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Effect of gauge-field interaction on fermion transport in 2D: conductivity correction and dephasing

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Effect of gauge-field interaction on fermion transport in 2D: conductivity correction and dephasing

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"Localization Phenomena in Novel Phases of Condensed Matter"
ICTP, 18 May 2010

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T. Ludwig, I. V. Gornyi, A.D. Mirlin, P. Wölfle, Phys. Rev. B 77, 235414 (2008)

Outline

- Transverse gauge fields in correlated Fermi systems
- Enhanced quantum corrections to the conductivity induced by gauge field interactions and disorder: exchange terms
- Dephasing by gauge field fluctuations
- Anomalously large quantum correction to the conductivity: Hartree terms and gauge invariance
- Summary and outlook

Transverse gauge fields in correlated Fermi systems

- Transverse electromagnetic field in metals

  T. Holstein, R.E. Norton, and P. Pincus, 1973; M. Yu. Reizer, 1989;
  G. Baym, H. Monien, C. J. Pethick, and D. G. Ravenhall, 1990.

  Induce current-current interaction, which remains unscreened
  → non-Fermi liquid effects, important only at very low energy (v/c << 1)

- Transverse gauge fields in models of cuprate superconductors

  G. Baskaran and P. W. Anderson, 1988; L. B. Ioffe and A. I. Larkin, 1989;
  N. Nagaosa and P. A. Lee, 1990; P.A. Lee and N. Nagaosa, 1992.

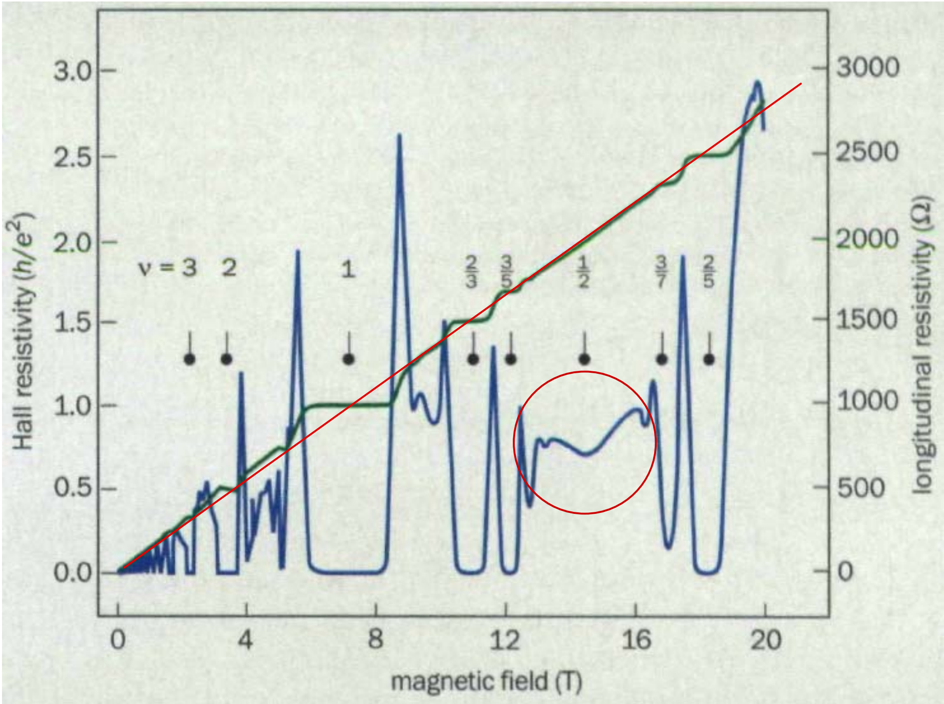
  Dynamics of fermions in constrained Hilbert space (infinite U Hubbard model)
  may be described by fictituous gauge field

- Transverse gauge fields in quantum Hall systems near $\nu=1/2$

  J. K. Jain, 1989; A. Lopez and E. Fradkin, 1991; B. I. Halperin, P. A. Lee, and N. Read, 1993.

  Composite fermions consisting of electron+2 flux quanta interact via
  Chern-Simons gauge field

Composite fermions in the half-filled lowest Landau level



Fractional Quantum Hall Effect

$$R_{xy}^{frakt} = \frac{1}{\nu_p^q} R_Q,$$

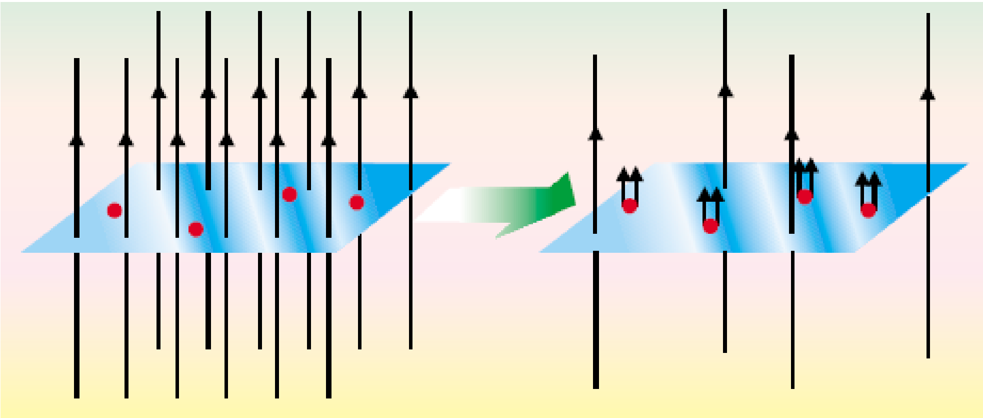
$$\nu_p^q = \frac{p}{pq+1}, \quad q = 2, 4, .. \quad p = 1, \pm 2, ..$$

Composite Fermion "absorbs" part of magnetic flux:

Effective magnetic field: $B_{eff} = B(1-2\nu)$

- **Fermi liquid at** $B_{eff} = 0, \quad \nu = \frac{1}{2}$

Model of infinitely thin flux lines : Chern-Simons gauge field theory



J. Jain (1989), Read, Halperin, Lee (1995)

Chern-Simons gauge field theory of composite fermions

Hamiltonian including fictitious gauge field a(r,t) of flux lines

$$H = \sum_j \frac{1}{2m_b}\left[\vec{p}_j + \frac{e}{c}\vec{A}(\vec{r}_j) - \frac{e}{c}\vec{a}(\vec{r}_j)\right]^2 + \sum_{i<j} v(\vec{r}_i - \vec{r}_j)$$

Density n(r) of flux lines determines fictitious magnetic field b(r) (p=1 near v=1/2)

$$\vec{b}(\vec{r}) = \vec{\nabla} \times \vec{a}(\vec{r}) = 2p\phi_o n(\vec{r})$$

Current density j(r) of CFs and associated motion of flux tubes induces electric field:

$$\vec{e} = 2p\frac{\phi_0}{ec}(\hat{z} \times \vec{j})$$

Ohm's law for CFs:

$$\vec{j} = \overleftrightarrow{\sigma}\,(\vec{E} + \vec{e})$$

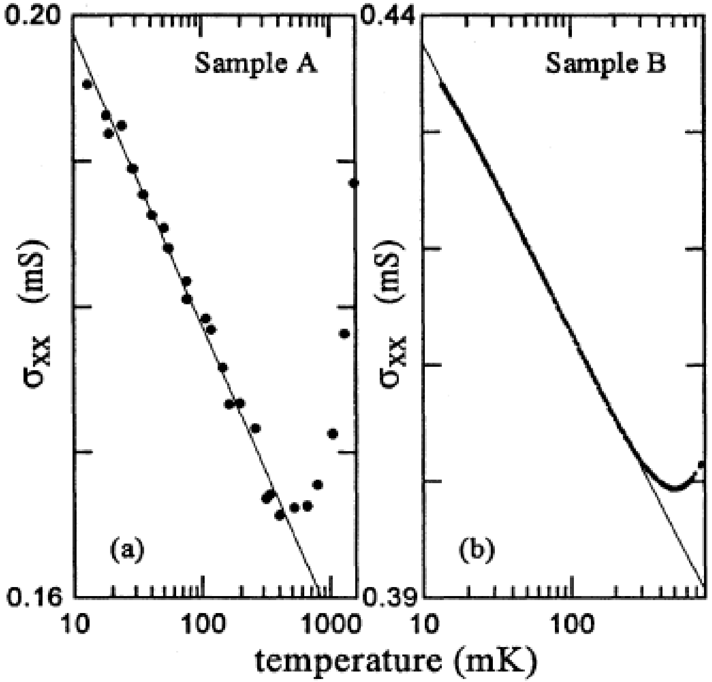
Relation of resistivity tensors of electrons and CFs:

$$\rho_{ij}^{\mathrm{el}} = \rho_{ij} + \rho_{ij}^{\mathrm{CS}} \qquad \rho_{ij}^{\mathrm{CS}} = 2p\frac{h}{e^2}\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

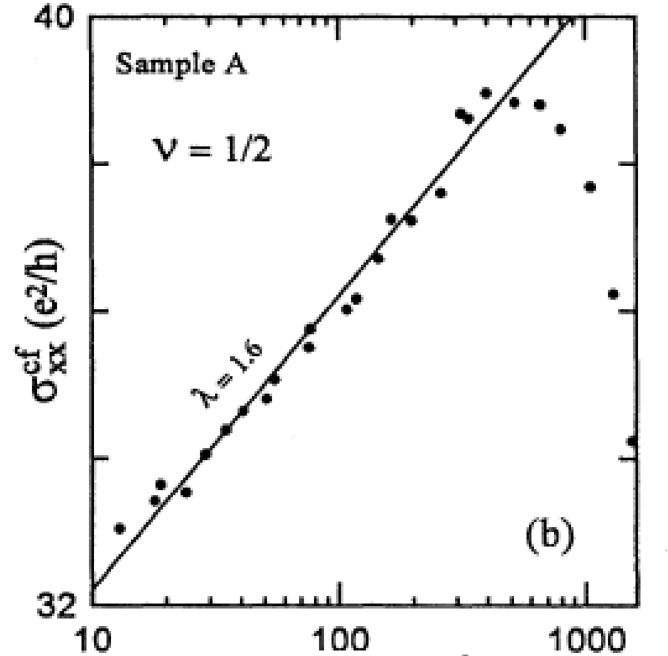
B. I. Halperin, P. A. Lee, and N. Read, 1993

Observation of quantum corrections to the conductivity of composite fermions

Longitudinal conductivity of quantum Hall system near half-filling



$$\sigma_{xx}^{CF} = (1/\rho_{xx}^{CF}) = \frac{\sigma_{xx}^2 + \sigma_{xy}^2}{\sigma_{xx}}$$



$$\sigma_{xx}^{CF} = \sigma_0^{CF} + \lambda \frac{e^2}{h} \ln \frac{T}{T_0}$$

L.P. Rokhinson, B. Su and V. J. Goldman, 1995

Possible explanation:

(1) Weak localization? No
(2) Kondo effect? No
(3) Interaction correction? Yes

Interaction correction to conductivity of electrons in disordered systems

- **Dynamics of electrons in disordered systems is diffusive:**

  → **slower than ballistic**

- **Coulomb interaction between electrons is enhanced by diffusive motion**

- **Temperature dependent quantum correction to conductivity**

- **In two dimensions (*B.L. Altshuler and A.G. Aronov, 1979*):**

$$\Delta\sigma = (e^2/h)\lambda_{AA}\ln(T\tau)$$

$$\lambda_{AA} = \pi^{-1}(1 - \tfrac{3}{2}F)$$

In well-screened metals F is small and positive:

→ the observed CF conductivity correction is larger by factor ~5

Enhancement of correction by gauge field interaction?

Effective current-current interaction of composite fermions

Current-current interaction

$$H_{current} = \sum_{k,k',q} c^{\dagger}_{k+q} c_k \frac{k_\mu}{m} D_{\mu\nu}(q,\omega) \frac{k'_\nu}{m} c^{\dagger}_{k'+q} c_{k'}$$

Transverse part of gauge field propagator:

$$D_{\mu\nu}(\boldsymbol{q},\omega) = \frac{\delta_{\mu\nu} - \hat{q}_\mu \hat{q}_\nu}{i\omega\sigma(q,\omega) + \chi q^2}$$

Diamagnetic susceptibility: $\chi(q) = \chi_0 + e^2 v(q)/(4\pi)^2$ $\chi_0 = 1/(24\pi m)$

Distinguish cases of unscreened and screened Coulomb interaction $v(q) = \dfrac{2\pi e^2}{q + \kappa_2}$

Conductivity in limit q,ω → 0: $\sigma_0 = k_F l / 4\pi$

Scattering of electrons by remote impurities: random magnetic field acting on composite fermions

Remote impurity potential causes static long range density fluctuations, leading to long range correlated fluctuations of magnetic flux

→ **random magnetic field b(r)**

Scattering cross section diverges at small scattering angles:

$$w(\phi) = v_0^2 \cot^2(\phi) \ , \ v_0^2 = \frac{e^2}{4m^2c^2}\langle b^2 \rangle$$

Single particle scattering rate $\tau_s^{-1} = \int_0^\pi \frac{d\phi}{\pi} w(\phi)$ **ill-defined (diverges)**

Transport relaxation rate $\tau^{-1} = \int_0^\pi \frac{d\phi}{\pi} w(\phi)[1-\cos\phi]$ **is well-defined**

Strongly anisotropic scattering causes large current vertex corrections

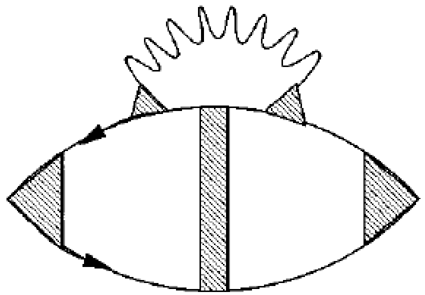
Gauge field induced quantum corrections to the conductivity: exchange diagrams

Kubo formula for longitudinal conductivity

Exchange diagrams in leading order in 1/g (g= dimensionless conductance)

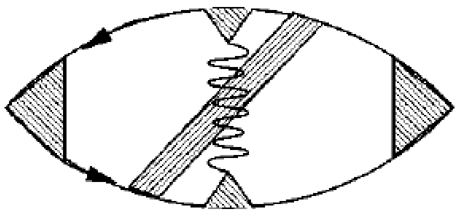
Gauge field propagator (wavy line):

$$D_{\mu\nu}(\boldsymbol{q},\omega)=\frac{\delta_{\mu\nu}-\hat{q}_{\mu}\hat{q}_{\nu}}{i\omega\sigma(q,\omega)+\chi q^{2}}$$



Single particle propagator (solid line):

$$G(\boldsymbol{k},\epsilon_n)=[i\epsilon_n-\xi_k+(i/2\tau_k)\mathrm{sgn}(\epsilon_n)]^{-1}$$



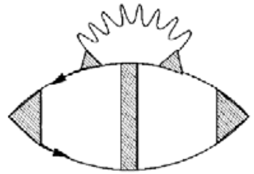
Diffuson: particle-hole impurity ladder (shaded rectangle):

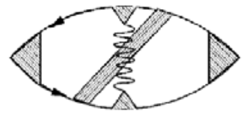
$$\Gamma_{kk'}(\boldsymbol{q},\omega_m)=(2\pi N_0)^{-1}\frac{\gamma_k\gamma_{k'}^{*}}{\omega_m+Dq^{2}}+\Gamma_{kk'}^{\mathrm{reg}}$$

$$D=\frac{1}{2}v_F^2\tau_{\mathrm{tr}}\ ,\qquad \tau_{\mathrm{tr}}=\frac{\tau}{1-\lambda_1}$$

*A.D. Mirlin and P. Wölfle, Phys.Rev. B**55**, 5141(1997)*

Gauge field induced quantum correction to conductivity: exchange diagrams, unscreened Coulomb





$$\Delta\sigma(T) = \frac{e^2}{2\pi h} \times \begin{cases} 2\pi \dfrac{k_F l}{C_*} \sqrt{T\tau_{\rm tr}}, & T \ll T_1 \\ C + \ln^2\left[\dfrac{2(k_F l)^2}{C_*^2} T\tau_{\rm tr}\right], & T_1 \ll T \ll T_2 \\ -\ln^2(T\tau_{\rm tr}), & T_2 \ll T \ll 1/\tau_{\rm tr} \end{cases}$$

$$T_1 \equiv C_*^2/[2(k_F l)^2 \tau_{\rm tr}]$$

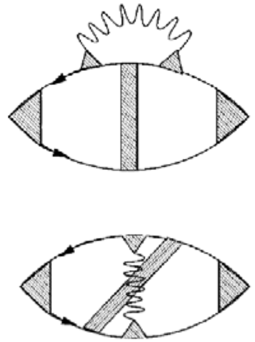
$$T_2 \equiv C_*/[2k_F l \tau_{\rm tr}]$$

$C_* \approx 10$

*A.D. Mirlin and P. Wölfle, Phys.Rev. B**55**, 5141(1997)*

Cannot explain experimental data

Gauge field induced quantum correction to conductivity: exchange diagrams, screened Coulomb interaction



$$\Delta\sigma(T)=\frac{e^2}{2\pi h}\times\begin{cases} 4\ln\left[\left(\frac{\kappa}{C_* k_F}\right)^{1/2} k_F l\right]\ln(T\tau_{\rm tr})\,, & T\ll T_0^* \\ -\ln^2(T\tau_{\rm tr})\,, & T_0^*\ll T\ll 1/\tau_{\rm tr}\,. \end{cases}$$

May explain experimental data

*A.D. Mirlin and P. Wölfle, Phys.Rev. B**55**, 5141(1997)*

Gauge field induced quantum corrections to the conductivity: Hartree diagrams

More recently, the Hartree type correction to the conductivity was calculated for the case of screened interaction:

*V.M. Galitski, Phys. Rev. B**72**, 214201 (2005)*

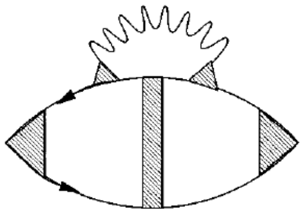
$$\delta\sigma_H^* = \frac{e_*^2 g^2 \sigma L}{4\pi^3 \delta} \ln \frac{1}{T\tau} \qquad \delta = \chi m$$

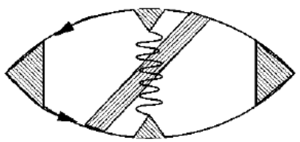
This result depends on the length L of the sample and therefore

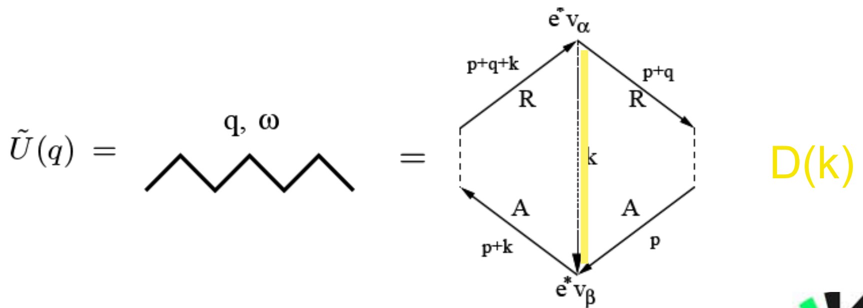
violates gauge invariance.

Galitski missed to include diagrams removing an unphysical singularity.

The Hartree diagrams may be represented like exchange diagrams, with interaction replaced by a “Hikami box”:

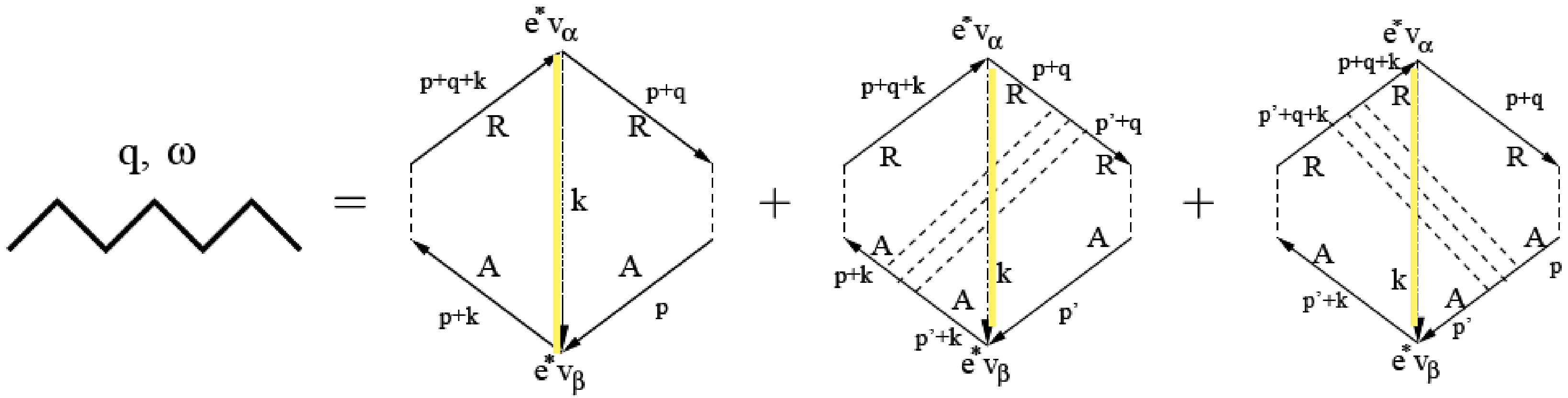






Gauge field induced quantum corrections to the conductivity: gauge invariant Hartree diagrams

$\tilde{U}(q) =$



singular at k<q

In the sum of the three terms, the strong singularity at k<q is cancelled (gauge invariance), resulting in (g is the dimensionless conductance)

$$\tilde{U}(q) \equiv \tilde{U}(q, \epsilon = 0) = (e^*)^2 \; u_1 \ln \frac{1}{q^2 l^2} \qquad u_1 \equiv \frac{3g}{\pi\nu}$$ screened Coulomb interaction

$$\tilde{U}(\epsilon = 0) = \frac{12}{\pi\nu} \frac{k_F}{\kappa} \ln \frac{\kappa g}{k_F}$$ unscreened Coulomb interaction, $\kappa \approx k_F$

T. Ludwig, I.V. Gornyi, A.D. Mirlin and P. Wölfle, 2008

Gauge field induced quantum correction to conductivity: Lowest order Hartree diagrams (screened Coulomb int.)

Evaluating the Hartree diagrams with full diffusion propagators and the bare gauge field interaction (λ=e*/e) one finds

$$\delta\sigma^H = \frac{3}{8\pi^2}\lambda^2\,\sigma\,\ln^2\frac{1}{T\tau}$$

At strong coupling, λ=e*/e ~ 1 , this result is

- **anomalously large (factor of σ) ,**
- **much larger than the exchange contribution**
- **positive (antilocalizing)**

Defining the characteristic temperatures:

$$T_n = g^n \frac{1}{12\pi g^2 \tau} \quad , \text{ where } D\chi_0 = 12\pi g \text{ and } \tau = \tau_{tr}$$

We find that at

$T<T_0$ the interaction is renormalized
$T>T_1$ dephasing cuts off the diffuson pole

Dephasing by gauge field fluctuations:Cooperon

Weak localization correction to conductivity

$$\delta\sigma_{\mathrm{WL}} = -\frac{2e^2 D}{\pi}\int_{\tau}^{\infty} dt\ \langle \mathcal{C}(0,0,t)\rangle$$

Cooperon equation of motion:

$$\left\{\partial_t + D\Big[-i\nabla - \lambda e\mathbf{a}\left(\mathbf{r}, t_0 + t/2\right) - \lambda e\mathbf{a}\left(\mathbf{r}, t_0 - t/2\right)\Big]^2\right\}\mathcal{C}^{t_0}(\mathbf{r},\mathbf{r}',t) = \delta(\mathbf{r}-\mathbf{r}')\,\delta(t)$$

Solution in path integral form:

$$\mathcal{C}^{t_0}(0,0,t) = \int_{\mathbf{r}(-t)=0}^{\mathbf{r}(t)=0} \mathcal{D}[\mathbf{r}(t')]\exp\{-S_0 + iS_1\} \qquad S_0 = \int_{-t}^{t} dt'\,\frac{\dot{\mathbf{r}}^2(t')}{4D}$$

$$\begin{aligned} S_1 &= -\lambda e\int_{-t}^{t} dt'\ \dot{\mathbf{r}}(t')\cdot\mathbf{a}[\mathbf{r}(t_0 + t'/2)] \\ &\quad -\lambda e\int_{-t}^{t} dt'\ \dot{\mathbf{r}}(t')\cdot\mathbf{a}[\mathbf{r}(t_0 - t'/2)] \end{aligned}$$

Cooperon averaged over Gauge field fluctuations

$$\langle\mathcal{C}(t)\rangle = \exp\{-\langle\Delta S\rangle(t)\}\int_{\mathbf{r}(-t)=0}^{\mathbf{r}(t)=0}\mathcal{D}[\mathbf{r}(t')]\exp\{-S_0\} = (4\pi Dt)^{-1/2} e^{-t/\tau_\varphi}$$

Phase relaxation rate:

$$\frac{1}{\tau_\varphi} = \begin{cases} \dfrac{3}{2}\lambda^2 gT\ln\dfrac{T_1}{\lambda^2 T}, & T << T_1 \\ \mathcal{O}(1)\cdot\lambda\left(\dfrac{gT}{\tau}\right)^{1/2} & T >> T_1 \end{cases}$$

*A.G. Aronov, P. Wölfle, PRB **50**, 16574(1994); P. Wölfle, Found. Phys. **30**, 2125 (2000); T. Ludwig, A.D. Mirlin, PRB **69**, 193306 (2004)*

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Dephasing induced by gauge field fluctuations: Delayed Diffuson

In Hartree type diagrams one has diffuson propagators, where particle and hole belong to different loops and may be delayed by a time η, corresponding in Fourier space to the energy E of the particle.
The diffusion pole arises as a consequence of particle number conservation.
However, the number of particles with given energy E is not conserved if inelastic processes are allowed.
This leads to a finite decoherence rate in the diffusion pole.
The equation of motion of the delayed diffuson is:

$$\left\{\partial_t + D\Big[-i\nabla - e\mathbf{a}\left(\mathbf{r}, t+\eta/2\right) + e\mathbf{a}\left(\mathbf{r}, t-\eta/2\right)\Big]^2\right\}\mathcal{D}^\eta(\mathbf{r},\mathbf{r}',t) = \delta(\mathbf{r}-\mathbf{r}')\,\delta(t)$$

$$\mathcal{D}(q,\omega,\eta) = \frac{2\pi\nu}{Dq^2 - i\omega + 1/\tau_\varphi(\eta)}$$

where

$$\frac{1}{\tau_\varphi(\eta)} \approx \begin{cases} \frac{3}{4} gT\ln(T_0\eta^*)\ , & 1/T \ll 1/T_0 \ll |\eta| \\ \frac{3}{2\pi} gTT_0|\eta|\ , & 1/T \ll |\eta| \ll 1/T_0 \\ \frac{3}{4\pi} gT^2T_0\eta^2\ , & |\eta| \ll 1/T \ll 1/T_0 \end{cases}$$

Conductivity correction at high T:

$$\frac{\delta\sigma^H}{\sigma} = \mathcal{O}(1)\cdot\frac{T_1}{T}\ , \quad T_1 \ll T \ll \frac{1}{\tau}$$

T. Ludwig, I. V. Gornyi, A.D. Mirlin, P. Wölfle, Phys. Rev. B 77, 235414 (2008)

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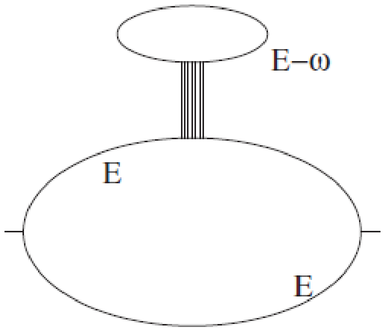
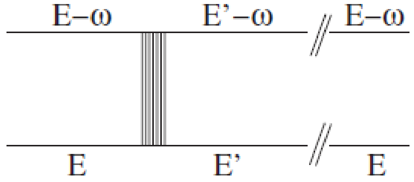
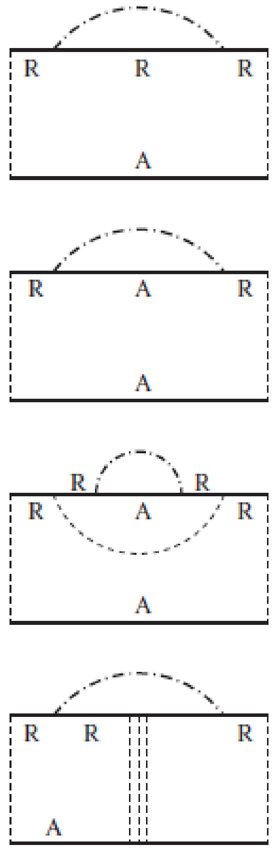
Renormalization of diffuson by gauge field interaction: Full self energy of Delayed Diffuson

In Hartree type diagrams one has diffuson propagators, where particle and hole belong to different loops and may have different energies E, E’







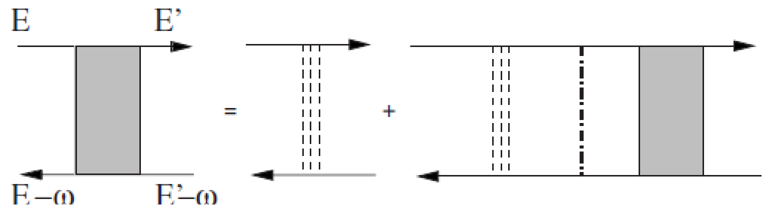
Define disconnected diffuson : only self energy contributions

$$\tilde{\mathcal{D}}_\infty = \frac{\mathcal{D}_0}{1+2\pi\nu\mathcal{D}_0\int_{E-\omega}^{E}\frac{d\epsilon}{2\pi}(-i)\mathrm{Re}\,\tilde{U}(\epsilon)} = \frac{1}{Dq^2 - i\omega - i\nu\int_{E-\omega}^{E} d\epsilon\,\mathrm{Re}\,\tilde{U}(\epsilon)}.$$

T. Ludwig, I. V. Gornyi, A.D. Mirlin, P. Wölfle, Phys. Rev. B 77, 235414 (2008)

Renormalization of gauge field interaction: Delayed Diffuson

Full dressing of delayed diffuson : vertex corrections



$$\widetilde{\mathcal{D}}(E-E') = \widetilde{\mathcal{D}}_\infty \delta(E-E') + 2\pi \widetilde{\mathcal{D}}_\infty \times \int_{-\omega}^{0} \frac{d\epsilon}{2\pi} (-i) \mathrm{Re}\, \widetilde{U}(\epsilon) \widetilde{\mathcal{D}}(E+\epsilon-E')$$

The lowest order diffuson dressed interaction is effectively replaced by

$$[\mathcal{D}_0 (-i) \mathrm{Re}\{\widetilde{U}\} \mathcal{D}_0]_\eta \rightarrow \frac{1}{2\pi\nu} [\widetilde{\mathcal{D}}_\eta - \widetilde{\mathcal{D}}_\infty]$$

T. Ludwig, I. V. Gornyi, A.D. Mirlin, P. Wölfle, Phys. Rev. B 77, 235414 (2008)

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Self energy correction to Delayed Diffuson

In addition to a finite decoherence rate the delayed diffuson propagator is renormalized by the real part of the self energy

$$\tilde{\mathcal{D}}_\eta = \frac{1}{Dq^2 - i\omega - i\Sigma_\eta^Z + \Sigma_\eta^\varphi}.$$

$$\Sigma_\eta^Z = \frac{3\lambda^2}{2\pi} g\omega \left[\ln\frac{T_0}{\omega}\left(1 - \frac{\sin \omega\eta}{\omega\eta}\right) + 1 - \frac{\mathrm{Si}(\omega\eta)}{\omega\eta} \right], \quad \omega \ll T_0,$$

Renormalization factor suppresses diffuson

$$\tilde{D}_\eta \approx \frac{z}{zDq^2 - i\omega}, \quad z = \frac{1}{1 - \partial\Sigma_\eta^Z / \partial\omega} \propto \frac{1}{g}$$

At T << T_0 : $\Sigma_\eta^Z >> \Sigma_\eta^\varphi$

At T >> T_0 : $\Sigma_\eta^Z >> \Sigma_\eta^\varphi, \quad \omega >> T(T/T_0)^{1/2}$

$$\Sigma_\eta^Z >> \Sigma_\eta^\varphi, \quad T << \omega << T(T/T_0)^{1/2}$$

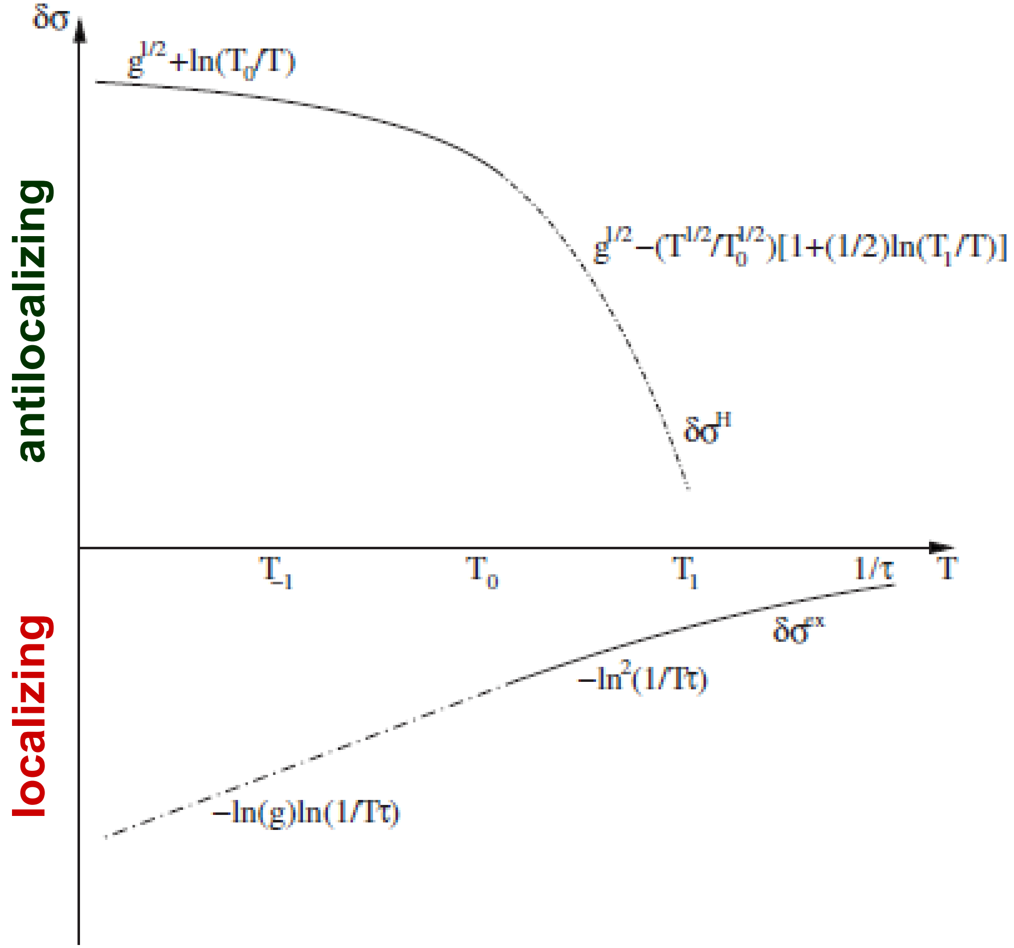
Hartree correction to conductivity: screened Coulomb interaction

Diffuson self energy at low energy leads to reduction in size and suppression of T-dependence of Hartree correction at low T

$$\delta\sigma^{H}(T) = e^{2}[c_{1}g^{1/2} + c_{2}\ln\frac{T_{0}}{T}]\,, \qquad T << T_{1}$$

- **Anti-localizing correction**
- **Linear in ln(T)**
- **Prefactor O(1)**

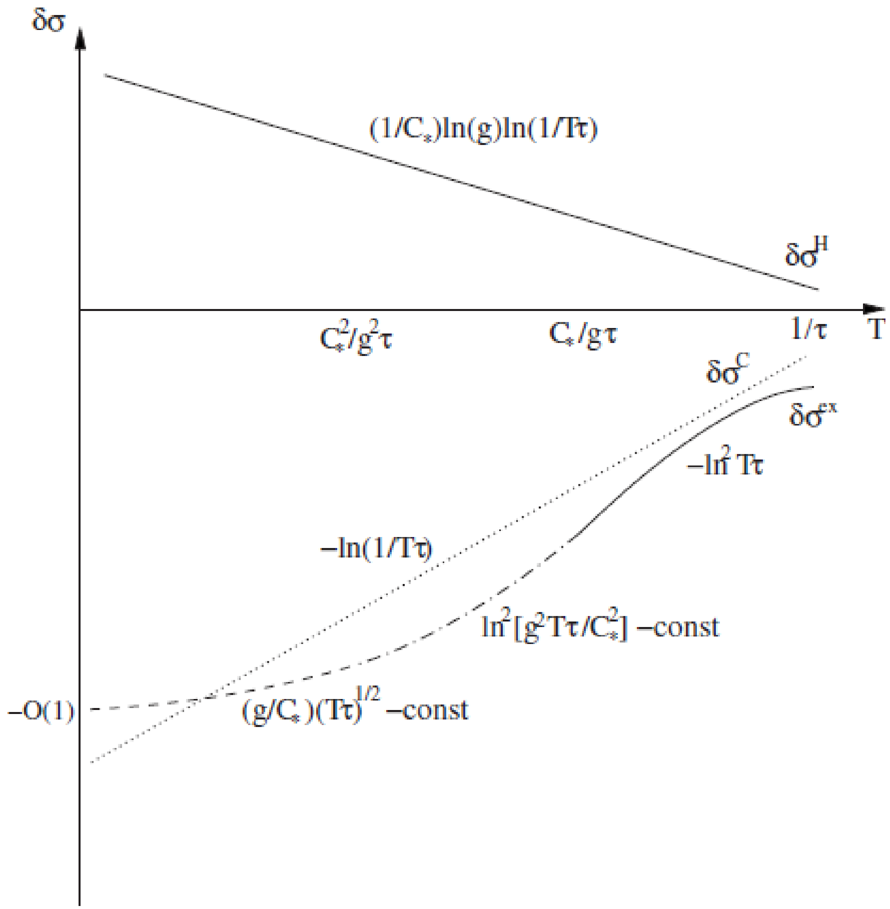
Hartree correction to conductivity: screened Coulomb interaction



At low T the localizing exchange contribution dominates over the antilocalizing Hartree contribution: interaction correction leads to localization

Hartree correction to conductivity: unscreened Coulomb interaction

Gauge field propagator has weaker singularity ~ 1/k
renormalization of gauge field interaction not important



Gauge field Interaction correction to conductivity: unscreened Coulomb interaction

At the lowest temperatures, the usual A-A-correction due to Coulomb interaction dominates the Hartree correction for not too high conductance,

$$g < \exp[\pi C_* / 4] \sim 1000.$$

$$\delta\sigma^{\text{int}}(T) = \frac{e^2}{h}\left[\frac{4}{\pi C_*}\ln(g) - 1\right]\ln\left(\frac{1}{T\tau}\right)$$

- **localizing**
- **linear in lnT**

Cooperon dephasing at strong coupling

Weak localization correction to conductivity

$$\delta\sigma_{\rm WL} = -\frac{2e^2 D}{\pi}\int_\tau^\infty dt\ \langle \mathcal{C}(0,0,t)\rangle$$

Cooperon averaged over Gauge field fluctuations

$$\langle \mathcal{C}(t)\rangle = \exp\{-\langle \Delta S\rangle(t)\}\int_{\mathbf{r}(-t)=0}^{\mathbf{r}(t)=0}\mathcal{D}[\mathbf{r}(t')]\exp\{-S_0\} = (4\pi Dt)^{-1/2}e^{-t/\tau_\varphi}$$

Renormalization of diffuson: replace time $t \longrightarrow t/Z.$

Renormalization leaves bare Cooperon unchanged, $\tilde{C}(t) = \frac{1}{Z}C^{(0)}(t/Z) = \frac{1}{Z}\frac{Z}{4\pi Dt} = \frac{1}{4\pi Dt}$

but changes ΔS:

$$\Delta\tilde{S}^{\rm eff}(t) \simeq 3\lambda^2 gT\frac{t}{Z(t)}\ln\left[\frac{T}{T_0}\frac{t}{Z(t)\tau}\right]$$

$$\simeq \frac{3\lambda^2 gTt}{(3/2\pi)\lambda^2 g\ \ln(T_0 t)}\ln\frac{Tt}{\lambda^2 gT_0\tau} \simeq 2\pi Tt\frac{\ln(gTt/\lambda^2)}{\ln(T_0 t)}$$

Phase relaxation rate: $\frac{1}{\tilde{\tau}_\varphi} \sim T\frac{\ln(g/\lambda^2)}{\ln(T_0/T)}.$

→ **prefactor of T is O(1) rather than O(g)**

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Summary

- **Transverse gauge fields in 2d correlated electron systems induce highly singular current-current interaction, depending on the screening of the Coulomb interaction (by external gates), leading to singular quantum corrections to the conductivity**

- **Exchange corrections to the conductivity are relatively small, and localizing, with T-dependence ~ - lng lnT (screened) and - const + √T (unscreened Coulomb interaction)**

- **Hartree corrections in case of screened interaction are antilocalizing : At weak coupling ~ g $\ln^2 T$ >> g . At strong coupling and high T dephasing of diffusons suppresses the correction. At low T renormalization of the diffusons and of the current-current-interaction reduce both size and T-dependence of the correction.**

- **Hartree corrections in case of long range Coulomb interaction are antilocalizing ~ lng lnT , but are dominated by the usual localizing A-A-correction for not too large g.**

- **The phase relaxation rate is proportional T, with prefactor ~ g at weak and ~ lng at strong coupling.**

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