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Temperature dependence of static spin conductivity of gapped graphene

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ABSTRACT

We address temperature dependence of static spin conductivity of gapped graphene for various magnetizations, coulomb repulsion interaction strengths and energy gap parameters. We have used Hubbard model for describing the electron dynamics of the system. Based on linear response theory, we have obtained the spin conductivity of the system using Green's function approach. Our results show the temperature dependence of static spin conductivity has a pick that moves to higher temperatures by increasing the magnetization, strength of coulomb repulsion interaction and energy gap. Furthermore, at fixed temperature, static spin conductivity decreases by increasing mentioned physical parameters.

1. Introduction

Graphene is a flat monolayer of carbon atoms tightly packed into a two-dimensional honeycomb lattice which was first fabricated experimentally by Novoselovetal in2004 [1,2], and it is a basic building block for all nano structure materials [3–5]. This stable structure has attracted considerable attention because of experimental progress and because of exotic chiral feature in its electronic properties and promising applications [6].

Among various types of nanoscale devices, carbon-based nanostructures, such as graphene, are appealing for spintronics or spin based electronics. What makes graphene a promising material in the field of spintronics, is its unique spin transport performance in particular at room temperature [7] where spin life times of up to 3.7 ns [8] and spin diffusion length of 12 μm [9] have been measured by means of electrical Hanle spin precession measurements in non-local spin-valve devices. The relatively weakness of spin-orbit and hyperfine interactions should lead to long spin diffusion length and long spin coherence times [10,11].

The transport of quantum information via spin degrees of freedom is a novle topic for both theoretical and experimental physicists. One of the most important physical quantity in relation to quantum information theory is spin current conductivity or spintronic of the electronic. The conductivity is defined as the linear current response to a uniform, frequency dependent, current-driving, external force field, e.g., an electric field in the case of charge transport or a gradient of the z-component of the magnetic field for spin transport. Spin transport in insulating antiferromagnets described by the *XXZ* Heisenberg model in two and three dimensions in Ref. [12]. Spin and charge transport properties in graphene-based single-layer and few-layer spin-valve devices is discussed in Ref. [13]. It is presented an overview of challenges and recent advances in the field of device fabrication. The static spin conductivity and spin Drude weight of one-dimensional spin-1/2 anisotropic antiferromagnetic Heisenberg chain in the finite magnetic field is investigated theoretically in Ref. [14]. It is used the self-consistent harmonic approximation together with the Linear Response Theory to study the effect of nonmagnetic disorder on spin transport in the quantum diluted two-dimensional anisotropic Heisenberg model with spin-1/2in a square lattice [15]. The spin transport, in the disordered phase, of the frustrated Heisenberg antiferromagnet with spin$S=1$ with next and next-nearest neighbor interactions on a square lattice is analyzed. The spin conductivity is calculated using a SU(3) Schwinger boson formalism and the Kubo theory, within the ladder approximation. The spin conductivity exhibits a nonzero Drude weight at finite temperature [16]. Using the SU(3) Schwinger's boson theory, it is studied the spin transport in the frustrated anisotropic three dimensional XY

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model at T = 0 with single ion anisotropy. It is investigated the behavior of the spin conductivity for this model that presents exchange interactions. The results showed a metallic spin transport for $\omega > 0$ and a superconductor spin transport in the limit of DC conductivity [17].

In this work we calculate static spin conductivity of gapped graphene in the context of Hubbard model. Using linear response theory and green's function approach, we calculate the static spin conductivity in terms of one particle Green's function. It can be seen that static spin conductivity has a pick at a characteristic temperature. We investigate the impact of magnetization, energy gap, strength of coulomb repulsion interaction on the static spin conductivity of gapped graphene.

2. Hamiltonian model and Green's functions of gapped graphene

Graphene is a two dimensional honeycomb lattice that carbon atoms located on the corner of hexagons with two different symmetries A and B as illustrated in Fig. 1. The electron dynamics has been described by the following expression

$$H = H^{(0)} - H_U \tag{1}$$

$$H^{(0)} = -\sum_{\substack{i,j,\sigma,\\ \alpha\neq\beta}} t_{ij}^{\alpha\beta}\left(c^{\dagger}_{i\alpha\sigma}c_{j\beta\sigma} + h.c.\right) + \sum_{i,\sigma,\alpha}\mu_\sigma c^{\dagger}_{i\alpha\sigma}c_{i\alpha\sigma}$$

$$H_U = U\sum_{i,\alpha} c^{\dagger}_{i\alpha\uparrow}c_{i\alpha\uparrow}c^{\dagger}_{i\alpha\downarrow}c_{i\alpha\downarrow}$$

where $H^{(0)}$denotes noninteracting tight binding model Hamiltonian and H_U is electron-electron repulsion strength. α and β refer to two different sublattices in the honeycomb structure and i,j introduces the nearest neighbor unit cells where each site belongs to one of two different sublattice A or B. $c^{\dagger}_{i\alpha\sigma}$ is creation operator of an electron with spin σ at subsite α on i^{th} unit cell site. μ_σ is spin dependent chemical potential. U is the repulsion coulomb interaction strength and $t_{ij}^{\alpha\beta}$ refers to hopping integral so that $t_{ii}^{AA} = \varepsilon_0$ and $t_{ii}^{BB} = -\varepsilon_0$.

Diagonalization of the Hubbard Hamiltonian Eq. (1), within Mean field approximation under nearest neighbor approximation, yields a two band spectrum for anti-ferromagnetic phase. The band

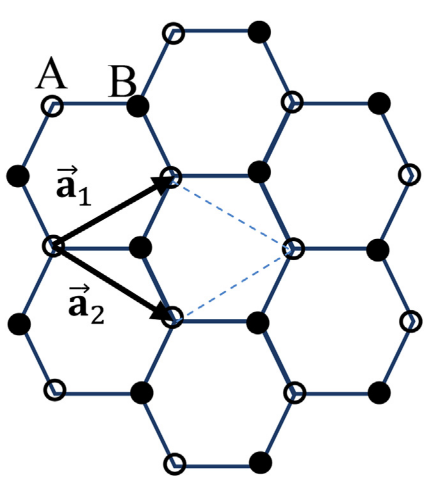

Fig. 1. Honeycomb lattice of graphene. A and B are two different symmetries.

energies of electrons takes the following form [18]:

$$E^{\pm}_{\sigma}\left(\vec{k}\right) = -\mu_\sigma + \frac{U}{2}n_\sigma \pm \sqrt{\left(\frac{Um}{2}\right)^2 + \left|\phi\left(\vec{k}\right)\right|^2 + \left(\frac{\triangle}{2}\right)^2} \tag{2}$$

n_σ is electron density with spin σ and m is staggered magnetization, $\triangle$ is energy gap and $\phi(\vec{k}) = -t\sum_i e^{i\vec{k}\cdot\vec{\delta}_i}$. Here $\vec{\delta}_i$ is connection vector of nearest neighbors.

The single particle Matsubara Green's function of gapped graphene in the atomic Hilbert space represents a 2×2 matrix so that each element of this matrix is given by:

$$\mathscr{G}^{\alpha\beta}_{\sigma}(k,\tau) = -Tc_{\alpha k\sigma}(\tau)c^{\dagger}_{\beta k\sigma}(0) \tag{3}$$

τ is the imaginary time. In the band space, the single particle Matsubara Green's functions elements are given by Ref. [18]:

$$\mathscr{G}^{AA}_{\sigma}(k,i\omega_n) = \sum_{j=\pm}\frac{|X_{\sigma j}(k)|^2}{i\omega_n - E^{j}_{\sigma}(k)} \tag{4}$$

$$\mathscr{G}^{BB}_{\sigma}(k,i\omega_n) = \sum_{j=\pm}\frac{|Y_{\sigma j}(k)|^2}{i\omega_n - E^{j}_{\sigma}(k)} \tag{5}$$

$$\mathscr{G}^{AB}_{\sigma}(k,i\omega_n) = \sum_{j=\pm}\frac{X_{\sigma j}(k)Y^{*}_{\sigma j}(k)}{i\omega_n - E^{j}_{\sigma}(k)} \tag{6}$$

$$\mathscr{G}^{BA}_{\sigma}(k,i\omega_n) = \sum_{j=\pm}\frac{X^{*}_{\sigma j}(k)Y_{\sigma j}(k)}{i\omega_n - E^{j}_{\sigma}(k)} \tag{7}$$

So that $X_{\sigma j}(k)$ and $Y_{\sigma j}(k)$ follow:

$$|X_{\sigma\pm}(k)|^2 = \frac{1}{2}\left[1 - \frac{Um\sigma}{2E^{\pm}_{\sigma}(k)}\right], \tag{8}$$

$$|Y_{\sigma\pm}(k)|^2 = \frac{1}{2}\left[1 + \frac{Um\sigma}{2E^{\pm}_{\sigma}(k)}\right], \tag{9}$$

$$X_{\sigma\pm}(k)Y^{*}_{\sigma\pm}(k) = -\frac{\phi(k)}{2E^{\pm}_{\sigma}(k)}. \tag{10}$$

In the section 3, we will use these Green's functions to obtain the spin conductivity of gapped graphene.

3. Static spin conductivity of gapped graphene

The spin conductivity is defined as linear current response to an external force field, Such asa gradient of the z-component of the magnetic field. Spin current density can be written as bellow:

$$\vec{j} \;=\; \sigma\vec{\nabla}h^z. \tag{11}$$

σ is conductivity tensor and h^z is

$$h^z(l,t) = g\mu_B B^z(l,t). \tag{12}$$

Here l, t, g, μ_B and B^z are respectively position, time, gyromagnetic constant, Bohr magneton and z component of magnetic field, respectively.The magnetic field depends on both time and position.

The x-component of spin current density due to the z-