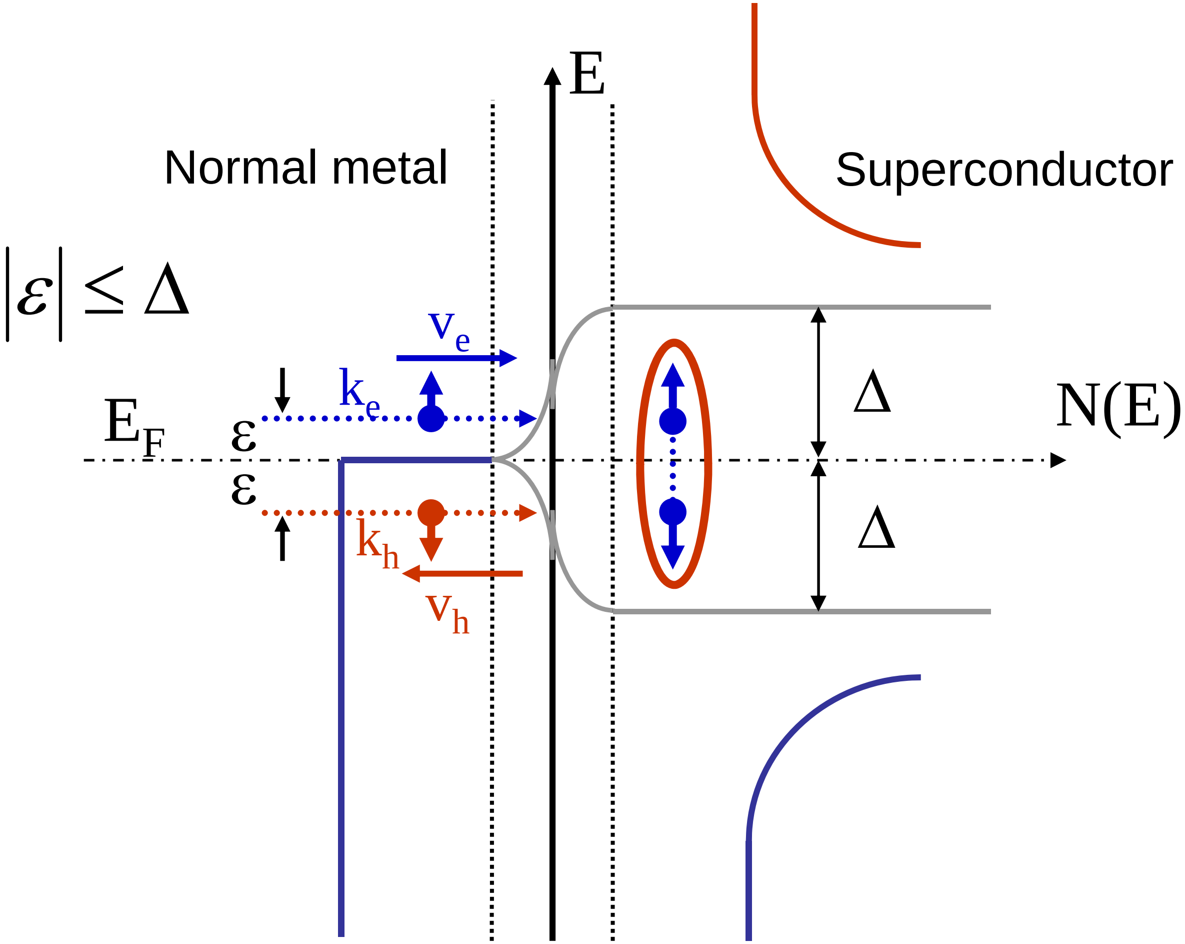
Andreev reflection in NS junctions



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

Andreev reflection in NS junctions

- ***Conversion of normal current to supercurrent: charge transfer by 2e***

- ***Momentum is changed by*** $\sim 2\varepsilon/v_F \ll p_F$ ***negligibly small for degenerate N***

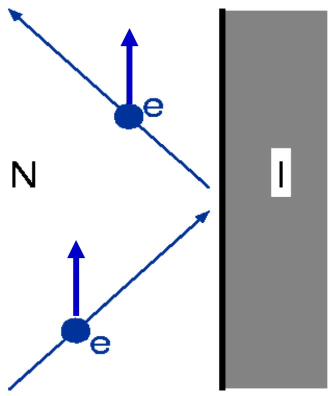
$\Delta \ll E_F$ $\vec{k}_e \cong \vec{k}_h$ ***AR is Retro Reflection***

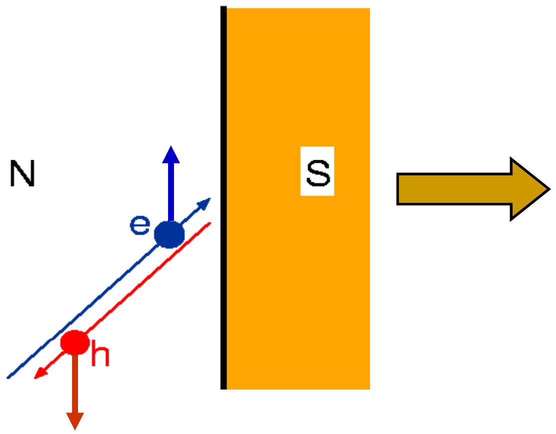
- ***Spin is inverted***

(has significant consequences if N is a ferromagnet)

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

Andreev reflection in NS junctions





Andreev Conductance:

finite G_{NS} of NS junction at voltages below the superconducting gap Δ/e,

for ideal interface at zero voltage

$G_{NS} = 2_{AR}\ G_{NN}$

Specular Normal Reflection

Retro Andreev Reflection

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

Superconducting proximity effect

Superconducting pair potential (order parameter)

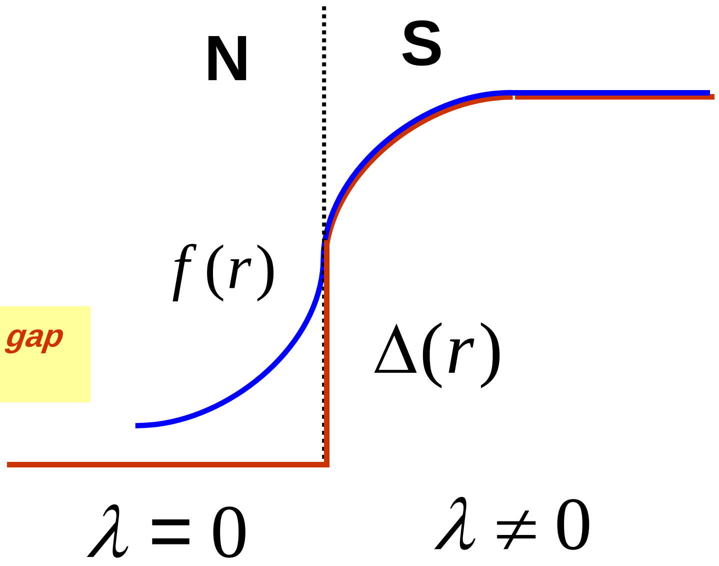
$$f \propto \Psi$$

$$\Delta(r) = \lambda f(r)$$

Superconducting gap function

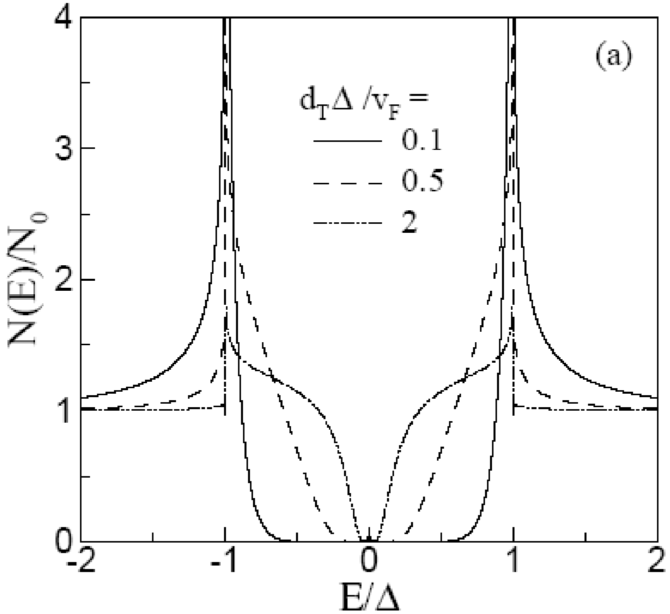
$$\lambda = gN_0$$

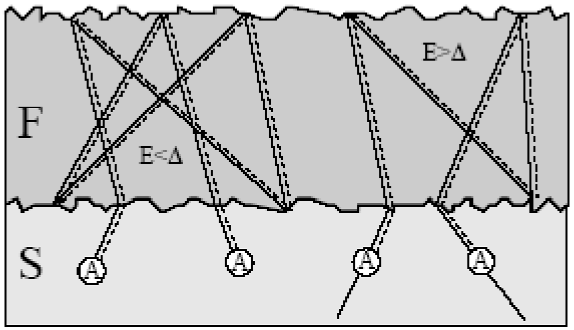
Electron-phonon coupling constant



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

Superconducting proximity effect

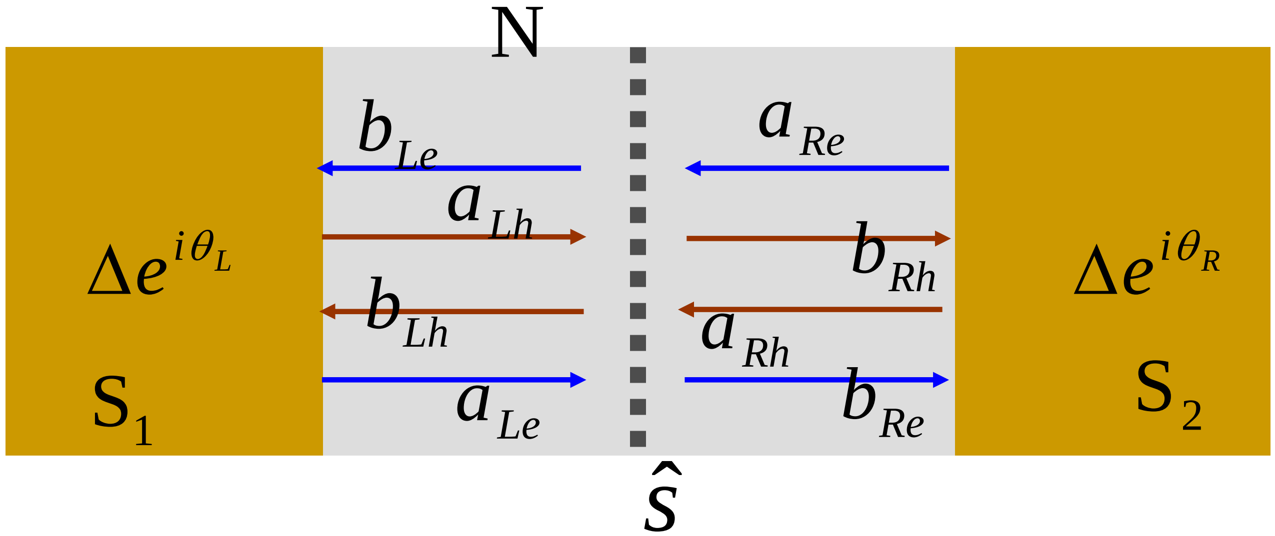




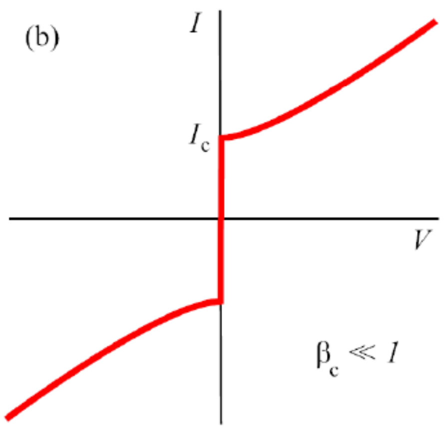
N metal acquirers characteristics of superconducting states

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

Josephson effect in SNS junctions



$$I(\varphi) = I_c \sin\varphi$$



Bogoliubov-deGennes equations

Scattering formalism of Abdreev reflection:
Blonder-Tinkham-Klapwijk (BTK formula)

electron-hole conversion: superconducting correlations

electron wave function

$$\begin{pmatrix} \hat{H} & \Delta e^{i\theta} \\ \Delta e^{-i\theta} & -\hat{H}^* \end{pmatrix} \begin{pmatrix} \psi_e(\boldsymbol{r}) \\ \psi_h(\boldsymbol{r}) \end{pmatrix} = E \begin{pmatrix} \psi_e(\boldsymbol{r}) \\ \psi_h(\boldsymbol{r}) \end{pmatrix}$$

Diagonal normal state Hamiltonian

hole wave function

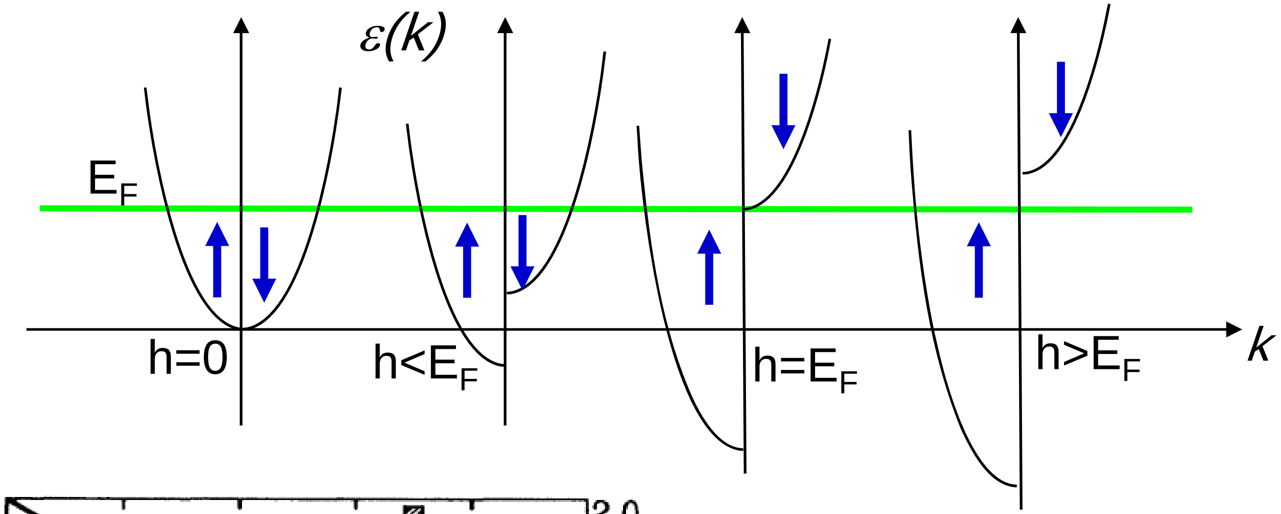
$$\hat{H} = \hat{H}_0 - E_F, \; \hat{H} = -(\hbar^2/2m)(\nabla + ie\boldsymbol{A}(\boldsymbol{r})/\hbar c)^2 + U(\boldsymbol{r})$$

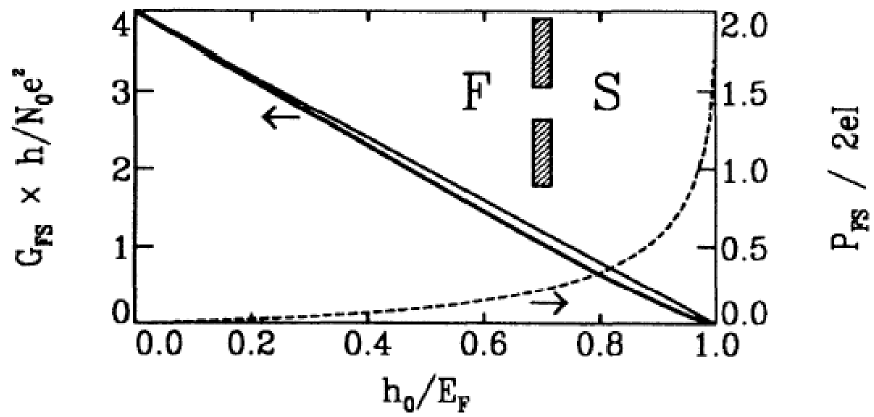
$$\Delta e^{i\theta}(\boldsymbol{r}) \propto \psi_e(\boldsymbol{r})\psi_h(\boldsymbol{r})$$

Superconducting pair potential (order parameter): self-consistency relation

Suppression of Andreev conductance in FS junctions

Spin is inverted (has significant consequences if N is a ferromagnet)



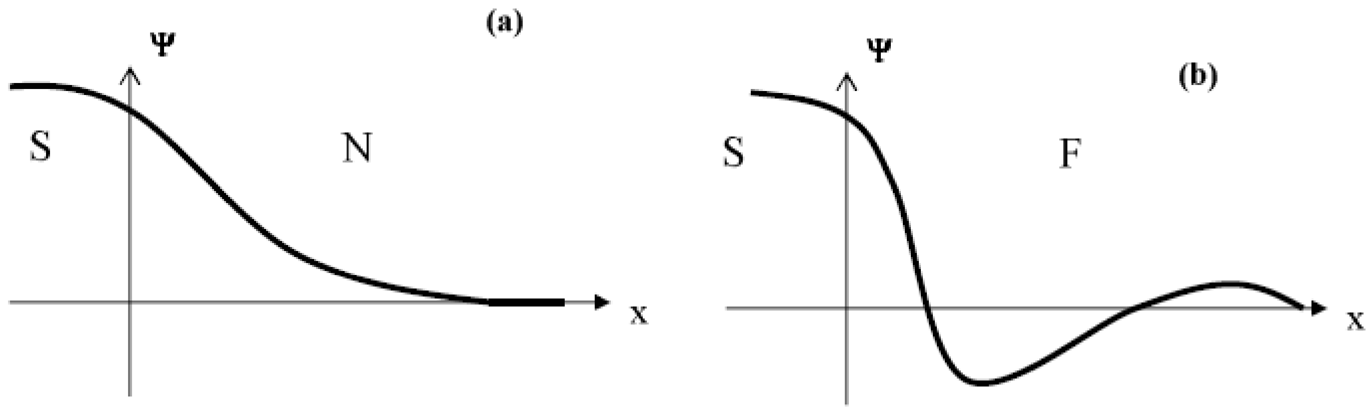


Ferromagnetism and singlet-spin superconductivity are exclusive phenomena

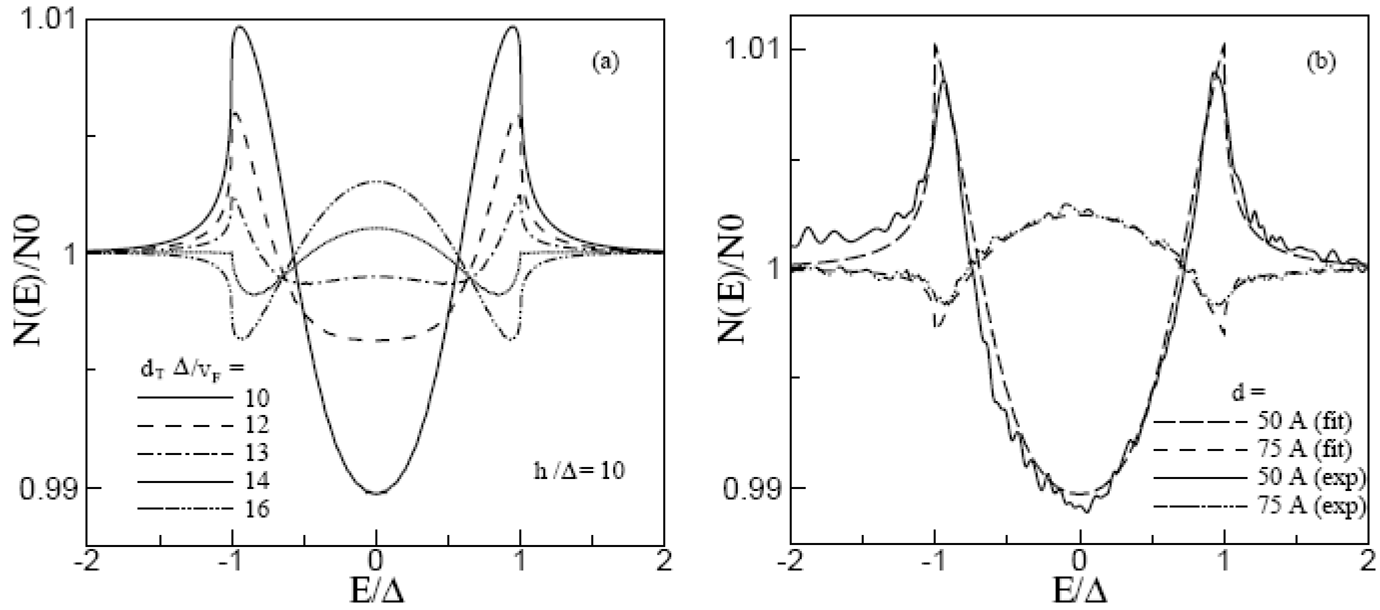
Their interplay in FS structures very active field:
Π–SFS junction qubits, long range triplet effects, entanglement,….

[M. J. M. de Jong and C. W. J. Beenakker Phys. Rev. Lett. **74**,1657 (1995);……..]

Oscillatory proximity effect in FS junctions

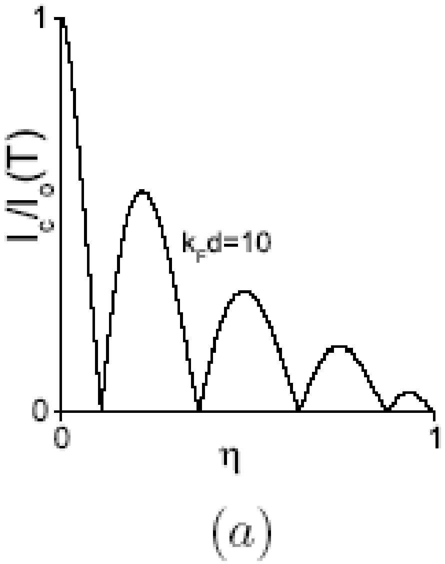


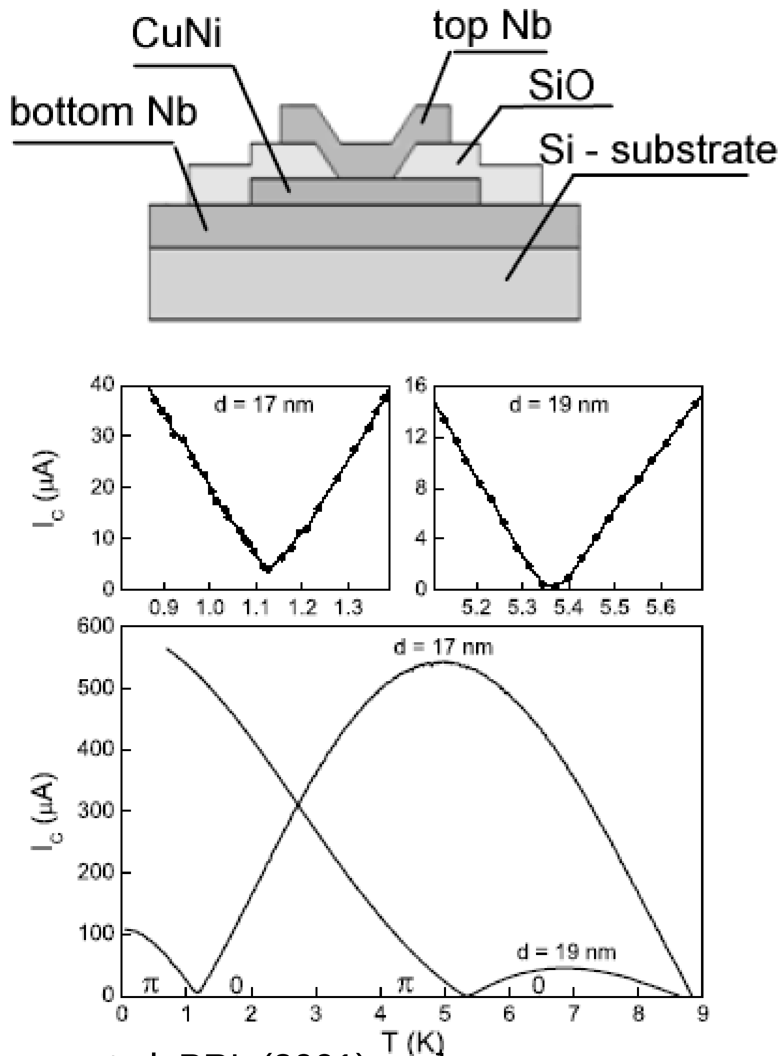
DOS oscillations in FS junctions



[M. Zareyan et al, PRL (2000); Kontos et al, PRL (2000); …]

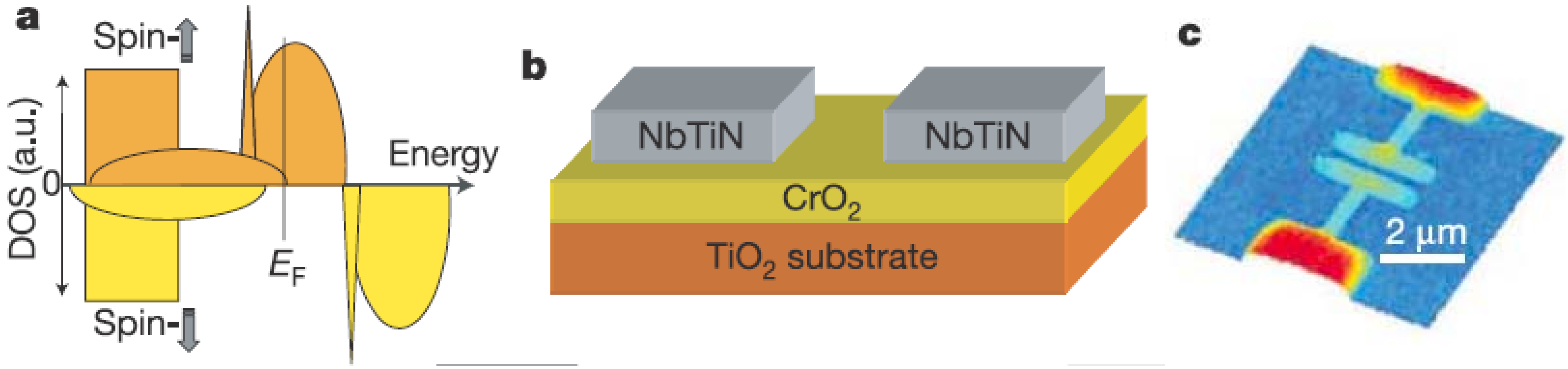
0–π transitions





[Ryazanov et al, PRL (2001); …]

Supercurrent through half-metal ferromagnetic layer

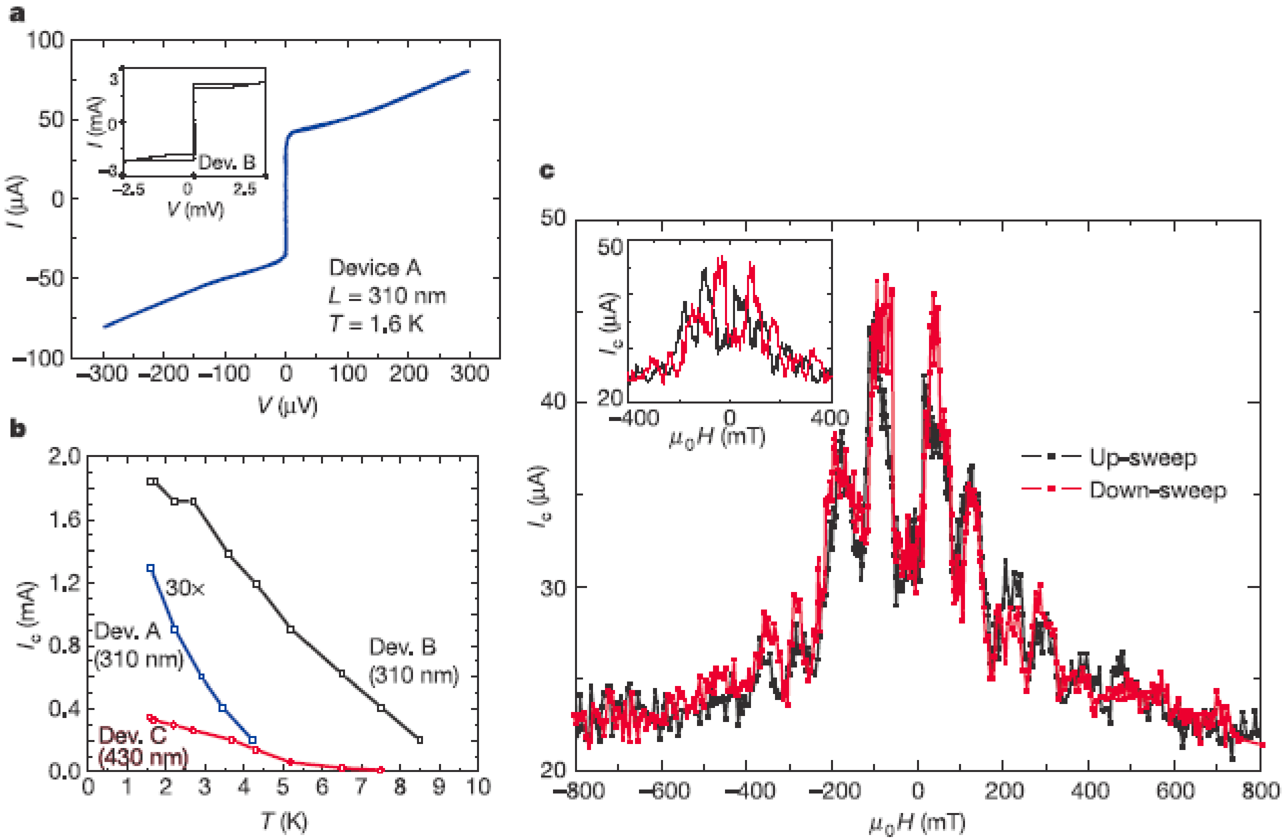


$$\xi_F \propto 1/E_{exh}\ or\ 1/\sqrt{E_{exh}}$$

In CrO2 (Eexh~ 2 eV) superconductivity should be destroyed over interatomic distance

[R. S. Keizer et al, Nature **439**, 825 (2006)]

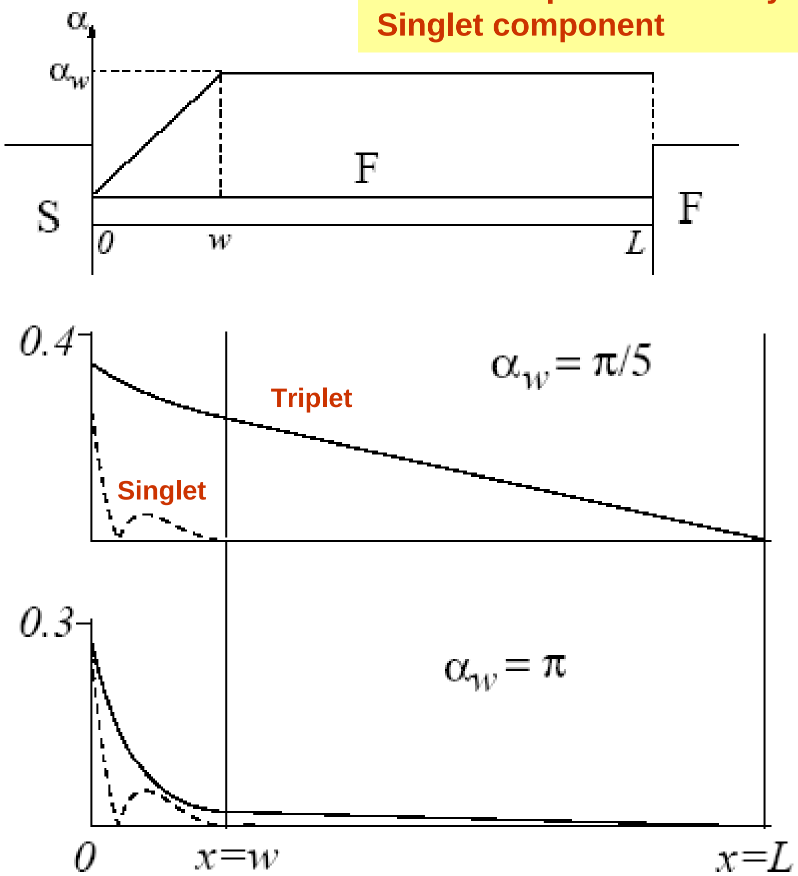
Supercurrent through half-metal ferromagnetic layer



[R. S. Keizer et al, Nature **439**, 825 (2006)]

Long range proximity in Ferromagnets

Inhomogeneous noncollinear configuration of magnetization: Induced superconductivity has Triplet component as well as Singlet component



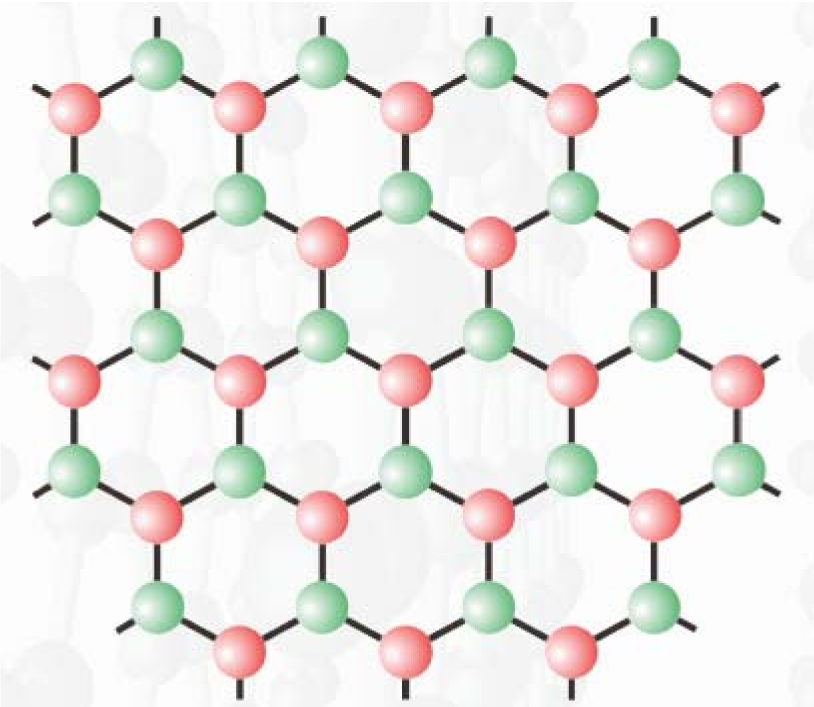
$$\xi_F \propto 1/E_{exh} \; or \; 1/\sqrt{E_{exh}}$$

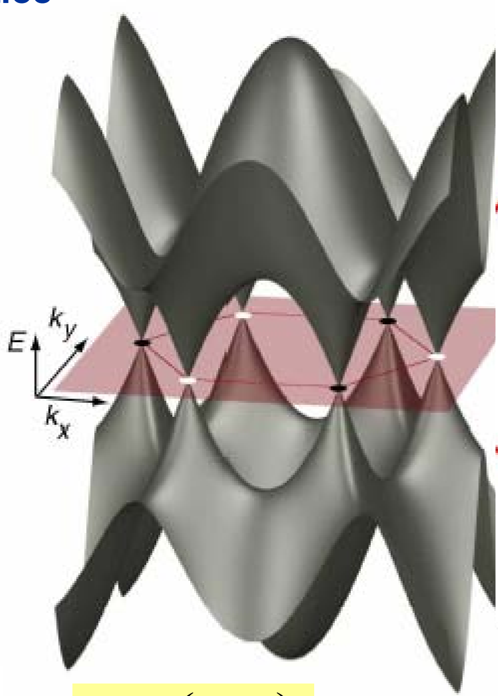
$$\xi_N \propto 1/T \; or \; 1/\sqrt{T}$$

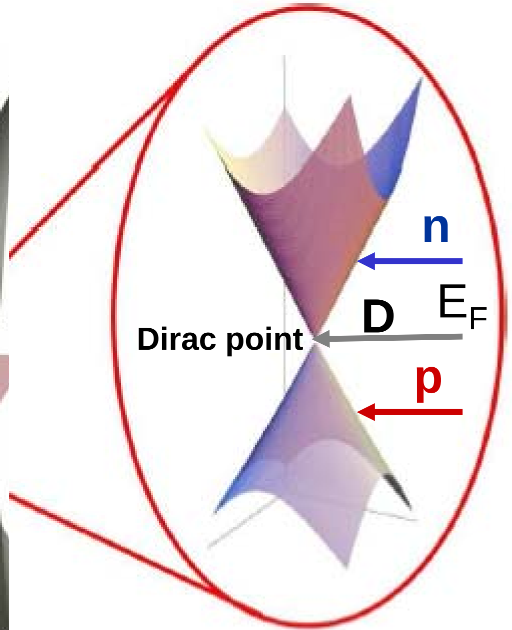
[F. S. Bergeret et al, PRL **86**, 4096 (2001)]

Graphene

Isolated single one atom thick honeycomb lattice of carbon atoms: Two (A and B) sublattices







$$\varepsilon(\mathbf{k}) = \pm\hbar v|\mathbf{k}|$$

4-component spinor in two (A,B)sublattices space (pseudospin) and two (-,+)-valley space

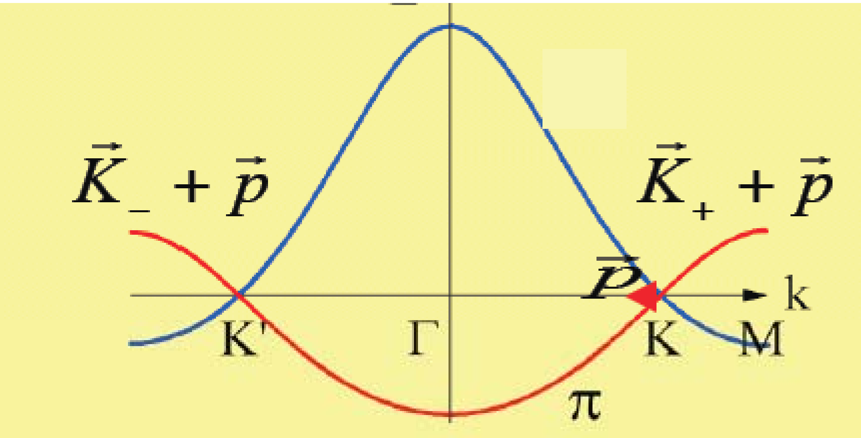
$$\hat{u} = \begin{pmatrix} \psi_A^+ \\ \psi_B^+ \\ \psi_A^- \\ \psi_B^- \end{pmatrix}$$

Carrier density and its type (n or p or D) tuned by gate voltage or doping of substrate

[Novesolov et al, Nature **438**, 197 (2005); Zhang et al, Nature **438**, 201 (2005); …]

PseudoRelativistic chirality

4-component spinor in two (A,B) sublattices space (pseudospin) and two (-,+)-valley space



Low excitation Dirac Hamiltonian

$$\hat{H} = v\begin{pmatrix} \sigma \cdot \vec{p} & 0 \\ 0 & -\sigma \cdot \vec{p} \end{pmatrix}$$

$$\hat{u} = \begin{pmatrix} \psi_A^+ \\ \psi_B^+ \\ \psi_A^- \\ \psi_B^- \end{pmatrix} \qquad \hat{H}\hat{u} = \varepsilon\hat{u}$$

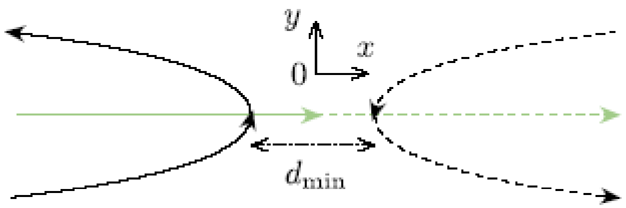
Chirality in valley K_+

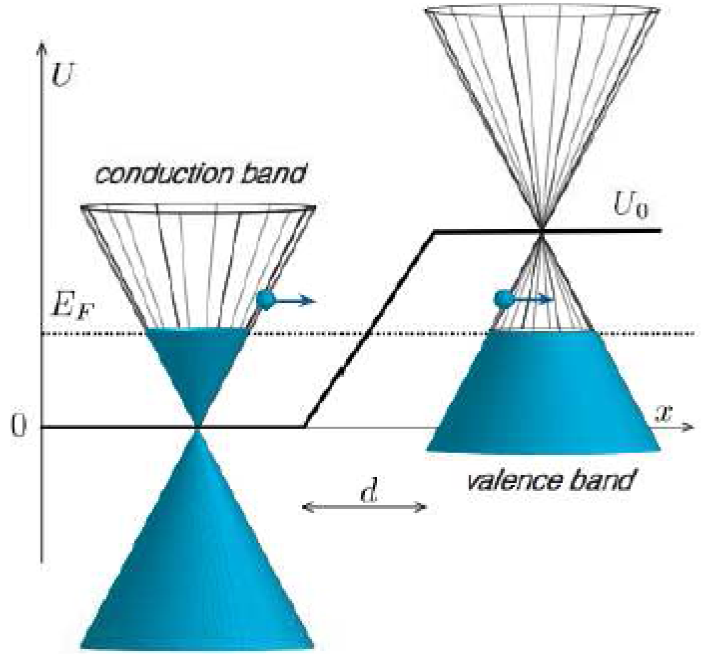
$$\sigma \cdot \hat{n} = +1$$ **for conduction band**

$$\sigma \cdot \hat{n} = -1$$ **for valance band**

[M. I. Katsnelson, K. S. Novesolov A. K. Geim, Nature Phys. **2**, 620 (2006);…..]

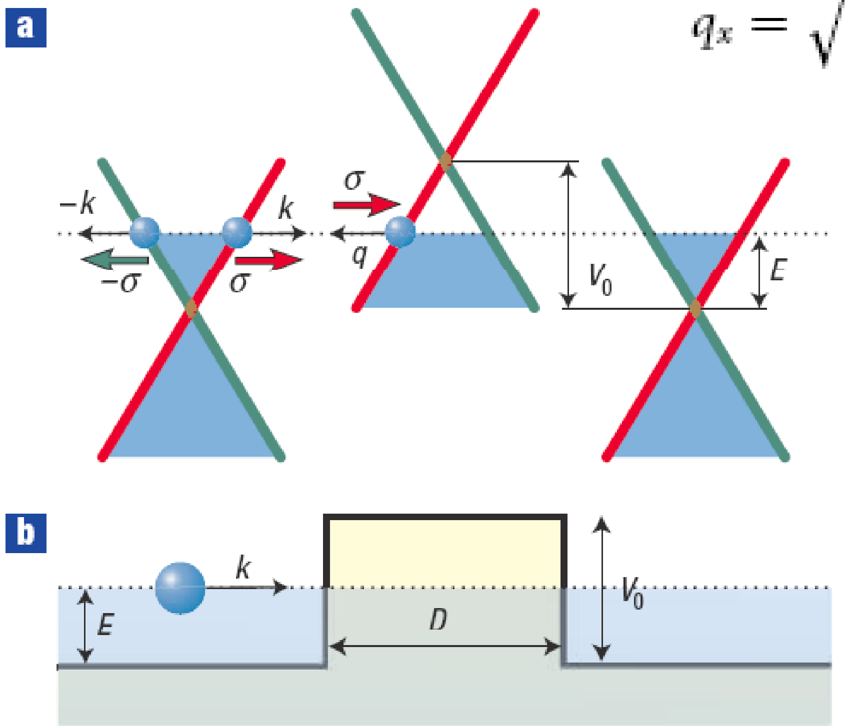
Klein tunnelling





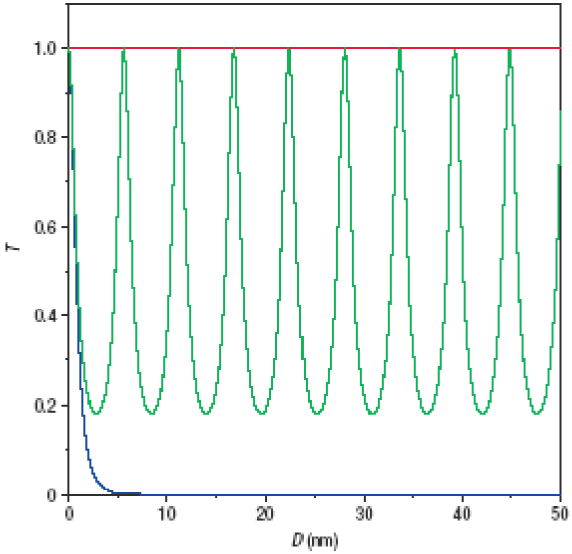
[M. I. Katsnelson, K. S. Novesolov A. K. Geiml, Nature Phys. **2**, 620 (2006);…..]

Klein tunnelling



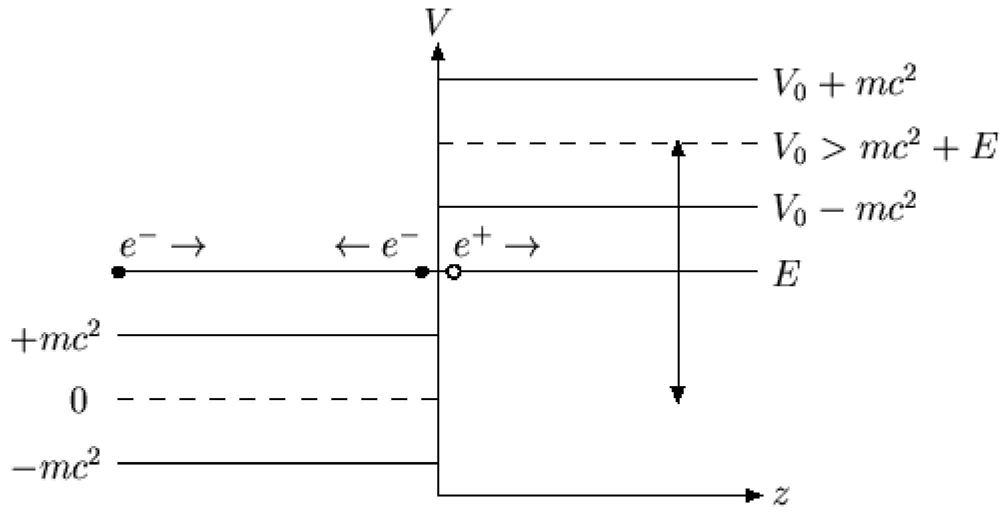
$$q_x = \sqrt{(E-V_0)^2/\hbar^2 v_F^2 - k_y^2},\ \theta = \tan^{-1}(k_y/q_x)$$

$$T = \frac{\cos^2\phi}{1-\cos^2(q_x D)\sin^2\phi}.$$



[M. I. Katsnelson, K. S. Novesolov A. K. Geim, Nature Phys. **2**, 620 (2006);…..]

Klein paradox in relativistic quantum theory

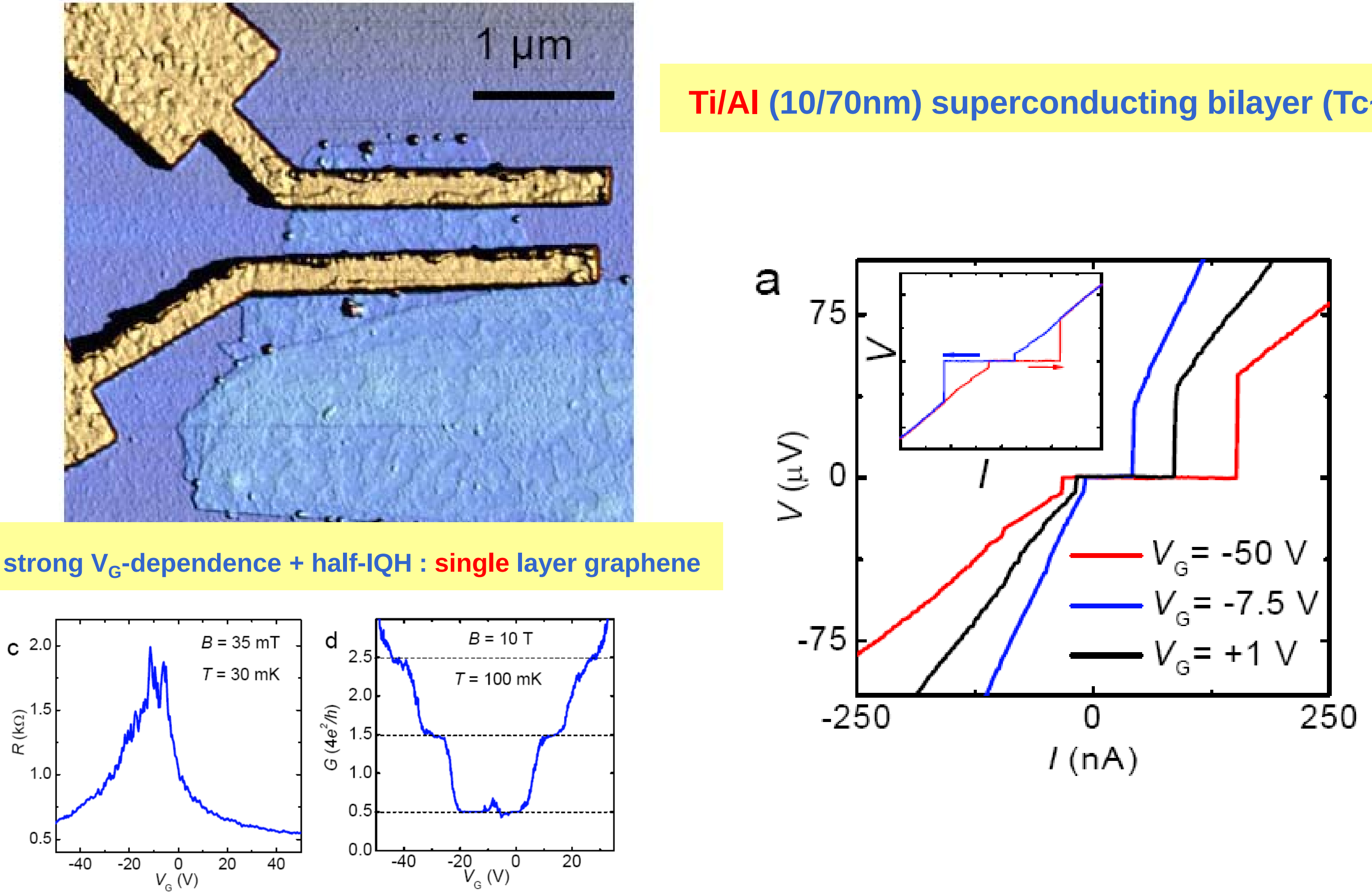


[O. Klein, Z. Phys. **53**, 157 (1929)]

Bipolar supercurrent in graphene Josephson contact

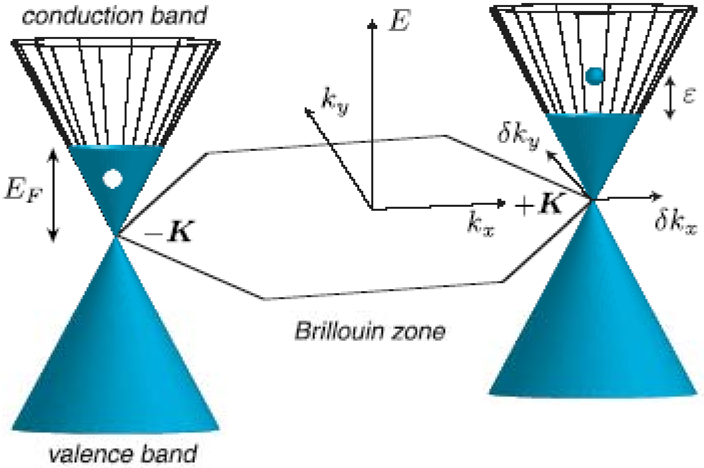
Ti/Al (10/70nm) superconducting bilayer (Tc~1.3 K)

strong V_G-dependence + half-IQH : single layer graphene

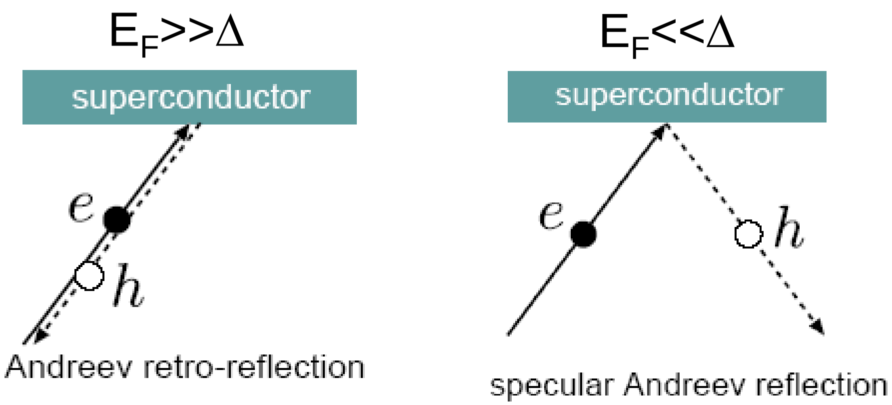


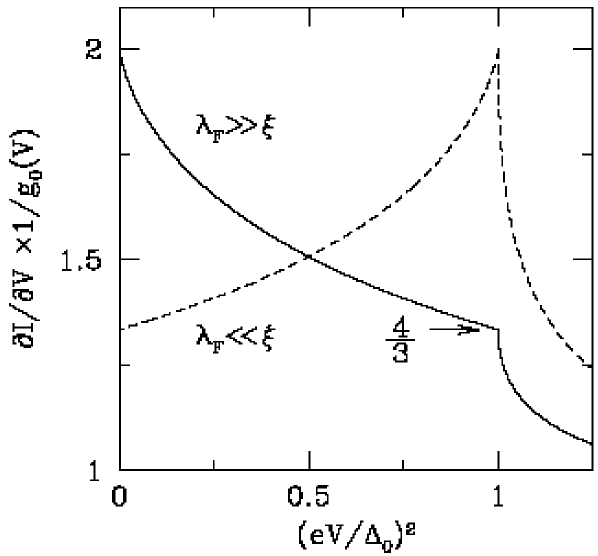
[Heersche et al, Nature **446,** 56-59 (2007);…]

Specular Andreev reflection in graphene NS junctions



Superconducting correlation of massless Dirac electrons with opposite spin and different valley

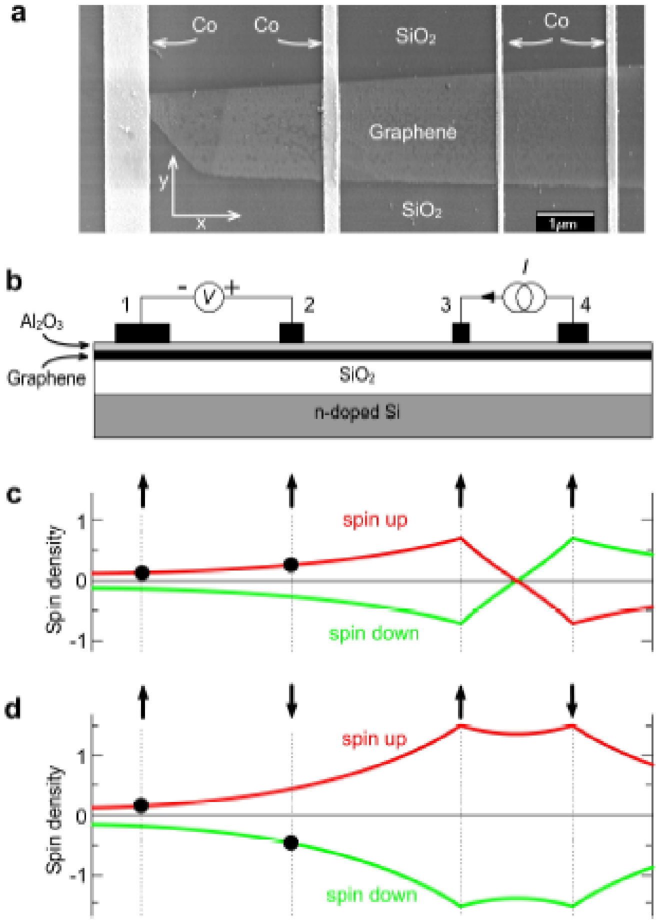


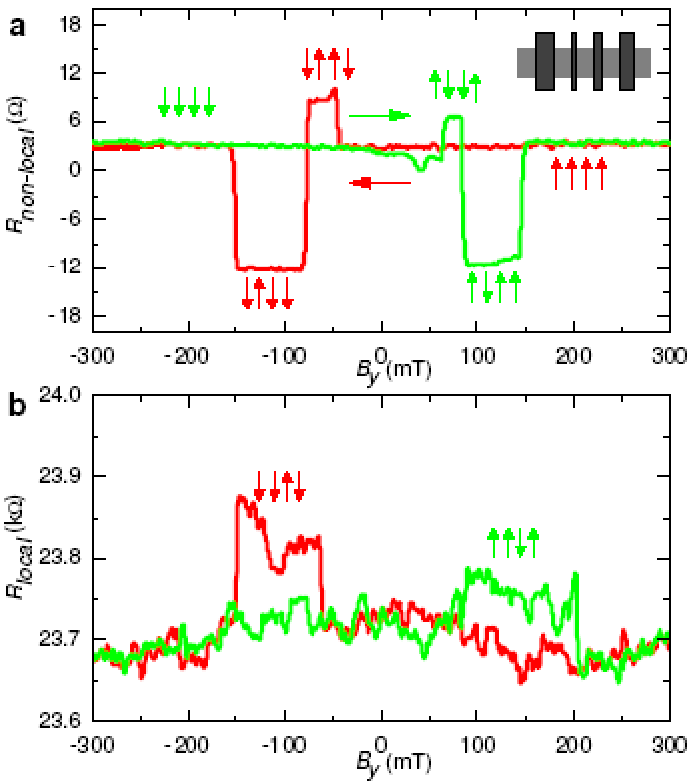


GS Junction

[C. W. J. Beenakker Phys. Rev. Lett. **97**,067007 (2006)]

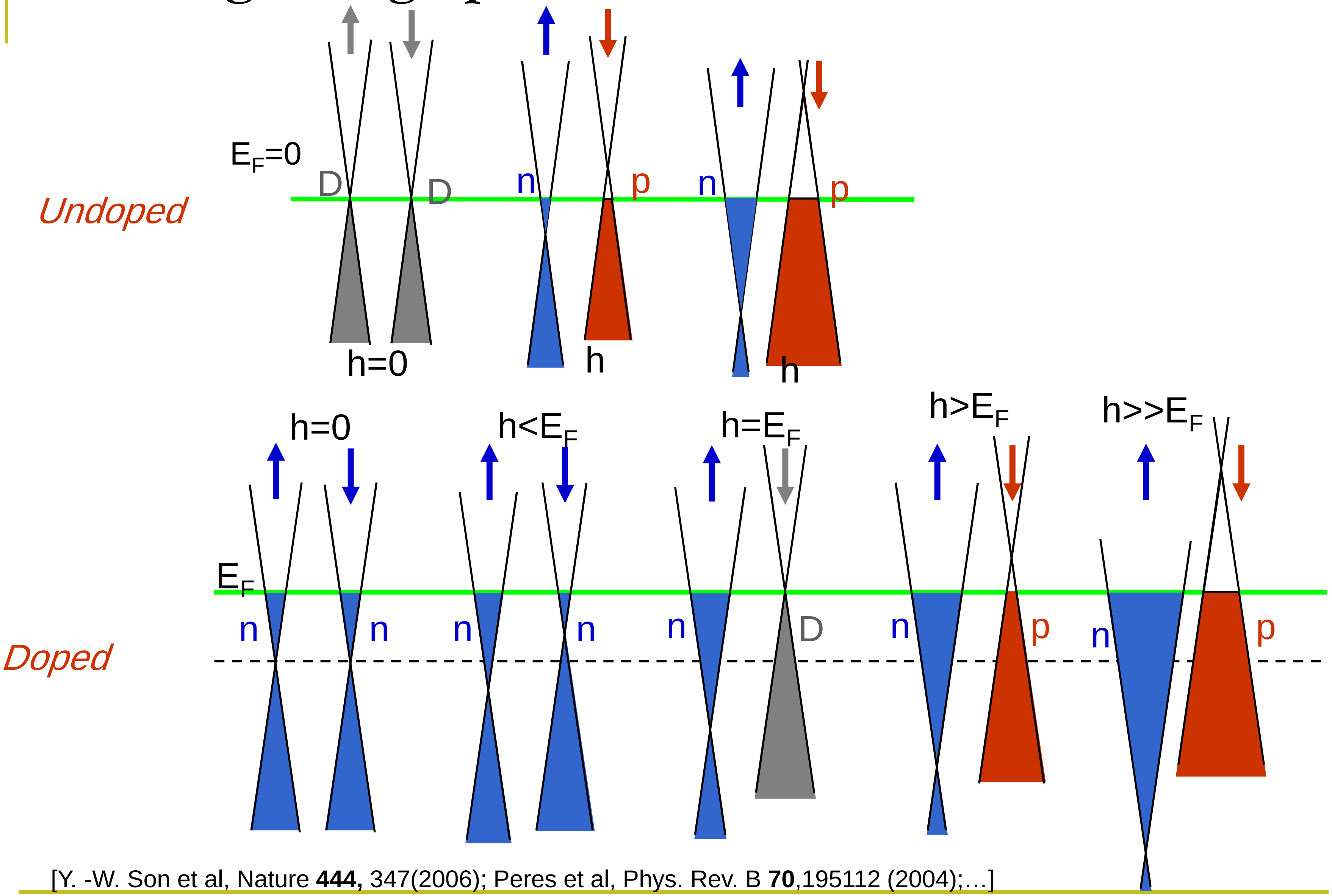
Graphene Spin-Valve





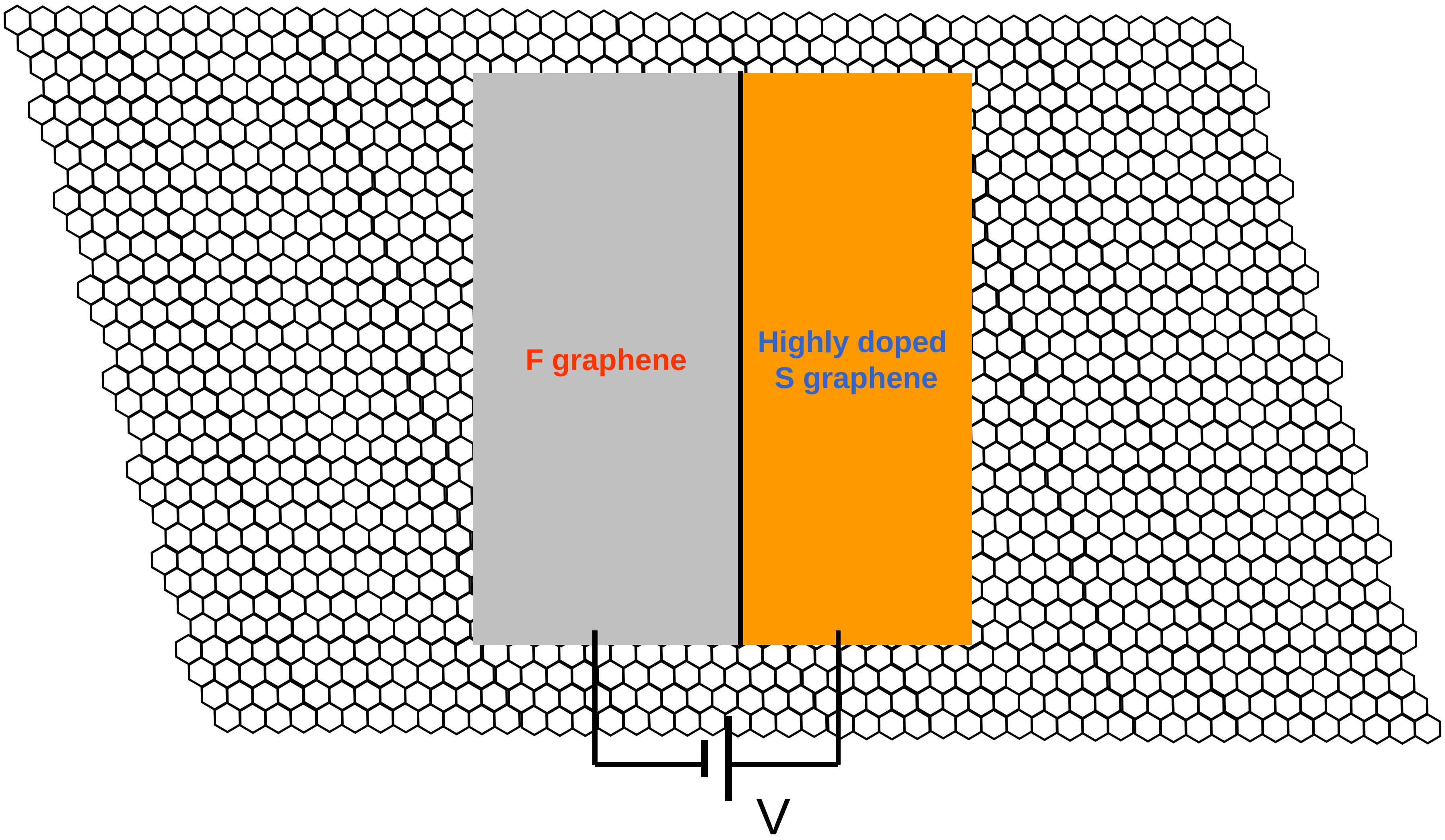
[N. Tomboros et al, Nature **448,** 571(2007);…..]

Ferromagnetic graphene



[Y. -W. Son et al, Nature **444,** 347(2006); Peres et al, Phys. Rev. B **70**,195112 (2004);…]

Graphene FS junction



Dirac-Bogoliubov-deGennes equations

Electron-hole conversion: superconducting correlations

electron 4-component spinor

$$\begin{pmatrix} v_F \hat{\sigma}\cdot\vec{p} - sh\hat{1} - E_F\hat{1} & \Delta\hat{1} \\ \Delta^*\hat{1} & -(v_F\hat{\sigma}\cdot\vec{p} - \bar{s}h\hat{1} - E_F\hat{1}) \end{pmatrix} \begin{pmatrix} \hat{u}_s \\ \hat{v}_{\bar{s}} \end{pmatrix} = \varepsilon_s \begin{pmatrix} \hat{u}_s \\ \hat{v}_{\bar{s}} \end{pmatrix}$$

Diagonal Dirac Hamiltonian with exchange field

hole 4-component spinor

$$s = \bar{s} = \pm 1$$

Superconducting correlation of massless Dirac electrons with opposite spin and different valley

Variety of Andreev processes

$$r_s = \frac{\sec\beta\sqrt{\cos\phi_s \cos\phi'_{\bar{s}}}}{\cos[(\phi_s - \phi'_{\bar{s}})/2] + i\tan\beta\cos[(\phi_s + \phi'_{\bar{s}})/2]}$$

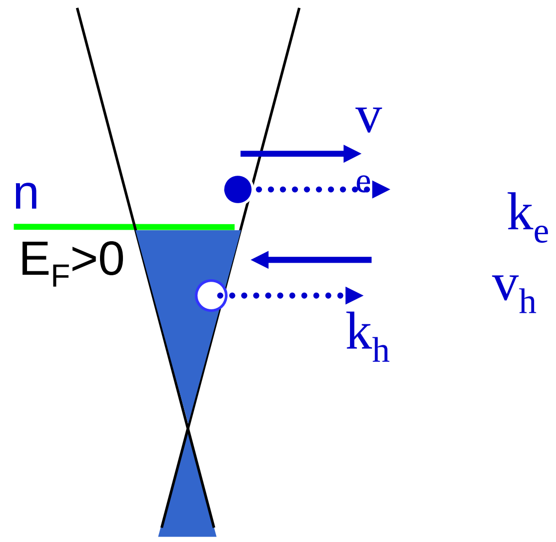
$$\beta = \cos^{-1}(\varepsilon/\Delta)$$

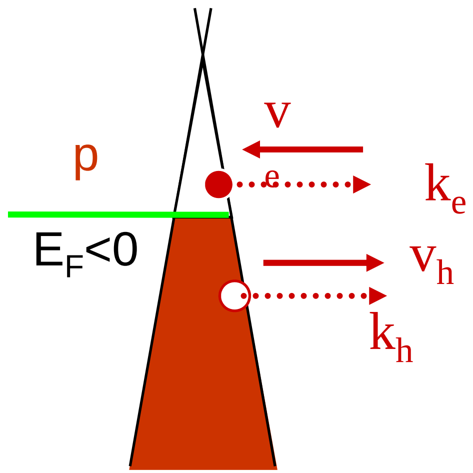
$$r_{As} = \frac{-\sin[(\phi_s + \phi'_{\bar{s}})/2] + i\tan\beta\cos[(\phi_s - \phi'_{\bar{s}})/2]}{\cos[(\phi_s - \phi'_{\bar{s}})/2] + i\tan\beta\cos[(\phi_s + \phi'_{\bar{s}})/2]}$$

$$\varepsilon_s = \left| E_F \pm \hbar v_F \sqrt{k_x^2 + k_y^2} + sh \right|, \quad \vec{v}_s = \frac{1}{\hbar}\frac{\partial \varepsilon_s}{\partial \vec{k}}$$

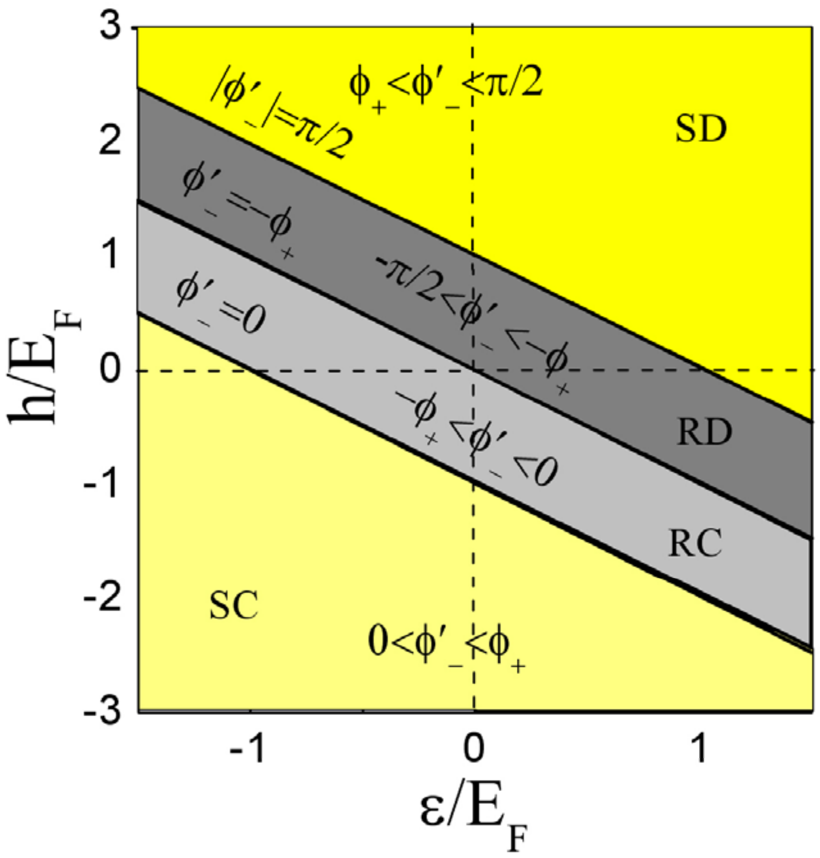
$$k'_{y-} = k_{y+}$$

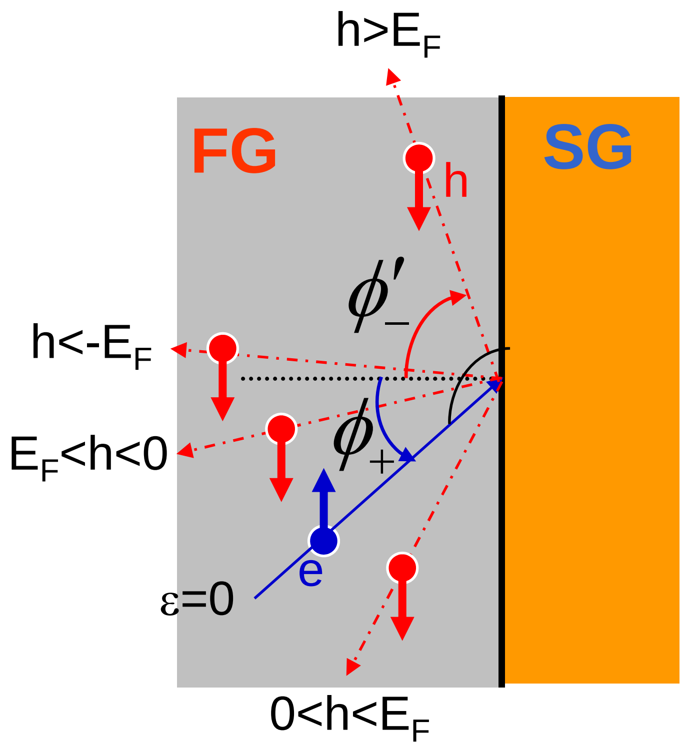
$$k'_{x-} = \sqrt{(\varepsilon + h + E_F)^2 - (\varepsilon + h + E_F)^2 \sin^2\phi_+}$$





Map of Andreev reflection angle

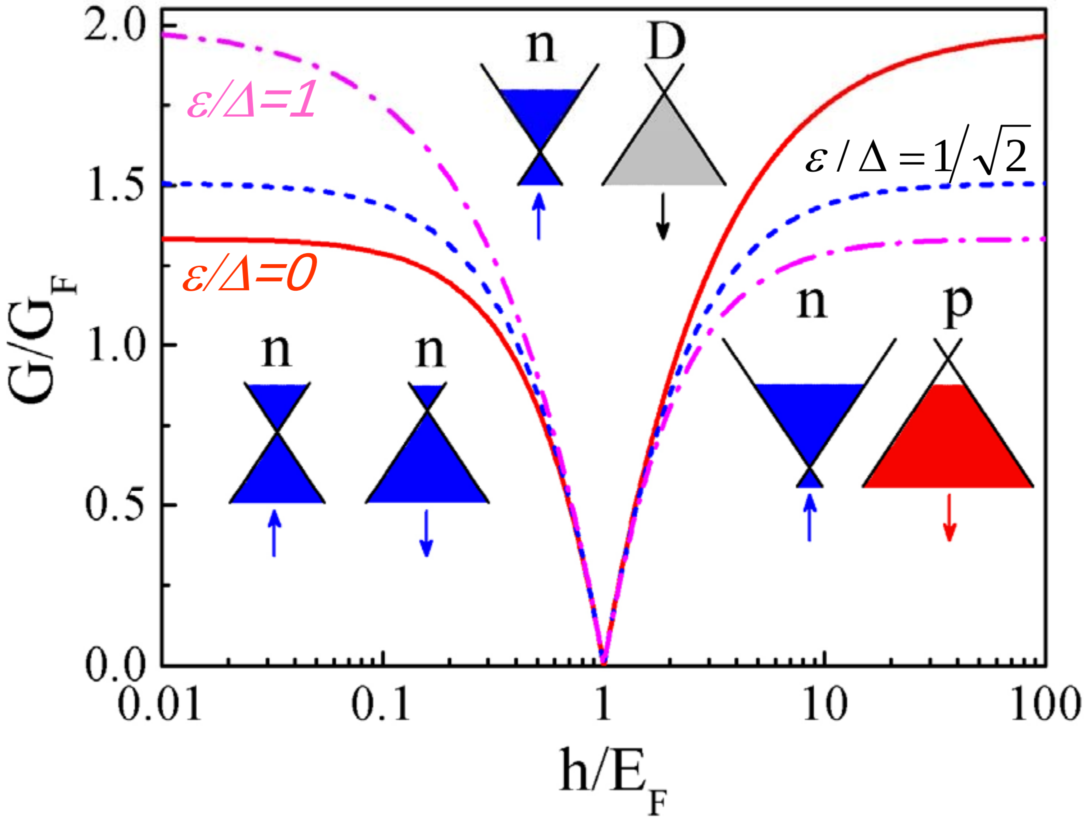




[M. Z. , H. Mohammadpour, A. G. Moghaddam, arXiv: 0804.2774v1(2008)]

Andreev-Klein conductance of FS contacts

$$G = \sum_{s=\pm} G_s \int d\phi_s \cos\phi_s (1 - r_s + r_{As}), \quad G_F = \sum_{s=\pm} G_s$$



[M. Z. , H. Mohammadpour, A. G. Moghaddam, arXiv: 0804.2774v1(2008)]

Conclusion

• AR from FS interface is fundamentally different for $h>E_F$: associated with spin Klein tunnelling of chiral electrons through exchange field p-n barrier: Andreev-Klein reflection

• It can be retro or specular in both convergent way and divergent way

• Exchange field induced enhancement of Andreev conductance: ferromagnetic ordering amplifies spin-singlet superconducting correlations!!!