Persistent Currents versus Phase Breaking in Mesoscopic Metallic Samples

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- Introduction
- Established theory
- Relation to the dephasing problem?

Eckern, Schwab JLTP **126**, 1291 (2002)

Electron phase coherence in disordered metals

- standard analysis:
  electron-phonon interaction, Coulomb interaction

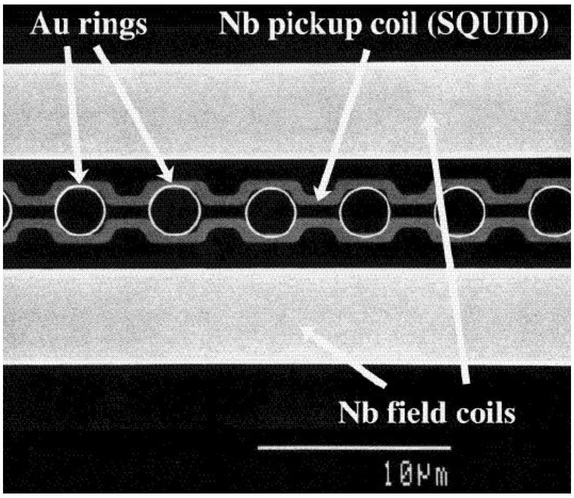
- problem:
  τ_φ often shorter than expected, e.g.
  In_2O_{3-x}, heavily doped Si: $1/\tau_\varphi \sim T$
  Au (sometimes): $1/\tau_\varphi \sim \sqrt{T}$
  many materials: low temperature saturation of τ_φ

- microscopic origin of strong phase breaking?
  extreme dilute magnetic impurities?

Persistent currents in normal conducting rings

- phase coherent motion of electrons necessary
  $\longrightarrow$ sensitive to phase breaking processes
- problem:
  sometimes larger than expected theoretically; "wrong" sign

Mohanty, Ann. Phys. '99; Jariwala et al, PRL '01

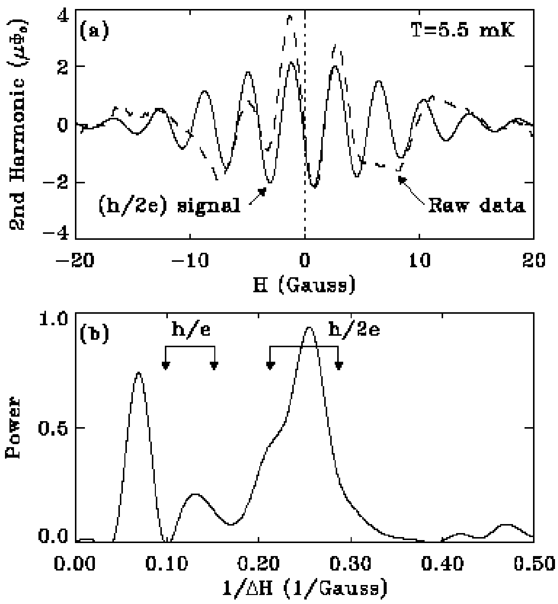


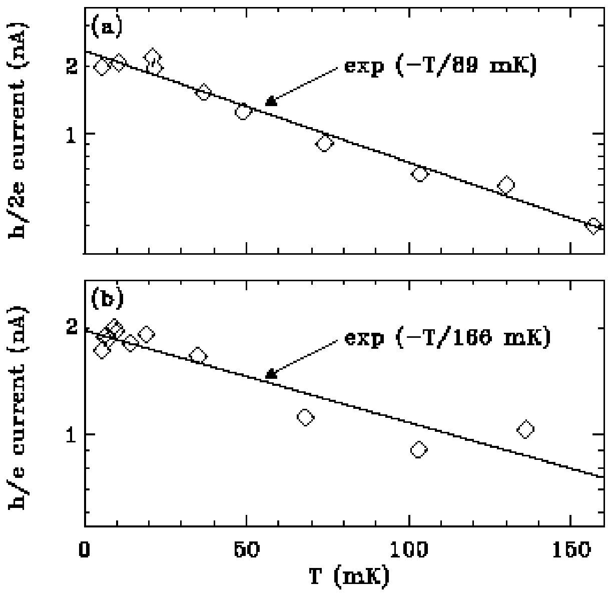
30 gold rings:

$I \approx e/\tau_d$

$\hbar/\tau_d = \hbar v_F l/3L^2 \approx 7$mK

$L \approx 8\mu$m, $l \approx 87$nm





Free fermions

persistent current

$$I = -\frac{\partial \Omega(\phi)}{\partial \phi}, \quad I = -\frac{\partial F(\phi)}{\partial \phi}$$

density of states determines thermodynamics

$$\Omega(\phi) = -2k_B T \int \mathrm{d}\epsilon N(\epsilon, \phi) \ln[1 + \mathrm{e}^{-(\epsilon-\mu)/k_B T}]$$

density of states for disordered metals

$$N(\epsilon, \phi) = \langle N(\epsilon) \rangle + \delta N(\epsilon, \phi)$$

Fluctuations in the density of states

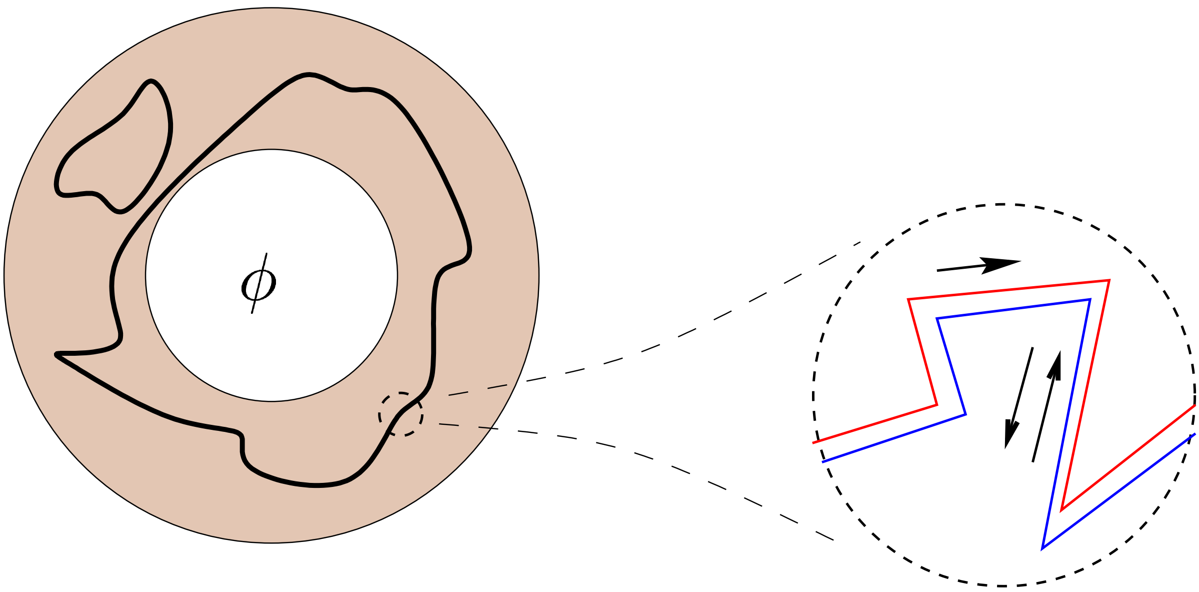
Altshuler & Shklovskii '87

Perturbation theory in $1/\epsilon_F\tau$, $\delta/(\hbar/\tau_d)$ (diffuson, cooperon)

$$\langle N(\epsilon+\omega,\phi)N(\epsilon,\phi')\rangle \propto \sum_q [P(q,\omega)]^2$$

$$\propto \int_0^\infty \mathrm{d}t e^{\mathrm{i}\omega t} t \left\{ P(0,t) + 2\sum P(mL,t)\cos\left(2\pi m \frac{\phi \pm \phi'}{\phi_0}\right)\right\}$$

$$P(q,\omega) = \frac{1}{-\mathrm{i}\omega + Dq^2}$$



$P(L,t) \propto TT^*$

magnetic field

$e^{\mathrm{i}(\eta+2\pi\phi/\phi_0)}[e^{\mathrm{i}(\eta\pm2\pi\phi/\phi_0)}]^*$

Persistent current for free fermions

Cheung et al '89, . . .

average value:

$$\langle I \rangle = -\frac{\partial \langle \Omega \rangle}{\partial \phi} = 0$$

statistical fluctuations:

$$\langle \Omega(\phi)\Omega(\phi') \rangle = \sum_m \mathcal{C}_m \cos\left(\frac{2\pi m\phi}{\phi_0}\right) \cos\left(\frac{2\pi m\phi'}{\phi_0}\right)$$

$$\mathcal{C}_m = \frac{8L}{\pi^2} \int_0^\infty \frac{\mathrm{d}t}{t} \left(\frac{\pi k_B T}{\sinh(\pi k_B T t/\hbar)}\right)^2 P(mL, t)$$

$T = 0$, typical current $I \approx 2\pi\sqrt{\mathcal{C}_1}/\phi_0 \approx 3.1 e/\tau_d$

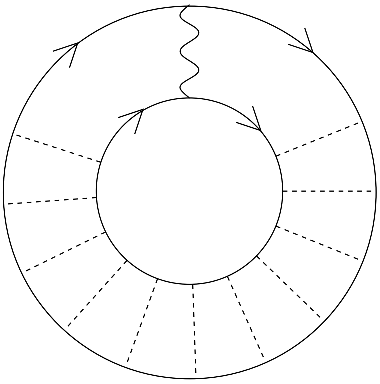
$T \neq 0$: exponential cut-off in long paths

$$\frac{1}{\sinh(\pi k_B T t/\hbar)} \approx 2\exp(-\pi k_B T t/\hbar)$$

temperature dependence on the scale $k_B T \approx \hbar/\tau_d$

Persistent current, weakly interacting system

Ambegaokar, Eckern '90



$$\delta\Omega_C = \frac{1}{2}\int \mathrm{d}\mathbf{r}\mathrm{d}\mathbf{r}' v(\mathbf{r}-\mathbf{r}')\delta n(\mathbf{r})\delta n(\mathbf{r}')$$

$$N_0\langle v(\mathbf{k}-\mathbf{k}')\rangle_{FS} = \mu_0 \leq 1/2$$

$$\langle\delta\Omega_C(\phi)\rangle = \mu_0\frac{4L}{\pi\hbar}\int_0^\infty \mathrm{d}t\left(\frac{\pi k_B T}{\sinh(\pi k_B T t/\hbar)}\right)^2 \times \sum_m P(mL,t)\cos(4\pi m\phi/\phi_0)$$

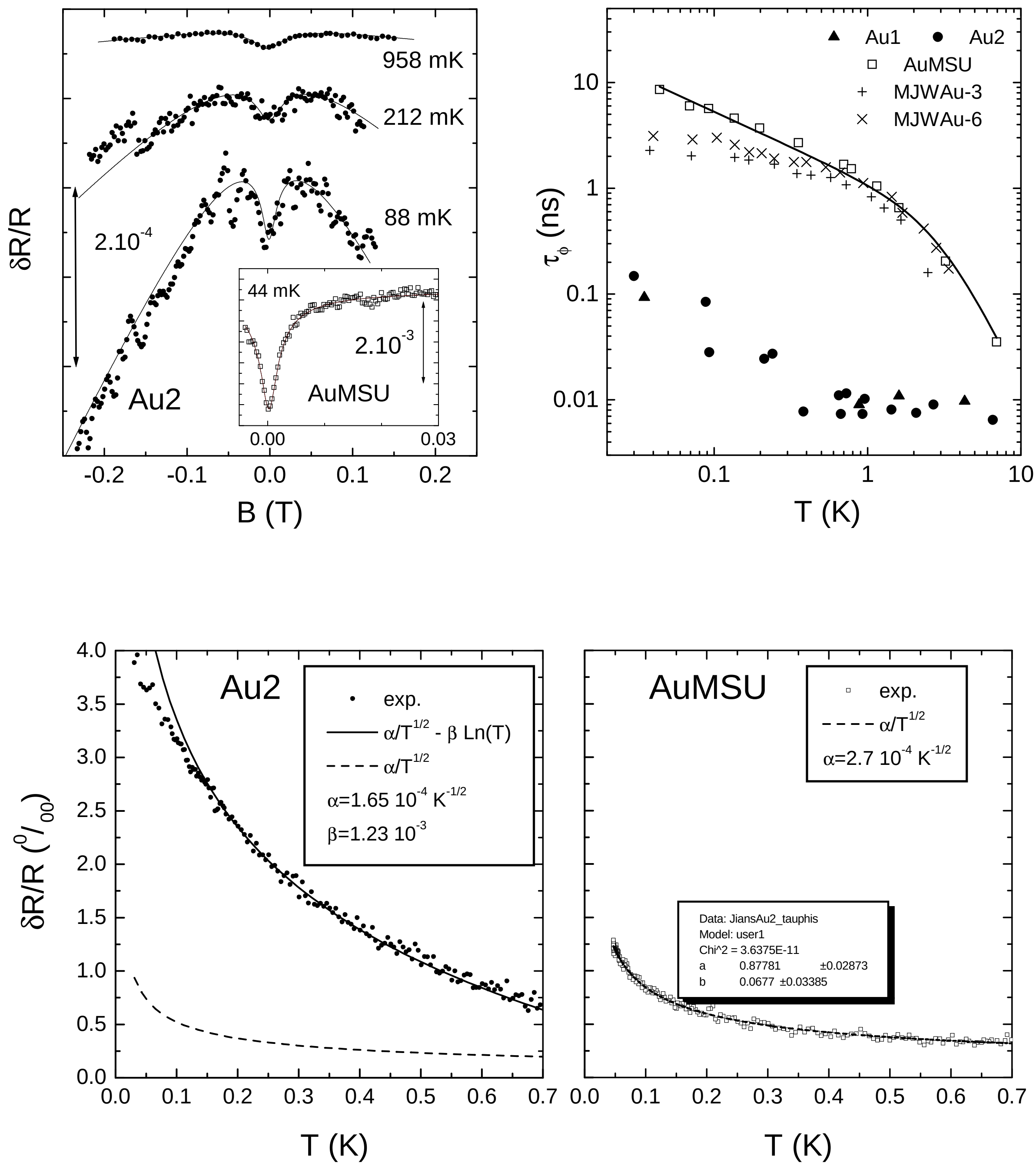
$T=0$: $I \sim \mu_0 e/\tau_d$, precise prefactor?

- exchange term
- renormalized interaction constant
  $\mu_0 \to \mu^* \approx \mu_0/\{1+\mu_0 \ln[\epsilon_F/(\hbar/\tau_d)]\}$
  μ^* depends on the material, $\mu^* < 0.1$ in Cu, Au
- $\mu^* \to \mu^* - \lambda$?

final result

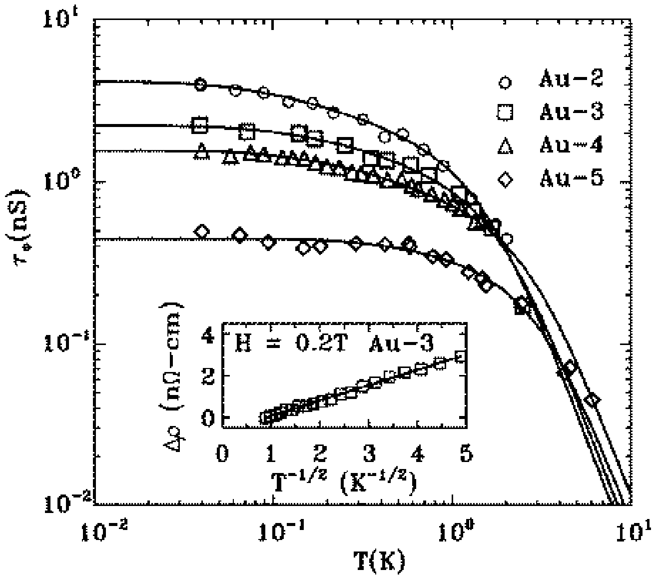
$$I = I_{h/2e}\sin(4\pi\phi/\phi_0) + \ldots, \quad I_{h/2e} \approx 8\mu^*/\pi(e/\tau_d)$$

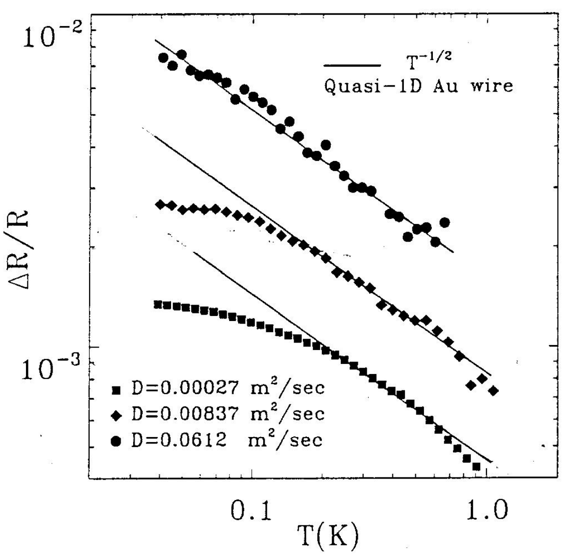
Phase breaking and resistance in gold wires



Pierre, Pothier, Esteve, Devoret, Gougam, Birge;
cond-mat/0012038

Phase breaking and resistance in gold wires

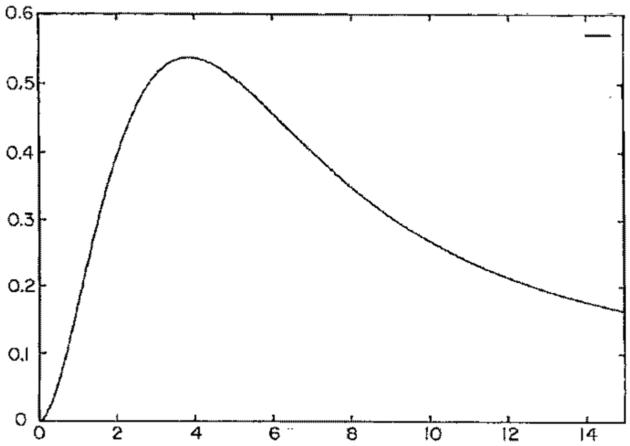




Mohanty, Jariwala, Webb '97

High frequency electric field

Kravtsov, Yudson '97



$$eE_\omega L \sim \hbar\omega \longrightarrow I_{\rm DC} \sim (e/\tau_d)\sin(4\pi\phi/\phi_0) + \ldots$$

generalization: noise

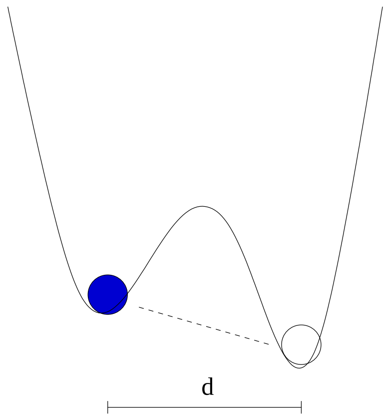
Altshuler, Kravtsov '00

noise: phase breaking & directed current

$$I_{h/2e} = \begin{cases} -(4/\pi)(e/\tau_\phi){\rm e}^{-L/L_\phi} & \tau_{\rm so} \gg \tau_d \\ (2/\pi)(e/\tau_\phi){\rm e}^{-L/L_\phi} & \tau_{\rm so} \ll \tau_d \end{cases}$$

in all experiments: $L \sim L_\phi \longrightarrow I \sim e/\tau_d$.

Electron-impurity interaction?



$$\hat{H}_{\rm TLS} = \begin{pmatrix} \epsilon & \Delta \\ \Delta & -\epsilon \end{pmatrix}$$

assumption: $P(\epsilon, \Delta) \propto 1/\Delta$

phase breaking:

$$\frac{1}{\tau_\phi} \sim \frac{1}{\tau} \left[1 - \left(\frac{\sin k_F d}{k_F d} \right)^2 \right] \frac{\Delta_{\rm max}}{\epsilon_{\rm max}} \frac{1}{\ln(\Delta_{\rm max}/\Delta_{\rm min})}$$

($\tau_\phi < \Delta_{\rm max} < k_B T$; weak coupling)

Imry,Fukuyama,Schwab,EPL 47, 608 (1999)

persistent current:

$$\begin{aligned} I_{h/2e} &\sim -|\mu_{\rm TLS}| e/\tau_d \\ |\mu_{\rm TLS}| &\sim \frac{\hbar/\tau_\phi}{\Delta_{\rm max}} \ln(\Delta_{\rm max}/\Delta_{\rm min}) \end{aligned}$$

Schwab, EPJ B 18, 198 (2000)

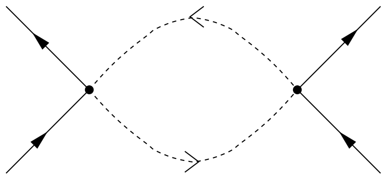
TLS relevant for phase breaking $\longrightarrow$ relevant for persistent current

Persistent current & magnetic defects

Schwab, Eckern '97

$$H = H_0 - \sum_{\text{magnetic defects}} J\mathbf{s}(\mathbf{x}_j) \cdot \mathbf{S}_j$$

effective interaction



$$V_{\text{eff}} \propto \frac{n_s}{N_0^2} \begin{cases} (N_0 J)^2 \chi(T) & T > T_K \\ T_K^{-1} & T < T_K \end{cases}$$

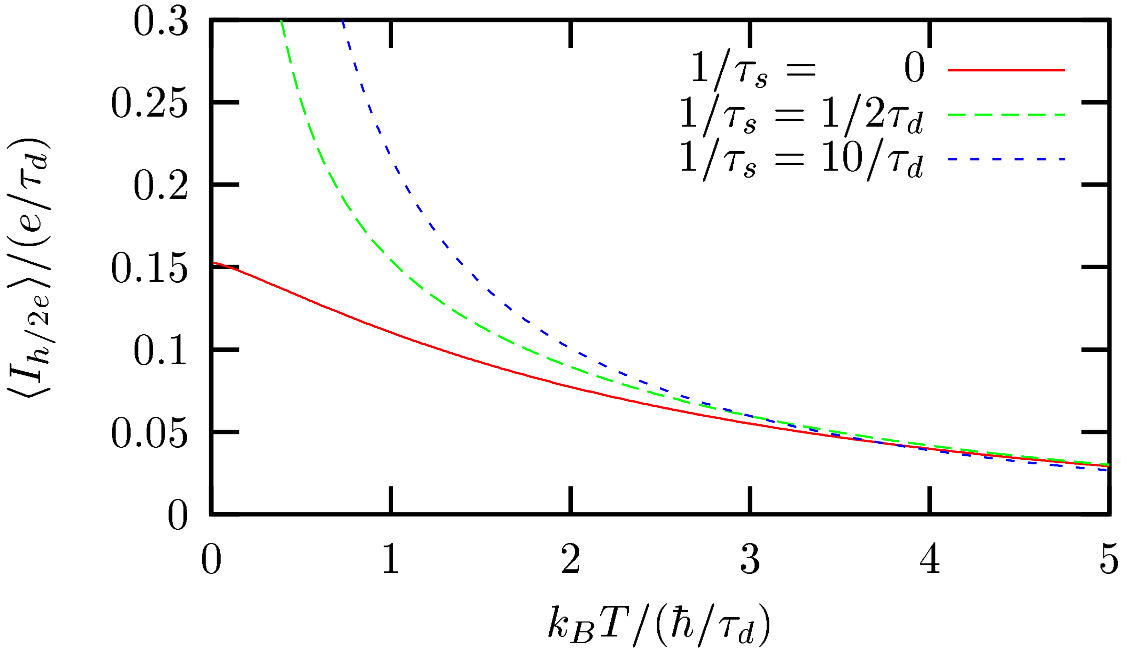
phase breaking

$$\hbar/\tau_s \propto \frac{n_s}{N_0} \begin{cases} (N_0 J)^2 & \text{for } T > T_K \\ (T/T_K)^2 & \text{for } T < T_K \end{cases}$$

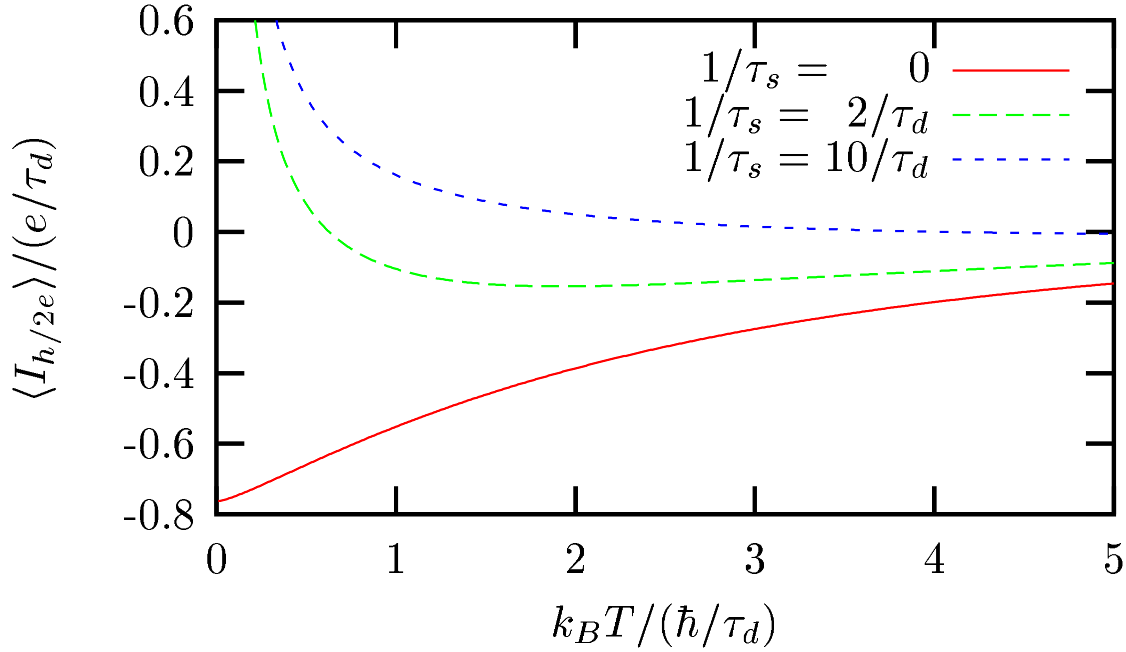
persistent current

$$\begin{aligned} I &\sim N_0 V_{\text{eff}} e/\tau_d \\ I &\sim \frac{\hbar/\tau_s}{k_B T} e/\tau_d \end{aligned}$$

$\mu^* = 0.06$ (Coulomb!)+ magnetic defects



$\mu^* = -0.3$ (experiment?) + magnetic defects



Summary

persistent currents in mesoscopic rings are partially understood:

- periodicity h/e, $h/2e$
- characteristic scale e/τ_d
- characteristic temperature scale $k_B T \sim \hbar/\tau_d$
- not understood: sign of $I_{h/2e}$

phase breaking versus persistent currents:

- higher amplitude possible, different T-dependence
- magnetic impurities should be visible