Magnetisation and magnetic susceptibility of Bi_2Se_3

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Magnetism of free electrons

Free electron trajectory is curved in magnetic field - orbital magnetism.
Spin magnetic moment is aligned along magnetic field - spin magnetism.

Magnetism of electrons in solids.

- Bound electrons(localized)
- Band electrons(delocalized)
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    - Diamagnetism Landau - orbital.
    - Pierls formula - obrbital
    - Pauli paramagnetism - spin magnetism.

McClure magnetism

Magnetic susceptibility of graphite is relatively big. For massive Dirac fermion.

$$\chi = -\frac{\mu_0 e^2 v^2}{6\hbar\pi}\frac{1}{m}$$

For massless Dirac fermion with non-zero temp.

$$\chi = -\frac{\mu_0 e^2 v^2}{24\hbar\pi}\frac{1}{T}$$

Gauge invariant calculation results

Pierls substitution - derivation from 1-st principles.

$$M = \sum_n \int_{BZ} [n_F(E_{n\mathbf{k}}) m_{n\mathbf{k}} + e\frac{T}{\hbar} \log(1 + e^{-\frac{E-\mu}{T}}) \Omega_{n\mathbf{k}}] \frac{d^2k}{4\pi^2}$$

$$\chi = -\frac{\mu_0 e^2}{12\hbar^2} \frac{Im}{\pi S} \int_{-\infty}^{+\infty} n_F(E)\, Tr[gh^{xx} gh^{yy} - gh^{xy} gh^{xy} - 4(h^x gh^x h^y gh^y - h^x gh^y h^x gh^y)] dE$$

Better than Landau diamagnetism.

Model of 3D topological insulator

Surface states Hamiltonian

$$\begin{bmatrix} \mathbf{h_1} & 0 \\ 0 & \mathbf{h_2} \end{bmatrix}$$

$$h_1 = v_f k_y \sigma_x - v_f k_x \sigma_y + (m_0 + Bk^2)\sigma_z$$

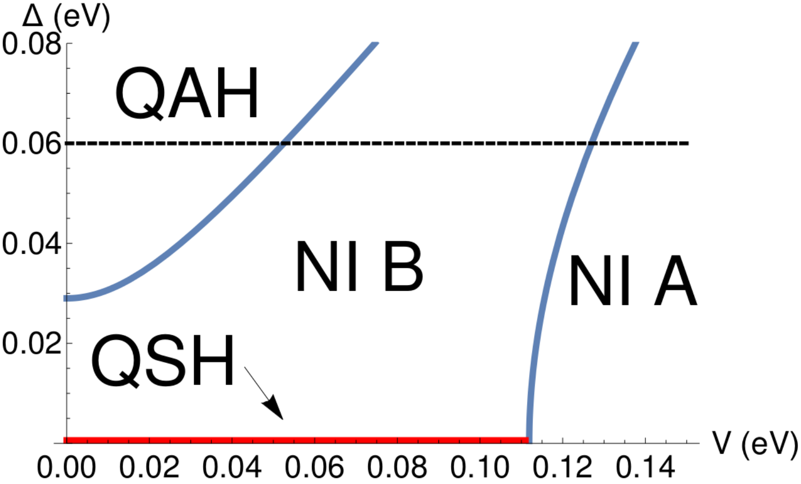
$$h_2 = v_f k_y \sigma_x + v_f k_x \sigma_y + (m_0 + Bk^2)\sigma_z$$

Model of 3D topological insulator

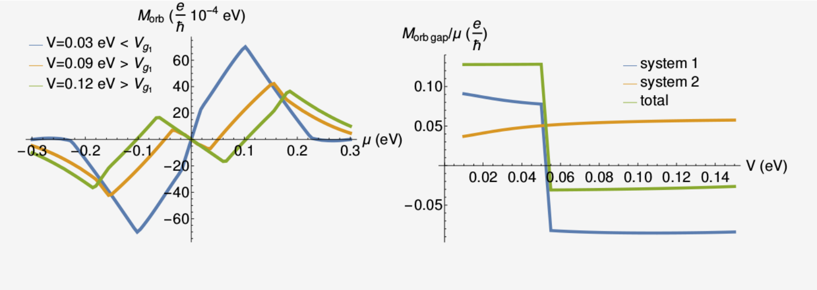
$$H_{imp} = \begin{bmatrix} \Delta\sigma_z & 0 \\ 0 & -\Delta\sigma_z \end{bmatrix}$$

$$H_{el.field} = \begin{bmatrix} 0 & V\sigma_x \\ V\sigma_x & 0 \end{bmatrix}$$

Phase structure



Magnetization



Magnetic susceptibility at $\mu = 0$

Gap closing between QAH and Insulator phase

$$\chi \propto -\frac{1}{gap}$$

$$\chi \propto -\frac{1}{T}$$

Gap closing between Insulator phases

$$\chi \propto +\frac{1}{gap^4}$$

$$\chi \propto +\frac{1}{T^4}$$

Conclusion

- Magnetization in gap is linear in chemical potential with coefficient proportional to topological invariant.
- Susceptibility when gap is closing is diamagnetic as in McClure magnetism in one point of gap closing and paramagnetic with different power law behavior($+\frac{1}{T^4}$ instead of $-\frac{1}{T^3}$) in other point.