Magneto-transport in the presence of spin-orbit coupling.

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Introduction

Studying the electronic transport properties in a system with spin-orbit coupling is a quite interesting problem. Hamiltonian for the system can be written as .

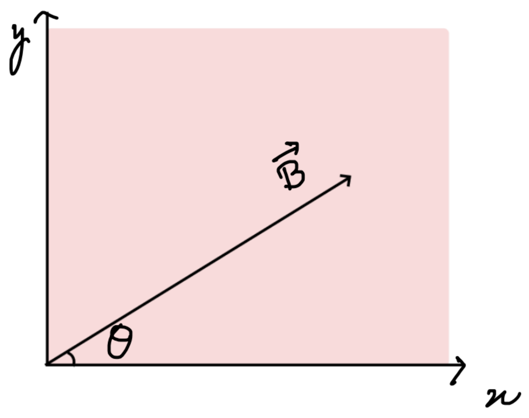
$$H = \sum_{k\rho} E_0(k)\ C^{\dagger}_{k\rho} C_{k\rho} + \tau \underbrace{\sum_{k\rho\rho'} (\vec{k}\times\vec{\sigma})_z\ C^{\dagger}_{k\rho} C_{k\rho'}}_{\text{spin-orbital term}} + \underbrace{\sum_{k\rho\rho'} (\vec{B}\cdot\vec{\sigma}) C^{\dagger}_{k\rho} C_{k\rho'}}_{\text{Zeeman term}}$$

$\vec{\sigma} = \sigma_x\hat{x} + \sigma_y\hat{y} + \sigma_z\hat{z}$, where $\sigma_x, \sigma_y, \sigma_z$ are *Pauli's matrices*.

Two eigen values are

$$E_- = E_0 - \sqrt{B^2 + \tau_z^2(k_x^2 + k_y^2) + 2\tau_z B(k_x \sin(\theta) - k_y \cos(\theta))}$$

$$E_+ = E_0 + \sqrt{B^2 + \tau_z^2(k_x^2 + k_y^2) + 2\tau_z B(k_x \sin(\theta) - k_y \cos(\theta))}$$



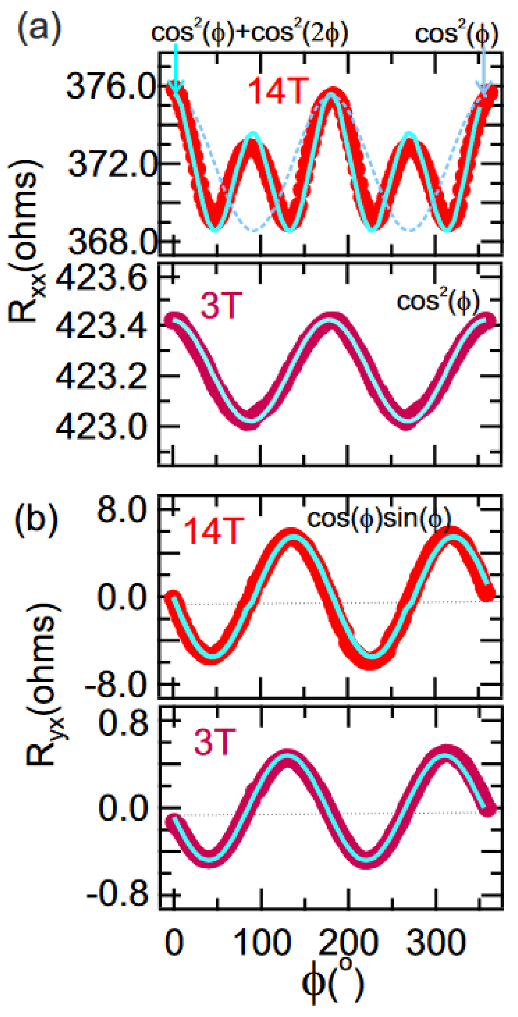
E_- and E_+ are dispersion relation for two new bands. Here θ is the angle planar B makes with k_x axis. σ_{xx} and σ_{xy} are two important components of the conductivity tensor σ and can be calculated as

$$\sigma_{xx} = \frac{e^2\tau}{4\pi^3}\int dk_x dk_y\ \ v_x(k_x,k_y)\ v_x(k_x,k_y)\ \left(-\frac{\partial f}{\partial E}\right)$$
$$\sigma_{xy} = \frac{e^2\tau}{4\pi^3}\int dk_x dk_y\ \ v_x(k_x,k_y)\ v_y(k_x,k_y)\ \left(-\frac{\partial f}{\partial E}\right)$$

Here v_x and v_y are velocities of electron given by $v_{x/y} = \dfrac{\partial E}{\partial k_{x/y}}$

Experimental Results and Motivation

Study conducted in 2019 ,involving investigation of the planar hall and Anisotropic Magnetoresistance in a conducting interface of LaVO3-KTaO3 , credited to INST-Mohali, show some quite interseting result. The experiment involves creating a conducting interface between $KTaO_3$ (KTO) and insulator $LaVO_3$ (LVO) and measuring Planar Hall effect (PHE) and anisotropic magnetoresistance (AMR).The results show a two-fold oscillatory behavior in the AMR at low magnetic fields that transitions into a four-fold oscillations at high fields, and the observation of PHE.



Reference: Wadehra, N., Tomar, R., Gopal, R.K., Singh, Y., Dattagupta, S., Chakraverty, S. (2019) arXiv:1908.06636v1 [cond-mat.mes-hall]

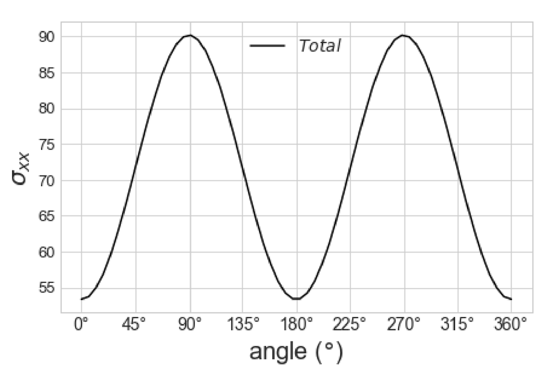
Model-3 (Lattice model)

$$H = -t\sum_{<ij>,\sigma} C^{\dagger}_{i,\sigma}C_{j\sigma} + C^{\dagger}_{j\sigma}C_{i\sigma} + iV_R\left(\sum_{j,\alpha,\beta} C^{\dagger}_{j,\alpha}\hat{\sigma_x}C_{j+\hat{y},\beta} - C^{\dagger}_{j,\alpha}\hat{\sigma_y}C_{j+\hat{x},\beta}\right) - h.c + \sum_{j,\alpha,\beta}(\vec{B}.\vec{\sigma})C^{\dagger}_{j,\alpha}C_{j,\beta}$$

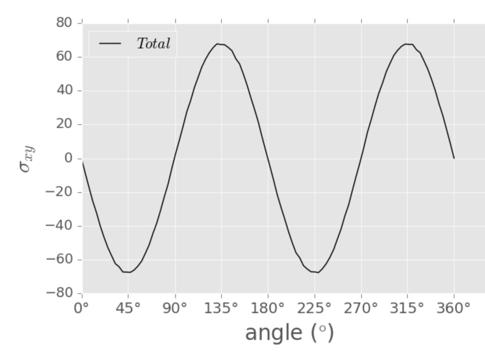
Dispersion relation for two bands

$$E_{\pm} = -2t\cos k_x - 2t\cos k_y \pm \sqrt{B^2 + 4V_R^2(\sin^2 k_x + \sin^2 k_y) + 4V_R B(\sin k_x \sin\theta - \sin k_y \cos\theta)}$$

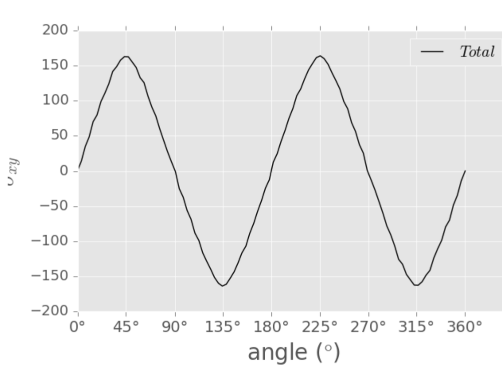
Results ($V_R/t = 0.3$)



(a) $\sigma_{xy}(\theta)$ vs θ



(b) $\sigma_{xy}(\theta)$ vs θ



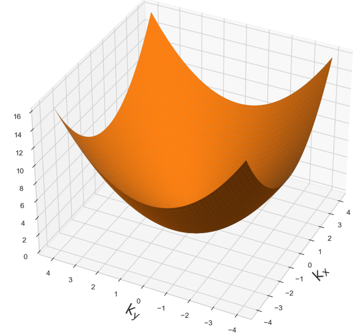
(c) $\sigma_{xy}(\theta)$ vs θ

- $\sigma_{xx}(\theta)$ shows a two fold oscillation with respect to θ.
- $\sigma_{xy}(\theta)$ shows two type of oscillations. Both are $\sin\theta\cdot\cos\theta$ like oscillations , but differ by a phase of $\pi/2$

Model-1 (Continuum Model)

Dispersion relation for continuum model (free electron model) is given by

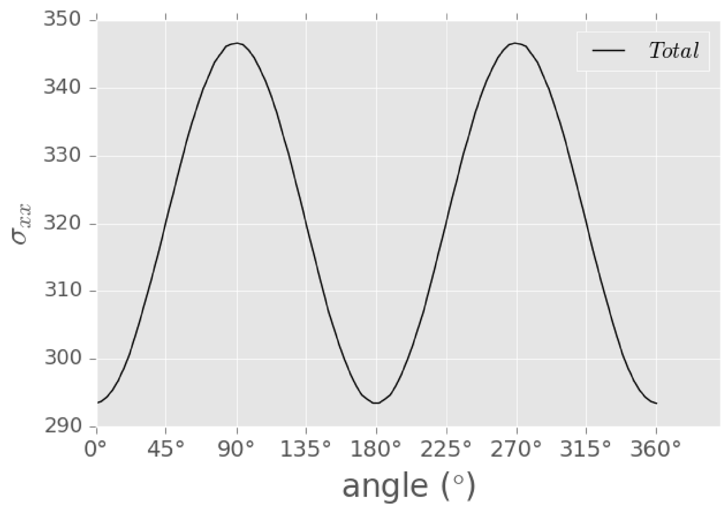
$$E_0 = \frac{1}{2}\vec{k}^2 = \frac{1}{2}(k_x^2 + k_y^2)$$



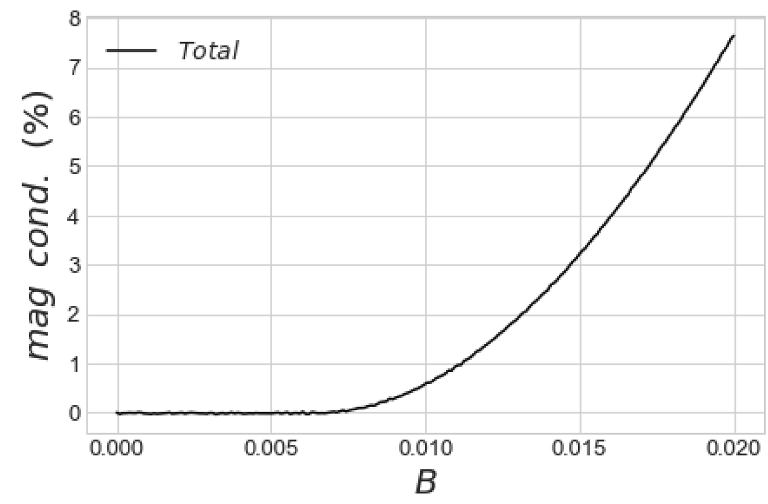
This parabolic band slits into two bands in the presence of s-o coupling and B.

Parameters : τ_z ,B , θ , E_f (four)

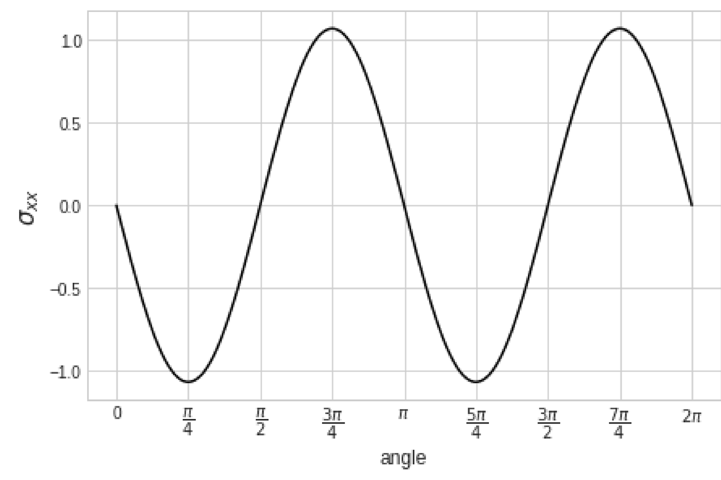
Results ($\tau = 0.05$)



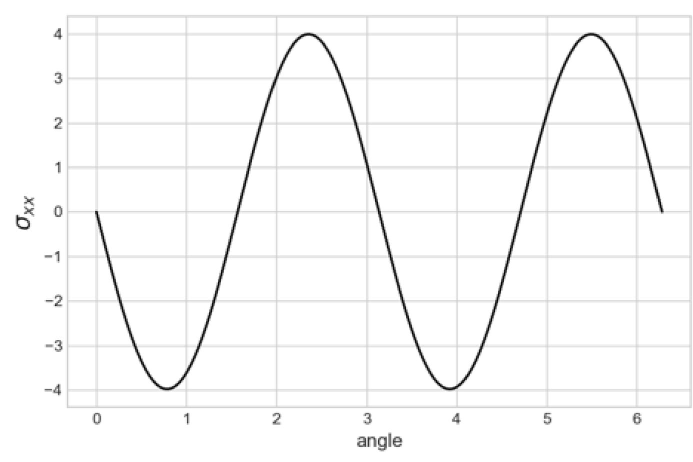
(a) $\sigma_{xx}(\theta)$ vs θ



(b) Magneto-conductivity



(c) $\sigma_{xy}(\theta)$ vs θ



(d) $\sigma_{xy}(\theta)$ vs θ

- $\sigma_{xx}(\theta)$ shows a two fold oscillation with respect to θ with $\sin^2\theta + const$ like dependence.
- Magneto-conductivity $\left(\frac{\sigma_{xx}(B)-\sigma_{xx}(0)}{\sigma_{xx}(0)}\times 100\right)$ shows a quadratic dependence on B and negative magneto-resistivity (MR).
- $\sigma_{xy}(\theta)$ shows oscillations with functional dependence like $\sin\theta\cdot\cos\theta$.

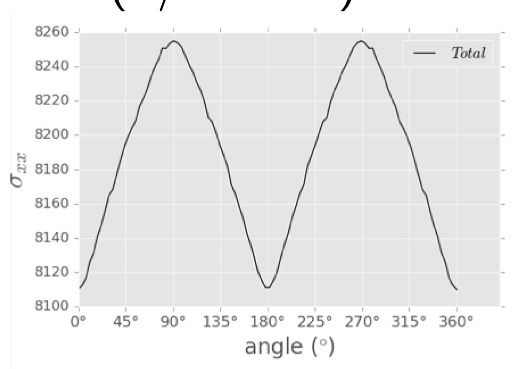
Model-2 (Tight-binding like)

Dispersion relation for square lattice tight binding model is given by

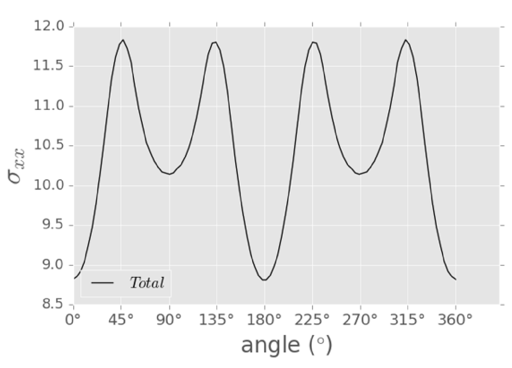
$$E_0 = -2t\cos(k_x) - 2t\cos(k_y)$$

Parameters : t , τ_z , B , θ ,E_f (five)

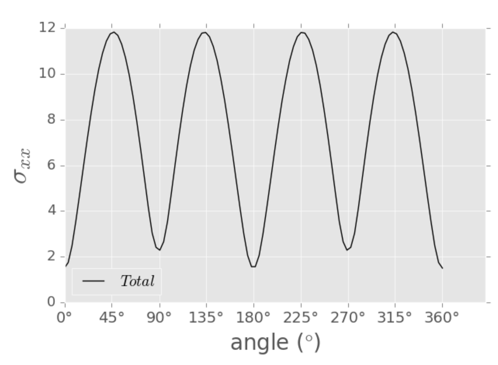
Results ($\tau/t = 0.2$)



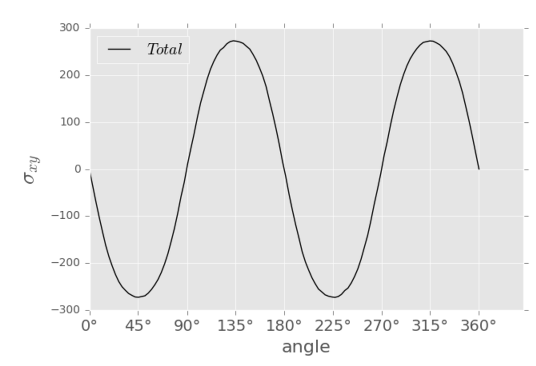
(a) $\sigma_{xx}(\theta)$ vs θ



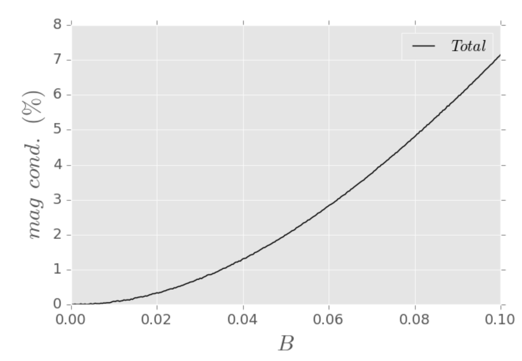
(b) $\sigma_{xx}(\theta)$ vs θ



(c) $\sigma_{xx}(\theta)$ vs θ



(d) $\sigma_{xy}(\theta)$ vs θ



(e) Magneto-conductivity

- σ_{xx} shows two fold oscillations and four fold oscillations. Some two period oscillations gradually transitions into fold oscillations with increasing B.
- Magneto-conductivity shows a quadratic dependence on B and negative magneto-resistivity (MR).
- $\sigma_{xy}(\theta)$ shows oscillations with functional dependence like $\sin\theta\cdot\cos\theta$.