10 ANNIVERSARY
GRAPHENE AND 2DM VIRTUAL CONFERENCE & EXPO
Graphene online 2020
October 19-23

Nonperturbative quantum diagrammatic theory of interfacial spin-orbit torques

Alessandro Veneri[1] and Aires Ferreira[1]
[1] University of York, Y010 5DD, York, UK

1. Introduction

- **Spin angular momentum transfer** between conduction electrons and localized magnetic moments at normal metal/ferromagnet interfaces enables **current-induced spin-orbit torque** (SOT), a crucial functionality in next-generation spin memories [1].
- We develop a **general nonperturbative framework to evaluate the SOT** in disordered Dirac materials. This allow us to develop a unified microscopic theory of SOT including **skew scattering** effects.

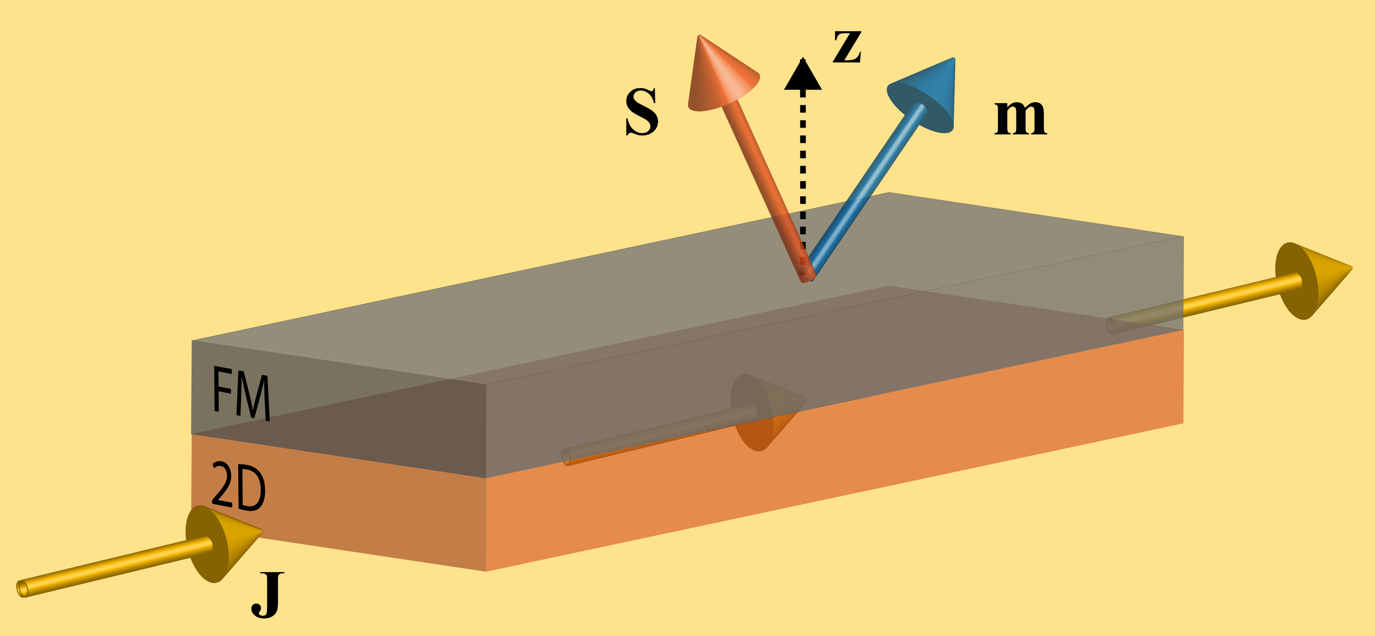


Fig.1 Metal/ferromagnet bilayer. The current **J** generates a spin density **S** that interacts with the local magnetization **m**, thereby exerting a torque.

2. Self-consistent diagrammatic theory

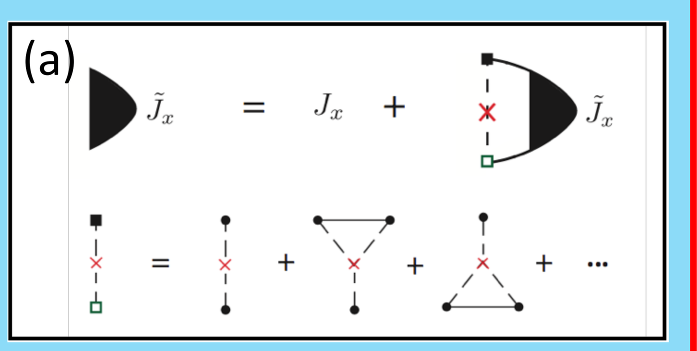
Our formalism is based on **linear response theory**. The nonequilibrium spin polarisation **S** is obtained as

$$S_i = K_{ij} J_j \qquad (1)$$

where $\hat{K}$ is the spin-density-charge-current response function. The response function is evaluated by means of the diagrammatic technique

$$K_{\alpha\beta} = \frac{1}{4\pi}\langle \sum_{\mathbf{p}} Tr[\gamma_\alpha (G_p^R - G_p^A) J_{\beta,0} G_p^A - \gamma_\alpha G_p^R J_{\beta,0}(G_p^R - G_p^A)]\rangle_{dis} \qquad (2)$$

where G is the Green's function, γ_α is the spin density vertex and J_α is current density. We perform the disorder average <...>dis non perturbatively in the impurity potential (Fig.2a), which allows us to investigate weak and unitary (resonant) scattering regimes alike (Fig.2b).



Finally, the torque is obtained as $\mathbf{T} \propto \mathbf{S} \times \mathbf{m}$

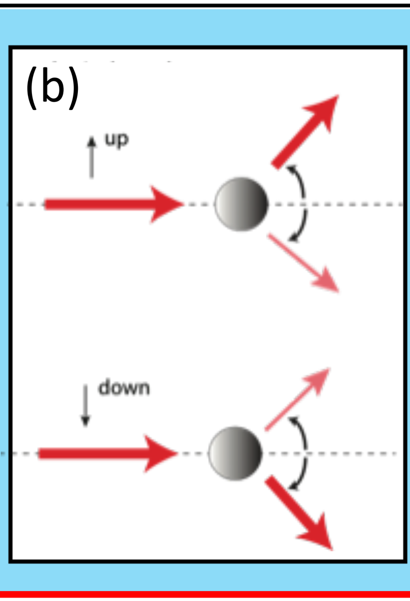


Fig.2 (a) Diagrammatic representation of the renormalised charge vertex. (b) Illustration of the skew scattering mechanism.

3. Application to TI/Ferromagnet bilayer

Surface states of 3D topological insulators are described by the Hamiltonian

$$H = v\hat{\boldsymbol{\sigma}} \cdot (\mathbf{k} \times \mathbf{z}) + \Delta \hat{\boldsymbol{\sigma}} \cdot \mathbf{m} \qquad (3)$$

where $\hat{\boldsymbol{\sigma}}$ is the vector of Pauli matrices, v is the Fermi velocity and Δ is the exchange coupling generated by the interaction between the TI and the ferromagnet. At low energy, the dispersion relation is well described by Dirac cones shifted and gapped by the magnetic interaction (Fig 3).

- Our theory is non perturbative in the exchange coupling, which allows us to study the torque angular dependence.
- Spin-momentum locking generates the familiar Edelstein spin accumulation, which corresponds to the elements $K_{12(21)}$ of the response function [3,4].

Skew scattering activates all the other entries of the matrix $\hat{K}$ that contribute significantly to the SOT (Fig.4).

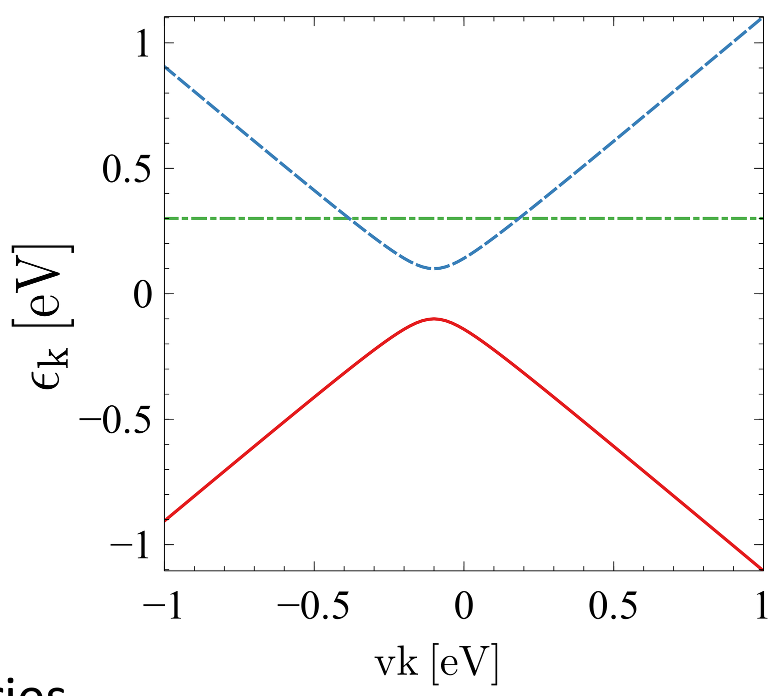


Fig.3 Band structure of the TI with exchange field Δ.

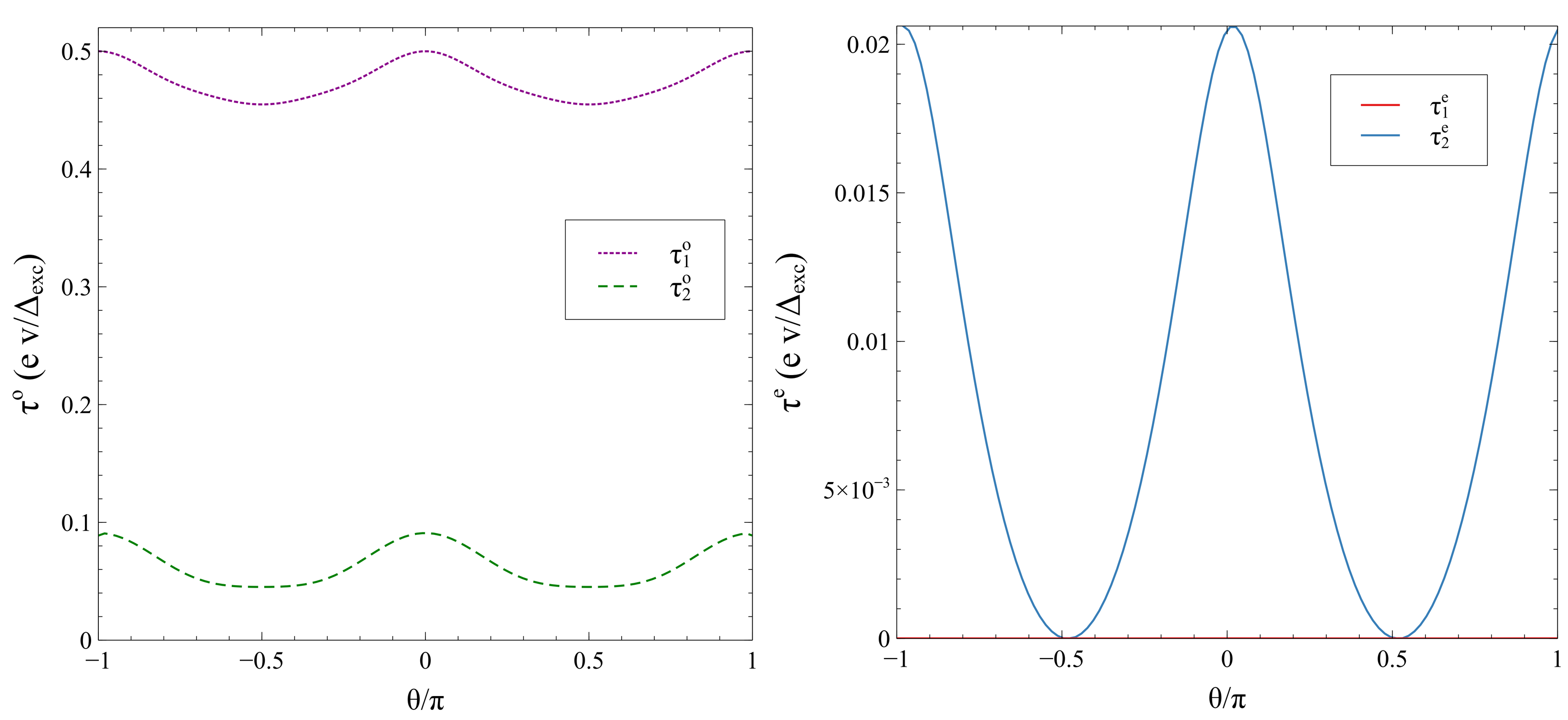


Fig.4 Torque efficiency as function of the magnetisation angle. Dilute resonant impurities have been used. (a) **m**-odd component. (b) **m**-even component.

We also obtain analytic results in the limit of weak exchange coupling and low magnetisation angles:

$$K_{xx(yy)} = \frac{m_z(m_z^2 - \epsilon_F^2)^2}{2n_i \pi u v (3m_z^2 + \epsilon_F^2)^2} \qquad K_{zy} = \frac{m_x m_z (m_z^2 - \epsilon_F^2)}{4n\pi^2 u v \epsilon (3m_z^2 + \epsilon_F^2)}$$

$$K_{zx} = \frac{m_x(m_z^2 - \epsilon_F^2)(m_z^4 + 6m_z^2(1-2\pi)\epsilon_F^2 + (1-4\pi)\epsilon_F^4)}{16n\pi^2 v^3 \epsilon (3m_z^2 + \epsilon_F^2)^2} \qquad (4)$$

where n is the impurity density and ϵ_F is the Fermi energy.

4. Acknowledgments

A.V. and A.F. acknowledge the financial support from the Royal Society (U.K.) through grant No. RGF\EA\180276.

CONTACT PERSON

av784@york.ac.uk

aires.ferreira@york.ac.uk

REFERENCES

[1]: A. Manchon et al, Rev. Mod. Phys., 91, 035004 (2019).
[2]: M. Milletarì, and A. Ferreira. Phys. Rev. B **94**, 134202 (2016);
M. Milletarì, and A. Ferreira. Phys. Rev. B **94**, 201402 (2016)
[3]: P. B. Ndiaye, C. A. Akosa, M. H. Fischer, A. Vaezi, E.- A. Kim, and A. Manchon, Phys. Rev. B **96**, 014408
[4]: I. A. Ado, O. A. Tretiakov, and M. Titov, Phys. Rev. B 95, 094401 (2017)
[5]: F. Sousa, G. Tatara, A. Ferreira, arXiv: (2020)

Graphene online 2020