Andreev Reflection in a Monolayer MoS_2

Leyla Majidi

with

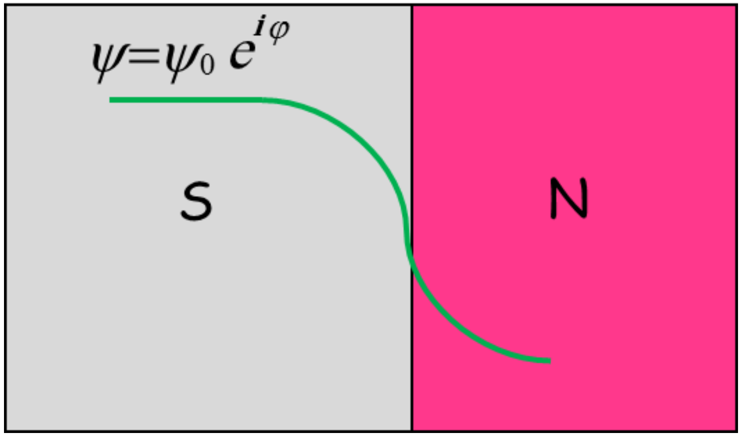
Habib Rostami and Dr. Reza Asgari

School of physics, Institute for Research in Fundamental Sciences (IPM), Tehran

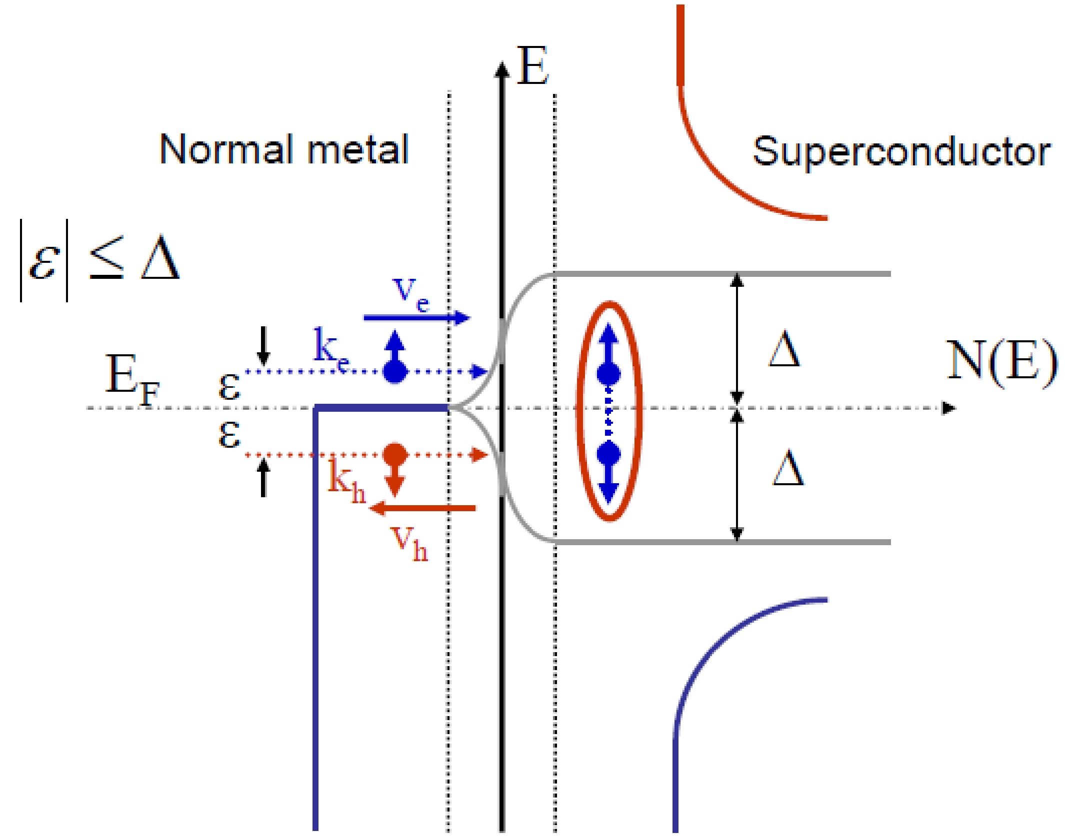
Workshop on Electronic Properties of MoS2

IPM 2013, October 2

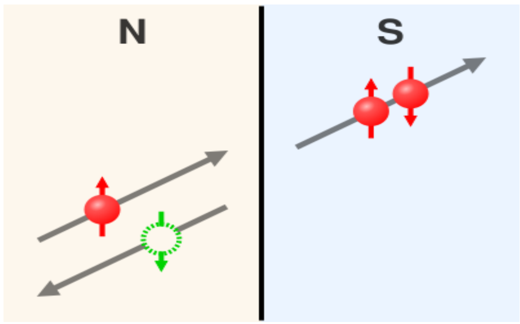
Superconducting Proximity Effect



Andreev Reflection in S/N Junctions

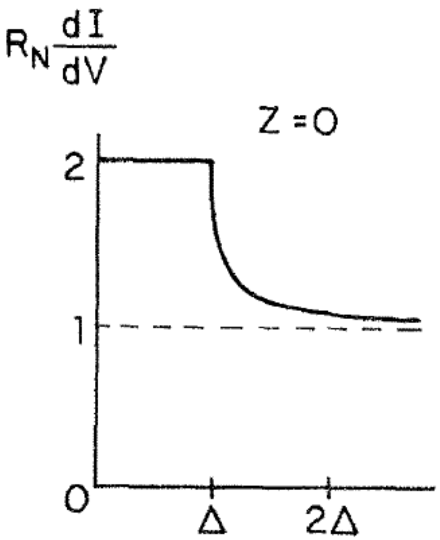


Retro Andreev Reflection



A. F. Andreev, Sov. Phys. JETP 19, 1228 (1964).

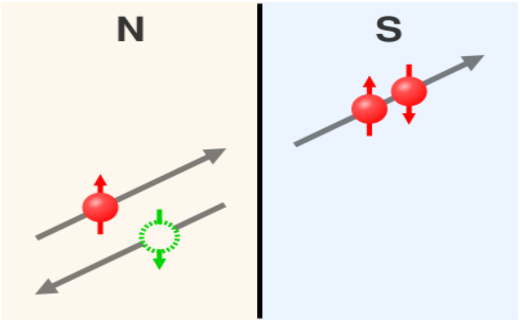
Andreev Reflection in S/N Junctions



Differential conductance vs voltage at T=0

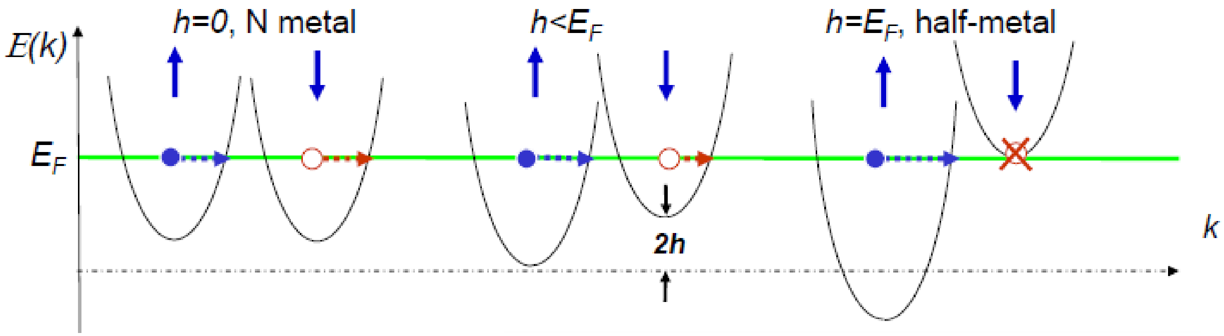
BTK, PRB **25**, 4515 (1982)

Retro Andreev Reflection



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

Andreev Reflection in F/S Junctions



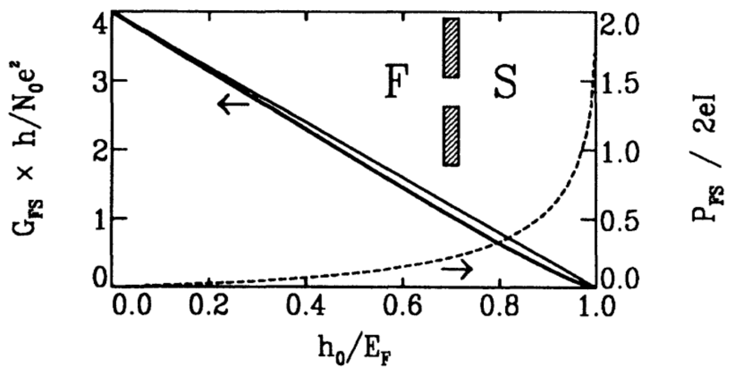
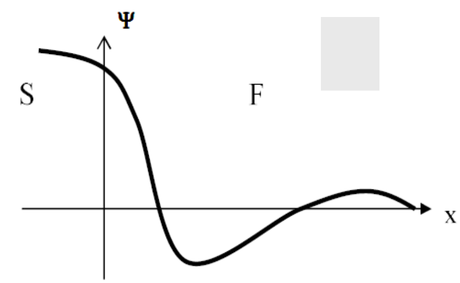


FIG. 1. The conductance G_{FS} (full curves) and the shot-noise power P_{FS} (dashed) of a ballistic point contact in a ferromagnet-superconductor junction (see inset), as a function of the exchange energy h_0. The thick line represents the exact result (7) for G_{FS}, the thin line the estimation (2).



Momentum change ~$2h/v_F$

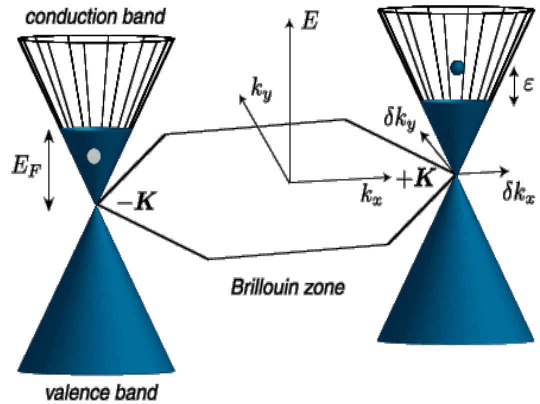
Ferromagnetism and singlet-spin superconductivity are exclusive phenomena

M. J. M. de Jong and C. W. J. Beenakker, Phys. Rev. Lett. 74, 1657 (1995).

Andreev Reflection in Atomically Thin 2D Crystals:

Graphene, Transition-Metal Dichalcogenids (TDMs), …

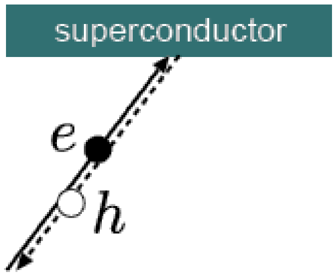
Andreev Reflection in Graphene S/N Junction



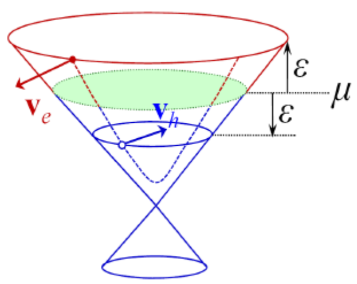
Superconducting correlation of massless Dirac electrons with opposite spin and different valley

Highly doped Graphene

$E_F >> \Delta$

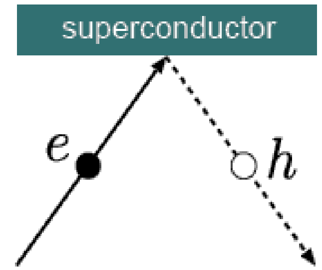


Andreev retro-reflection

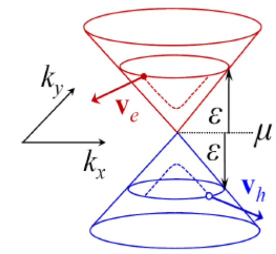


Undoped Graphene

$E_F << \Delta$

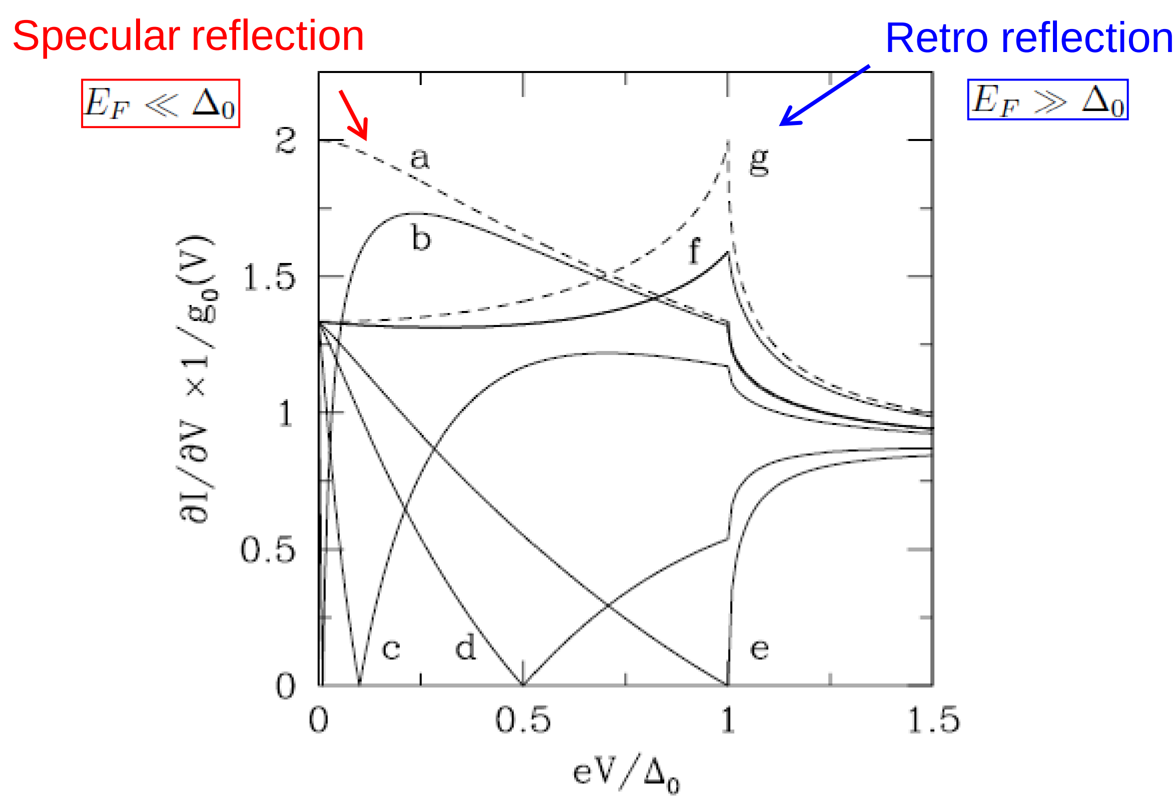


specular Andreev reflection



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

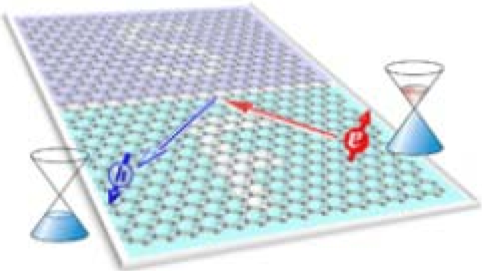
Andreev Reflection in Graphene S/N Junction

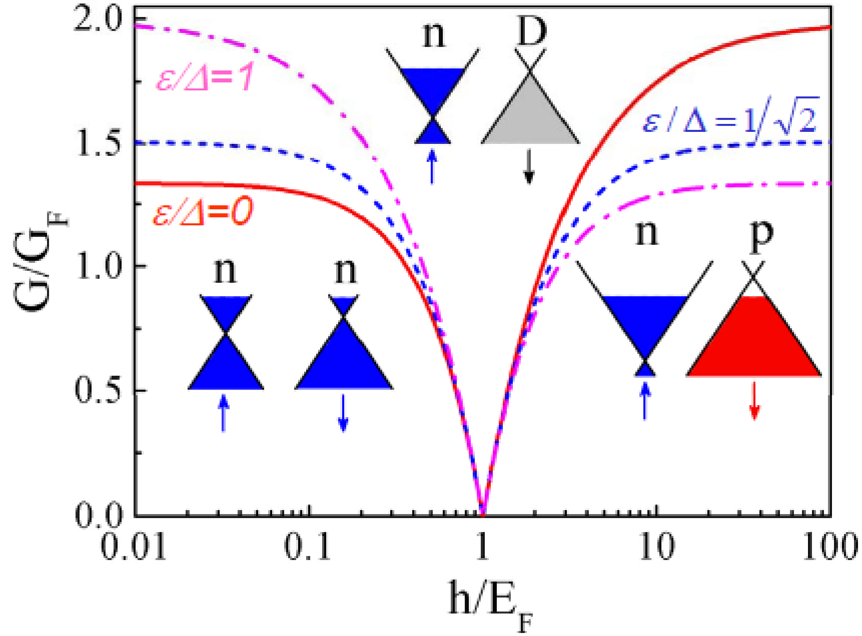


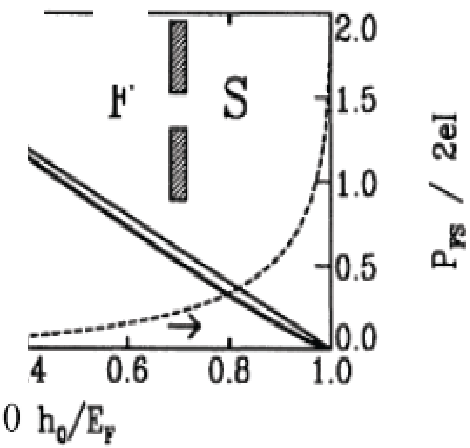
Differential conductance of the NS interface for E_F/Δ_S = 0.01, 0.1, 0.5, 1, 10 (solid curves labeled b,c,d,e,f, respectively). The dashed curves are the asymptotes for $E_F/\Delta_S \to 0,\infty$ (labeled a,g, respectively).

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

Andreev Reflection in Graphene S/F Junction





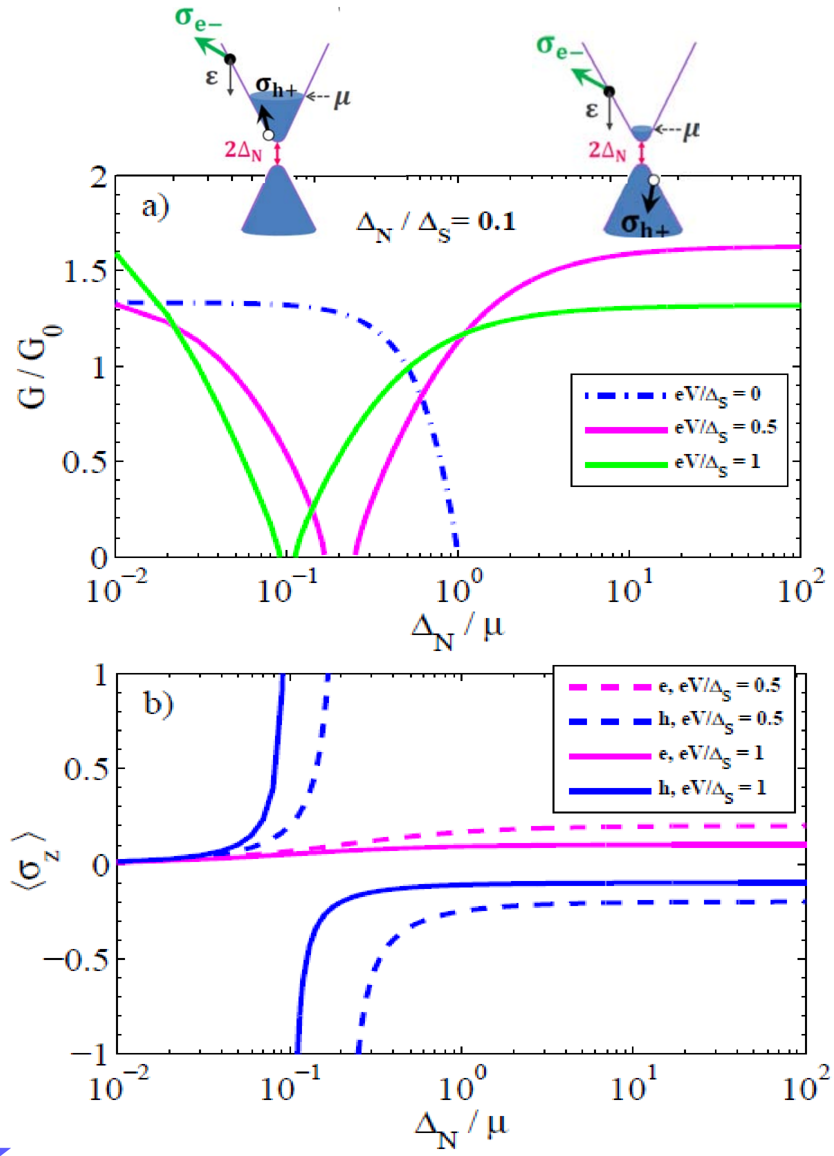


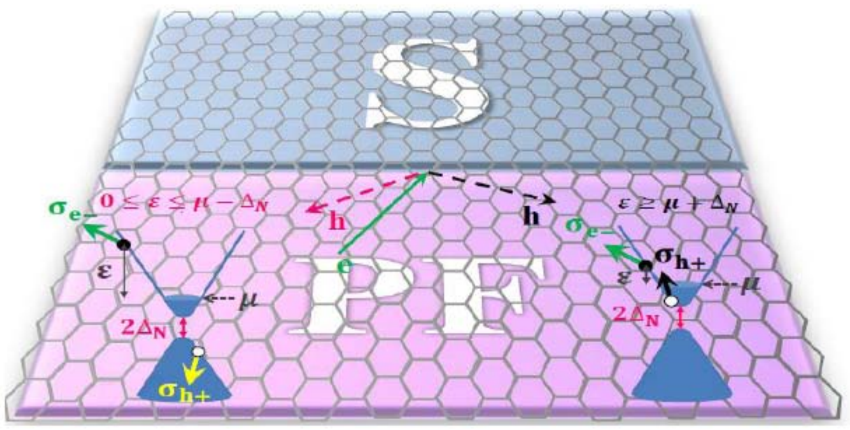
...g and C. W. J. Beenakker, Phys. Rev. Lett. **74**, 1657 (1995).

for a highly doped F, $E_F \gg \Delta$

M. Zareyan, H. Mohammadpour, and A. G. Moghaddam, Phys. Rev. B 78, 193406 (2008)

Andreev Reflection in Graphene S/PF Junction





$\Delta_N < \mu/(1+eV/\Delta_N)$ AR without $<\sigma_z>$ inversion

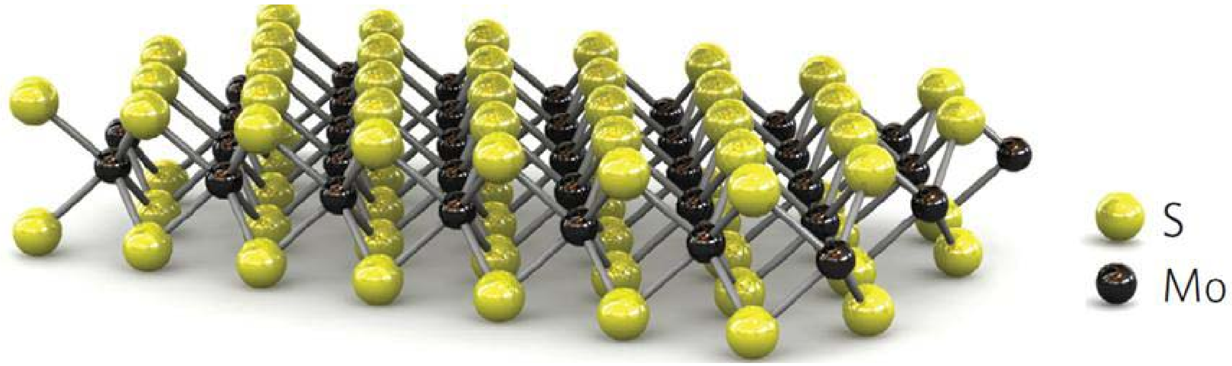
$\mu/(1+eV/\Delta_N) < \Delta_N < \mu/(eV/\Delta_N - 1)$ Gap

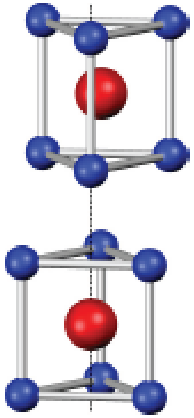
$\Delta_N \geqslant \mu/(eV/\Delta_N - 1)$ AR with $<\sigma_z>$ inversion

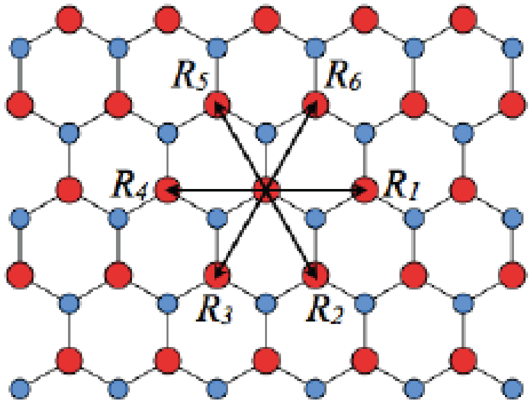
FIG. 2. (Color online) (a) Dependence of Andreev conductance of graphene S/PF contact on the gap Δ_N/μ (in units of the chemical potential) at three bias voltages $eV/\Delta_S = 0, 0.5, 1$. (b) The behavior of the z component of the pseudospin vector $\langle\sigma_z\rangle$ vs Δ_N/μ for the incident electron from the conduction band and the reflected hole from the conduction (before the gap) or valence band (after the gap) at two values of the bias voltage $eV/\Delta_S = 0.5,\ 1$, when $\Delta_N/\Delta_S = 0.1$.

L. Majidi and M. Zareyan, Phys. Rev. B 86, 075443 (2012)

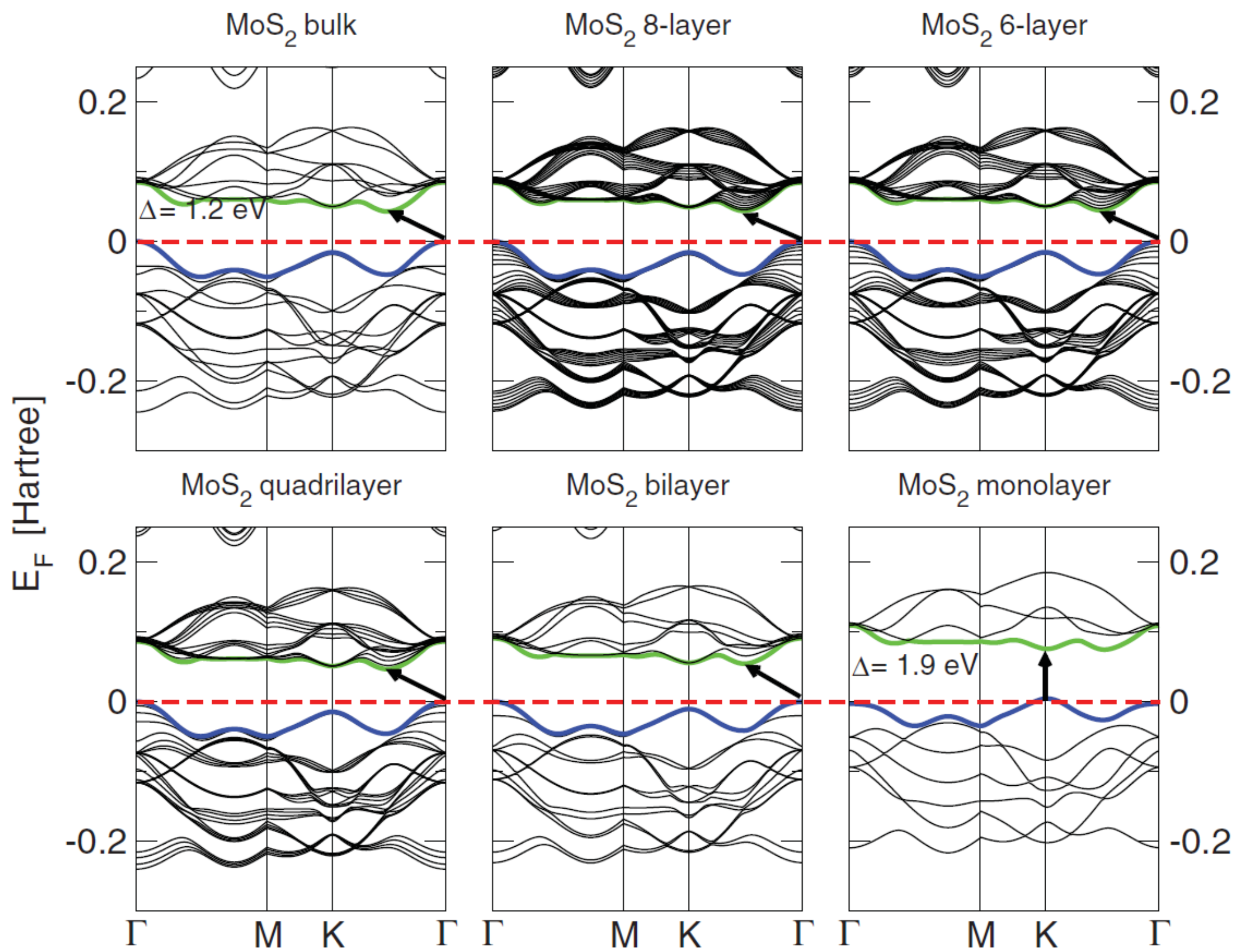
TMDCs: MoS_2 Crystal





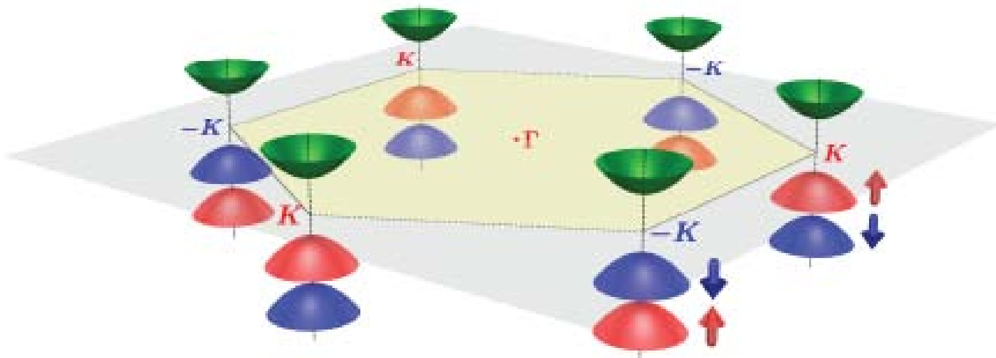


Band Structure



Kuc, *et al*, *Phys. Rev. B* ***83, 245213 (2011)***

Low-energy Hamiltonian



$$\hat{H} = at(\tau k_x \hat{\sigma}_x + k_y \hat{\sigma}_y) + \frac{\Delta}{2}\hat{\sigma}_z - \lambda\tau\frac{\hat{\sigma}_z - 1}{2}\hat{s}_z$$

$$\Delta = 1.9\text{eV}$$
$$\lambda = 80\text{meV}$$

Di Xiao, *et al* , *Phys. Rev. Lett.* ***108,196802 (2012)***

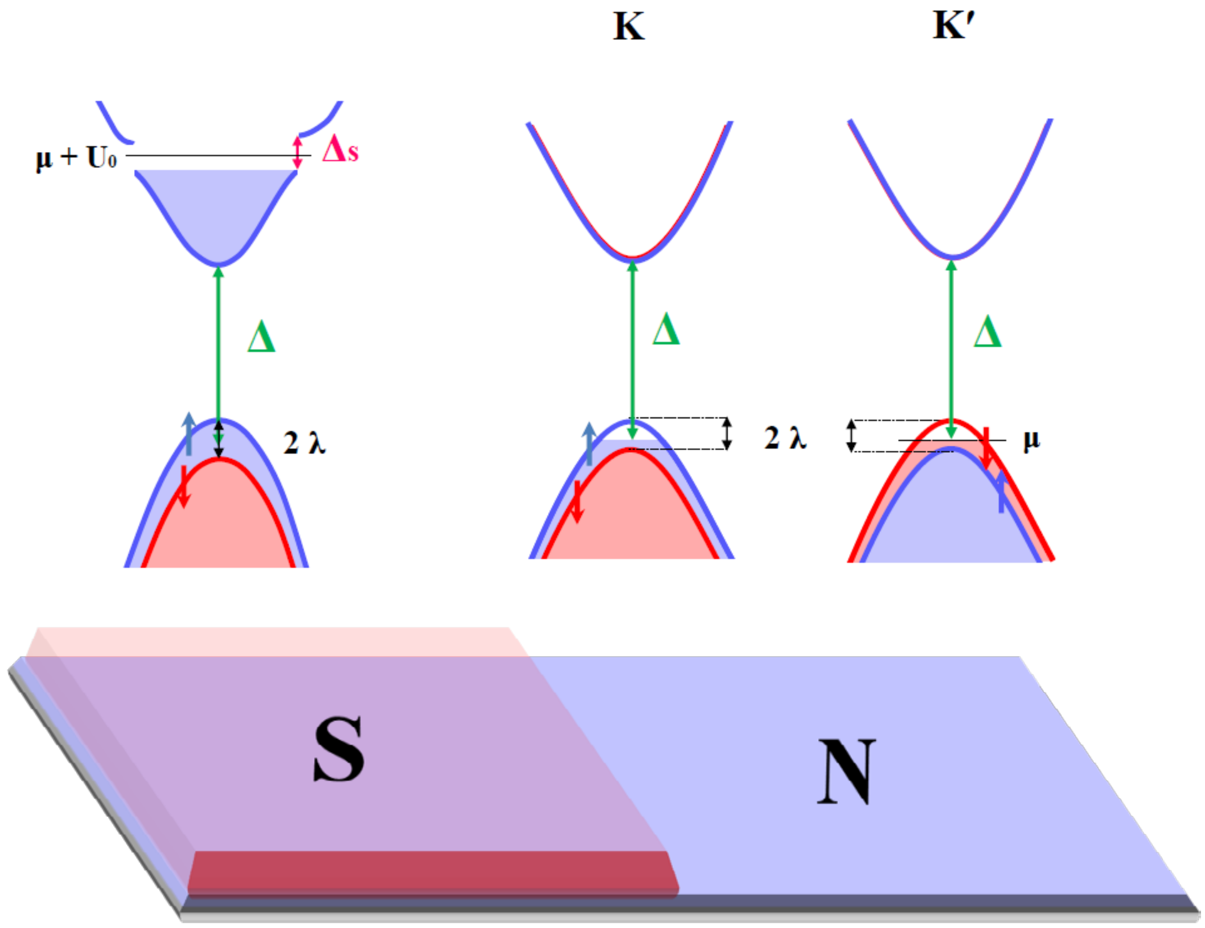
The difference between electron and hole masses recently reported by using ab initio calculations
Phys. Rev. B 86, 241401(R) (2012).

$$H_{\tau s} = \frac{\Delta}{2}\sigma_z + \lambda\tau s\frac{1-\sigma_z}{2} + t_0 a_0 \mathbf{q}\cdot\boldsymbol{\sigma}_\tau + \frac{\hbar^2|\mathbf{q}|^2}{4m_0}(\alpha + \beta\sigma_z) + t_1 a_0^2 \mathbf{q}\cdot\boldsymbol{\sigma}_\tau^* \sigma_x \mathbf{q}\cdot\boldsymbol{\sigma}_\tau^*$$

$$\alpha = 0.43$$
$$\beta = 2.21$$

H. Rostami, A. G. Moghaddam, R. Asgari, ***Phys. Rev. B 88, 085440 (2013)***

MoS_2-based S/N junction



Dirac-Bogoliubov-de Gennes (DBdG) equation

DBdG equation describes the superconducting correlations between relativistic electrons and holes with opposite spins and different valley indices

Electron-hole conversion: superconducting correlations

$$\begin{pmatrix} H - U(\boldsymbol{r}) - \mu & \Delta_S \\ \Delta_S^* & \mu + U(\boldsymbol{r}) - H \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = \varepsilon \begin{pmatrix} u \\ v \end{pmatrix}$$

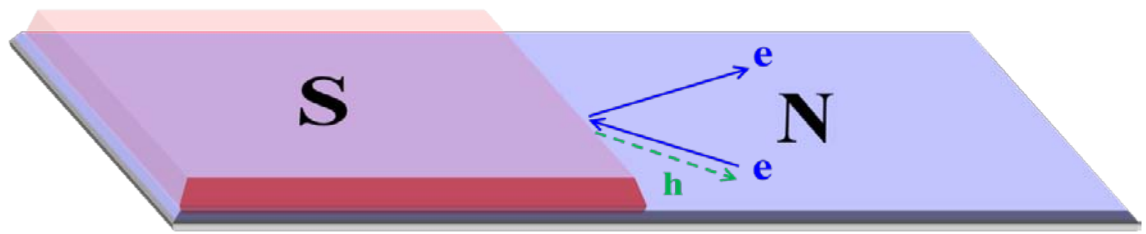
2D Hamiltonian of a monolayer *MoS_2*

$$H = v_F(\boldsymbol{\sigma}.\boldsymbol{p}) + \frac{\Delta}{2}\sigma_z + \lambda s\tau \left(\frac{1-\sigma_z}{2}\right) - \frac{\hbar^2\boldsymbol{\nabla}^2}{4m_0}(\alpha + \beta\sigma_z)$$

$$\begin{cases} \Delta = 1.9eV \\ \lambda = 80meV \\ \alpha = 0.43 \text{ and } \beta = 2.21 \end{cases}$$

$$s = \pm 1$$
$$\tau = \pm 1$$

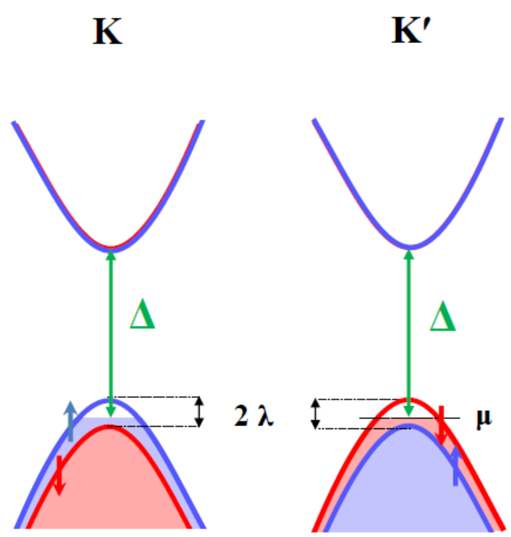
Andreev Reflection in MoS_2



$-\Delta/2 - \lambda - \varepsilon < \mu_N < -\Delta/2 + \lambda - \varepsilon$

Spin-valley polarized AR process

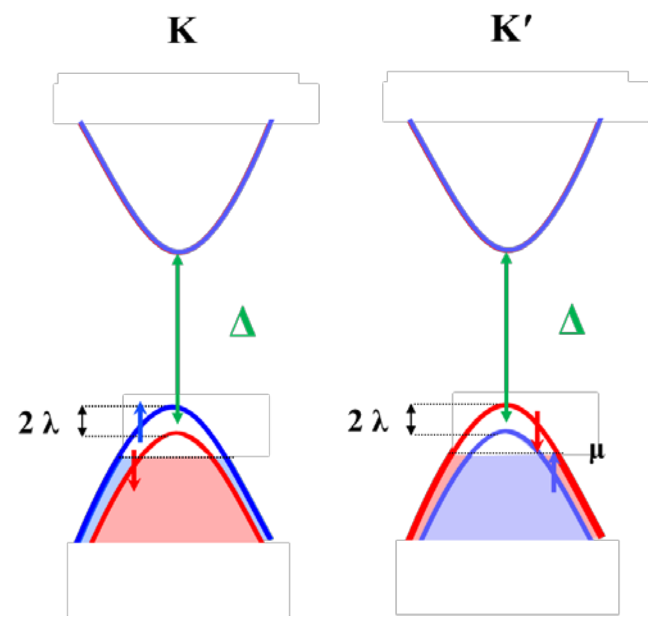
$\boxed{s\tau = 1}$



$s = \tau = 1$ $\quad$ $s = \tau = -1$

$\mu_N \leq -\Delta/2 - \lambda - \varepsilon$

$\boxed{s\tau = \pm 1}$



normal reflection

Andreev reflection

$$\begin{cases} \psi_N = \psi^{e-} + r^{s,\tau}\ \psi^{e+} + r_A^{s,\tau}\ \psi^{h+}, \\ \psi_S = t\ \psi^{S+} + t'\ \psi^{S-}. \end{cases}$$

Andreev conductance (BTK formula)

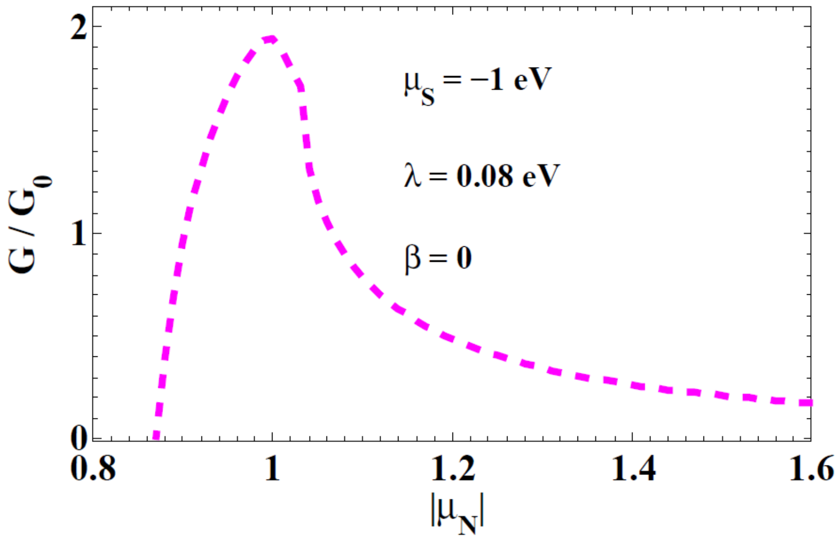
$$G = \sum_{\tau,s=\pm 1} G_0^{\tau,s} \int_0^{\theta_c} (1 - |r^{\tau,s}|^2 + |r_A^{\tau,s}|^2) \cos\theta_e \ d\theta_e$$

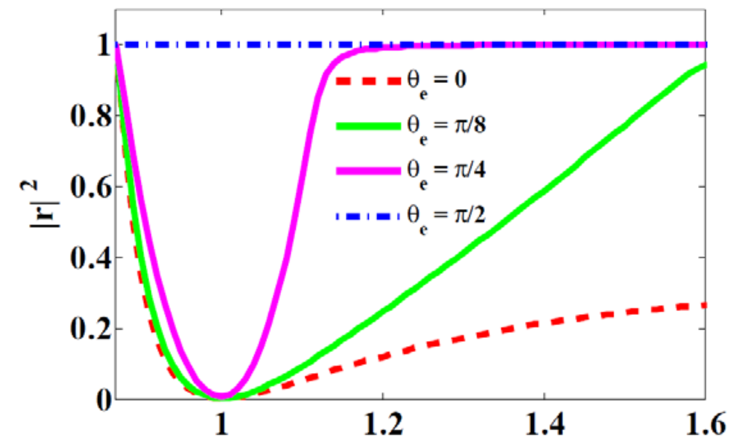
$$G_0^{\tau,s} = \frac{e^2}{h} N_{\tau,s}(eV)$$

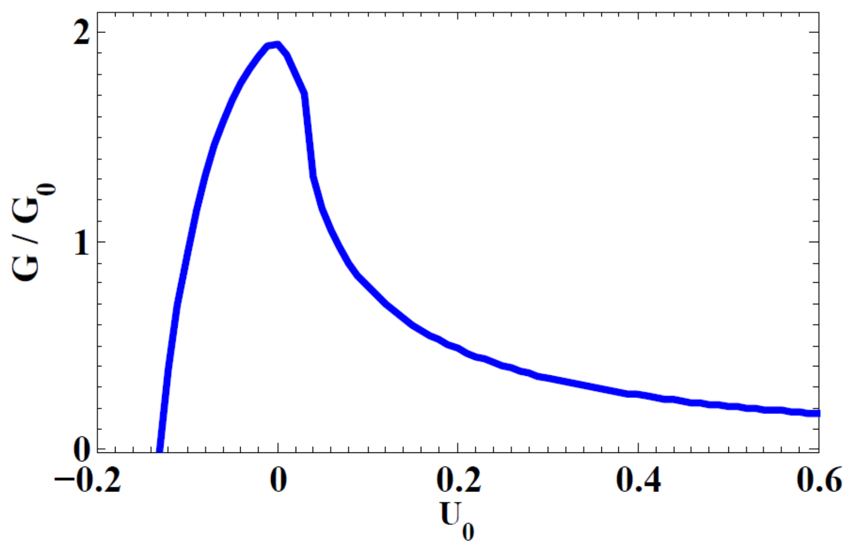
Andreev Reflection in S(p)/N(p) Junction

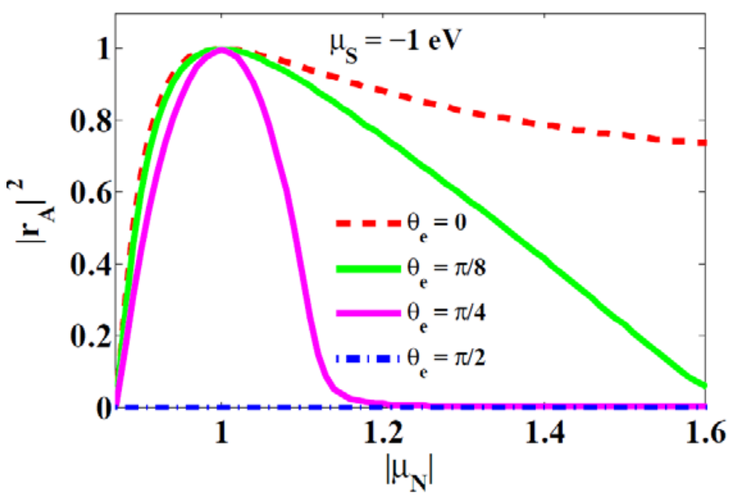
$$\mu_S = \mu + U_0$$

$$\mu_N = \mu \quad (\mu_N < 0)$$

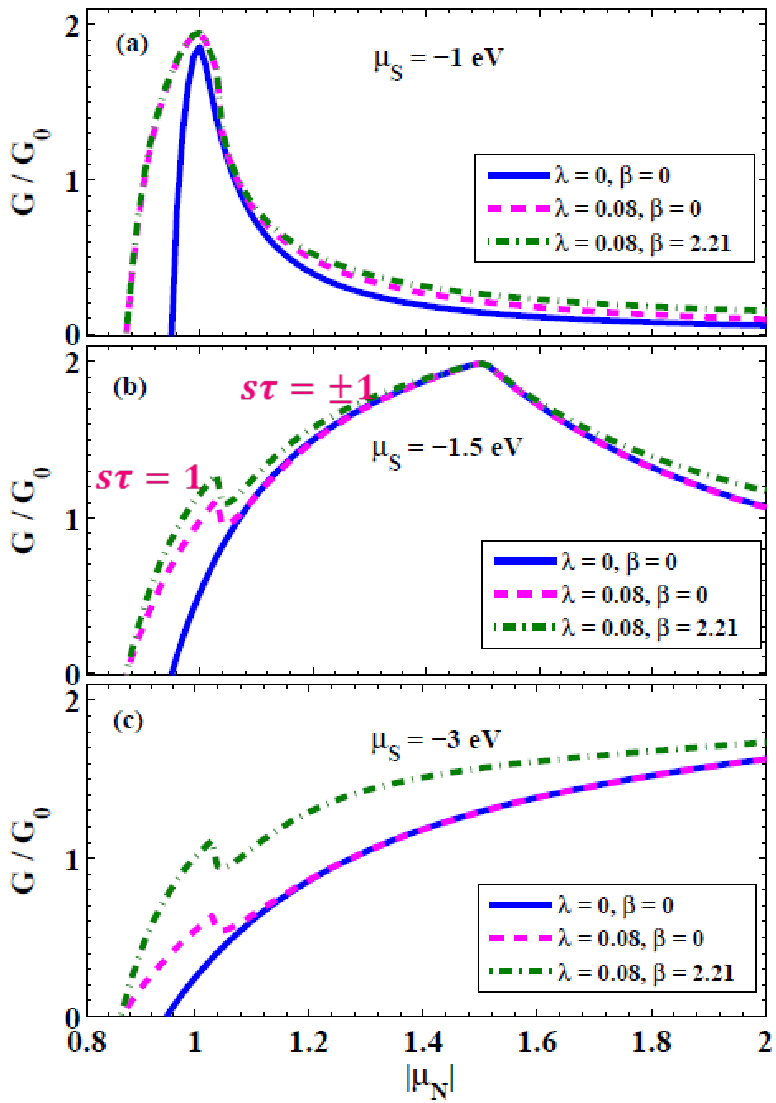








Andreev Reflection in S(p)/N(p) Junction



L. Majidi, H. Rostami, R. Asgari (to be submitted)

- ❖ **Gapped Graphene (λ=0, β= 0)**
- ❖ **MoS_2 (λ=0.08 eV) with β= 0**
- ❖ **MoS_2 (λ=0.08 eV) with β= 2.21**

$\alpha = 0$

Amplification of the proximity inducing superconductivity in N region

FIG. 2: Dependence of the Andreev conductance of S/N contact with p-doped S region on the chemical potential $|\mu_N|$ (in units of eV) at three chemical potentials $\mu_S = -1, -1.5, -3\ eV$, for gapped graphene ($\lambda = 0, \beta = 0$), MoS_2 ($\lambda = 0.08eV$) with $\beta = 0$ and $\beta = 2.21$, when $\alpha = 0$, $\Delta_S = 0.01eV$ and $eV/\Delta_S = 0$.

Andreev Reflection in S(p)/N(p) Junction

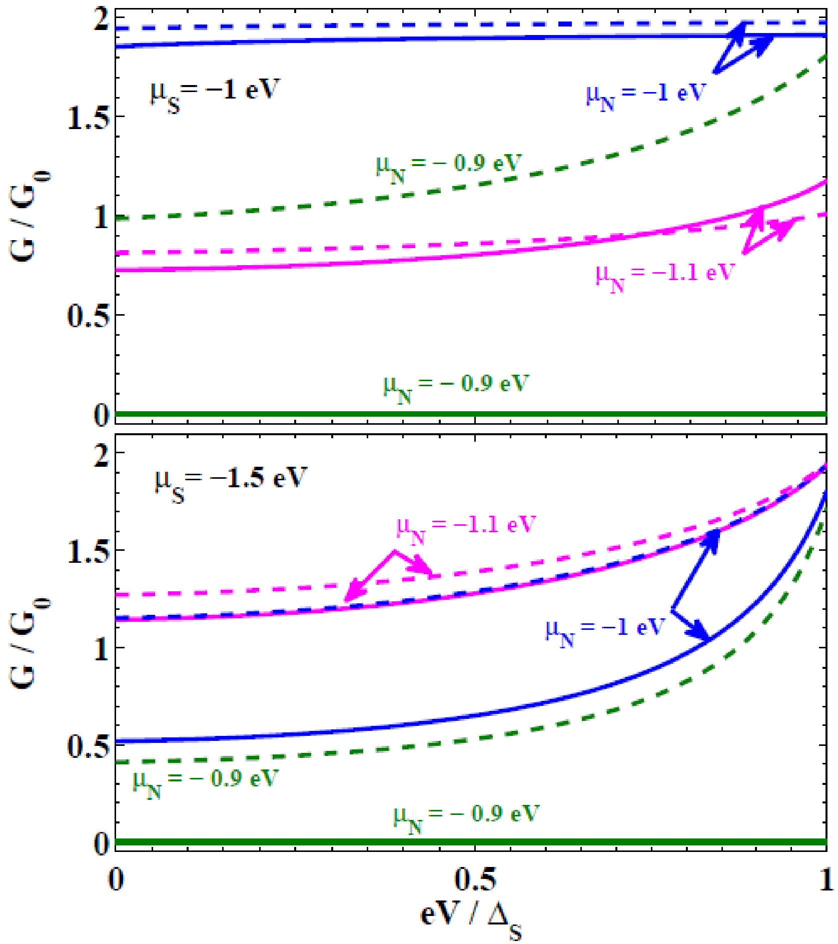


FIG. 3: Plot of the Andreev conductance of S/N contact (with p-doped S region) versus the bias voltage eV/Δ_S (in units of the superconducting gap Δ_S) at two values of $\mu_S = -1, -1.5\ eV$, for gapped graphene with $\lambda = 0, \beta = 0$ (solid lines) and MoS_2 with $\lambda = 0.08eV, \beta = 2.21$ (dashed lines), when $\mu_N = -0.9, -1, -1.1\ eV$ and $\alpha = 0$.

Andreev Reflection in S(n)/N(p) Junction

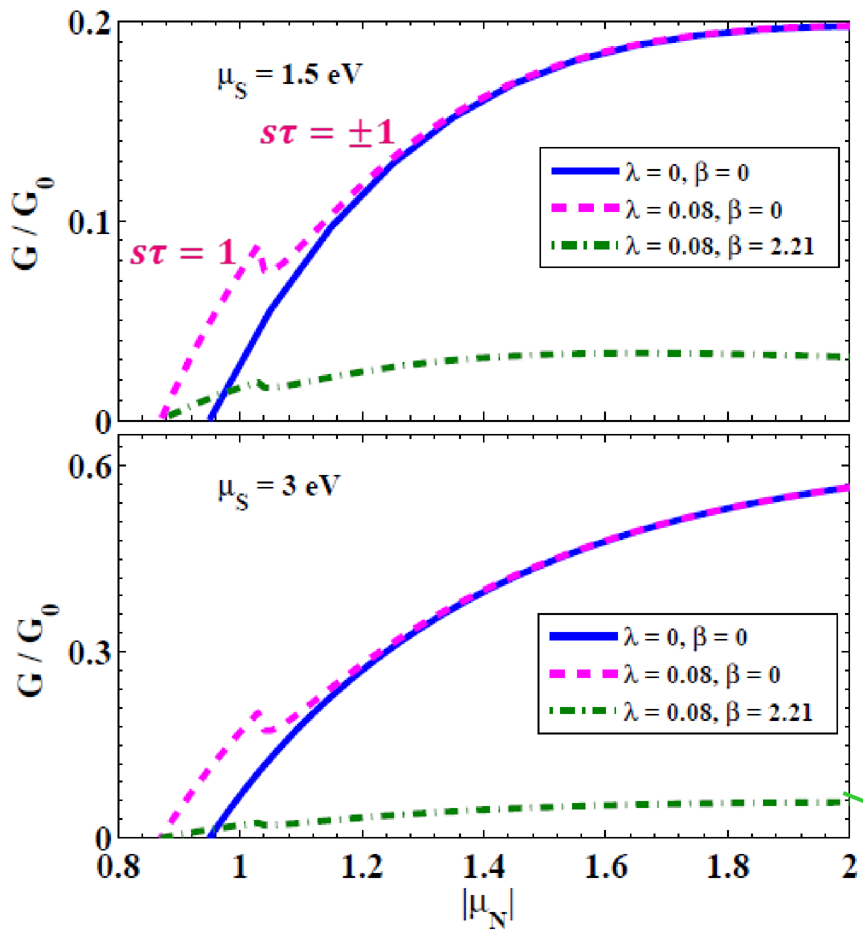


FIG. 4: Andreev conductance of S/N contact with n-doped S region versus $|\mu_N|$ at two chemical potentials $\mu_S = 1.5, 3\ eV$, for gapped graphene ($\lambda = 0, \beta = 0$), MoS_2 ($\lambda = 0.08eV$) with $\beta = 0$ and $\beta = 2.21$, when $\alpha = 0$, $\Delta_S = 0.01eV$ and $eV/\Delta_S = 0$.

$$\mu_S = \mu + U_0$$

$$\mu_N = \mu \quad (\mu_N < 0)$$

- ❖ **Gapped Graphene (λ=0, β= 0)**
- ❖ **MoS_2 (λ=0.08 eV) with β= 0**
- ❖ **MoS_2 (λ=0.08 eV) with β= 2.21**

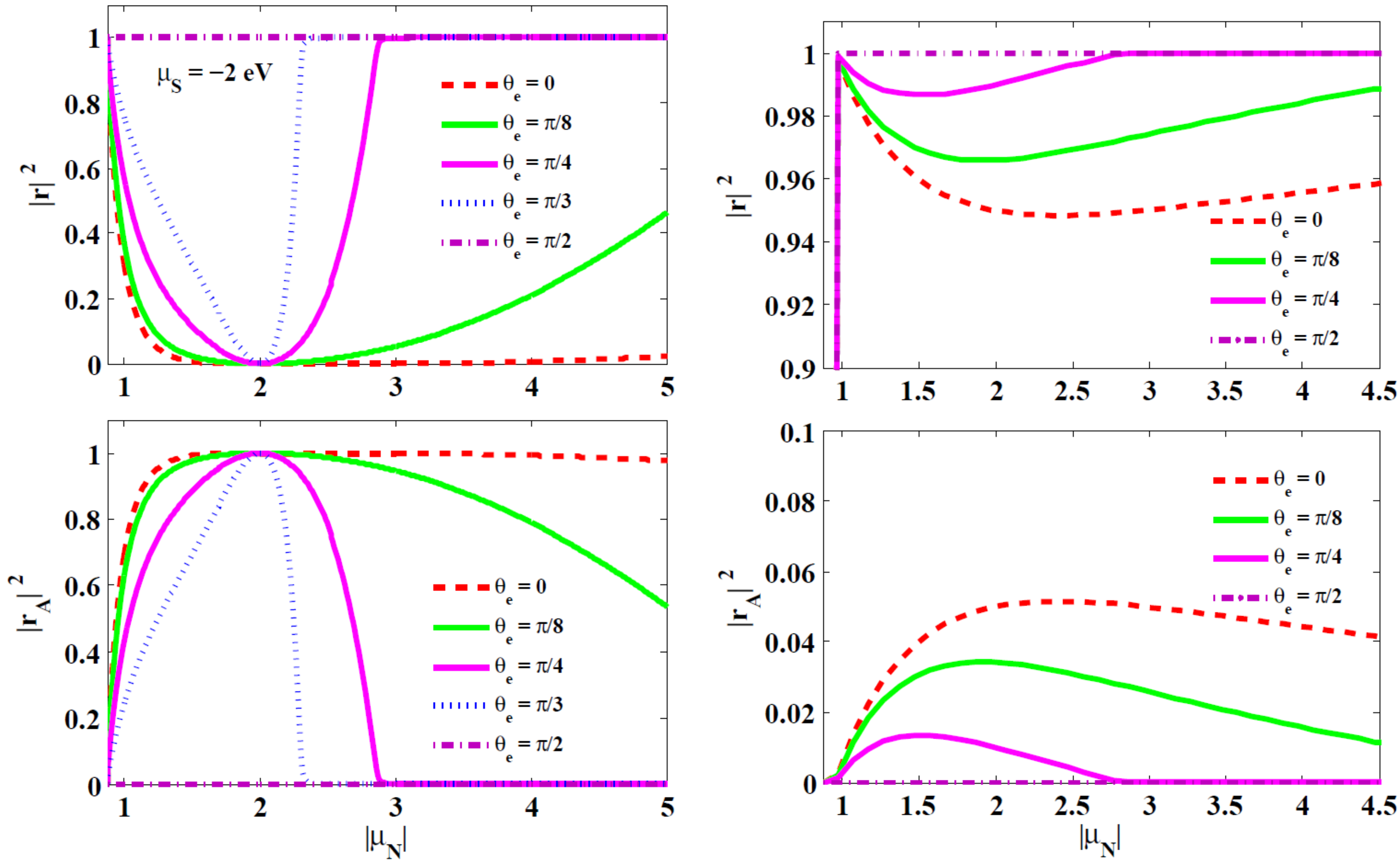
Attenuation of the proximity inducing superconductivity in N region

L. Majidi, H. Rostami, R. Asgari (to be submitted)

Andreev Reflection in S/N Junction

λ=0.08 eV, β= 2.21

S(p)/N(p) S(n)/N(p)



Conclusion

- Presence of strong spin-orbit interaction in MoS2 enhances the amplitude of Andreev reflection and the resulting Andreev conductance in *MoS*2-based S/N structures with n-(p-) doped S and p-doped N regions.

- Presence of β term enhances the Andreev conductance in *MoS*2-based S/N structures with p-doped S, while it decreases the Andreev conductance in S/N structure with n-doped S region.

$$H = v_F(\boldsymbol{\sigma}.\boldsymbol{p}) + \frac{\Delta}{2}\sigma_z + \lambda s \tau\ (\frac{1-\sigma_z}{2}) - \frac{\hbar^2 \boldsymbol{\nabla}^2}{4m_0}(\alpha + \beta\sigma_z)$$


Thank You!