Thermoelectric Anomaly in A 2D Electron System with SOI ?

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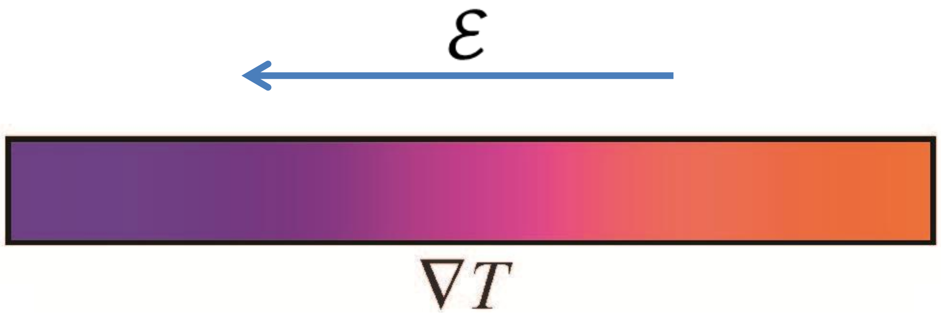
Outline

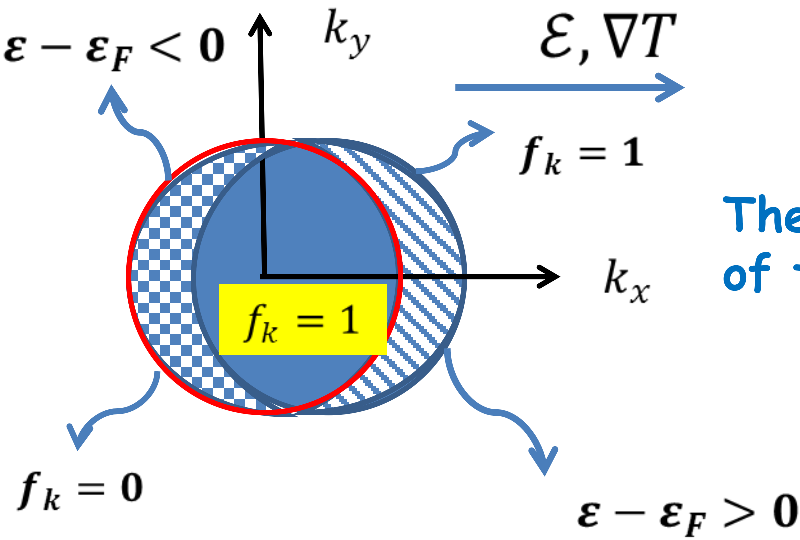
- How does a thermoelectric anomaly appear?
- Is it possible to have one in a semiconductor?
- Is a 2D system with Rashba-Dresselhaus SOI adequate for this purpose?
- Charge and Spin Thermoelectrics
- Results
- Conclusions

The Seebeck Effect Phenomelogy



$$\mathcal{E} = S\nabla T$$

Semiclassical Picture of Thermoelectric Transport



The Fermi sea is displaced along the direction of the perturbation

The cancellation of the states above and below the Fermi energy is exact at T = 0K and of the order of $\left({}^{k_B T}/_{\varepsilon_F}\right)^2$ at finite temperature

SMALL !

How Can Be S Increased?

Single electron states: momentum $\vec{k}$, energy $\varepsilon(\vec{k})$, velocity $\vec{v}(\vec{k})$ and occupation number $f(\vec{k})$

$$S = -\frac{\sum_{\vec{k}} \Delta f(\vec{k})\,\vec{v}(\vec{k})\left[\varepsilon(\vec{k}) - \varepsilon_F\right]}{eT\sum_{\vec{k}} \Delta f(\vec{k})\, v(\vec{k})}$$

Slowly varying function of energy

Slowly varying function of energy

$\Delta f(\vec{k})$ has to be a strongly varying, asymmetric function of the energy in the neighborhood of the Fermi surface

What is needed for a thermoelectric anomaly?

A. Inelastic scattering

$$\frac{dP(\boldsymbol{k}',\boldsymbol{k})}{dt} = -W(\boldsymbol{k}',\boldsymbol{k})f(\boldsymbol{k})[1-f(\boldsymbol{k}')] + W(\boldsymbol{k},\boldsymbol{k}')f(\boldsymbol{k}')[1-f(\boldsymbol{k})]$$

In equilibrium: $W(\boldsymbol{k}',\boldsymbol{k})exp\left(\frac{\varepsilon_{k'}}{k_B T}\right) = W(\boldsymbol{k},\boldsymbol{k}')exp\left(\frac{\varepsilon_{k}}{k_B T}\right)$

$$f(\boldsymbol{k}) = f^0(\boldsymbol{k}) + \Delta f(\boldsymbol{k})$$

$$\frac{dP(\boldsymbol{k}',\boldsymbol{k})}{dt} = W(\boldsymbol{k}',\boldsymbol{k})\{\Delta f(\boldsymbol{k})[1-f^0(\boldsymbol{k}') + e^{\beta\Delta\varepsilon}f^0(\boldsymbol{k}')] - \Delta f(\boldsymbol{k}')[f^0(\boldsymbol{k}') + e^{\beta\Delta\varepsilon}(1-f^0(\boldsymbol{k}'))]\}$$

$$= W(\boldsymbol{k}',\boldsymbol{k})\left\{\Delta f(\boldsymbol{k})e^{\beta\Delta\varepsilon}\boxed{\frac{e^{\beta(\varepsilon-\varepsilon_F)}+1}{e^{\beta(\varepsilon-\varepsilon_F)+\beta\Delta\varepsilon}+1}} - \Delta f(\boldsymbol{k}')\frac{e^{\beta(\varepsilon-\varepsilon_F)+\beta\Delta e}+1}{e^{\beta(\varepsilon-\varepsilon_F)}+1}\right\}$$

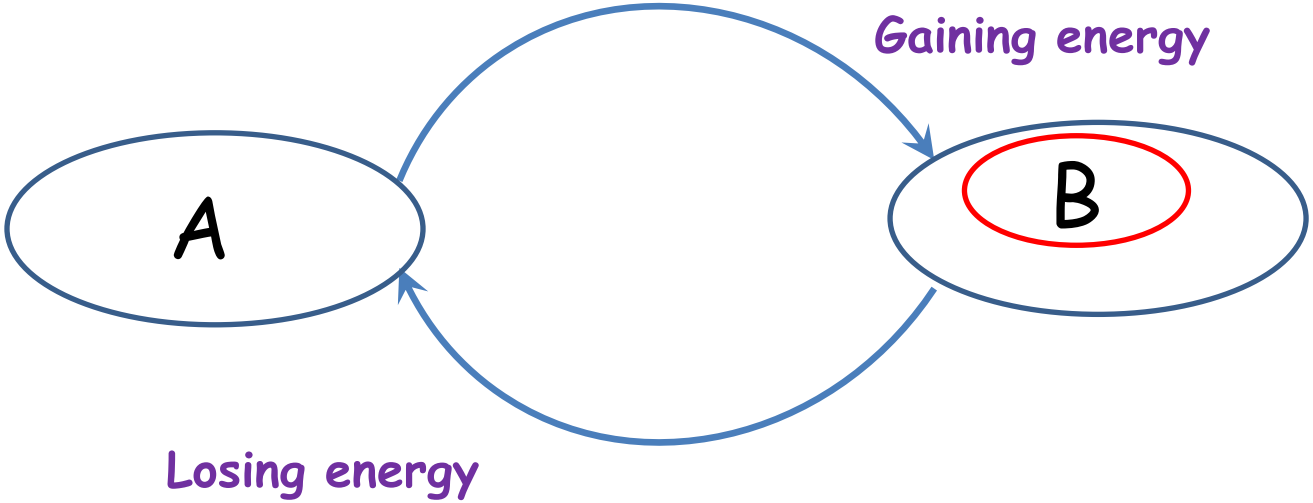
Summation over k cancels this effect

$$= \begin{cases} \boldsymbol{e^{-\beta\Delta\varepsilon}}, & \boldsymbol{\varepsilon > \varepsilon_F} \\ \boldsymbol{1}, & \boldsymbol{\varepsilon < \varepsilon_F} \end{cases}$$

The inelastic scattering has to have unidirectional character.

Spin scattering on magnetic impurities has a one dimensional character as it depends on the relative alignment of the electron and impurity spins

B. Population Imbalance



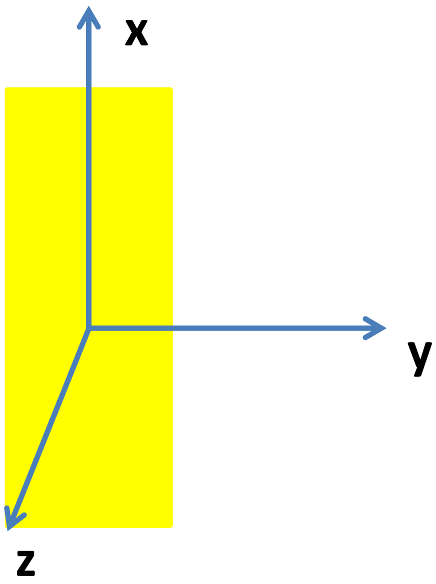
The two populations have to be unequal

Spin Polarized System with Population Imbalance
(no magnetic fields allowed)

Classic literature: Spin Density Waves-Itinerant Antiferromagnetism

Contemporary case study: 2D electron system with linear Rashba-Dresselhaus SOI coupling, in the $\alpha = \beta$ regime

2D Electron System with Rashba-Dresselhaus SOI



$$\boldsymbol{H_{SOI} = \alpha(p_x\sigma_z - p_z\sigma_x) + \beta(p_x\sigma_x - p_z\sigma_z)}$$

Special case : $\boxed{\alpha = \beta}$

$$H = \frac{p^2}{2m} + 2\alpha\frac{(\sigma_x+\sigma_z)}{\sqrt{2}}\frac{(p_z-p_x)}{\sqrt{2}}$$

In a rotated coordinate system:

$$\sigma_z' = \frac{(\sigma_x + \sigma_z)}{\sqrt{2}} \qquad p_z' = \frac{(p_x + p_z)}{\sqrt{2}}$$

$$\sigma_x' = \frac{(\sigma_x - \sigma_z)}{\sqrt{2}} \qquad p_x' = \frac{(p_x - p_z)}{\sqrt{2}}$$

$$H = \frac{1}{2m}(p_x - \hbar Q\sigma_z)^2 + \frac{p_z^2}{2m} - \frac{\hbar^2 Q^2}{2m}$$

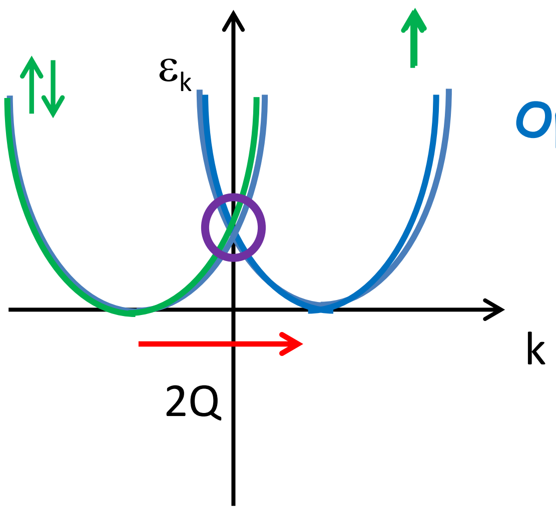
where $Q = \dfrac{2m\alpha}{\hbar}$

The Spin Instability

In the rotated reference frame, the eigenstates of the single-particle Hamiltonian are

$$\varepsilon_{\vec{k},\sigma} = \frac{\hbar^2}{2m}(k_x - Q\sigma)^2 + \frac{\hbar^2 k_z^2}{2m}$$

$$\psi_{k,\sigma}(\boldsymbol{r}) = \frac{1}{\sqrt{A}} e^{i\boldsymbol{k}\cdot\boldsymbol{r}}|\sigma\rangle$$



Opposite spin single particle states are degenerate

ε $\boxed{\varepsilon_{\vec{k},\uparrow}(0) = \varepsilon_{\vec{k},\downarrow}(0)}$ (k)

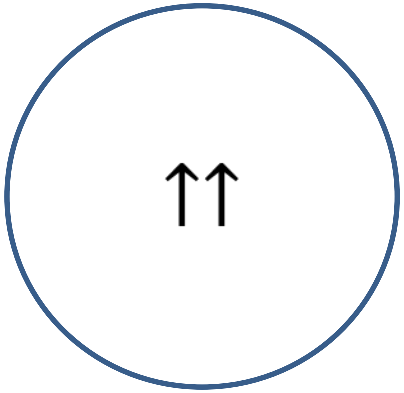
$$S_Q = \sum_k c^\dagger_{k\downarrow} c_{k+2Q\uparrow} \qquad S^\dagger_Q = \sum_k c^\dagger_{k+2Q\uparrow} c_{k\downarrow}$$

S_Q and $S_Q^\dagger$ have only zero matrix elements between Slater determinants constructed out of states $\psi_{k+2Q,\uparrow}$ and $\psi_{k,\downarrow}$, since this is a paramagnetic configuration

The instability condition leads to a magnetic phase if it is supported by the Coulomb interaction, realizing long-range ordering

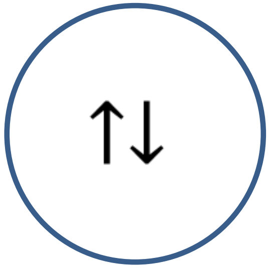
Non-zero matrix elements are obtained only if the single particle states in the Slater determinant are linear combinations of $\psi_{k+2Q,\uparrow}$ and $\psi_{k,\downarrow}$. Such a superposition will generate a total energy higher than the paramagnetic state

Possible Ground States of a Fermi Liquid



Ferromagnetic

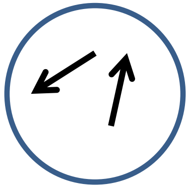
Parallel spin alignment decreases the potential energy because of the exchange interaction, but increases the kinetic energy on account of Pauli principle; higher energy than that of the paramagnetic state



Paramagnetic

Minimizes kinetic energy, but increases the potential energy because it reduces the exchange interaction

Spin Density Wave



Balances the kinetic energy with the potential energy by removing the parallel/anti-parallel spin alignment; lowers the energy of the paramagnetic state

A. W. Overhauser, Phys. Rev. Lett., **4**, 462 (1960); A. W. Overhauser, Phys. Rev., **128**, 1437 (1962).

Giant Spiral Spin Density Waves vs. Itinerant AF

Uniform Fermi liquid

2D + SOI

The single particle Hamiltonian:

$$H_1 = -\frac{\hbar^2 \nabla^2}{2m}$$

$$H_1 = -\frac{\hbar^2 (\nabla_x - iQ\sigma_z)^2}{2m}$$

The single particle energies

$$\varepsilon_\uparrow(k) = \varepsilon_\downarrow(k) = \frac{\hbar^2 k^2}{2m}$$

$$\varepsilon_\sigma(k) = \frac{\hbar^2 (k_x - Q\sigma)^2}{2m}$$

A configuration with a single point of degeneracy has to be created by displacing the single particle states of one spin orientation
in k space

A configuration with a single point of degeneracy is naturally created by SOI coupling

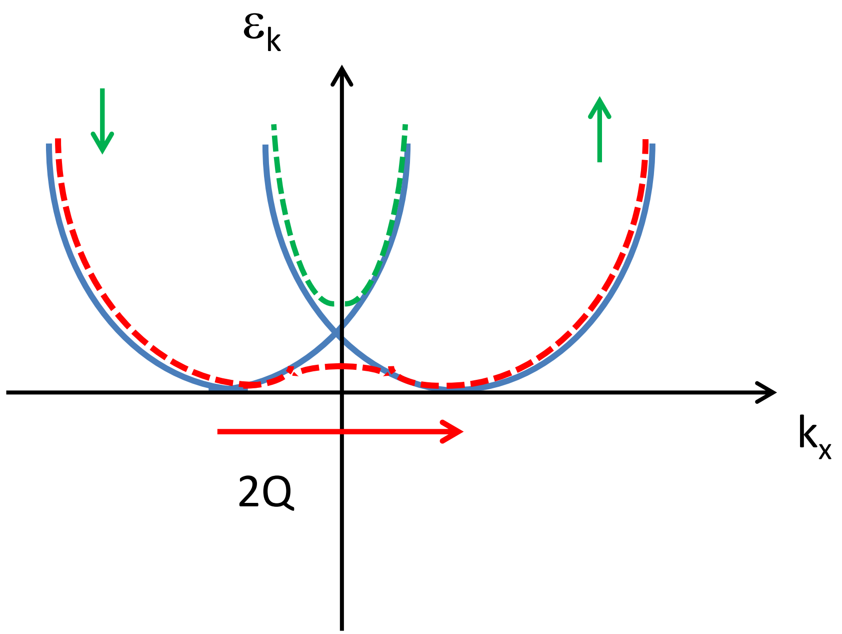
New Quasiparticles

Uniform Fermi liquid

$$\psi_{k,-}(r) = \cos\theta_k\, e^{ik\cdot r}|\uparrow\rangle + \sin\theta_k e^{i(k+2Q)\cdot r}$$
$$\psi_{k,+}(r) = -sin\,\theta_k\, e^{ik\cdot r}|\uparrow\rangle + \cos\theta_k e^{i(k+2Q)\cdot}$$

2D + SOI

$$\psi_{k,-}(r) = \cos\theta_k\, e^{ik\cdot r}|\uparrow\rangle + \sin\theta_k e^{ik\cdot r}|\downarrow\rangle$$
$$\psi_{k,+}(r) = -sin\,\theta_k\, e^{ik\cdot r}|\uparrow\rangle + \cos\theta_k e^{ik\cdot r}|\downarrow\rangle$$



Uniform Fermi liquid

$$\psi(k) = cos\theta_k \boxed{e^{ikr}|\uparrow\rangle} + \sin\theta_k \boxed{e^{i(k+2Q)r}|\downarrow\rangle}$$

Real space polarization effects are produced by the superposition of the two plain waves of different phases

2D + SOI

$$\psi(k) = cos\theta_k \boxed{e^{ikr}|\uparrow\rangle} + \sin\theta_k \boxed{e^{ikr}|\downarrow\rangle}$$

No real space polarization effects are created because the two plain waves have the same phase

The polarization

$$P = \vec{i}\sum_k \langle\psi_k|\sigma_x|\psi_k\rangle + \vec{j}\sum_k \langle\psi_k|\sigma_y|\psi_k\rangle + \vec{k}\sum_k \langle\psi_k|\sigma_z|\psi_k\rangle$$

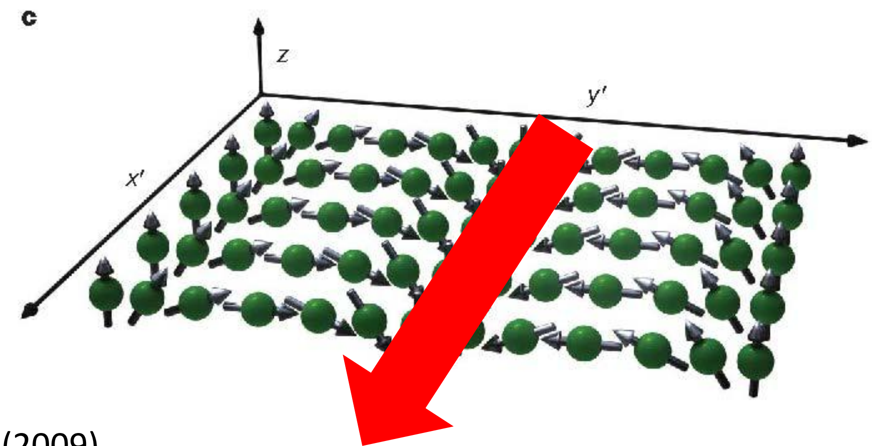
$$\boldsymbol{P} = \sum_k sin2\theta_k(\vec{i}cos2Qr + \vec{j}sin2Qr)$$

$$P_z = \sum_k cos2\theta_k = 0$$

$$\boldsymbol{P} = \vec{i}\sum_k sin2\theta_k$$

$$P_z = \sum_k cos2\theta_k = 0$$

Antiferromagnetic Alignment



Koralek et al, Nature 458, 610 (2009)

Fractional Polarization is aligned parallel with the direction of the displacement vector of the single particle states

Is the long-range antiferromagnetic alignment real?

Only if supported by the Coulomb interaction

$$v_{k\sigma;k'\sigma'}(q) = \int dr_1 \int dr_2 \psi^{\dagger}_{k,\sigma}(\boldsymbol{r}_1)\psi^{\dagger}_{k'+q,\sigma'}(\boldsymbol{r}_2)\frac{e^2}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|}\psi_{k',\sigma'}(\boldsymbol{r}_2)\psi_{k+q,\sigma}(\boldsymbol{r}_1)$$

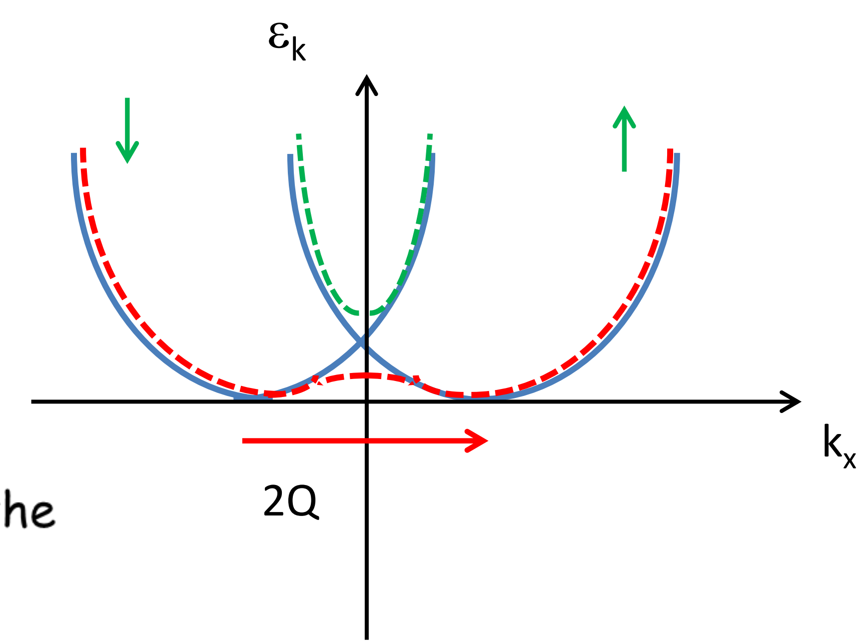
The Fundamental Paradigm Of The IAF Formation

The no kinetic energy cost pairing at the point of degeneracy :$|k,\uparrow\rangle \Leftrightarrow |k,\downarrow\rangle$ favors the formation of a new type of quasiparticle whose spin is not constant

In this ground state $\boxed{\left\langle c^{\dagger}_{k\uparrow} c_{k\downarrow} \right\rangle_0 \neq 0}$

Canonical transformation:

$$c_{k\uparrow} = \cos\theta_k a_k + \sin\theta_k b_k$$
$$c_{k\downarrow} = -\sin\theta_k a_k + \cos\theta_k b_k$$



θ_k becomes the variational parameter of the problem

The Many-Body Hamiltonian

$$H_0 = \sum_k \varepsilon_{k,\uparrow} c^\dagger_{k,\uparrow} c_{k,\downarrow} + \varepsilon_{k,\downarrow} c^\dagger_{k,\downarrow} c_{k,\downarrow}$$

$$H_{int} = \frac{1}{2} \sum_{k,k',q} \sum_{\sigma,\sigma'} v(q) c^\dagger_{k,\sigma} c^\dagger_{k'+q,\sigma'} c_{k',\sigma'} c_{k+q,\sigma}$$

Ground state energy is calculated within the Hartree-Fock approximation

$$\left\langle c^\dagger_{k,\sigma} c^\dagger_{k'+q,\sigma'} c_{k',\sigma'} c_{k+q,\sigma} \right\rangle_0 = \underbrace{\left\langle c^\dagger_{k,\sigma} c_{k+q,\sigma} \right\rangle_0}_{\text{Direct interaction}} \left\langle c^\dagger_{k'+q,\sigma'} c_{k',\sigma'} \right\rangle_0 - \underbrace{\left\langle c^\dagger_{k,\sigma} c_{k',\sigma'} \right\rangle_0}_{\text{Exchange}} \left\langle c^\dagger_{k'+q,\sigma'} c_{k+q,\sigma} \right\rangle_0$$

$\boxed{\left\langle c^\dagger_{k\uparrow} c_{k\uparrow} \right\rangle_0 \neq 0}$ Regular exchange

$\boxed{\left\langle c^\dagger_{k\uparrow} c_{k\downarrow} \right\rangle_0 \neq 0}$ Itinerant antiferromagnetic exchange

$$
\langle H \rangle_{HF} = \sum_k \varepsilon_{k,\uparrow}(cos^2\theta_k f_{1k} + sin^2\theta_k f_{2k}) + \sum_k \varepsilon_{k,\downarrow}(sin^2\theta_k f_{1k} + cos^2\theta_k f_{2k})
$$

$$
-\frac{1}{2}\sum_{k,k'} v(k-k')(cos^2\theta_k f_{1k} + sin^2\theta_k f_{2k})(cos^2\theta_{k'} f_{1k'} + sin^2\theta_{k'} f_{2k'})
$$

$$
-\frac{1}{2}\sum_{k,k'} v(k-k')(sin^2\theta_k f_{1k} + cos^2\theta_k f_{2k})(sin^2\theta_{k'} f_{1k'} + cos^2\theta_{k'} f_{2k'})
$$

$$
\underbrace{-\frac{1}{4}\sum_{k,k'} v(k-k') sin2\theta_k sin2\theta_{k'}(f_{1k} - f_{2k})(f_{1k'} - f_{2k'})}
$$

The IA potential created by the exchange interaction between electrons whose spins are not parallel

Finite Temperature Treatment

The Grand Canonical Function

$$\Omega(T,V,\mu) = \langle H_{HF}\rangle - \mu \sum_{k,i} f_{k,i} - k_B T \sum_{k,i} \left[f_{k,i} \ln f_{k,i} + \left(1 - f_{k,i}\right) \ln\left(1 - f_{k,i}\right)\right]$$

$$N = \sum_{k,\sigma} c_{k\sigma}^{\dagger} c_{k\sigma}$$

$$\boxed{\left\langle a_k^{\dagger} a_k \right\rangle_0 = f_{1k}}$$

$$\boxed{\left\langle b_k^{\dagger} b_k \right\rangle_0 = f_{2k}}$$

The occupation numbers of the two new quasiparticles

The Ground State Configuration

$$\frac{\partial \langle \Omega \rangle_{HF}}{\partial \theta_k} = 0$$

$$\frac{\partial^2 \langle \Omega \rangle_{HF}}{\partial \theta_k^2} < 0$$

$$\Longrightarrow \quad \boxed{\tan 2\theta_k = \frac{g_k}{\tilde{\varepsilon}_{k\downarrow} - \tilde{\varepsilon}_{k\uparrow}}}$$

Symmetric in k space

$$g_k = \sum_{k'} v(k-k') \sin 2\theta_{k'} (f_{1k'} - f_{2k'})$$

$$\left.\begin{aligned}
\tilde{\varepsilon}_{k,\uparrow} &= \varepsilon_{k,\uparrow} - \sum_{k,k'} v(k-k')(cos^2\theta_k f_{1k} + sin^2\theta_k f_{2k}) \\
\tilde{\varepsilon}_{k,\downarrow} &= \varepsilon_{k,\downarrow} - \sum_{k,k'} v(k-k')(sin^2\theta_k f_{1k} + cos^2\theta_k f_{2k})
\end{aligned}\right\}$$

Single particle energies in HF

Quasiparticle Energies

$$\frac{\partial\langle\Omega\rangle_{HF}}{\partial f_{1k}} = 0$$

$$\frac{\partial\langle\Omega\rangle_{HF}}{\partial f_{2k}} = 0$$

$\longrightarrow$

$$f_{ik} = \frac{1}{e^{\beta(E_i-\mu)}+1}$$

$$E_{\pm}(k) = \frac{\tilde{\varepsilon}_{k,\downarrow}+\tilde{\varepsilon}_{k,\uparrow}}{2} \pm \frac{1}{2}\sqrt{\left(\tilde{\varepsilon}_{k,\uparrow}-\tilde{\varepsilon}_{k,\downarrow}\right)^2+g_k^2}$$

$$E_+ - E_- = \sqrt{\left(\tilde{\varepsilon}_{k,\uparrow}-\tilde{\varepsilon}_{k,\downarrow}\right)^2+g_k^2}$$

At the point of degeneracy the energy difference is gapped

The Gap Equation

$$g_k = \sum_{k'} v(k-k') \frac{g_{k'}}{\sqrt{\left(\tilde{\varepsilon}_{k',\uparrow} - \tilde{\varepsilon}_{k',\downarrow}\right)^2 + g_{k'}^2}} \quad (f_{1k'} - f_{2k'})$$

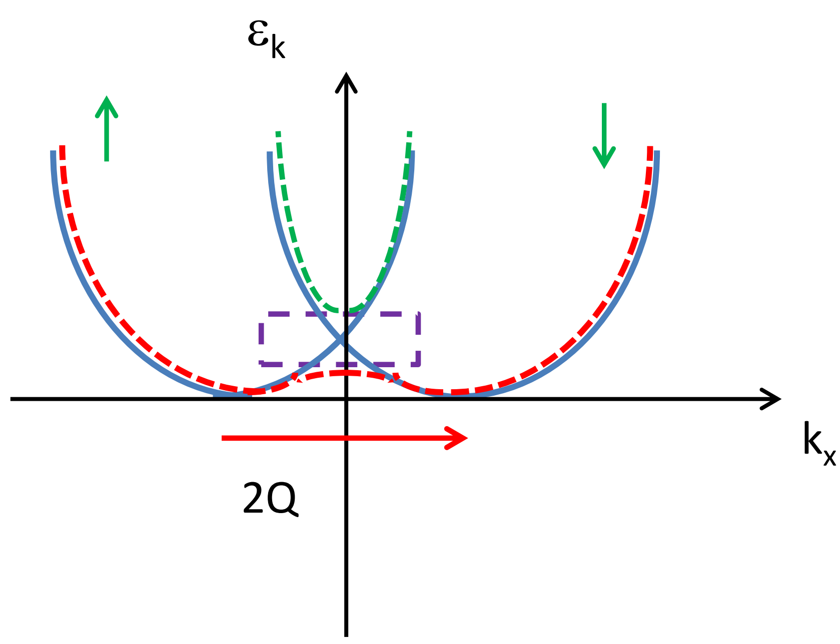
Integral equation that is solved iteratively; major simplifications

1. Constant interaction potential: γ
2. The single particle energies are approximated by the kinetic part only
3. Low temperature, such that only the lowest energy eigenstate is occupied

$$g = \frac{\gamma}{(2\pi)^2} \int \frac{g}{\sqrt{\left(\varepsilon_{k,\uparrow} - \varepsilon_{k,\downarrow}\right)^2 + g^2}} dk^2$$

Integration domain is chosen as a rectangle centered at k = 0

$$g = \frac{2\hbar^2 L_x Q}{m^* \sinh\left(\frac{4\hbar^2 Q \pi^2}{m^* \gamma L_y}\right)}$$



Boltzmann Transport Equation

$$\psi_{k,-}(r) = \cos\theta_k\, e^{ik\cdot r}|\uparrow\rangle + \sin\theta_k\, e^{ik\cdot r}|\downarrow\rangle$$

Lowest occupied level

$$E_{k,-} = \frac{\varepsilon_{k,\downarrow} + \varepsilon_{k,\uparrow}}{2} - \frac{1}{2}\sqrt{\left(\varepsilon_{k,\uparrow} - \varepsilon_{k,\downarrow}\right)^2 + g_k^2}$$

$$\boxed{\frac{-e\mathcal{E}\cdot\nabla_k E_k}{\hbar}\frac{df_k^0}{dE_k} = \left(\frac{\partial f_k}{\partial t}\right)_{coll.} = -\frac{f_k - f_k^0}{\tau(k)}}$$

$$\left(\frac{\partial f_k}{\partial t}\right)_{coll.} = -\sum_{k'} W(\boldsymbol{k}',\boldsymbol{k})\left\{\Delta f(\boldsymbol{k})\frac{e^{\beta E_{k'}} + e^{\beta\Delta E}}{1 + e^{\beta E_{k'}}} - \Delta f(\boldsymbol{k}')\frac{1 + e^{\beta\Delta E + \beta E_k}}{1 + e^{\beta E_k}}\right\}$$

Charge and Spin Currents

$$j_c = -e\sum_k \boldsymbol{v}(k)\, f_k = e^2 \sum_k v(k)\tau(k)\mathcal{E}\cdot v(k)\left(-\frac{df_k^0}{dE_k}\right)$$

$$j_s^x = \frac{\hbar}{2}\sum_k \left\langle \psi_k \middle| \frac{p}{m}\sigma_x \middle| \psi_k \right\rangle v(k) f_k = -\mathrm{e}\frac{\hbar}{2}\sum_k sin2\theta_k\, v(k)\tau(k)\mathcal{E}\cdot v(k)\left(-\frac{df_k^0}{dE_k}\right)$$

$$\sigma_c = e^2 \sum_k \tau(k)v(k)v(k)\left(-\frac{df_k^0}{dE_k}\right)$$

$$\sigma_s = -e\frac{\hbar}{2}\sum_k \tau(k)v(k)v(k)\left(-\frac{df_k^0}{dE_k}\right)$$

The Mott Formula

$$S = -\frac{\pi^2 k_B^2 T}{3e\varepsilon_F}\frac{\partial\sigma(E)}{\partial E}\Big|_{\varepsilon_F}$$

Impurity Scattering and The Relaxation Time

$$\boxed{\sum_i V\delta(r-R_i) + J\bar{\sigma}\cdot S\delta(r-R_i)}$$

$\bar{\sigma}$ is the the electron spin
along the direction of the local polarization

$$\bar{\sigma}_z = \sigma_x \quad \bar{\sigma}_x = -\sigma_z \quad \bar{\sigma}_y = \sigma_y$$

Fermi's Golden Rule

$$W(k',k) = \frac{2\pi N_i}{\hbar}\left[|\langle\psi_{k'}|V|\psi_k\rangle|^2 \delta(E_k - E_{k'}) + \left|\left\langle \psi_{k'} \middle| J\frac{\bar{\sigma}^+ S^-}{2} \middle| \psi_k \right\rangle\right|^2 \delta(E_{k'} - E_k + \Delta E) \right.$$

$$\left. + \left|\left\langle \psi_{k'} \middle| J\frac{\bar{\sigma}^- S^+}{2} \middle| \psi_k \right\rangle\right|^2 \delta(E_{k'} - E_k - \Delta E) \right]$$

The Transverse Relaxation Rate

$$\left(\frac{\partial f_k}{\partial t}\right)_{coll.} = -\sum_{k'} W(\boldsymbol{k}',\boldsymbol{k})\left\{\Delta f(\boldsymbol{k})\frac{e^{\beta E_{k'}} + e^{\beta\Delta E}}{1+e^{\beta E_{k'}}} - \Delta f(\boldsymbol{k}')\frac{1+e^{\beta\Delta E+\beta E_k}}{1+e^{\beta E_k}}\right\}$$

$$\Delta f(k) = -e\frac{1}{\hbar}\nabla_k E_k \cdot \mathcal{E}\left(\frac{df_k^0}{dE_k}\right)$$

$$\frac{1}{\hbar}\nabla_k E_k \cdot \mathcal{E} = \begin{cases} \frac{\hbar k}{m}\cdot\mathcal{E}, \quad \mathcal{E} \perp Q \\ \left(\frac{\hbar k}{m} - \frac{\hbar Q}{m}cos\theta_k\right), \mathcal{E} \parallel Q \end{cases}$$

$$\frac{1}{\tau_n} = \frac{\pi N_i}{\hbar}[(V^2 + \langle S_z^2\rangle)(N_0 + P_0 sin2\theta_k) + 2VJ\langle S_z\rangle(N_0 sin2\theta_k + P_0)$$
$$+ \frac{e^{\beta E_k}+1}{e^{\beta E_k} + e^{-\beta\Delta E}}\frac{(J^2\langle S_+^2\rangle)}{2}(N_0 - P_0)(1+sin2\theta_k)$$
$$+ \frac{e^{\beta E_k}+1}{e^{\beta E_k} + e^{-\beta\Delta E}}\frac{(J^2\langle S_-^2\rangle)}{2}(N_0 - P_0)(1+sin2\theta_k)]$$

$$N_0 = \sum_k \delta(E_k - E_F) \qquad P_0 = \sum_k sin2\theta_k\delta(E_k - E_F)$$

The Longitudinal Relaxation Time

$$\tau_p = \tau_n \left[1 + \frac{\left(1 - \frac{J^2}{V^2}\langle S_z^2 \rangle\right) cos2\theta_k}{v_p(k)} \times \frac{\tau_0^{-1} \sum_{k'} cos2\theta_{k'} v_p(k')\tau_n(k')\delta(E_{k'} - E_F)}{1 - \tau_0^{-1} \sum_{k'} cos^2\theta_{k'}\, \tau_n(k')\delta(E_{k'} - E_F)} \right]$$

$$\tau_0^{-1} = \frac{\pi N_i}{\hbar} V^2$$

Experimental Numbers

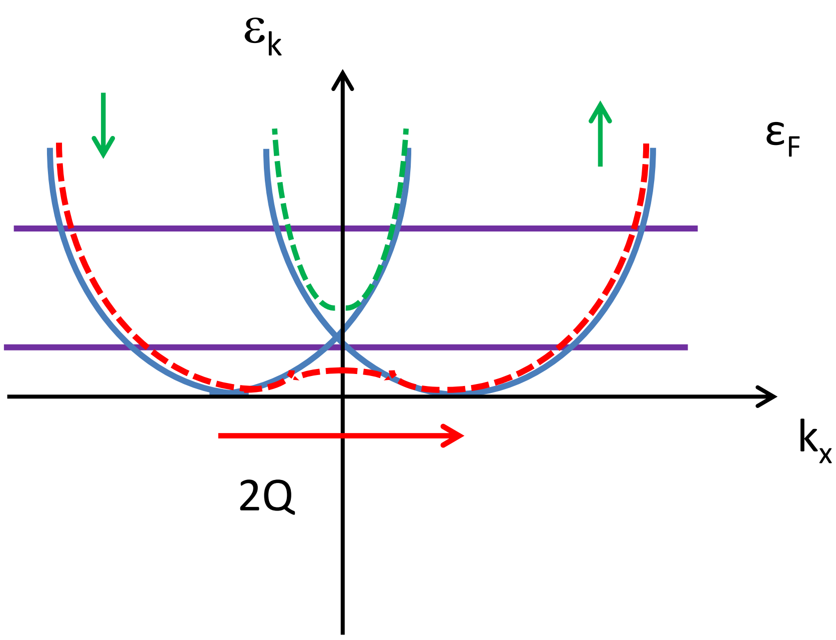
PRB **86**, 081306(R) (2012), Khoda et al.

$$n_0 = 4 \times 10^{12} cm^{-2} \qquad k_{F0} = \sqrt{2\pi n_0} = 5 \times 10^{8} m^{-1}$$

$$\alpha = \beta = 5 \times 10^{4} m/s \qquad Q = \frac{2m\alpha}{\hbar} = 2 \times 10^{7} m^{-1}$$

$$\frac{Q}{k_{F0}} = 0.04$$

Multiple band occupancy



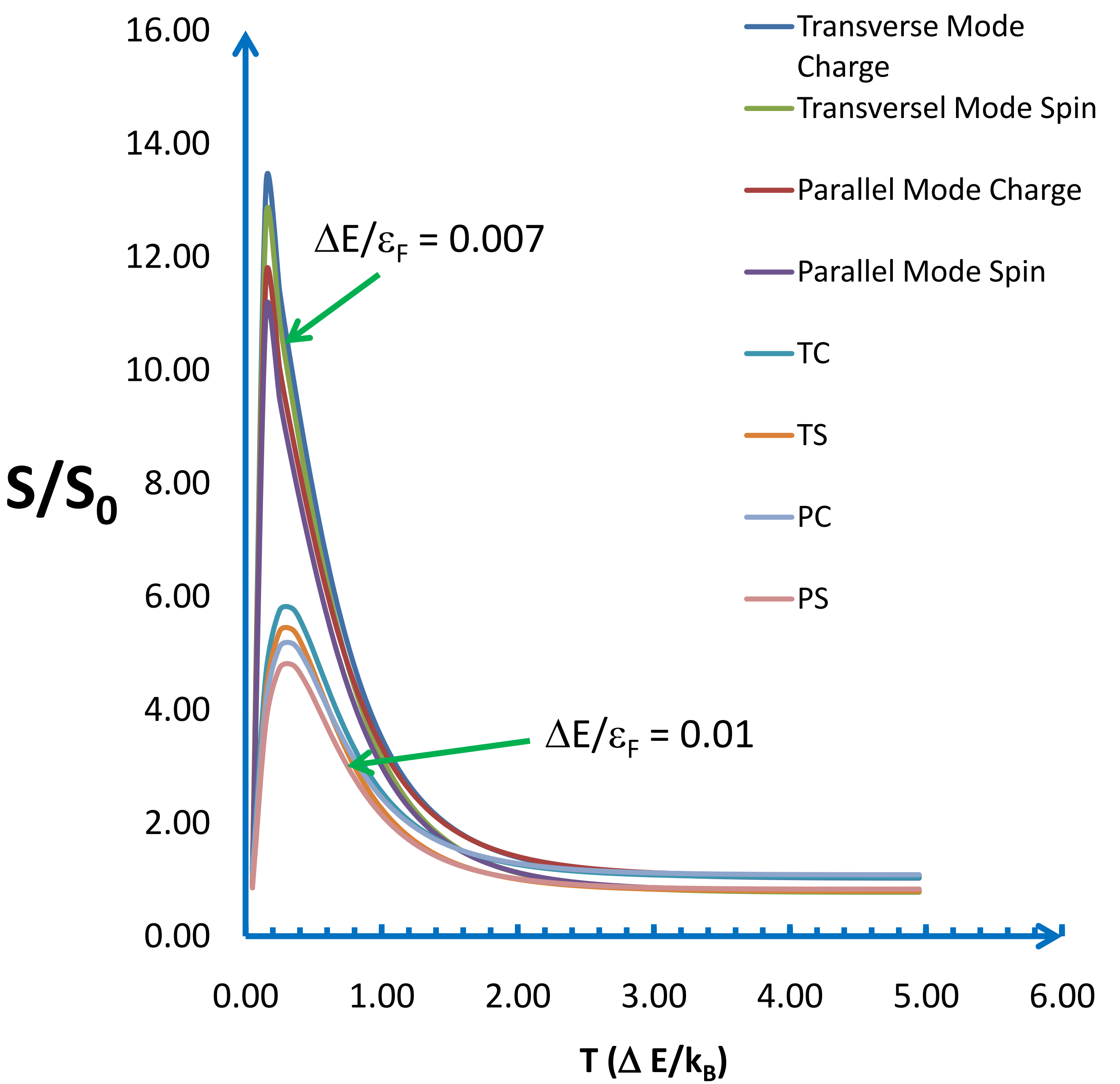
$$k_{max}^{-} = \sqrt{\varepsilon_F + Q^2 + \sqrt{4\varepsilon_F Q^2 + \frac{g^2}{4}}}$$

$$k_{min}^{-} = \sqrt{max\left\{0, \varepsilon_F + Q^2 - \sqrt{4\varepsilon_F Q^2 + \frac{g^2}{4}}\right\}}$$

$$k_{max}^{+} = \sqrt{\varepsilon_F + Q^2 + \sqrt{4\varepsilon_F Q^2 + \frac{g^2}{4}}}$$

$$k_{min}^{-} = 0$$

Results



$$\frac{J}{V} = 0.5$$

$$\frac{\Delta E}{\varepsilon_F} = 1 \times 10^{-2}$$

$$S = 5/2$$

$$T = 69K \rightarrow 1$$

$$\varepsilon_F = 1.6 * 375 meV$$

Conclusions

1. In the presence of the Coulomb interaction, the state of an electron system with SOI at $\alpha = \beta$ is that of a paramagnet or an itenerant antiferromagnet polarized along the direction of Q.

2. If the AF state exists, they are highly susceptible to variations in the particle density, screening, etc.

3. Thermoelectric measurements in this state should indicate a thermoelectric anomaly