Enhancement of Kondo effect through Rashba spin-orbit interactions: applications to graphene.

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NSF

Why Kondo and Rashba?

Kondo effect on surfaces

Madhavan et al Science 1998

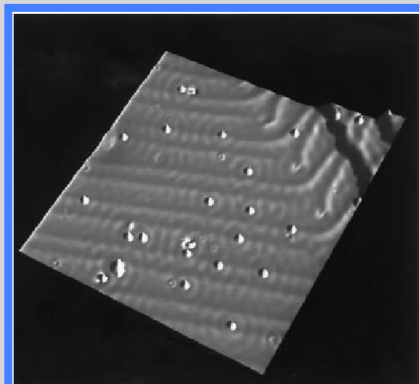


Fig. 1. Constant-current image (400 Å by 400 Å) of the Au(111) surface after deposition of 0.001 monolayer of Co at 4 K (tunnel parameters: $I = 0.5$ nA, $V = 0.1$ V). Approximately 22 Co atoms can be seen nestled among the ridges of the Au(111) herringbone reconstruction.

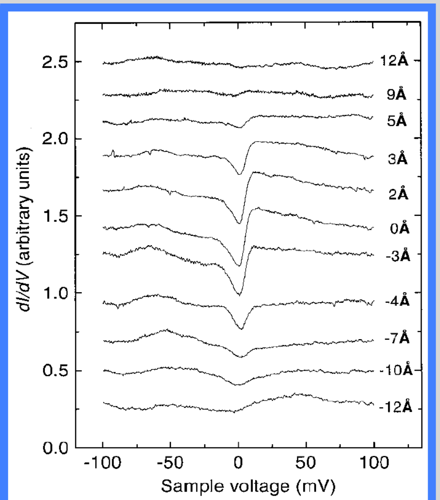
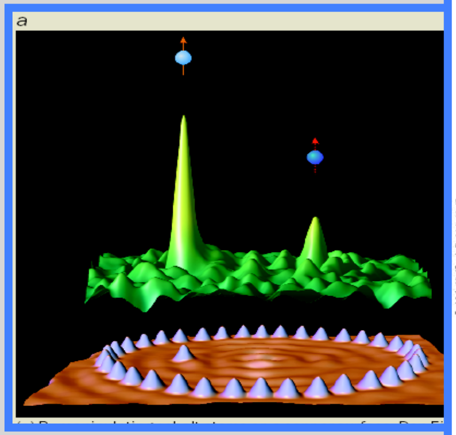
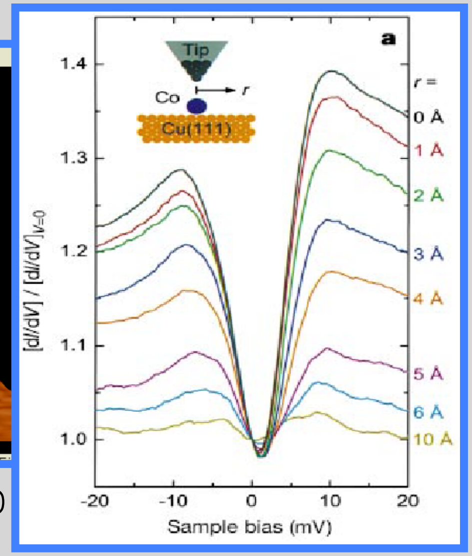


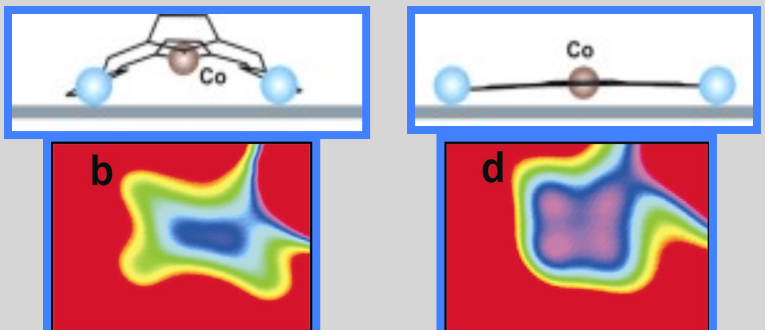
Fig. 3. A series of *dI/dV* spectra taken with the STM tip held at various lateral spacings from the center of a single Co atom on Au(111). (These



Manoharan et al Nature 2000

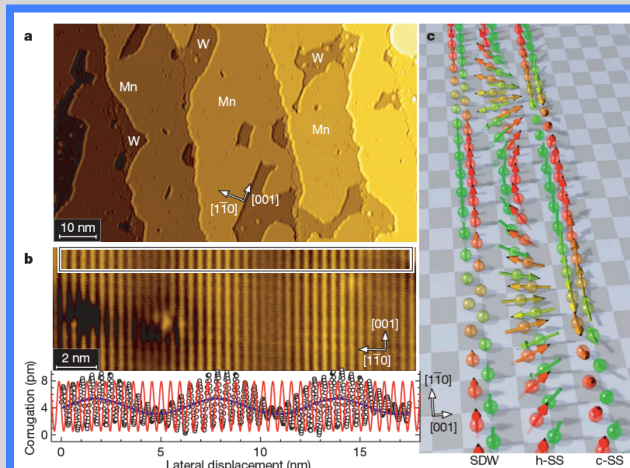


Kondo Switch



V. Iancu, A. Deshpande, S.-W. Hla, Nano Lett. (2006)

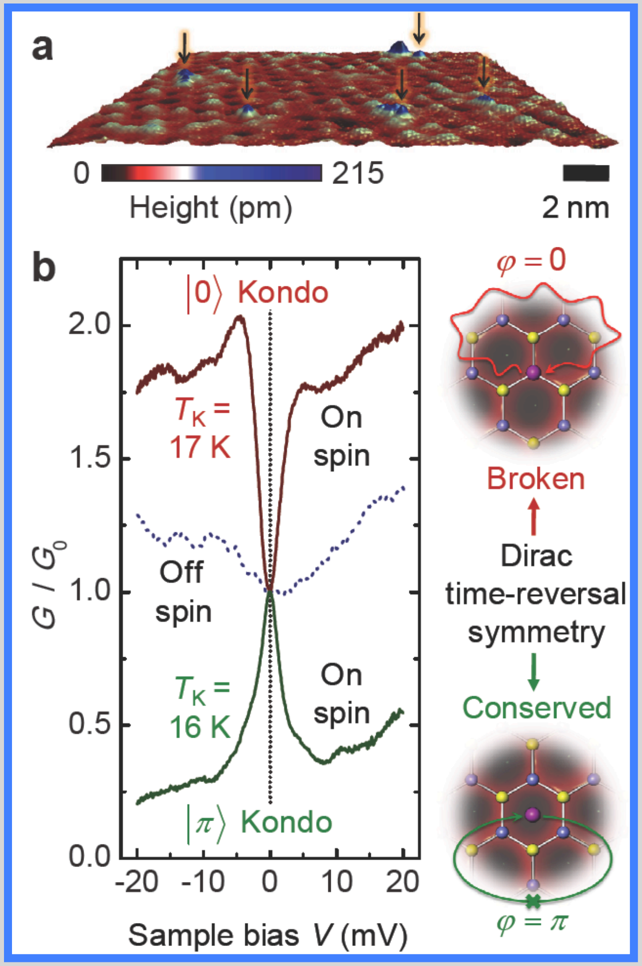
Rashba effect on surfaces



M. Bode et al, Nature (2007)

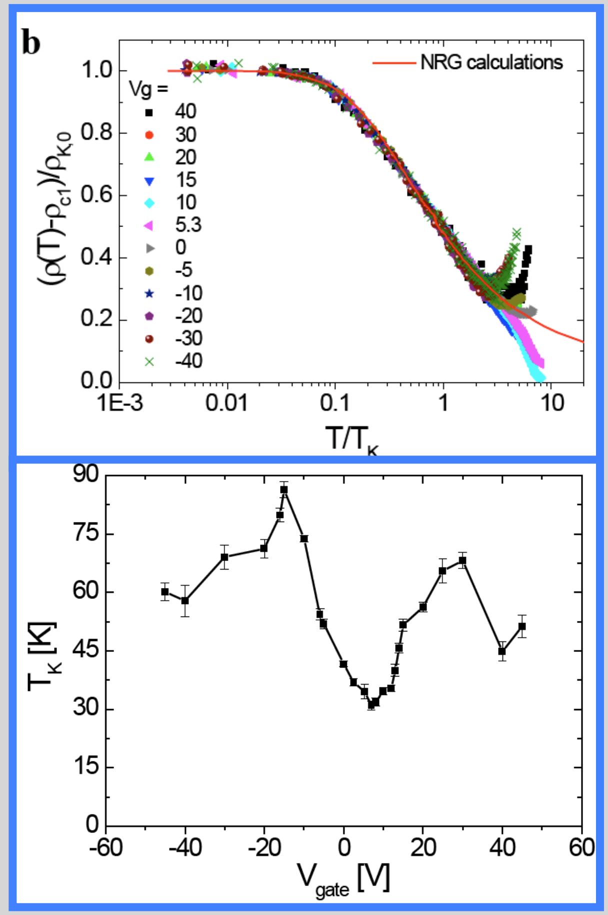
More recently: graphene…

Graphene on SiC with Co



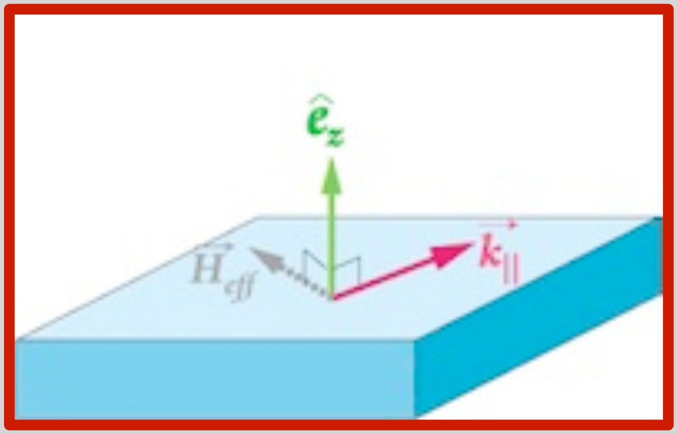
Mattos et al, unpublished

HOPG with defects



Chen et al, Nature Physics (2011)

Rashba spin-orbit interaction



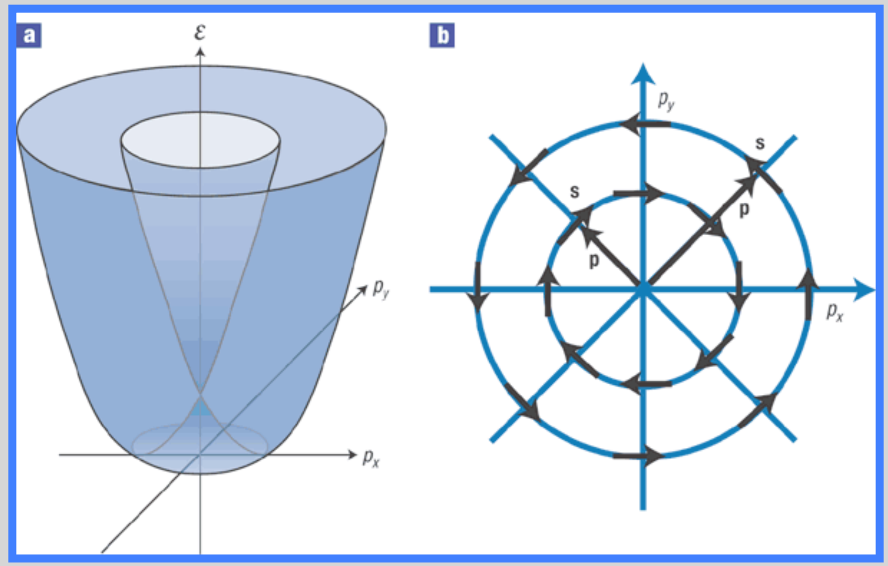
$$H = \hbar\vec{\sigma}\bullet\left(\vec{\nabla}V\times\vec{p}\right)\sim\vec{L}\bullet\vec{\sigma}$$

Time reversal symmetry: preserved
Inversion symmetry: broken

$$H_R = \sum_{\vec{k}} \lambda_R\left(k_y + ik_x\right)c^+_{\vec{k}\uparrow}c_{\vec{k}\downarrow} + h.c.$$

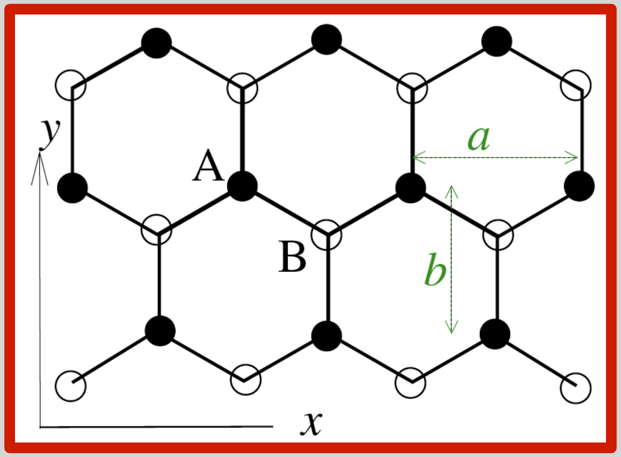
$$H_R = \sum_{\vec{k}} \lambda_R k e^{-i\theta_{\vec{k}}} c^+_{\vec{k}\uparrow}c_{\vec{k}\downarrow} + h.c.$$

$$\lambda_R \propto \left|\vec{\nabla}V\right| = \left|\vec{E}\right|$$



Semiconductor physics: Electric fields drive spins.
E. I. Rashba Nature Physics (2006).

Rashba spin-orbit in graphene



$$H_R = \sum_{<ij>} i c_i^+ \left(\vec{u}_{ij} . \sigma\right) c_j + h.c.$$

$$\vec{u}_{ij} = -\frac{\lambda_R}{d} \hat{z} \times \vec{\delta}_{ij}$$

Pauli matrix (spin operator)

Vector in graphene plane

$$d = \frac{a}{\sqrt{3}}$$

$$\Psi = \begin{pmatrix} u_{A\uparrow} \\ u_{B\uparrow} \\ u_{A\downarrow} \\ u_{B\downarrow} \end{pmatrix}$$

$$H = \begin{pmatrix} 0 & \varphi_0 & 0 & i\varphi_+ \\ \bar{\varphi}_0 & 0 & -i\bar{\varphi}_- & 0 \\ 0 & i\varphi_- & 0 & \varphi_0 \\ -i\bar{\varphi}_+ & 0 & \bar{\varphi}_0 & 0 \end{pmatrix}$$

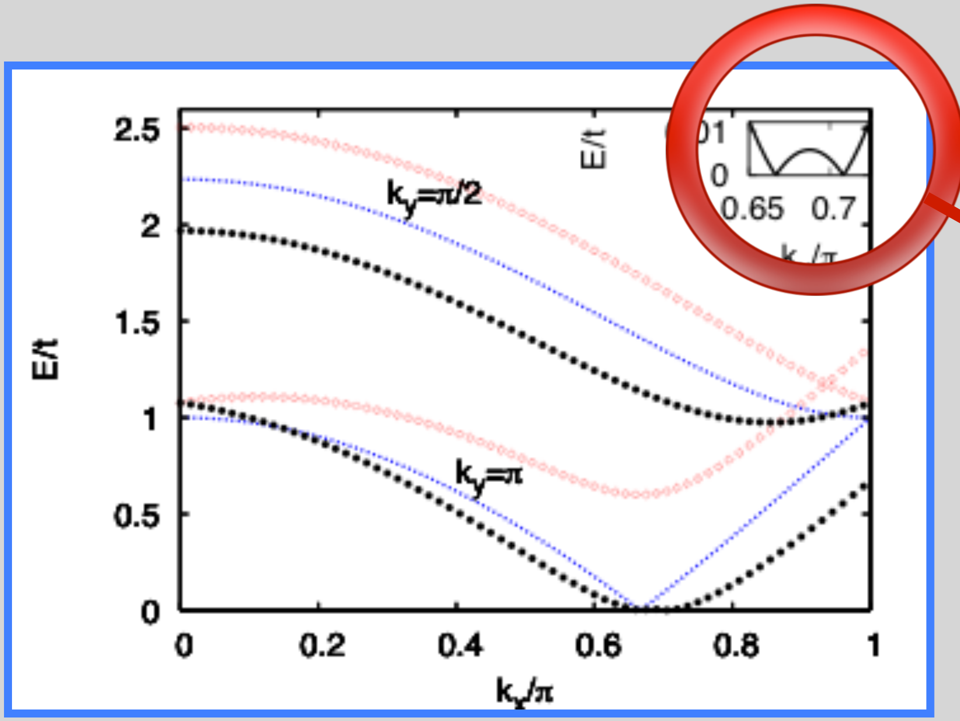
$$\varphi_0 = t\left(1 + 2e^{-ik_y b} \cos\left(k_x a/2\right)\right)$$

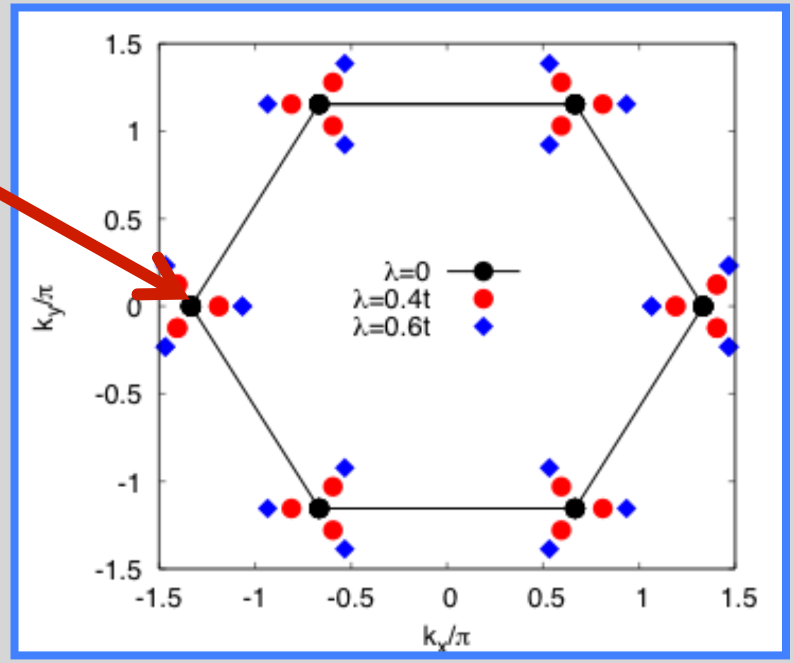
$$\varphi_+ = \lambda_R\left(1 + 2e^{-ik_y b} \cos\left(k_x a/2 + 2\pi/3\right)\right)$$

$$\varphi_- = \lambda_R\left(1 + 2e^{-ik_y b} \cos\left(k_x a/2 - 2\pi/3\right)\right)$$

Rashba spin-orbit in graphene II

Band structure: Bulk





$\lambda_R = 0.4\ t$

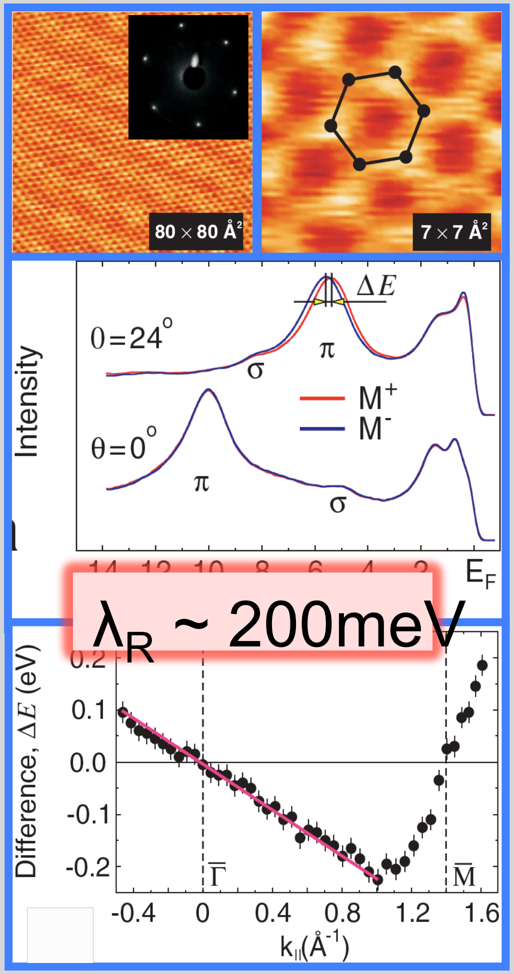
Splitting of bands

New Dirac points (trigonal symmetry)

M Zarea and NS, PRB (2009)

What about experiments?

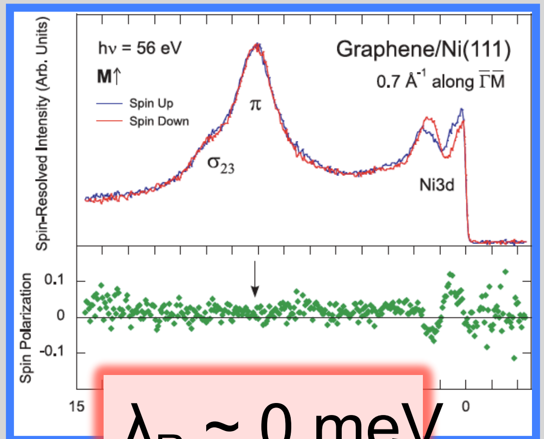
Graphene/Ni (111)



$\lambda_R \sim 200 meV$

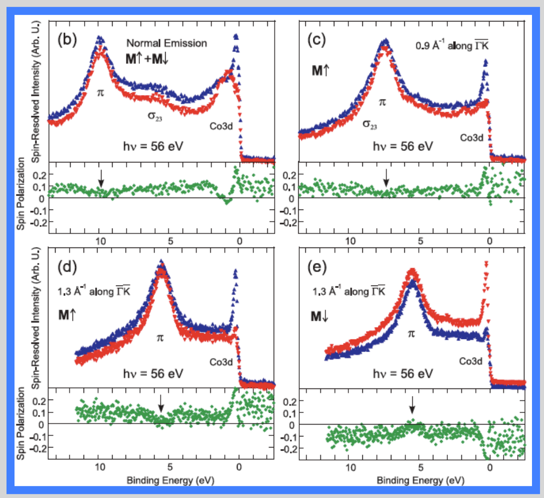
Dedkov et al, PRL 100 (2008)

Graphene/Ni (111)



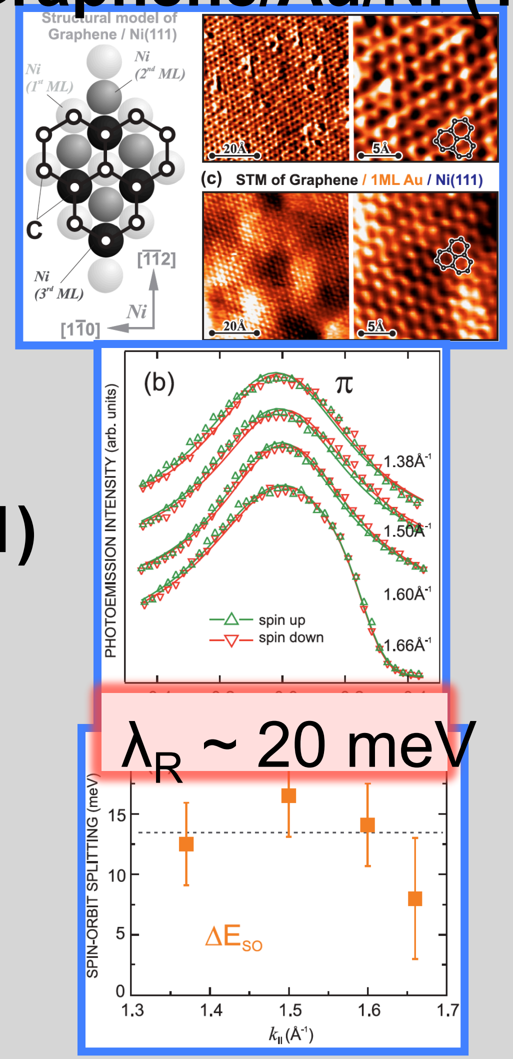
$\lambda_R \sim 0 meV$

Graphene/Co (0001)



Rader et al, PRL 102 (2009)

Graphene/Au/Ni (111)



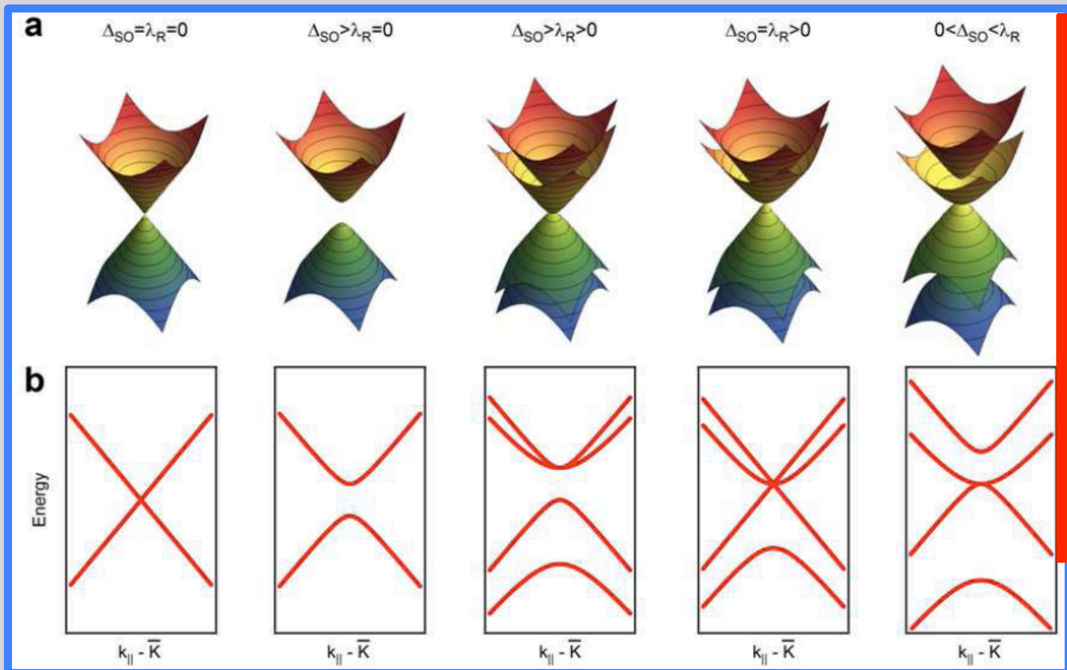
$\lambda_R \sim 20 meV$

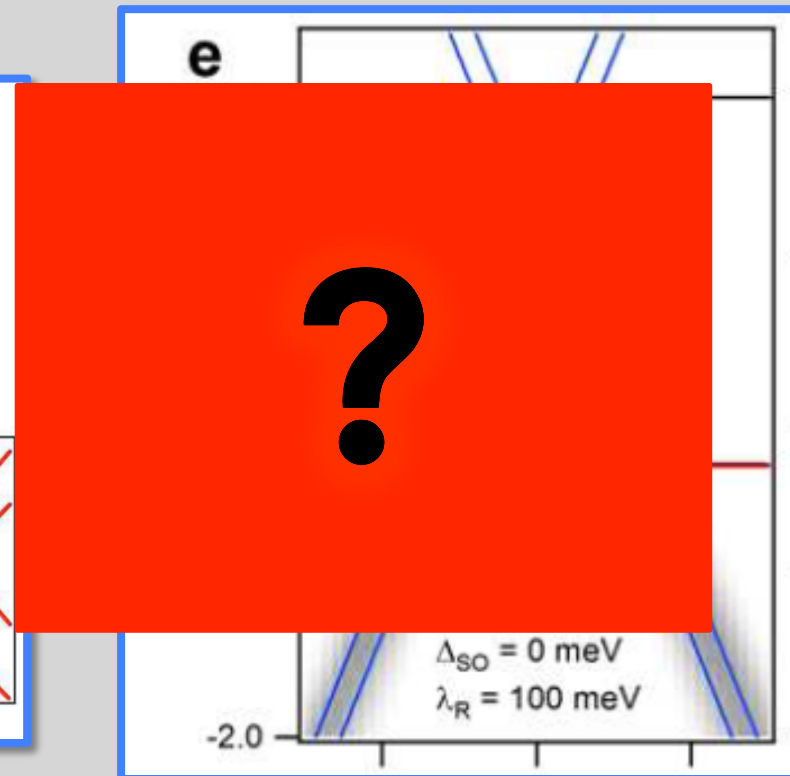
Varykhalov et al, PRL 101 (2008)

What about experiments? II

Gierz et al arXiv (2010) Stuttgart

Graphene on SiC(0001)





λ_R up to 200meV

What does Rashba do to Kondo?

Many answers since 1969…

SUPPRESSION OF THE KONDO MANY-BODY SCATTERING EFFECT

D. Gainon and A. J. Heeger*
Institut de Physique de la Matière Condensée, University of Geneva, Geneva, Switzerland
(Received 5 May 1969)

An experimental study of the electrical resistivity in dilute Cu:Mn doped with Pt impurities is presented. The results indicate a suppression of the Kondo divergence in the conduction-electron scattering amplitude as a result of the spin-orbit interaction at the Pt impurities. The results are interpreted in terms of a reduction in the spin "memory" time.

Gainon and Heeger, PRL 22 (1969)

On the Influence of Spin-Orbit Scattering on the Kondo Effect

H. U. Everts
Institut für Festkörperforschung der Kernforschungsanlage Jülich

Received December 8, 1971

The question of whether spin-orbit interaction of the conduction electrons of dilute magnetic alloys has an influence on the low temperature properties of such alloys is investigated. It is assumed that the spin-orbit interaction is induced by nonmagnetic impurities present in the alloy. In the course of this study, two different models for the interaction between the conduction electrons and the magnetic impurities, the *s-d* exchange model and the Anderson model, are considered. It is shown that for neither of these models the spin-orbit interaction of the conduction electrons gives rise to a characteristic change in the temperature dependence of the impurity-spin relaxation time and of the electrical resistivity.

Everts, Z. Phys. 251 (1972)

Spin-orbit scattering and the Kondo effect

Yigal Meir
Physics Department, University of California, Santa Barbara, California 93106

Ned S. Wingreen
NEC Research Institute, 4 Independence Way, Princeton, New Jersey 08540
(Received 16 May 1994)

The effects of spin-orbit scattering of conduction electrons in the Kondo regime are investigated theoretically. It is shown that due to time-reversal symmetry, spin-orbit scattering does not suppress the Kondo effect, even though it breaks spin-rotational symmetry, in full agreement with experiment. An orbital magnetic field, which breaks time-reversal symmetry, leads to an effective Zeeman splitting, which can be probed in transport measurements. It is shown that, similar to weak localization, this effect has anomalous magnetic-field and temperature dependence.

Wingreen and Meir PRB 50 (1994)

The Two Dimensional Kondo Model with Rashba Spin-Orbit Coupling

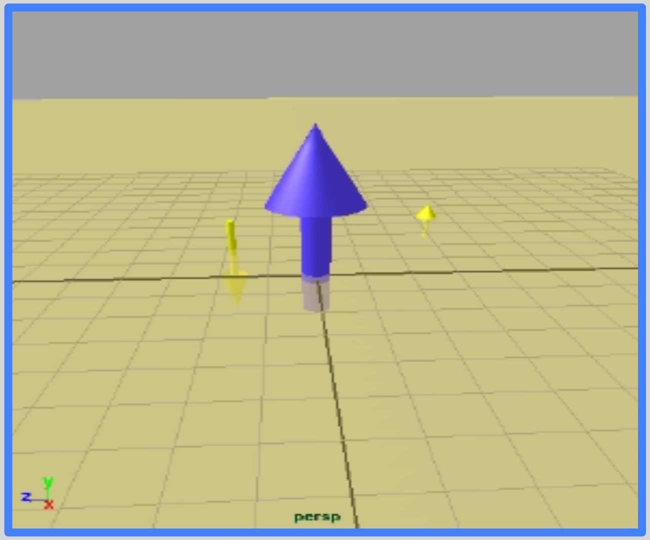
Justin Malecki

Abstract We investigate the effect that Rashba spin-orbit coupling has on the low energy behaviour of a two dimensional magnetic impurity system. It is shown that the Kondo effect, the screening of the magnetic impurity at temperatures $T < T_K$, is robust against such spin-orbit coupling, despite the fact that the spin of the conduction electrons is no longer a conserved quantity. A proposal is made for how the spin-orbit coupling may change the value of the Kondo temperature T_K in such systems and the prospects of measuring this change are discussed. We conclude that many of the assumptions made in our analysis invalidate our results as applied to recent experiments in semi-conductor quantum dots but may apply to measurements made with magnetic atoms placed on metallic surfaces.

Malecki, J. Stat. Phys. 129 (2007)

Anderson impurity model: Kondo

$$\begin{aligned} H &= H_0 + H_{imp} + H_{hyb} \\ H_0 &= \sum_{\vec{k},s} \epsilon_k c^\dagger_{\vec{k},s} c_{\vec{k},s} \\ H_{imp} &= \sum_s \epsilon_d c^\dagger_{ds} c_{ds} + U n_{d\downarrow} n_{d\uparrow} \\ H_{hyb} &= \sum_{\vec{k},s} V_{\vec{k}} c^\dagger_{\vec{k},s} c_{ds} + h.c. \end{aligned}$$



Schrieffer-Wolff Transformation → **Kondo model**

$$H_{Kondo} = J_{\vec{k}\vec{k}'} (\Psi^\dagger_{\vec{k}'} \vec{S} \Psi_{\vec{k}}) \cdot (\Psi^\dagger_{d'} \vec{S} \Psi_d)$$

Kondo temperature

$$T_K \sim e^{-\frac{1}{2J\rho(\epsilon_F)}}$$ → $$J = J(U, \epsilon_d, V_{\vec{k}})$$

Anderson model with RSO I

$$
\begin{aligned}
H_0 &= \sum_{\vec{k},s} \epsilon_k c^\dagger_{\vec{k},s} c_{\vec{k},s} + \sum_s \epsilon_d c^\dagger_{ds} c_{ds} \\
H_U &= U n_{d\downarrow} n_{d\uparrow} \\
H_{hyb} &= \sum_{\vec{k},s} V_{\vec{k}} c^\dagger_{\vec{k},s} c_{ds} + h.c. \\
H_{RSO} &= \lambda_R \sum_{\vec{k}} k e^{-i\theta_{\vec{k}}} c^\dagger_{\vec{k},\uparrow} c_{\vec{k},\downarrow}
\end{aligned}
$$

Bath

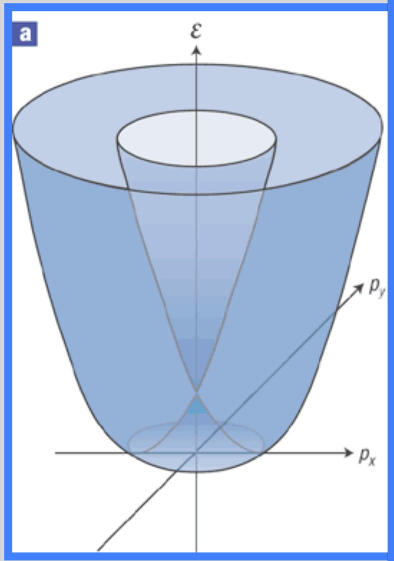
Coupling to impurity spin: select channels in the bath

S=1/2

L = 0

One-channel Kondo model

What is it expected?



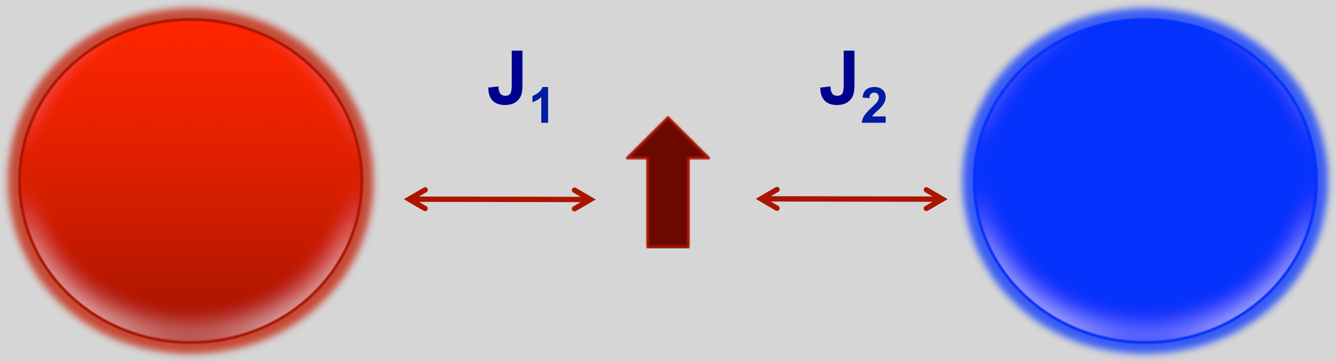
SU(2) Spin-symmetry: broken

Two-bands:

$$\varepsilon_{k,\sigma} = \varepsilon_k + \lambda_R k \sigma$$

$$\sigma = \begin{cases} +1 & \text{'left'} \\ -1 & \text{'right'} \end{cases}$$

Total Hamiltonian describes a *two-band Anderson model*



Anderson model with RSO II

In 2d: polar symmetry

$$c^m_{k,s} = \sqrt{\frac{k}{2\pi}} \int d\theta_{\hat{k}} e^{-im\theta_{\hat{k}}} c_{\vec{k},s}$$

$$c_{\vec{k},s} = \sqrt{\frac{1}{2\pi k}} \sum_m e^{im\theta_{\hat{k}}} c^m_{k,s}$$

'Helicity states' diagonalize bath

$$c^{j_m = m+\frac{1}{2}}_{k,h=\pm 1} = \frac{c^m_{k,\uparrow} + h c^{m+1}_{k,\downarrow}}{\sqrt{2}}$$

Anderson Hamiltonian with RSO:

$$H_0 = \sum_{k,h,j_m} \epsilon_{kh} (c^{j_m}_{kh})^\dagger c^{j_m}_{kh} + \sum_s \epsilon_d c^\dagger_{ds} c_{ds}$$

$$H_U = U n_{d\downarrow} n_{d\uparrow}$$

$$H_{hyb} = \sum_{k,h} V_k \sqrt{2} [(c^{j_m = 1/2}_{kh})^\dagger c_{d\uparrow} + (c^{j_m = -1/2}_{kh})^\dagger c_{d\downarrow} + h.c.$$

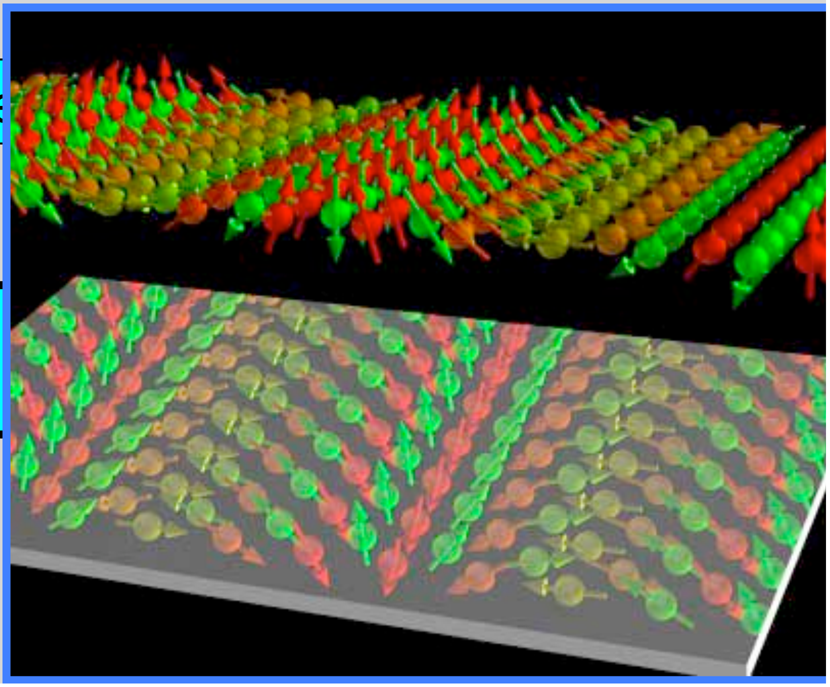
Anderson model with RSO III: SWT

- At particle-hole symmetry (and large U limit)

$$H_{Kondo} = -J_{k,k'}(\mathbf{s}_{\vec{k},\vec{k'}}.\mathbf{S} - \frac{1}{4}\rho^c_{\vec{k},\vec{k'}}\rho^d)$$

- Away from particle-hole symmetry: extra te

$$H_{DM} = i\lambda_R C_k(\vec{k} - \vec{k'}) \cdot ($$



Bode et al, Nature (2007) (Mn on W)

Kondo regime with RSO

Renormalization group: new term

$$J_1 = \frac{J_+ + \sqrt{J_-^2 + \lambda_R^2}}{2}$$

$$J_2 = \frac{J_+ - \sqrt{J_-^2 + \lambda_R^2}}{2}$$

$$J_\pm = J \pm \gamma$$

$$\lambda_F = 2C\lambda_R k_F$$

With RG equations:

$$\dot{J}_1 = J_1^2 \quad , \quad \dot{J}_2 = J_2^2$$

$$T_K = De^{-\frac{1}{\rho J}}$$

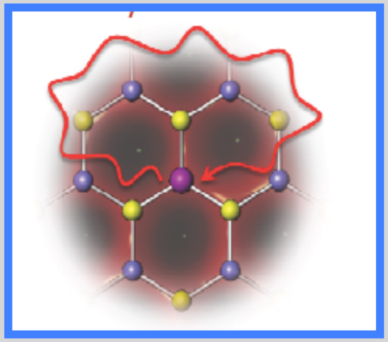
$$T_K = T_0(\frac{T_0}{D})^{1-\frac{J}{J1}}$$

Exponential increase of T_K

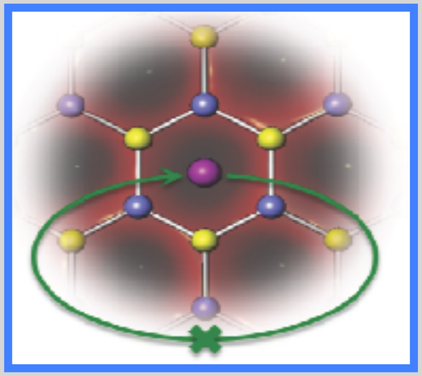
M Zarea, SE Ulloa and NS arXiv: cond-mat 1105.3522, PRL (to appear).

Kondo in graphene with Rashba

$$
\begin{aligned}
H &= H_0 + H_{imp} + H_{hyb} + H_{RSO} \\
H_0 &= t \sum_{\vec{r}, i=1,2,3; s} c^\dagger_{A,\vec{r},s} c_{B,\vec{r}+\vec{\delta}_i,s} \\
H_{hyb} &= \sum_{\vec{k},s} [V_{A,\vec{k}} c^\dagger_{\vec{k},s} c_{ds} + V_{B,\vec{k}} c^\dagger_{\vec{k},s} c_{ds} + h.c.] \\
H_{RSO} &= \lambda_R \sum_{(l,l'=A,B);\vec{k}} k e^{-i\theta_{\vec{k}}} c^\dagger_{l,\vec{k},\uparrow} c_{l',\vec{k},\downarrow}
\end{aligned}
$$

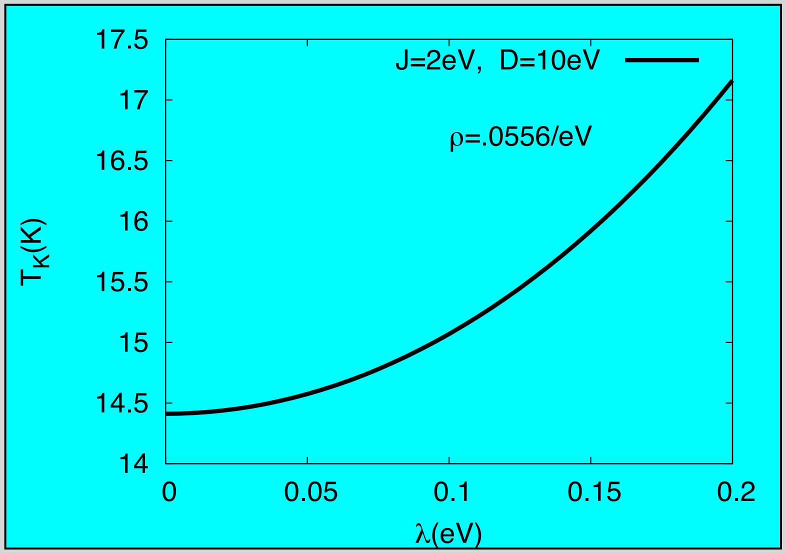


On top or substitutional



Symmetric

Increase of Kondo temperature



No evidence of two-channel Kondo regime.

Conclusions

- Rashba interactions in graphene: new Dirac points
- Anderson impurity model with Rashba bath: 2-channel Kondo
- Ferro and anti-ferromagnetic cases flow to strong coupling (antiferro)
- Kondo in graphene: 1-channel Kondo effect
- Graphene: promising substrate to test effect of Rashba in Kondo