

RKKY Interaction In Bilayer Graphene

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Outline

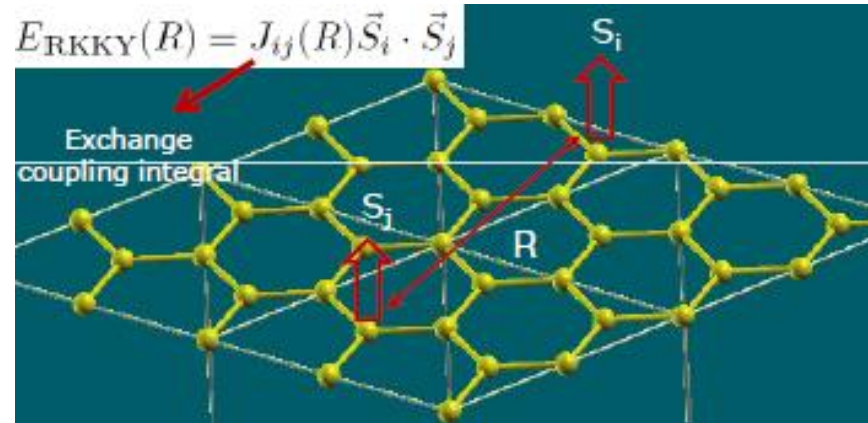
- RKKY Interaction
- Graphene & It's bilayer
- RKKY in 2D system
- RKKY in un-biased bilayer graphene
- RKKY in biased bilayer graphene

RKKY INTERACTION



Motivation

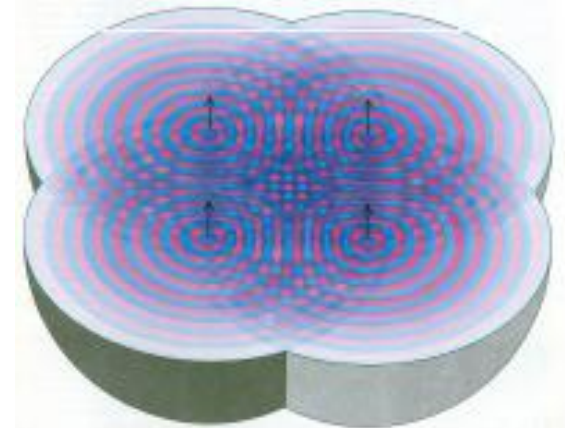
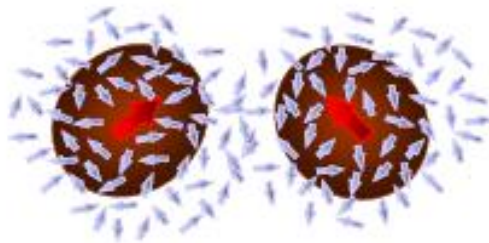
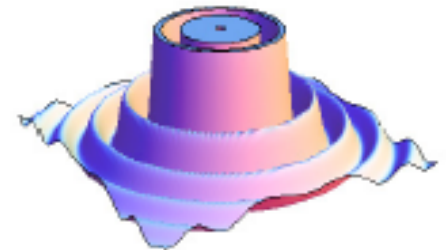
- **RKKY**: Indirect Exchange interaction between two magnetic impurities via host material electrons.



- Adatom properties
- Spintronic applications

Motivation

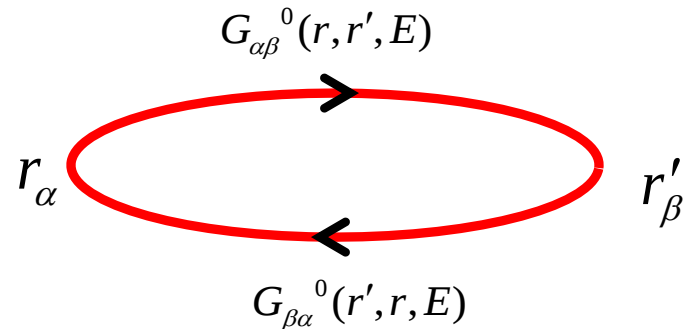
- Electron spin oscillation around magnetic impurity
- Ordering of impurities:



RKKY Interaction (Formalism)

$$H_{RKKY} = -\lambda^2 \sum_{ij} I_{1i} \chi_{ij}(R_1, R_2) I_{2j}$$

$$i, j = x, y, z$$



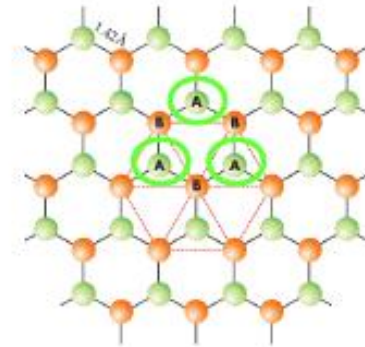
$$\chi_{ij}(R_1, R_2) = \text{Im} \left[\int_{-\infty}^{\epsilon_F} d\epsilon \text{Tr} [\hat{\sigma}_i G^0(R_1, R_2, \epsilon) \hat{\sigma}_j G^0(R_2, R_1, \epsilon)] \right]$$

GRAPHENE & IT'S BILAYER



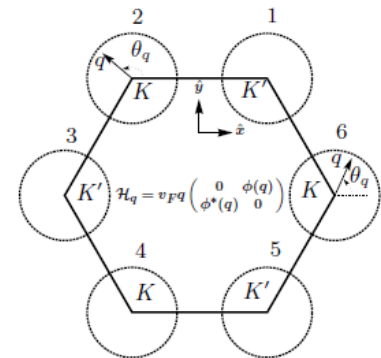
Graphene Structure

- Pseudo spin (A,B)



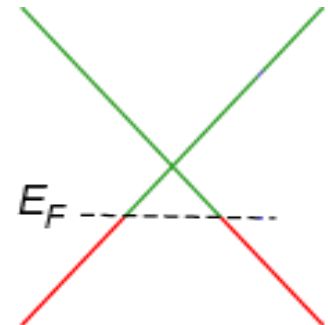
- Valley degeneracy

$$H_0 = \begin{pmatrix} 0 & v_F q \Phi_q \\ v_F q \Phi_q^* & 0 \end{pmatrix}$$

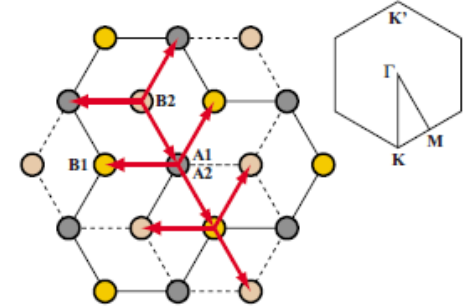
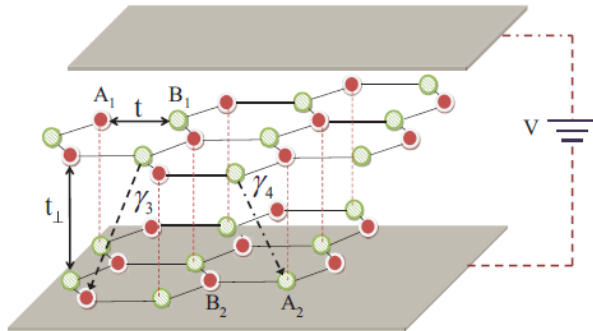


- Tunable Fermi energy

$$E(k) = \pm v_F k$$



Bilayer Graphene

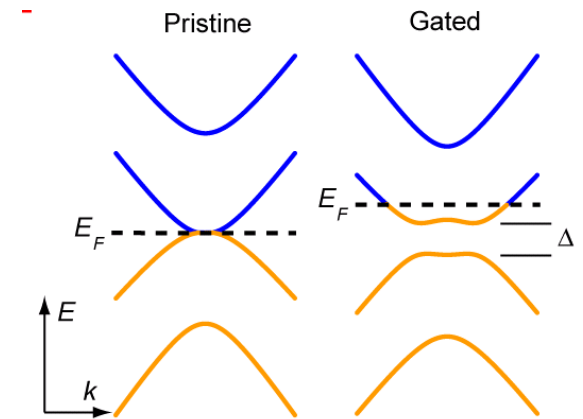


$$H = \sum_k \Psi^\dagger(k) \begin{pmatrix} \Delta & f(k) & t_{\perp} & \gamma_4 f^*(k) \\ f^*(k) & \Delta & \gamma_4 f^*(k) & \gamma_3 f(k) \\ t_{\perp} & \gamma_4 f(k) & -\Delta & f^*(k) \\ \gamma_4 f(k) & \gamma_3 f^*(k) & f(k) & -\Delta \end{pmatrix} \Psi(k)$$

Bilayer Graphene: Band Structure

- Dispersion relation:

$$\varepsilon^2 = v^2 p^2 + \frac{t_{\perp}^2}{2} + \frac{V^2}{4} - \sqrt{v^2 p^2 (V^2 + t_{\perp}^2) + t_{\perp}^4 / 4}$$



- 2Band effective model:

$$H_{low} = \frac{-1}{2m} \begin{pmatrix} 0 & (\pi^\dagger)^2 \\ (\pi)^2 & 0 \end{pmatrix} + \frac{V}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Klein Tunneling in Bilayer Graphene

$$H = \begin{pmatrix} 0 & (p_x - ip_y)^j \\ (p_x + ip_y)^j & 0 \end{pmatrix}$$

Diagram (a) illustrates the Dirac cone structure of bilayer graphene. It shows two cones (red and green) separated by a gap. Incident and reflected states are labeled with momenta k and q , and energies E and V_0 . Diagram (b) shows a potential barrier of height V_0 and width D . Incident and transmitted states are labeled with momenta k and q , and energies E and V_0 . Diagram (c) shows the energy bands of bilayer graphene, with incident and reflected states labeled with momenta k and q , and energies E and V_0 .

The top diagram shows a potential barrier of height V_0 and width D in the x -direction. The bottom diagram shows the resulting wave functions in three regions (I, II, III) with angles ϕ , θ , and ϕ .

Two polar plots (a) and (b) showing the transmission and reflection coefficients as a function of the angle ϕ . Plot (a) shows the transmission coefficient T and plot (b) shows the reflection coefficient R .

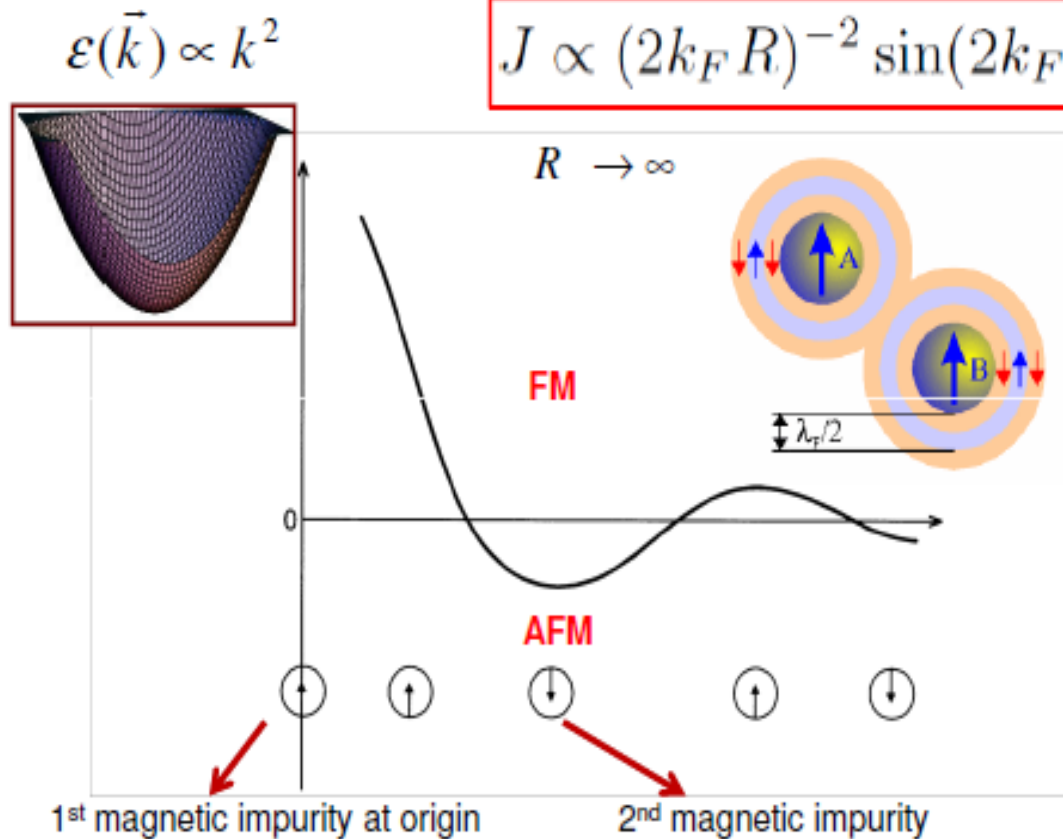
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RKKY INTERACTION IN 2D SYSTEMS



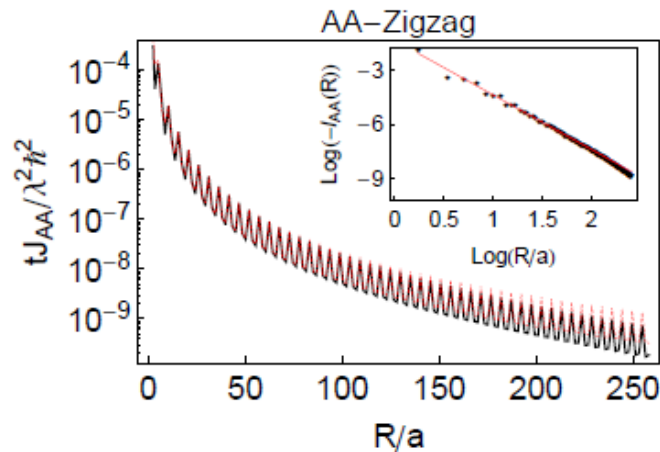
RKKY in 2DEG

$$\hat{H}^{RKKY} = J \mathbf{S}_1 \cdot \mathbf{S}_2$$

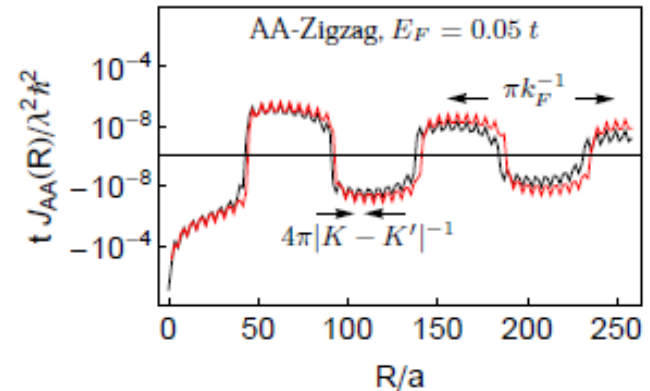


B. Fisher, et al., Phys. Rev. B (1975)

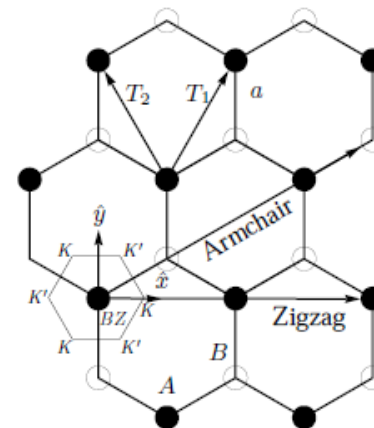
RKKY in Graphene



$$J_{AA} = C \frac{1 + \cos((K - K') \cdot R)}{(R/a)^3}$$



$$J_{AA} = C \frac{1 + \cos((K - K') \cdot R)}{(R/a)^2} \sin(2k_F R)$$

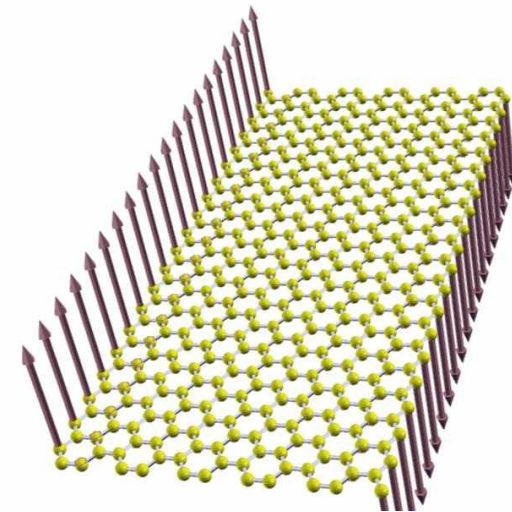
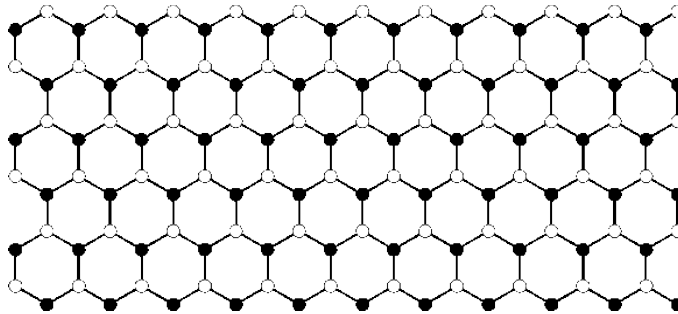


Sherafati et. al. PRB, 84, 125416

Sherafati et. al. PRB, 83, 165425

RKKY in spin polarized Graphene

$$H^{\alpha\beta}_{RKKY} = \frac{\lambda^2}{\pi} [J_x^{\alpha\beta} (S_{1x} S_{2x} + S_{1y} S_{2y}) + J_z^{\alpha\beta} (S_{1z} S_{2z})]$$



Parhizgar et. al. PRB, **87**, 125402

RKKY in Rashba spin orbit systems

$$\hat{H}^{RKKY} = J_H S_1 \cdot S_2 + J_I S_1^z S_2^z + J_{DM} (S_1 \times S_2)_z$$

- Topological Insulators
- 2DEG + Rashba spin orbit
- MoS_2



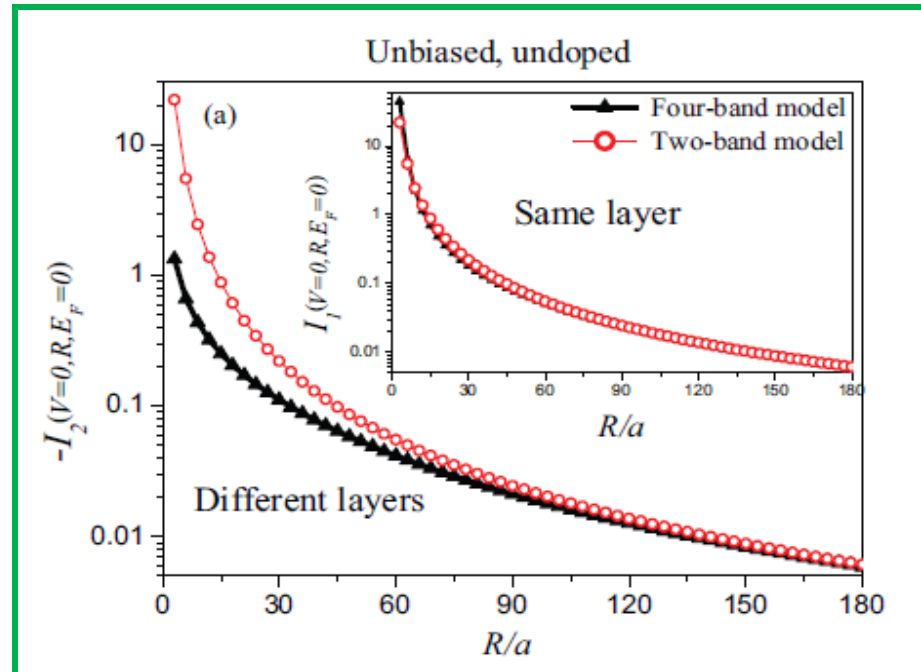
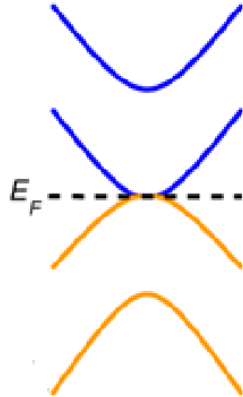
Parhizgar et. al. PRB, **87**, 125401

RKKY INTERACTION IN UN-BIASED BILAYER GRAPHENE



Un-biased, undoped

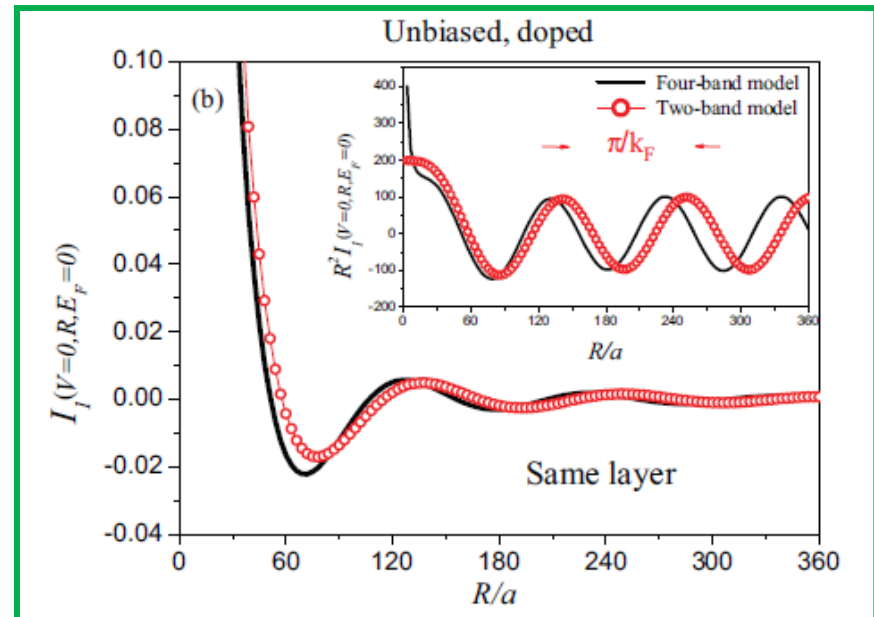
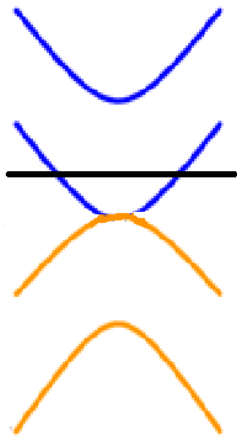
$$\hat{H}^{RKKY} = I(V, R, E_F) \phi_{\alpha\beta}$$



Parhizgar et al. Phys. Rev. B **87**,165429 (2013)

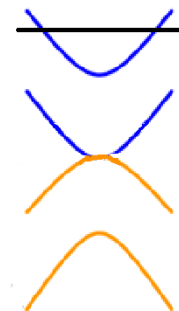
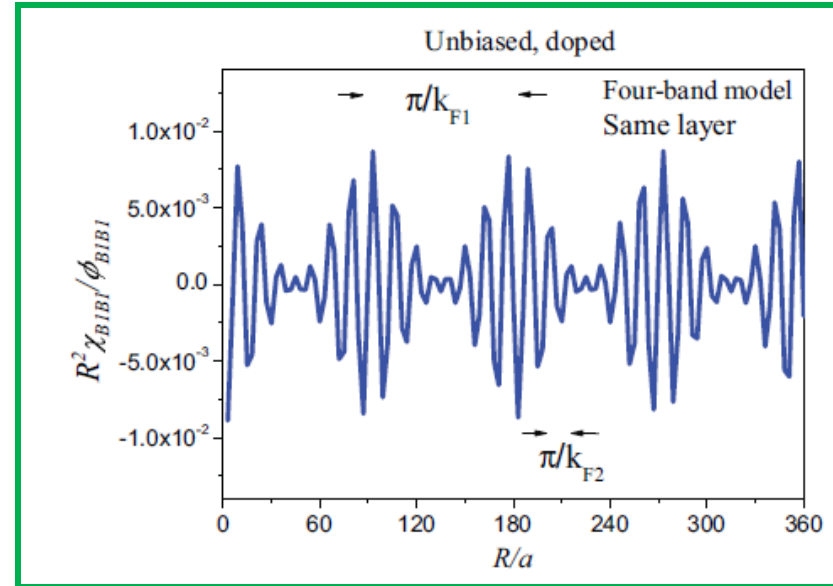
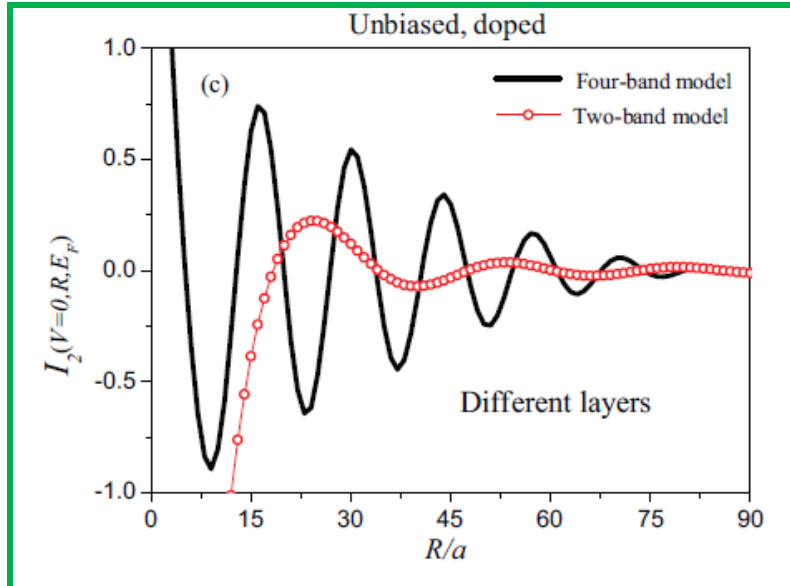
Un-biased, doped

$$J_{B1B1}(R) = \frac{-C\Phi_{B1B1}}{R^2} \sin(2k_F R)(e^{-k_F R} + C')$$



Parhizgar et al. Phys. Rev. B **87**,165429 (2013)

Necessity of 4-band model



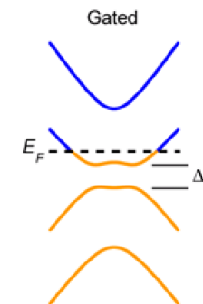
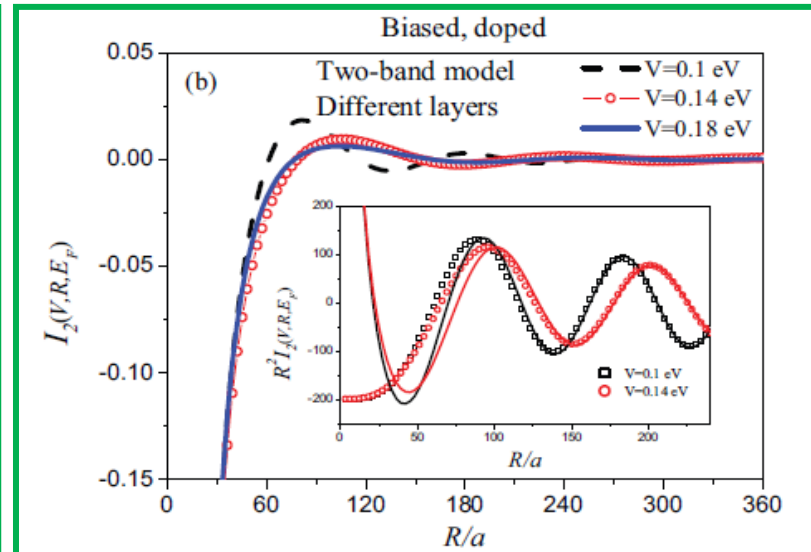
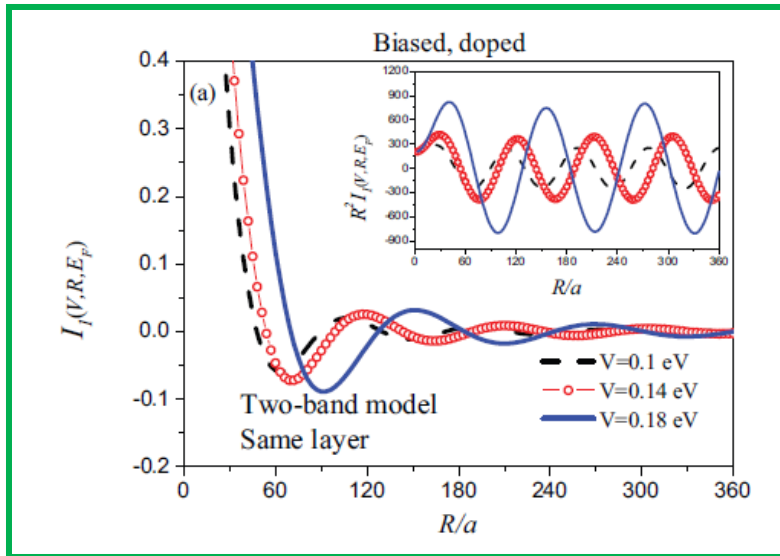
Parhizgar et al. Phys. Rev. B **87**,165429 (2013)

RKKY INTERACTION IN

BIASED BILAYER GRAPHENE

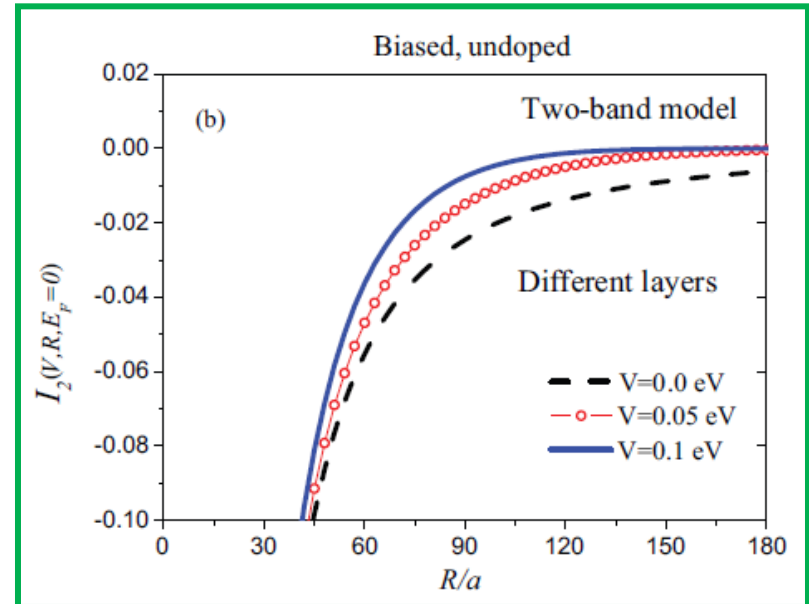
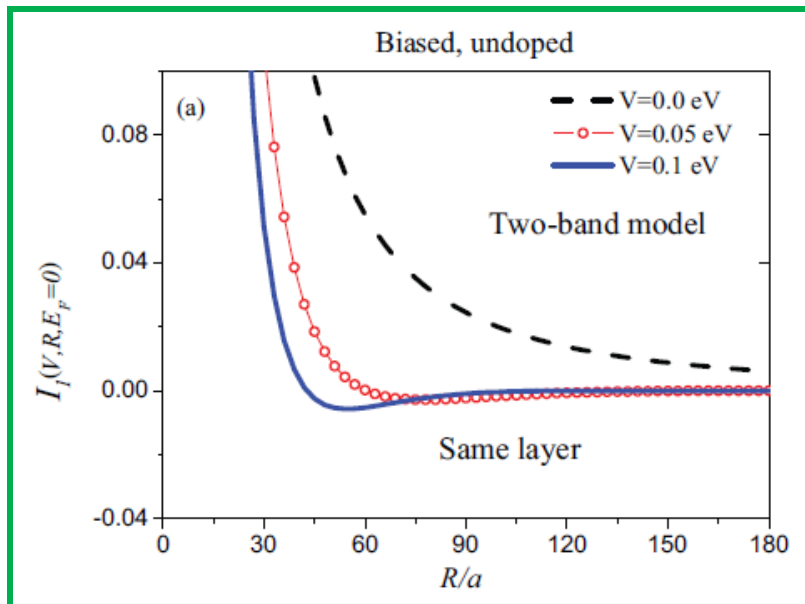


Biased, doped



Parhizgar *et al.* Phys. Rev. B **87**,165429 (2013)

Biased, undoped



Parhizgar et al. Phys. Rev. B **87**,165429 (2013)



Thanks For your Attention