Exchange interaction mediated by Weyl Fermi arcs

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Abstract

The interest in unconventional quasi-particles in condensed matter systems has been renewed in the last decade, fuelled by the avalanche of experimental data on topological semimetals, also referred to as Weyl semimetals [1]. These states refer to topological 3D band-crossings characterized by the degeneracy and the functional form of these crossings. Surface states known as Fermi arcs may appear connecting pairs of these so called "topological nodes", Fermi arcs have deep penetration to the bulk, in contrast with surface states of other topological systems.

By inserting magnetic impurities in these systems, we expect a long-range coupling between the impurities in the form of the famous Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction [2, 3]. In this work, we theoretically study how the Fermi arcs in Weyl systems can mediate (and perhaps enhance) RKKY interactions between impurities located on surfaces (even opposite surfaces) and in the bulk of Weyl semimetals.

Based on the description of long-range coupling between magnetic impurities in a metallic nanowire [4], we analytically study the generalized case for an 3D Dirac Hamiltonian in the form $H_k = \epsilon_0 \sigma_0 + d(k) \cdot \sigma$, where ϵ_0 is the Fermi energy, d is an arbitrary 3D vector field in k-space and (σ_0, σ) is the 4-vector of Pauli matrices. This choice gives a Dirac-like spectrum $E_k = \epsilon_0 \pm |d(k)|$, with Weyl nodes at the points where $d(k) = 0$ and with linear dispersion around these points.

We consider coupling between our system and two magnetic impurities, using the interaction term as a generalization of the one used in [4] for 2 impurities. By writing the interaction operators in the basis that diagonalizes the Hamiltonian, we have found that, in second order perturbation theory, there are complex interaction terms between all 3 spin directions of both impurities (9 terms, in total). These terms can be classified as generalizations of RKKY, Ising and Dzyaloshinskii–Moriya interactions. In addition, we compared these analytical results with numerical calculations for a minimal Weyl model with only two Weyl nodes, which can be written in a tight-binding form.

By discretizing the model and placing magnetic impurities at opposite surfaces, we can numerically obtain the leading contribution of the effective RKKY long-range interaction through the bulk and Fermi arc states as a function of the surface separation.

References

[1] B. Q. Lv, T. Qian, and H. Ding, Experimental perspective on three-dimensional topological semimetals, Rev. Mod. Phys. 93, 025002 (2021).
[2] Kaladzhyan, A. A. Zyuzin, and P. Simon, Rkky interaction on the surface of three-dimensional dirac semimetals, Phys.Rev. B 99, 165302 (2019).
[3] Verma, D. Giri, H. A. Fertig, and A. Kundu, Rkky coupling in weyl semimetal thin films, Phys. Rev. B 101, 085419 (2020).
[4] J. F. Silva and E. Vernek, Modified exchange interaction between magnetic impurities in spin orbit coupled quantum wires, Journal of Physics: Condensed Matter 31, 135802 (2019).