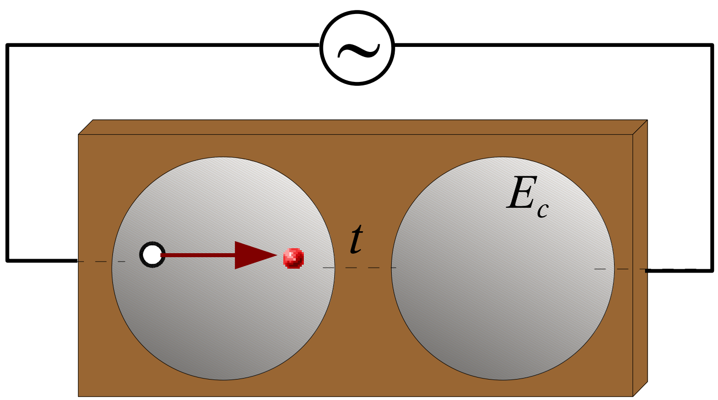
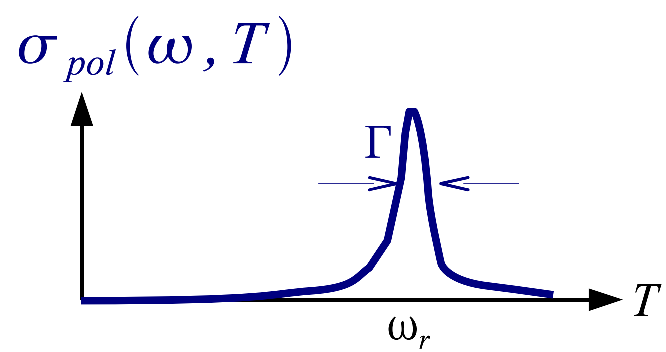
Optical Conductivity of Granular Metals

Yen Lee Loh[1] and Vikram Tripathi[2]
[1]Physics Department, Purdue University
[2]Theory of Condensed Matter Group, Cavendish Laboratory, Cambridge, UK





New effective field theory enables calculation of AC properties

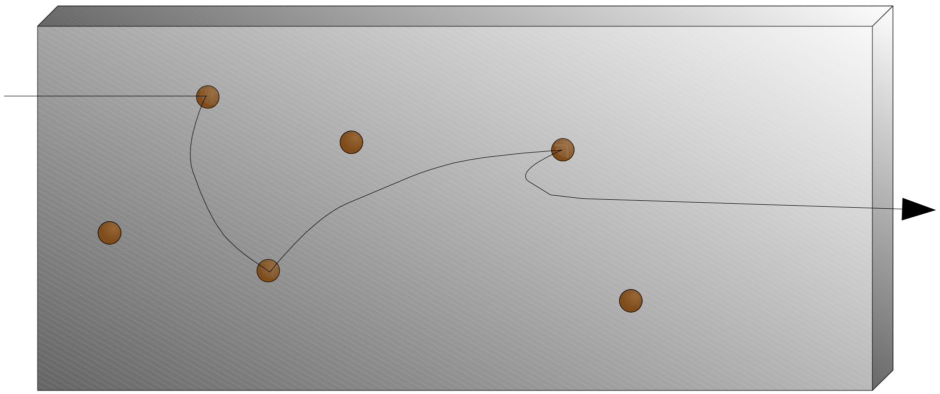
AC conductivity is dominated by intra-grain polarization resonance

Width of resonance is related to inelastic cotunneling:

$$\Gamma(\omega, T) \sim g^2 \left(T^2 + \omega^2\right) / E_c$$

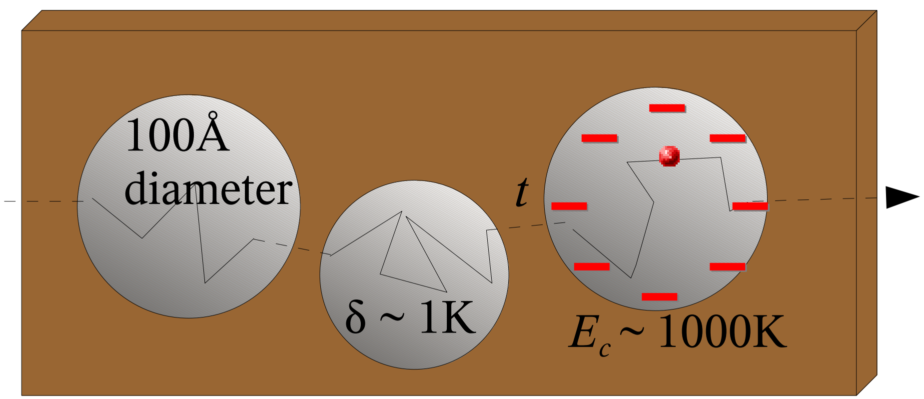
APS March Meeting 2006

Charge Transport in Metal-Insulator Composites



Dirty metal

Conductivity limited by
impurity scattering



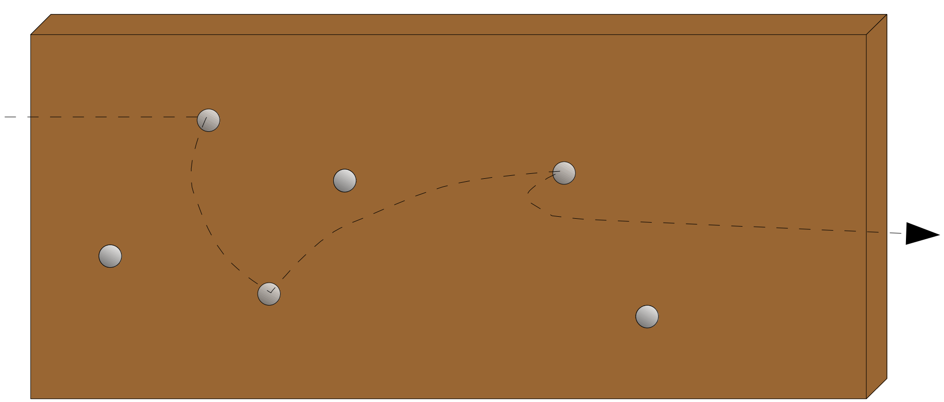
Granular metal

Tunneling

Near-continuum of energy levels

Coulomb blockade

→ Interesting physics for $\delta < T < E_c$!



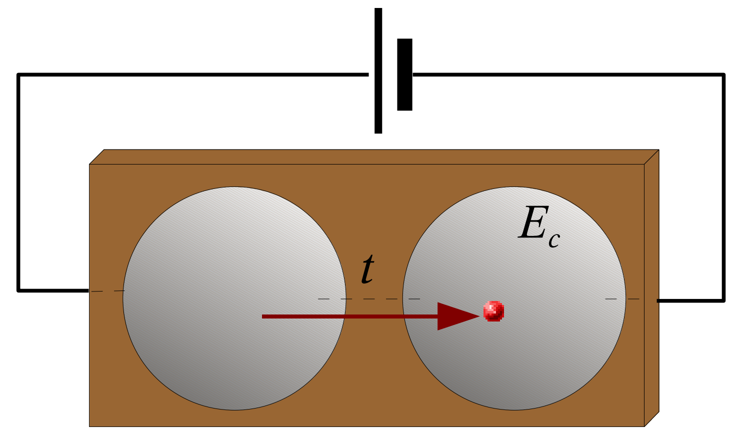
Dirty insulator

Conduction due to
thermally activated hopping

Granular metals: DC conductivity

Electron Hamiltonian

$$\hat{H} = \sum_{i\lambda} \xi_\lambda c^+_{i\lambda} c_{i\lambda} + \underbrace{\sum_{ij\lambda\lambda'} t_{ij} c^+_{i\lambda} c_{j\lambda'}}_{tunneling} + \underbrace{\sum_{i} E_c Q_i^2}_{charging}$$



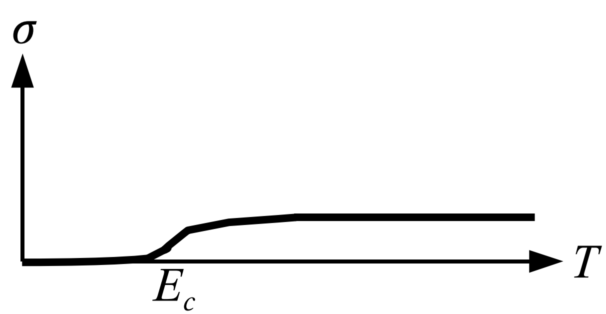
Hubbard-Stratonovich transformation
Gauge transformation

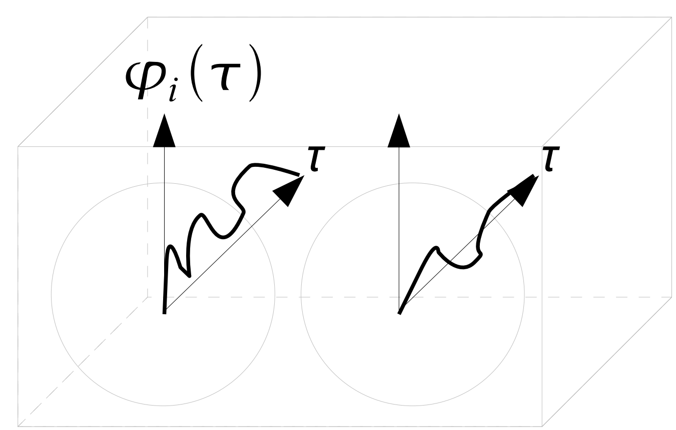
Ambegaokar-Eckern-Schön phase action

$$S[\varphi] = \int_{\tau\tau'} \sum_{ij} \frac{\pi^2 \nu^2 t^2}{\sin^2 \pi T \tau} \cos(\varphi_{i\tau} - \varphi_{i\tau'} - \varphi_{j\tau} + \varphi_{j\tau'}) - \int_{\tau=0}^{\beta} \sum_i \frac{1}{4E_c} \left(\frac{d\varphi}{d\tau}\right)^2$$

functional integration
analytic continuation

$$\sigma(T) = \sigma_0 e^{-E_{eff}/T}$$



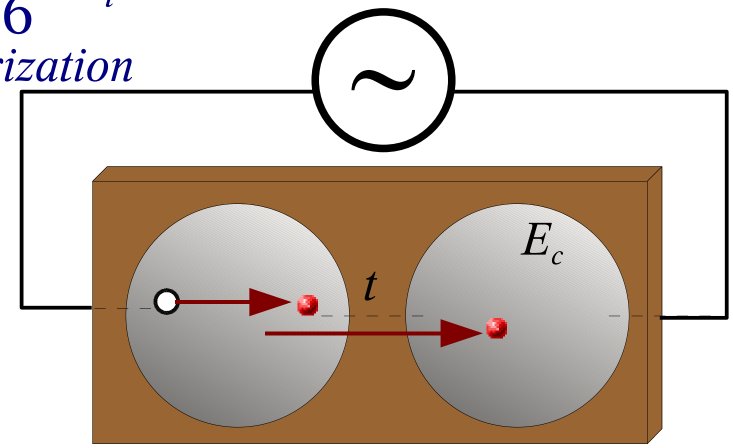


Granular metals: AC (optical) conductivity

Electron Hamiltonian

$$\hat{H} = \sum_{i\lambda} \xi_\lambda c^+_{i\lambda} c_{i\lambda} + \sum_{ij\lambda\lambda'} t_{ij} c^+_{i\lambda} c_{j\lambda'} + \sum_i E_c Q_i^2 + \sum_i \frac{V}{6} P_i^2$$

tunneling charging polarization



Hubbard-Stratonovich transformation
Gauge transformation

Ambegaokar-Eckern-Schön phase action

$$S_{AES}[\varphi] = \int_{\tau\tau'} \sum_{ij} \frac{\pi^2 \nu^2 t^2}{\sin^2 \pi T \tau} \cos(\varphi_{i\tau\tau'} - \varphi_{j\tau\tau'}) - \int_{\tau=0}^{\beta} \sum_i \frac{1}{4E_c} \left(\frac{d\varphi}{d\tau}\right)^2$$

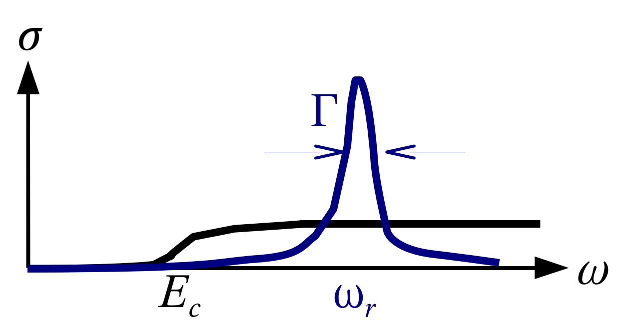
$$S_{pol}[\varphi,\theta] = -b \int_{\tau\tau'} \sum_{ij} \frac{\pi^2 \nu^2 t^2}{\sin^2 \pi T \tau} \cos(\varphi_{i\tau\tau'} - \varphi_{j\tau\tau'}) \left[\theta^2_{i\tau\tau'} + \theta^2_{j\tau\tau'}\right] - \int_\tau \sum_i \frac{1}{4E_c} \left[\left(\frac{d\theta}{d\tau}\right)^2 + \omega_r^2 \theta^2\right]$$

$$\omega_r^2 = 4\pi n e^2 / 3\mathrm{m}$$

functional integration
analytic continuation

$$\sigma(\omega, T) = \sigma_{AES}(\omega, T) + \sigma_{pol}(\omega, T)$$

$$\propto \frac{-i\omega}{\omega^2 - \omega_r^2 - i\Gamma\omega}$$

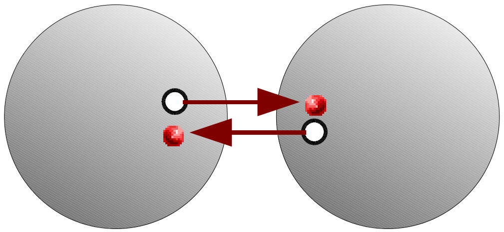


Summary

Thermal conductivity has direct contribution from **inelastic cotunneling** of neutral pairs (Tripathi & Loh, PRL 96, 046805; abstract B35.00007)

$$\kappa(T) \propto \frac{g^2 T^3}{E_c^2}$$

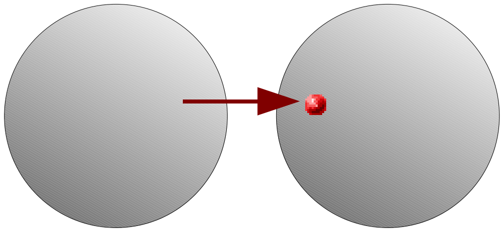
$$g \propto t^2$$



DC conductivity dominated by **inter-grain tunneling**
Activation energy reduced by inelastic cotunneling

$$\sigma(T) \propto g e^{-E_{eff}/T}$$

$$E_{eff}(g) \approx E_c e^{-\alpha g}$$



AC conductivity dominated by **intra-grain polarization resonance**
Resonance width related to inelastic cotunneling
(Tripathi & Loh, cond-mat/0601138)

$$\sigma(\omega, T) \propto -\frac{ine^2 f}{m} \frac{\omega}{\omega^2 - \omega_r^2 - i\Gamma\omega}$$

$$\Gamma(\omega, T) \propto \frac{g^2 (T^2 + \omega^2/4\pi^2)}{E_c}$$