NTT BRL School 2005 – Lecture #1

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Quantum Transport and Electron Dephasing in Diffusive Metal Wires:

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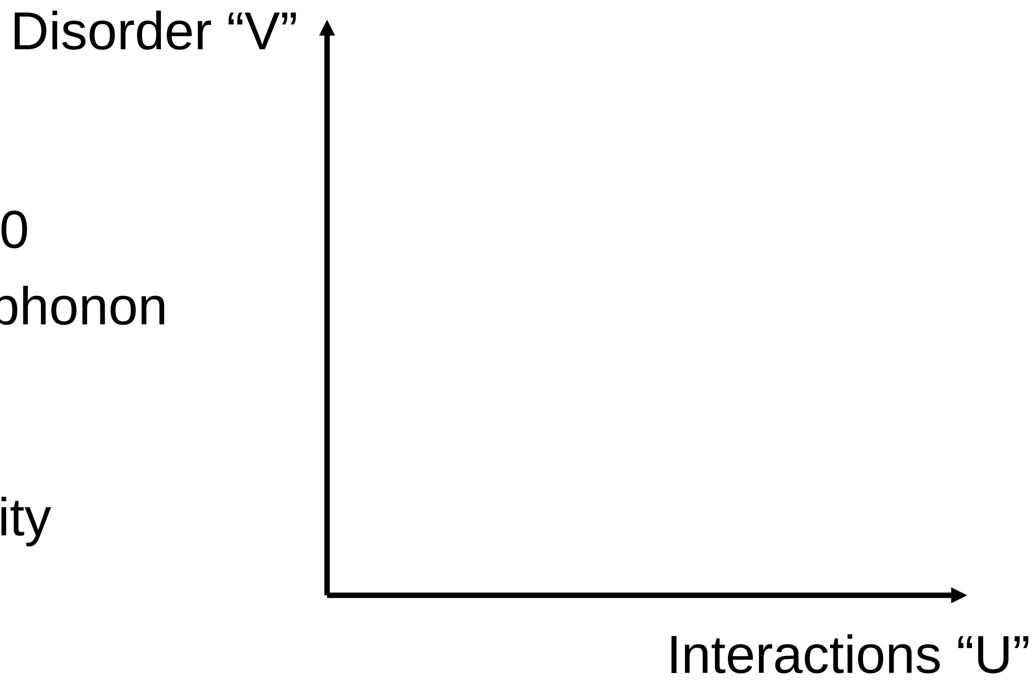
Work supported by NSF DMR

Disorder and Interactions – The Big Picture



1. V =0, U=0

Bloch’s Thm. ❾ $\rho(T=0) = 0$

❒☎❄✆ from electron-phonon scattering

2. V small, U=0

$\rho(T=0) = \rho_{\text{🗀}} \neq 0$, impurity scattering

3. V =0, U small

Fermi liquid theory of metals (Landau)

4. V large, U=0

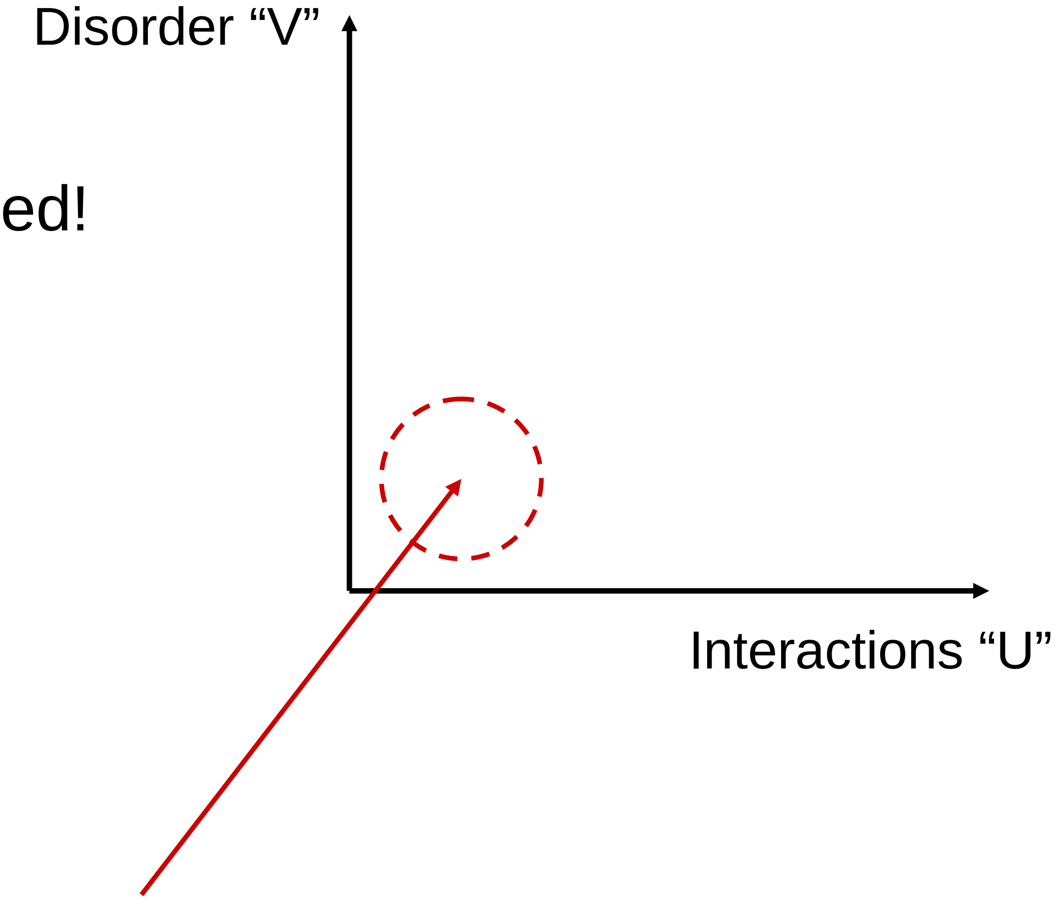
localization of 1-particles wavefunctions (Anderson)

5. V =0, U large

Wigner crystal – Coulomb repulsion

Disorder and Interactions – The Big Picture

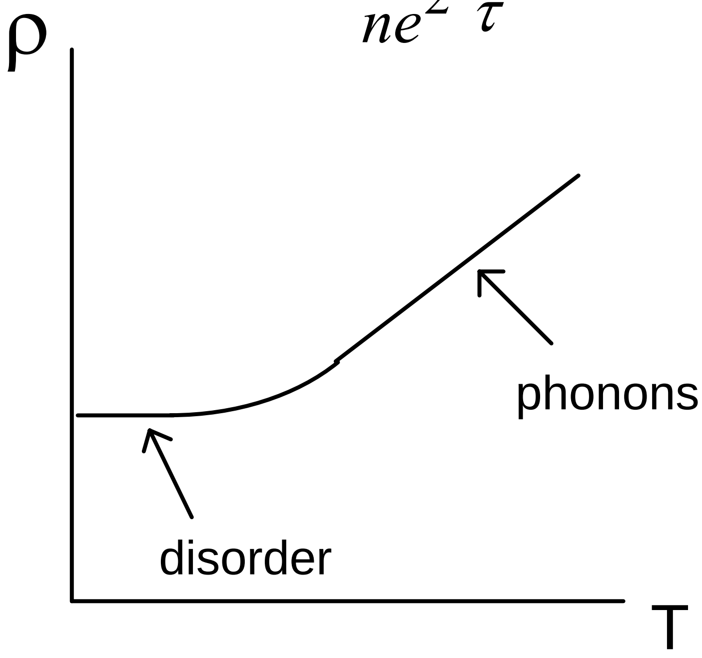
6. V ≠ 0, U ≠ 0   complicated!



My lectures: V, U are both small

Weakly-disordered metals … 1980's

$$\rho = \frac{m}{ne^2}\frac{1}{\tau}$$



Matthiessen's rule: IS WRONG!

$$\frac{1}{\tau} = \frac{1}{\tau_{disorder}} + \frac{1}{\tau_{el-ph}} + \ldots$$

elastic

preserves quantum phase coherence

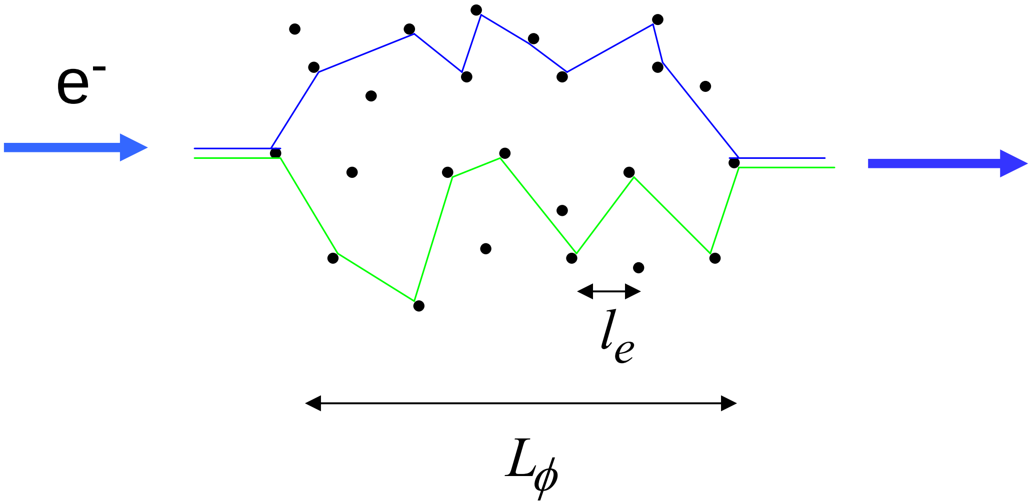
inelastic

destroys quantum phase coherence

Low T: $\frac{1}{\tau_{inelastic}} << \frac{1}{\tau_{elastic}}$

Electrons maintain quantum phase coherence over distance $L_\phi >> l_e$

Phase-coherent diffusive electron transport

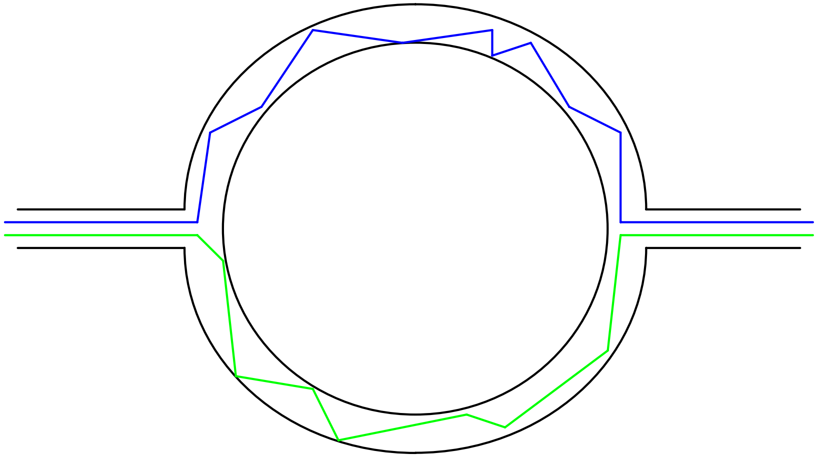


Diffusion: $D = v_F l_e/3$ (elastic)

Quantum interference over distance L♐ (inelastic)

Interference effects and L_ϕ

- *Aharonov-Bohm effect*

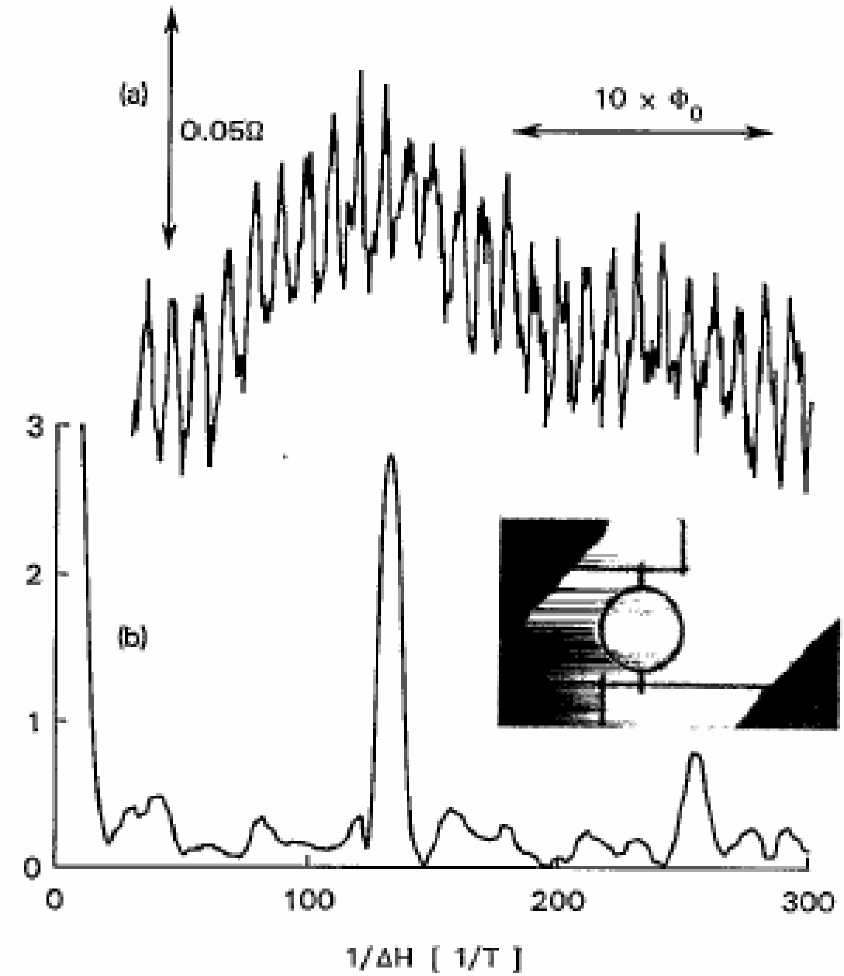


$$P_{trans} = \left| A_{up} + A_{down} \right|^2$$

$$= P_{up} + P_{down} + 2\,\mathrm{Re}\left(A_{up} A_{down} \right)$$

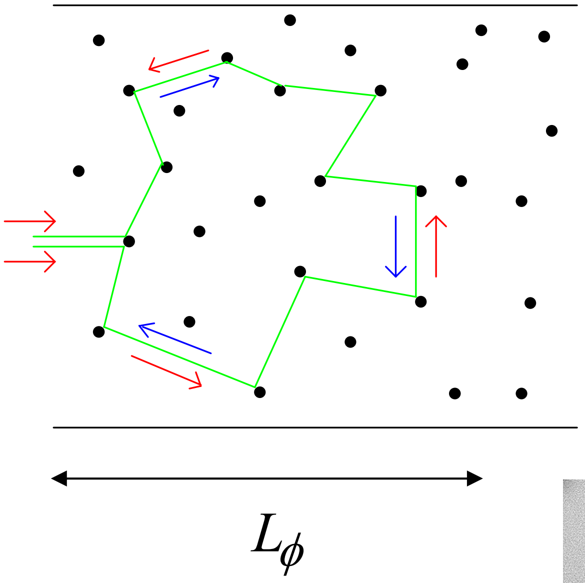
$$\Delta G \propto \exp\left(-\frac{\pi r}{L_\varphi} \right)$$

Washburn & Webb, 1984

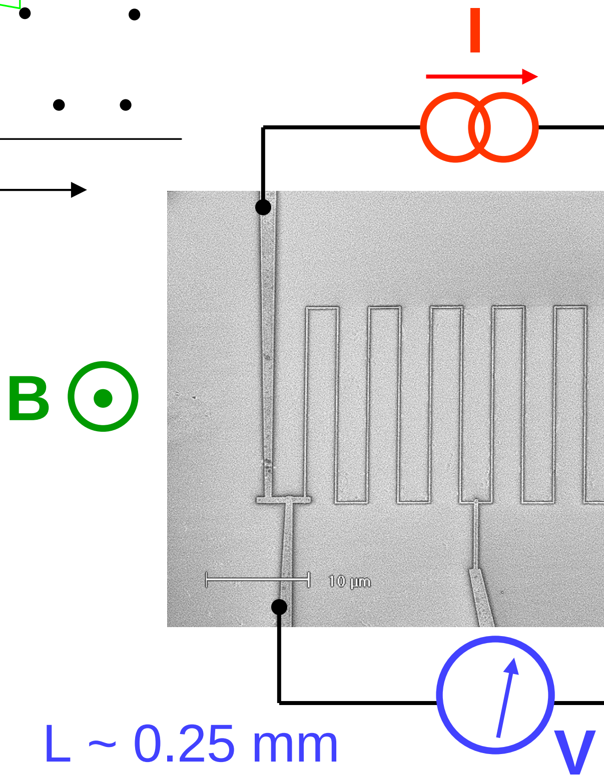


Interference effects and L_ϕ

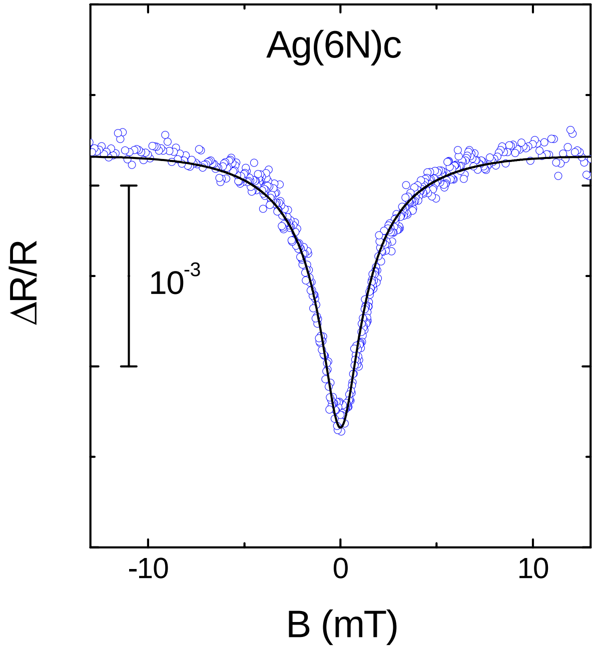
- *Aharonov-Bohm effect*
- *Weak localization*



$$P_{return} = \left|A_{\rightarrow} + A_{\leftarrow}\right|^2 = \underbrace{P_{\rightarrow} + P_{\leftarrow}}_{\text{classical}} + \underbrace{2\mathrm{Re}\left(A_{\rightarrow} A_{\leftarrow}\right)}_{\text{quantum interference}}$$

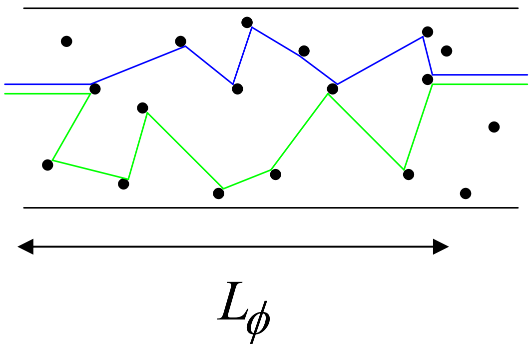


L ~ 0.25 mm

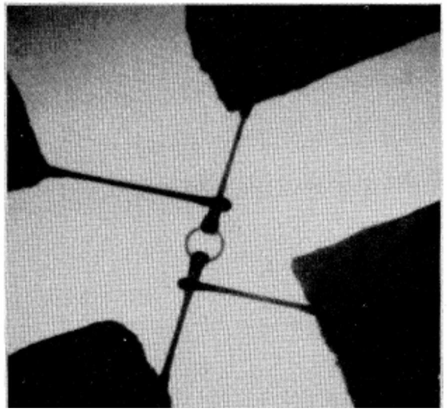


Interference effects and L_ϕ

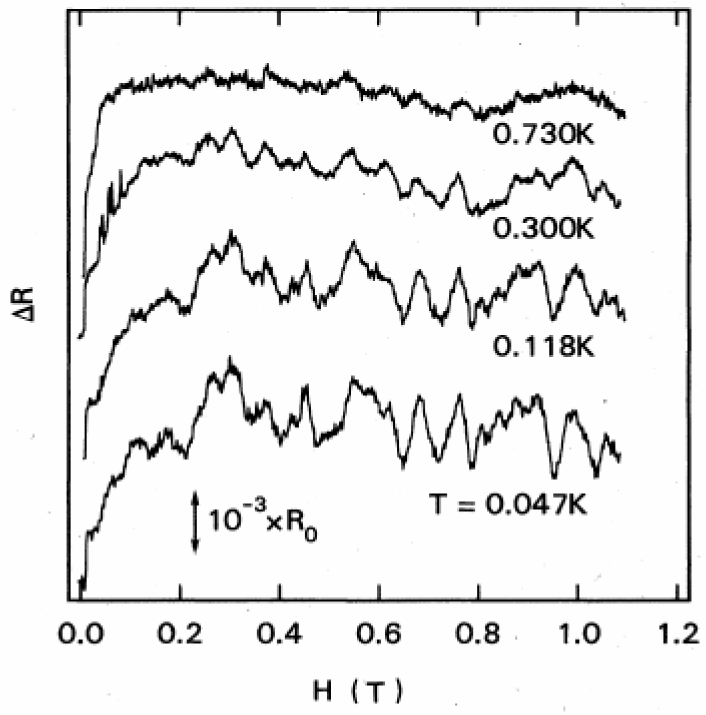
- *Aharonov-Bohm effect*
- *Weak localization*
- *Conductance Fluctuations*



$$P_{trans} = \left| \sum_{paths\ \alpha} A_\alpha \right|^2$$



Umbach, Washburn, Laibowitz, and Webb (1984)



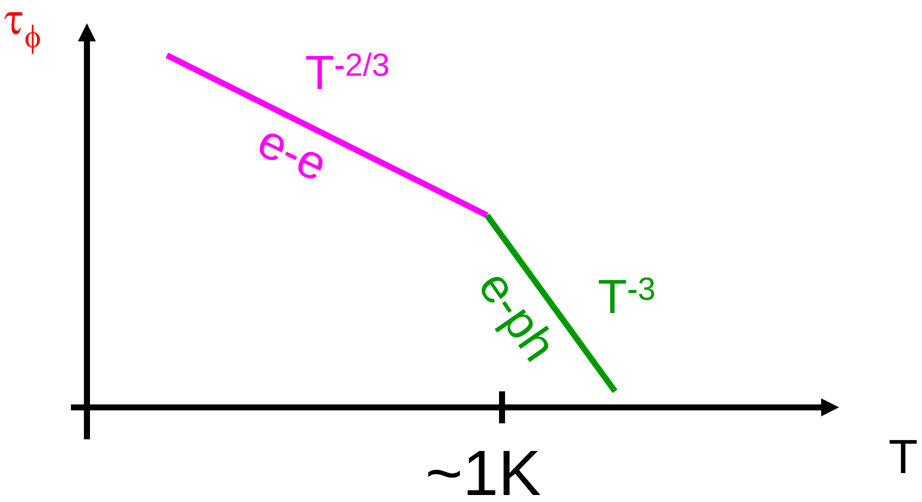
Interference effects and L_ϕ

- *Aharonov-Bohm effect*
- *Weak localization*
- *Conductance Fluctuations*
- *Persistent currents*
- *Superconducting proximity effect*
- ...

Size of the effects depends on $L_\phi = \sqrt{D\tau_\phi}$

Mechanisms of inelastic scattering: $\tau_\phi(T)$ in wires: theory

Altshuler, Aronov, Khmelnitskii, 1982



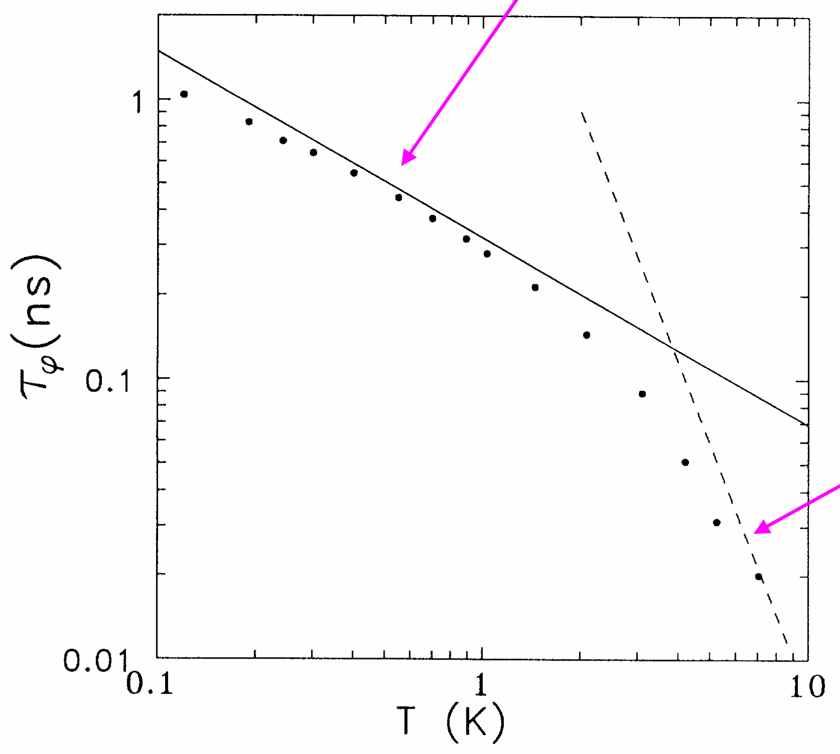
$$\tau_\phi = (A\,T^{2/3} + B\,T^3)^{-1}$$

$$A = \frac{1}{\hbar}\left(\frac{\pi k_B^2}{4\nu_F Lwt}\frac{R}{R_K}\right)^{1/3}$$

Screened Coulomb Interaction for d=1

$\tau_\phi(T)$ in wires: experiment

Echternach, Gershenson, Bozler, Bogdanov & Nilsson, PRB **48**, 11516 (1993)

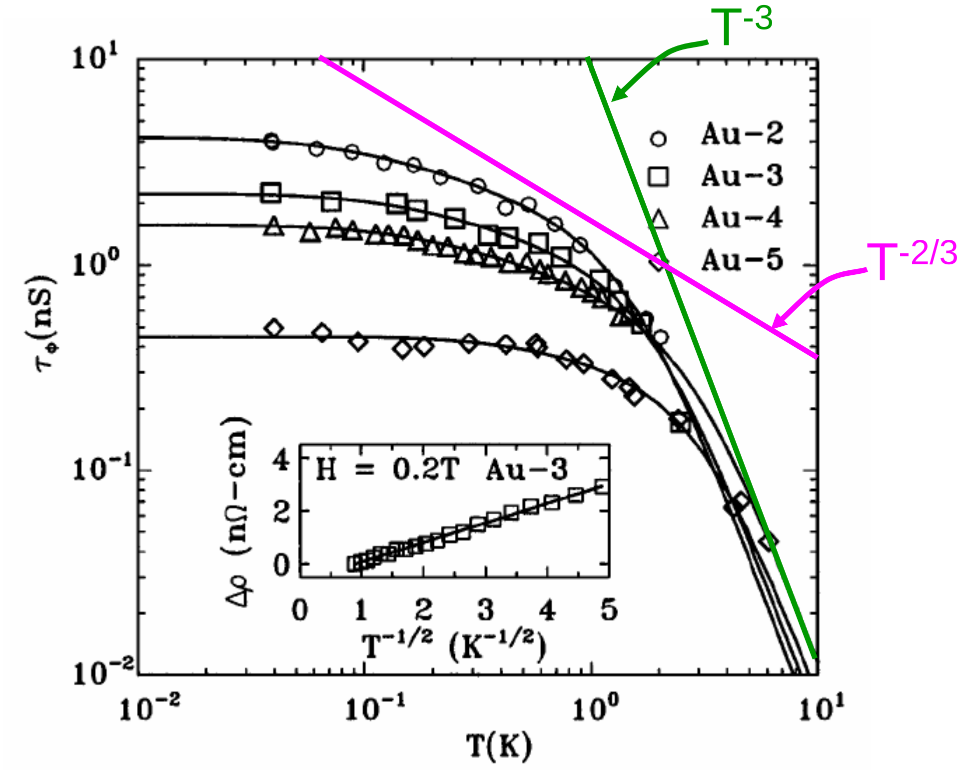


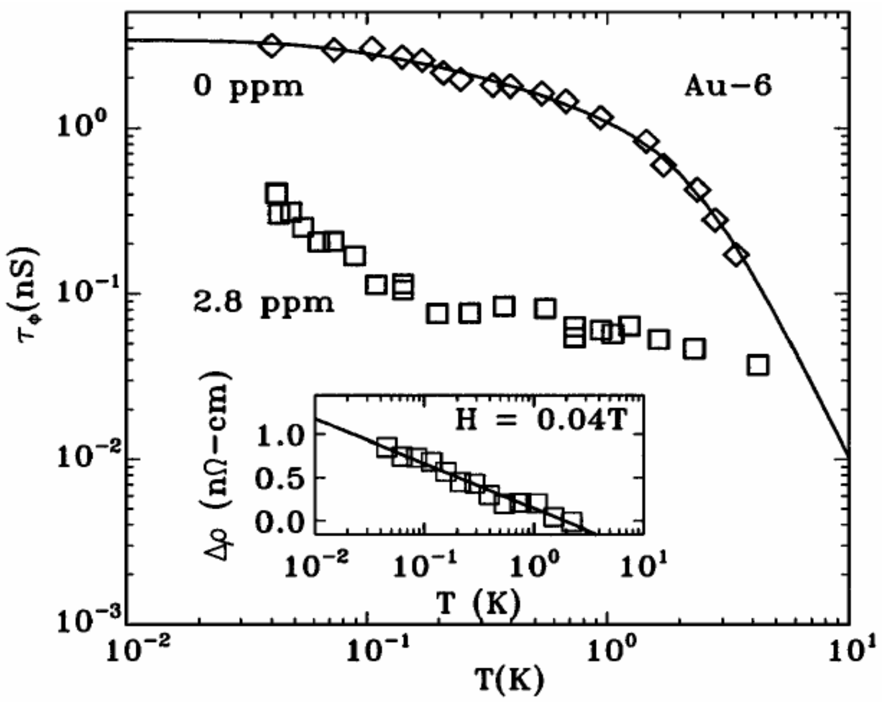
electron-electron scattering ($\tau_\phi \sim T^{-2/3}$)

electron-phonon scattering

A few years later … a puzzle

Mohanty, Jariwala and Webb, PRL **78**, 3366 (1997)

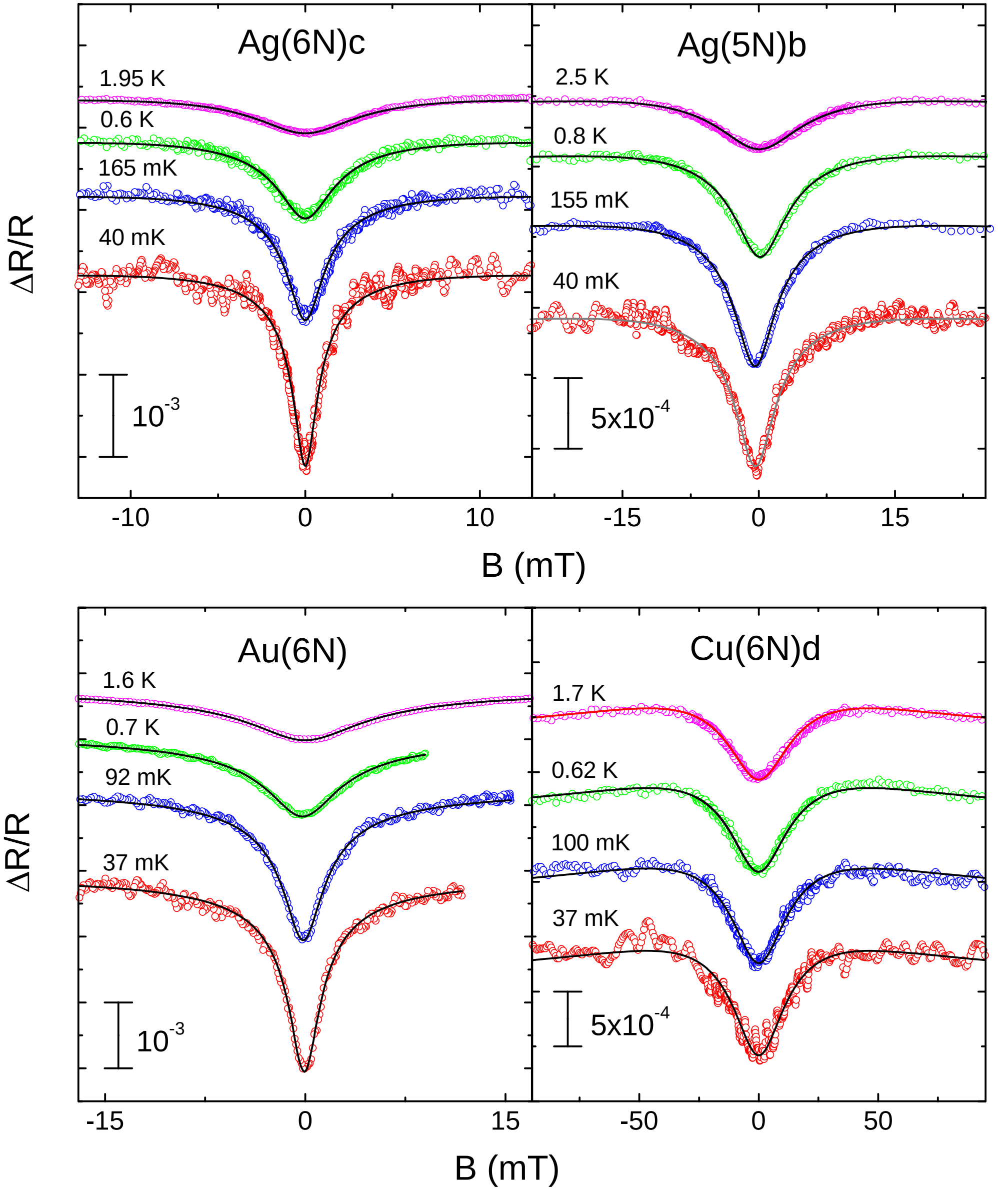




“Saturation” of τ_ϕ:

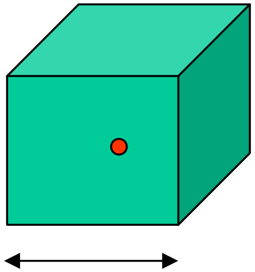
e-e interaction badly understood ?
another process dominates ?

Measuring $\tau_\phi(T)$: raw data



5N = 99.999 % source purity
6N = 99.9999 %   “   “

1 ppm of
impurities :



100 atoms ~ 25 nm

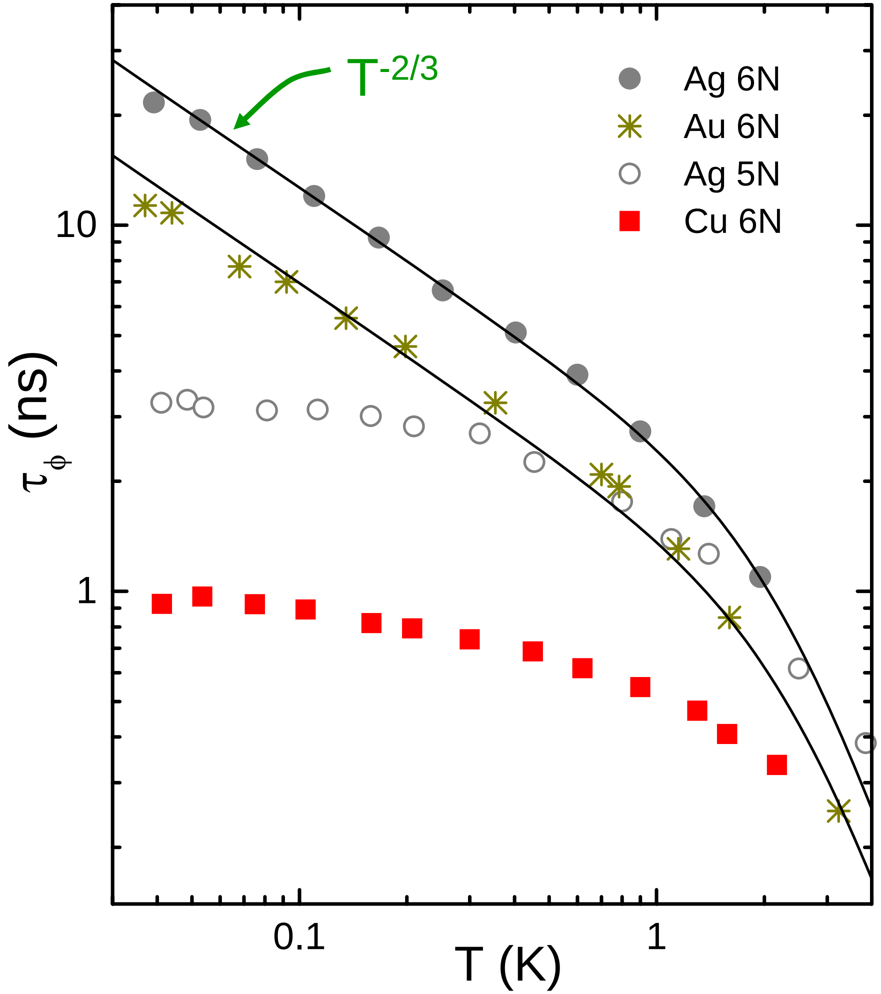
Ag(6N) & Au(6N):

ΔR grows as T decreases

Ag(5N) & Cu(6N):

ΔR saturates below ~ 100mK

$\tau_\phi(T)$ in Ag, Au & Cu wires



5N = 99.999 % source material purity
6N = 99.9999 % " " "

Low T behavior vs. Purity:

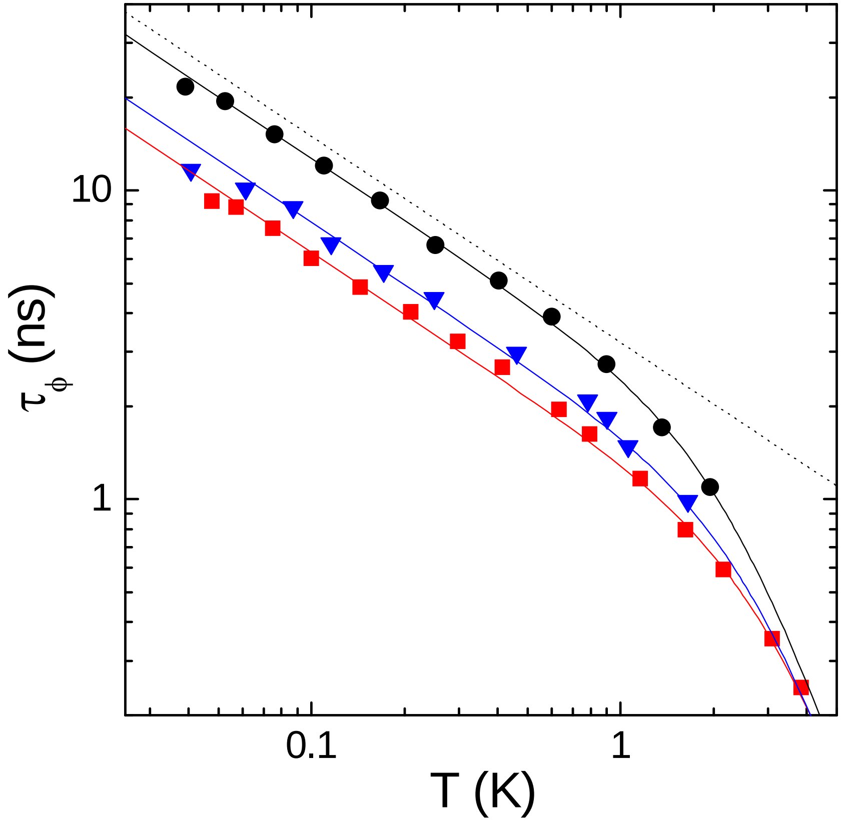
- **Ag 6N**, **Au 6N**
  → agreement with AAK theory

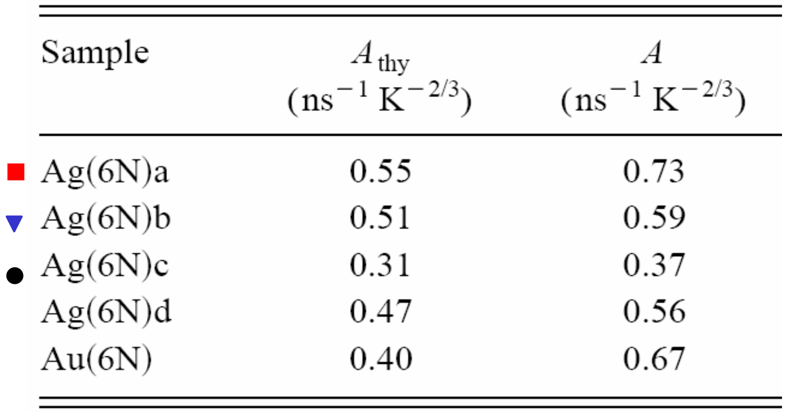
- **Ag 5N**, **Cu 6N**
  → saturation of $\tau_\phi(T)$

Saturation of τ_ϕ is sample dependent

Quantitative comparison with AAK theory for high-purity samples

$$\tau_\phi = (A\,T^{2/3} + B\,T^{3})^{-1}$$





	Sample	A_{thy} ($\mathrm{ns}^{-1}\,\mathrm{K}^{-2/3}$)	A ($\mathrm{ns}^{-1}\,\mathrm{K}^{-2/3}$)
■	Ag(6N)a	0.55	0.73
▼	Ag(6N)b	0.51	0.59
●	Ag(6N)c	0.31	0.37
	Ag(6N)d	0.47	0.56
	Au(6N)	0.40	0.67

F. Pierre *et al.*,
PRB **68**, 0854213 (2003)

$$A_{thy} = \frac{1}{\mathrm{h}}\left(\frac{\pi k_B^2}{4\nu_F L w t}\,\frac{R}{R_K}\right)^{1/3}$$

Detour: The Kondo Effect

Resistivity of metals

High T, phonons

Low T, impurities & disorder

Pt

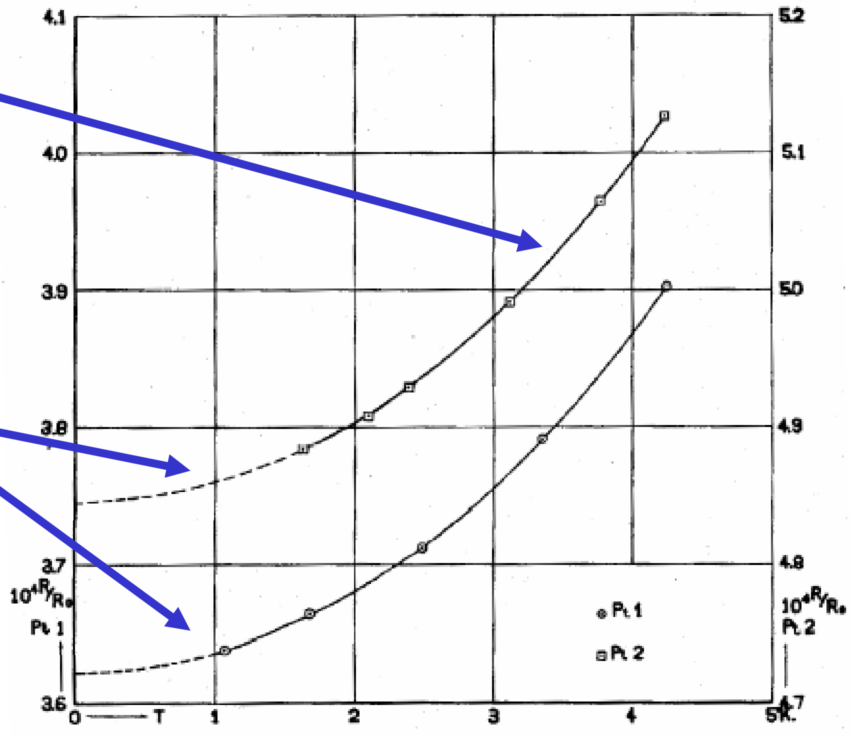


Fig. 1. Electrical resistance of Pt between 0°K. and 4.2°K.

De Haas & de Boer, 1934

dR/dT>0 usually

But dR/dT<0 in some samples!

Au

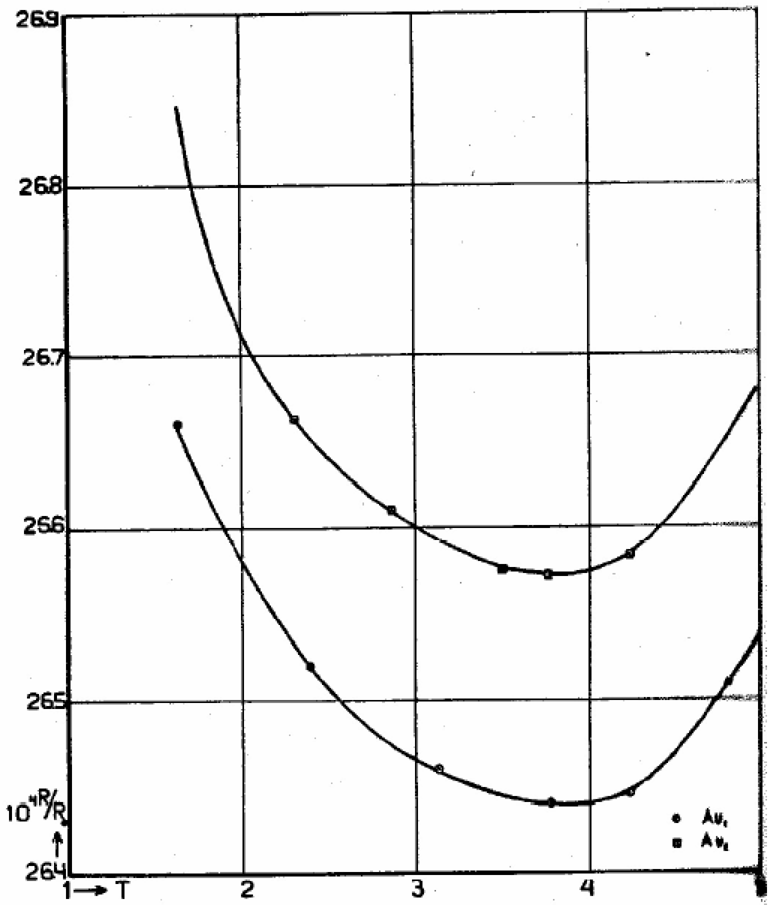


Fig. 1. Resistance of *Au* between 1°K. and 5°K.

De Haas, de Boer, & van den Berg, 1934

Suspect magnetic impurities

Fe in Cu:

J.P. Franck, Manchester, Martin (1961)

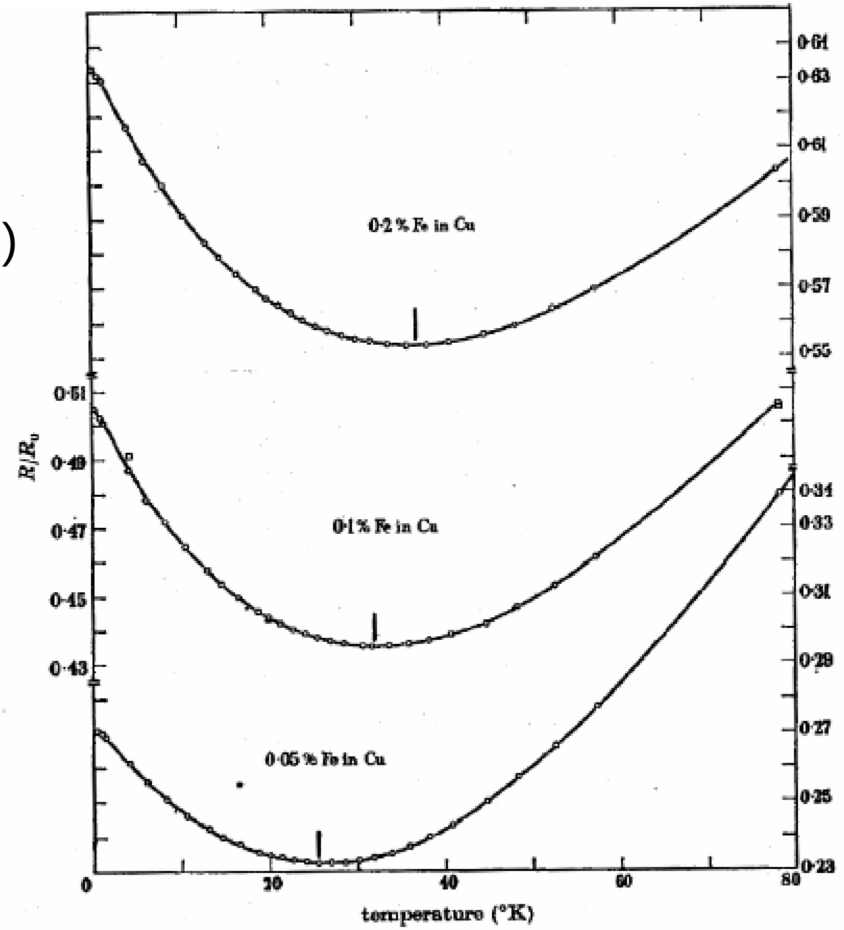
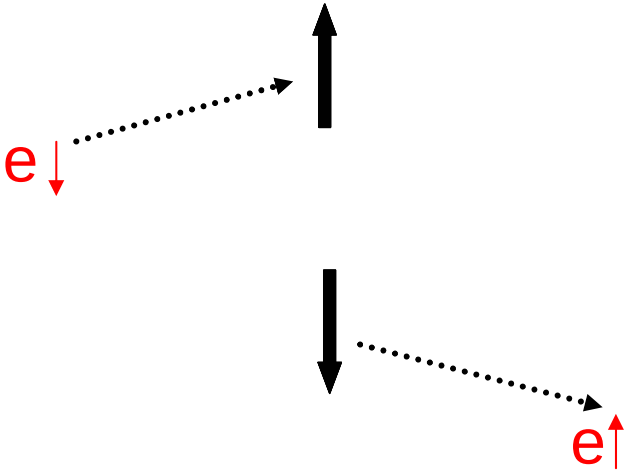


FIGURE 3. The electrical resistance of dilute copper + iron alloys. The bars indicate the point of minimum resistance. The points shown □ were taken after re-annealing the 0·1% alloy.

But how do they work?

Kondo (1964): $H = \sum_i J \vec{s}_i \cdot \vec{S}$

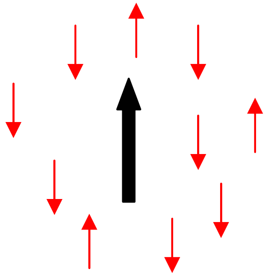
$J \vec{\sigma} . \vec{S}$



Spin-flip scattering

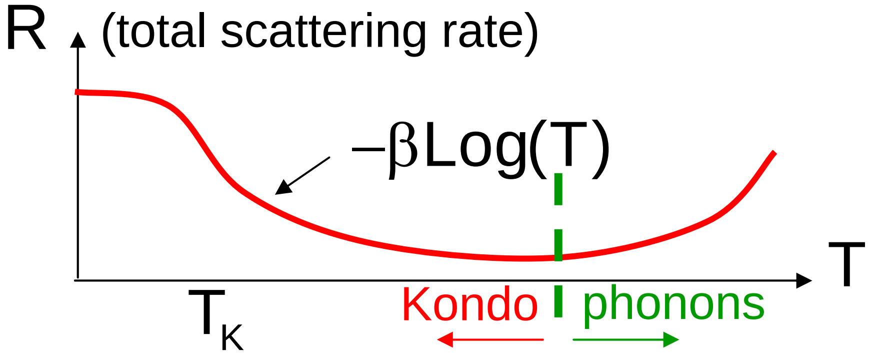
⇨ increased resistivity

Collective effect:

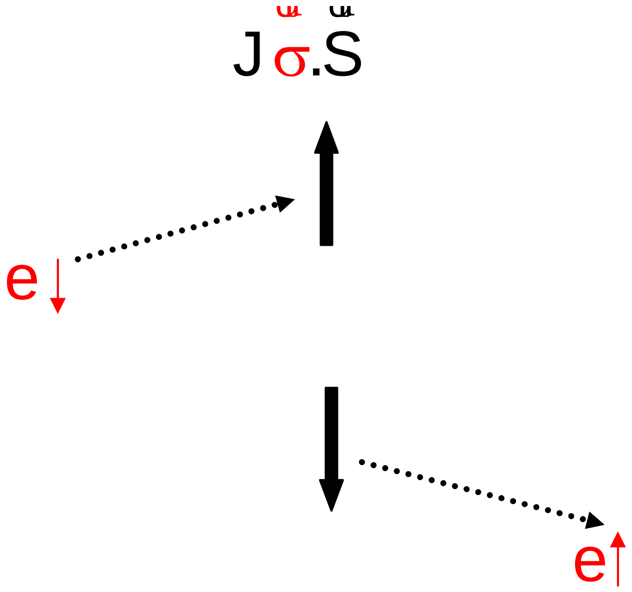


Formation of a
singlet spin state

$$k_B T_K \approx E_F e^{-1/\nu J}$$



The Kondo effect and $\tau_\phi(T)$

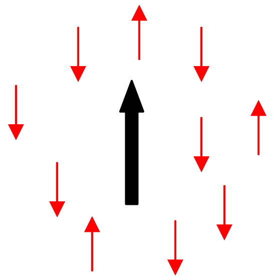


Spin-flip scattering

⇨ increased resistivity

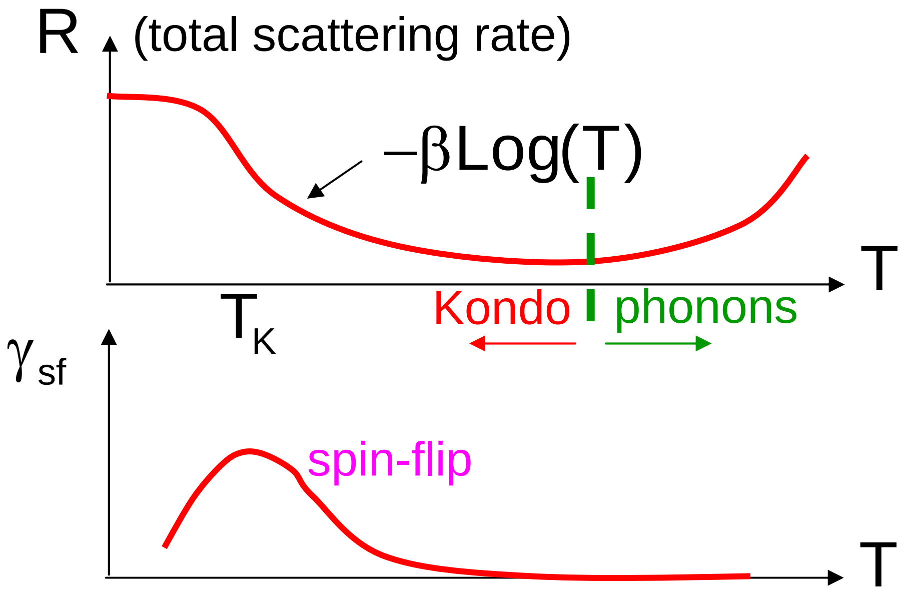
⇨ reduction of τ_ϕ

Collective effect:

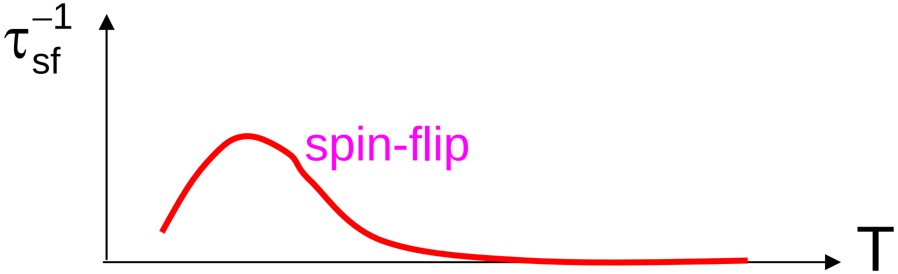


Formation of a singlet spin state

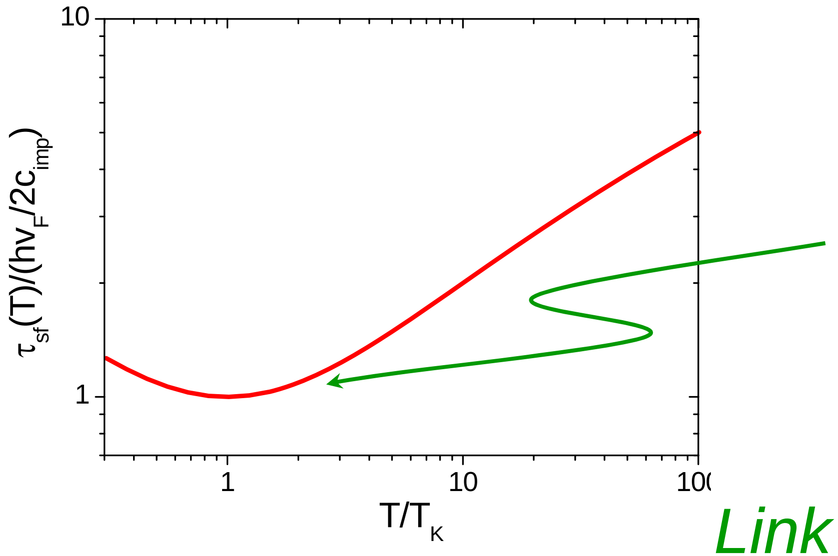
$$k_B T_K \approx E_F e^{-1/\nu J}$$



Nagaoka-Suhl expression of the spin-flip scattering rate near T_K



$$\frac{1}{\tau_{sf}} = \frac{c_{mag}}{\pi \hbar \nu_F} \frac{\pi^2 S(S+1)}{\pi^2 S(S+1) + \ln^2(T/T_K)}$$

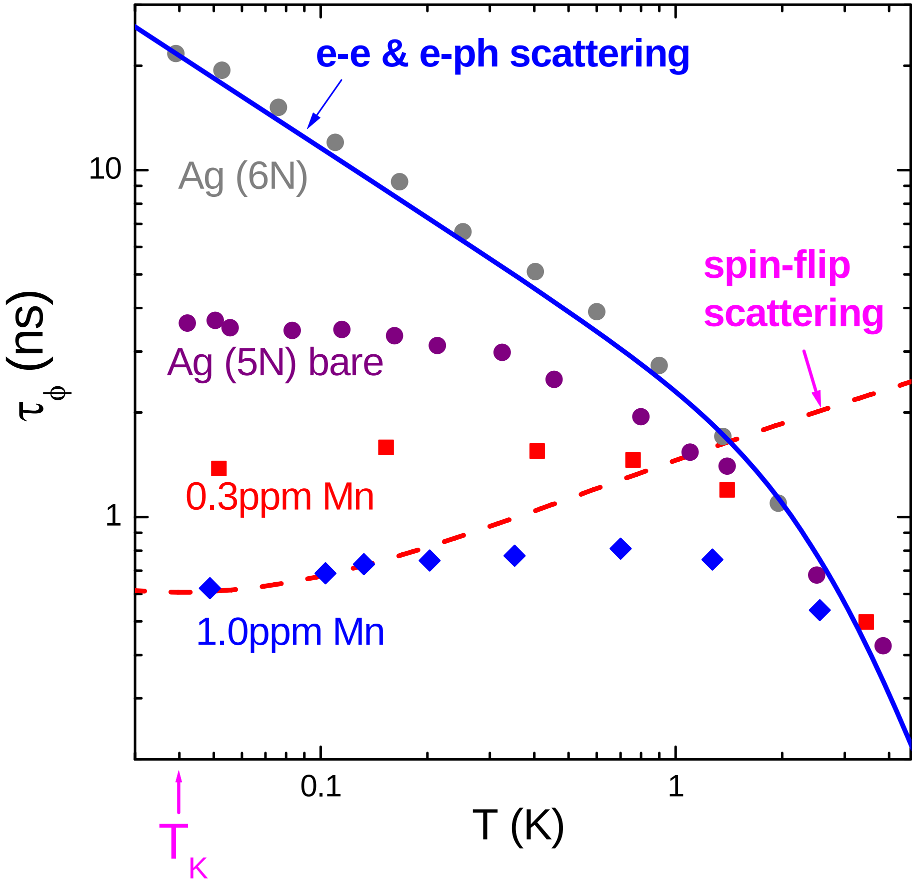


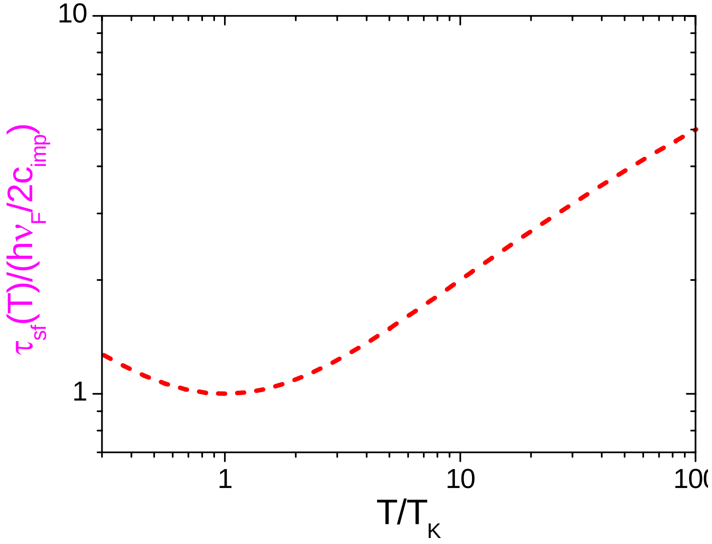
Weak temperature dependance near T_K !!

⬇

Link to $\tau_\phi(T)$ saturation?

Effect of magnetic impurities on τ_ϕ



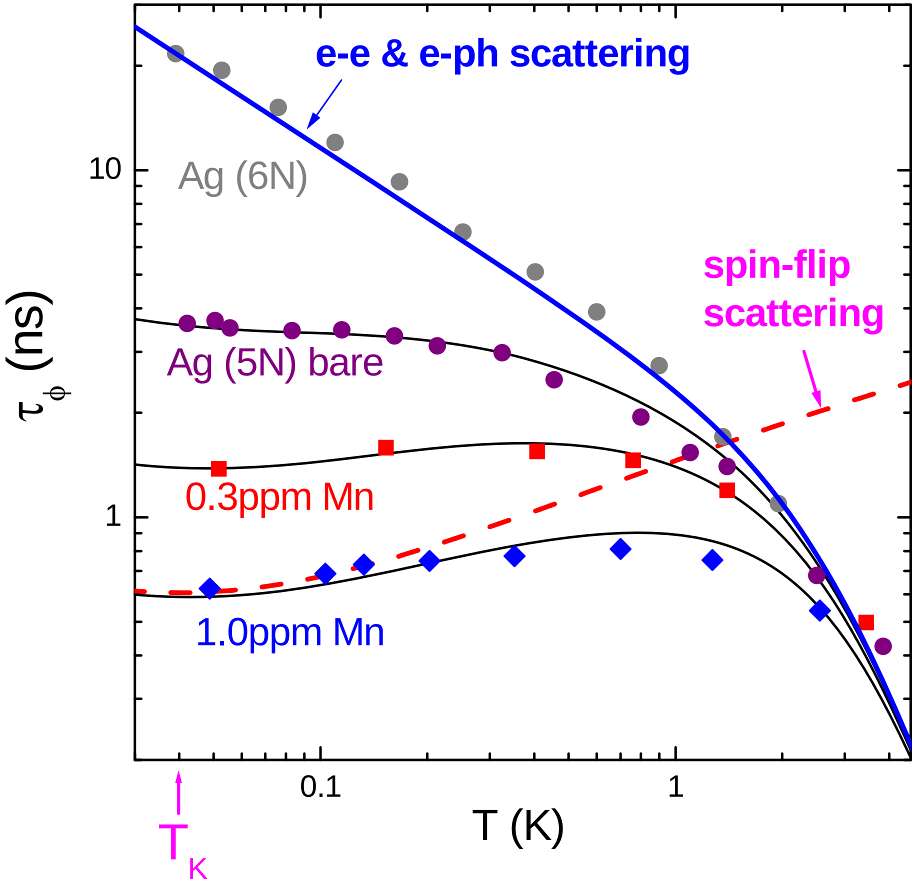


Spin-flip rate peaks at T_K:

$$\tau_\phi(T_K) = \frac{0.6\ \text{ns}}{c_{imp}\ (\text{ppm})}$$

$$\frac{1}{\tau_\phi} = \frac{1}{\tau_{ee}} + \frac{1}{\tau_{e-ph}} + \frac{1}{\tau_{sf}}$$

Effect of magnetic impurities on τ_ϕ



F. Pierre *et al.*,
PRB **68**, 0854213 (2003)

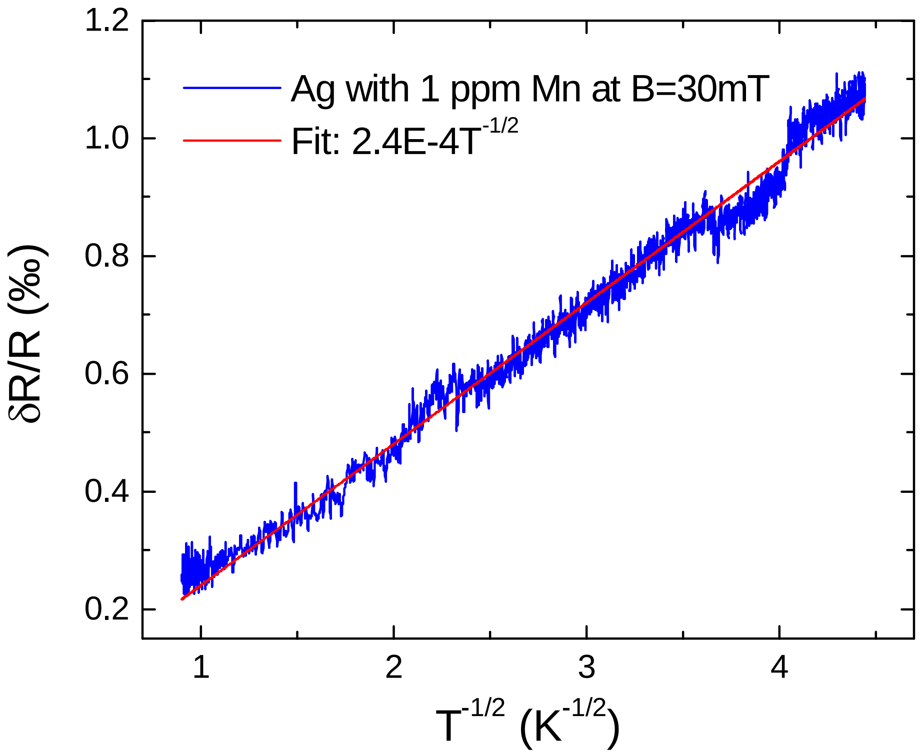
<u>Fit parameters:</u>

Ag(5N) bare: *0.13 ppm*
+ 0.3 ppm : *0.40 ppm*
+ 1 ppm : *0.96 ppm*

Above T_K : partial compensation of e-e and s-f

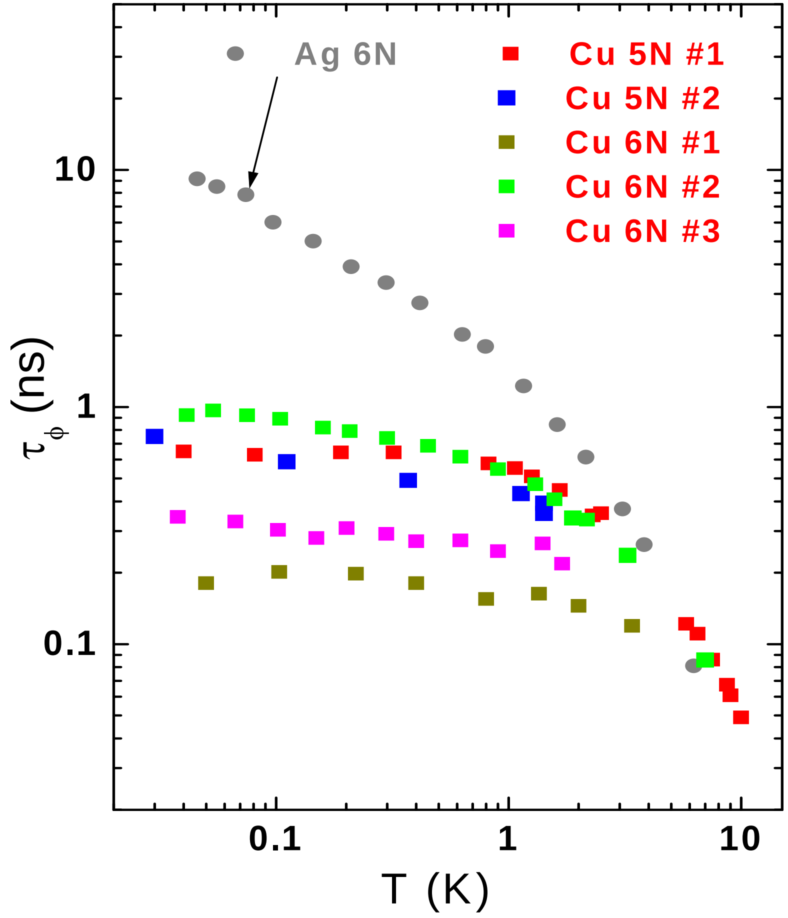
→ apparent saturation

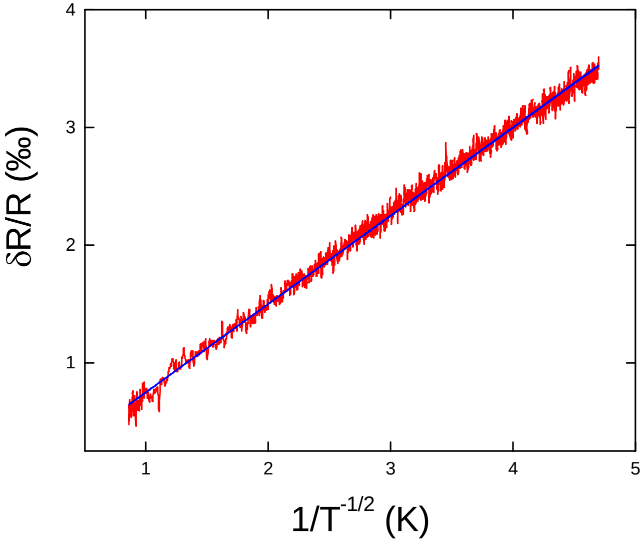
Why can't we just detect magnetic impurities with R(T) (the original Kondo effect)?



1 ppm of Mn is invisible in R(T)
(hidden by e-e interactions)

Source material purity vs. sample purity: Cu samples

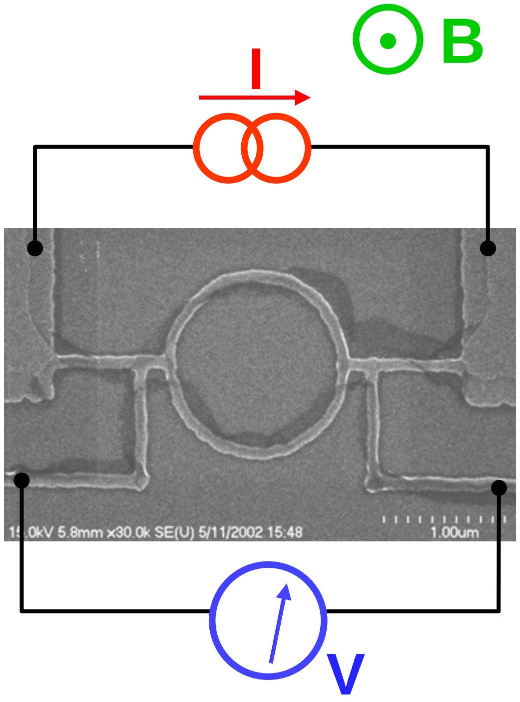




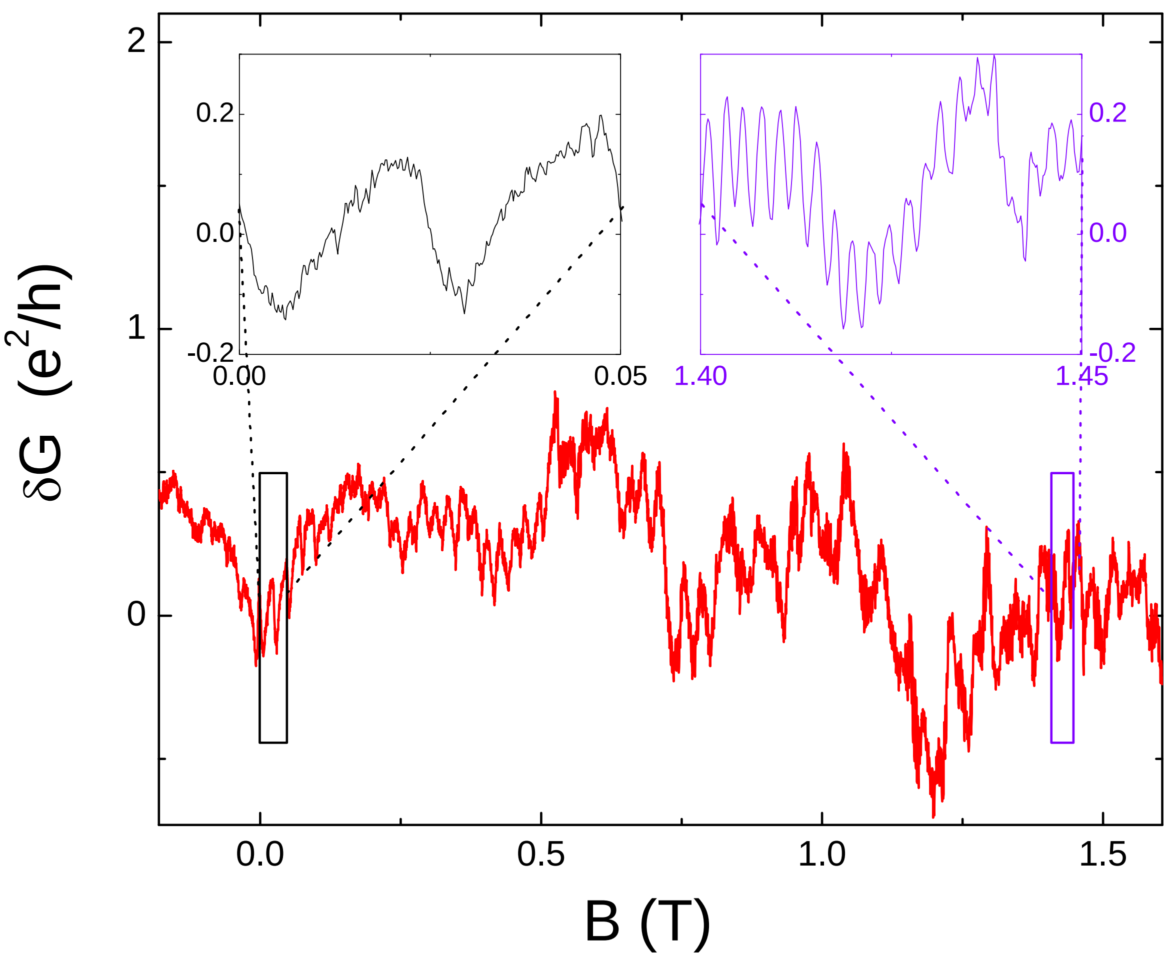
Magnetic impurities
are invisible in R(T)

- **In all Cu samples τ_ϕ(T) saturates at low T**
- **τ_ϕ(T) is strongly reduced but shows no dip**

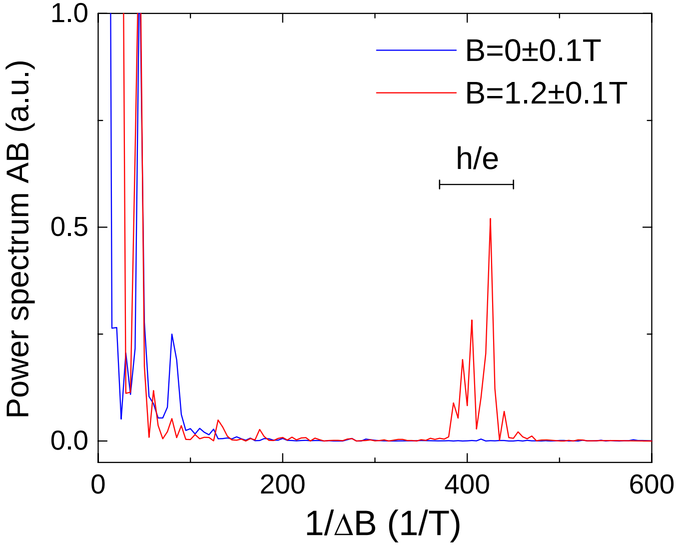
Measure $\tau_\phi(B)$ from Aharonov-Bohm oscillations

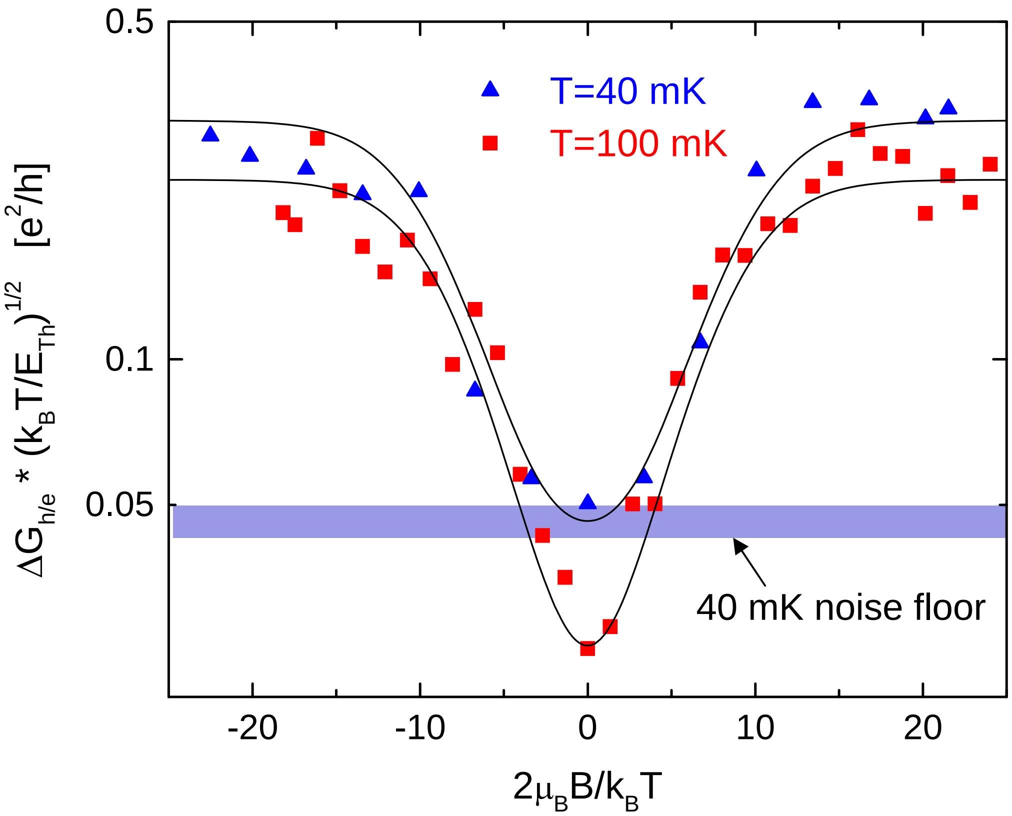


Cu ring


T=100 mK

Aharonov-Bohm oscillations vs. magnetic field

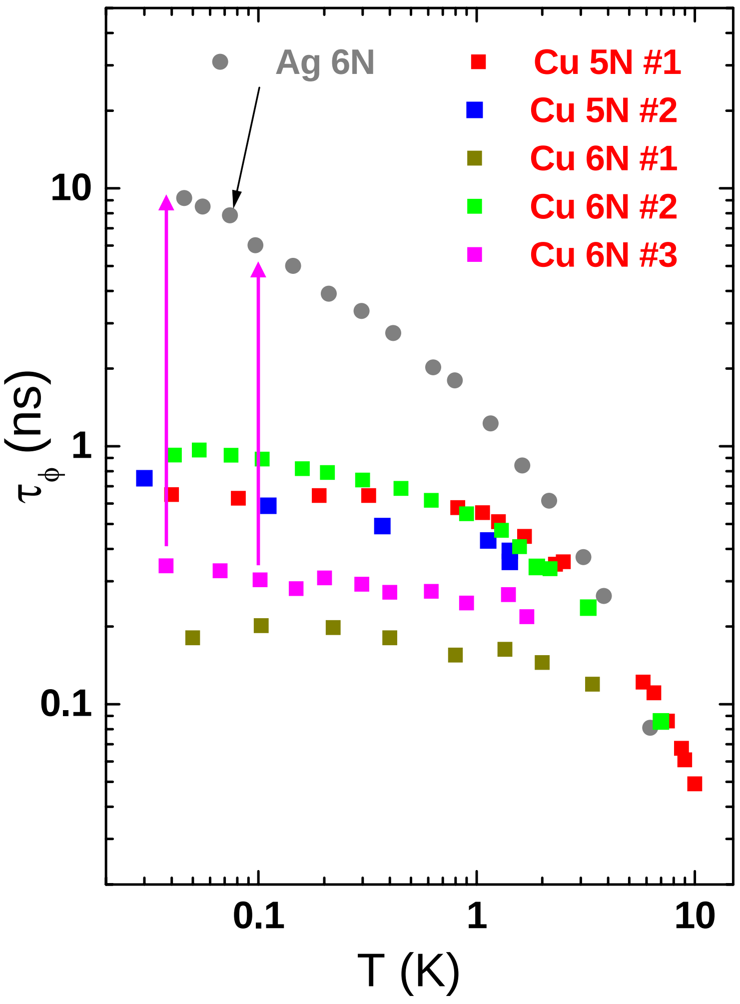

Fourier Transform
(T=100 mK)



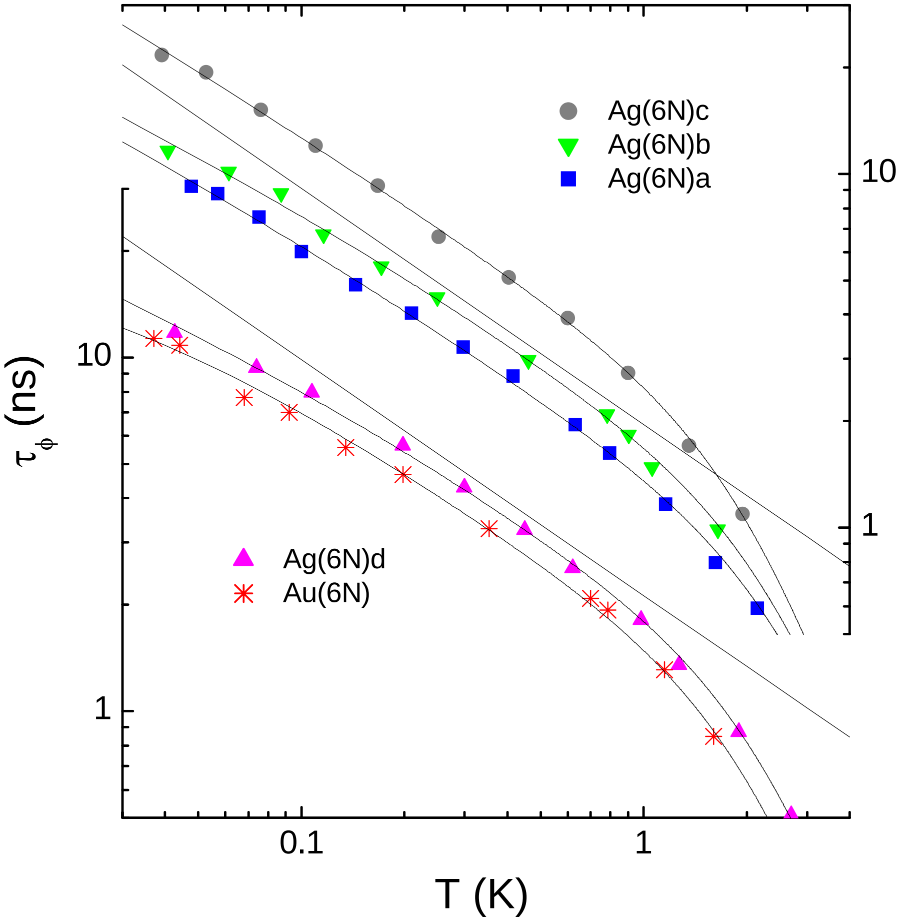
AB oscillations increase with B
⇒ presence of magnetic “impurities” !

In Cu, $\tau_\phi(B>B_c) >> \tau_\phi(B=0)$

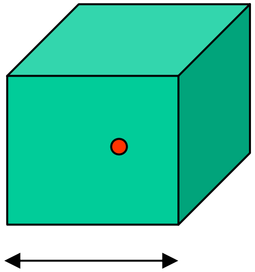
Apply B



Evidence for extremely dilute magnetic impurities even in purest samples



Sample	Imp.	T_K(K)	c (ppm)
Ag(6N)a	Mn	0.04	0.009
" b	"	"	0.011
" c	"	"	0.0024
" d	"	"	0.012
Au(6N)	Cr	0.01	0.02

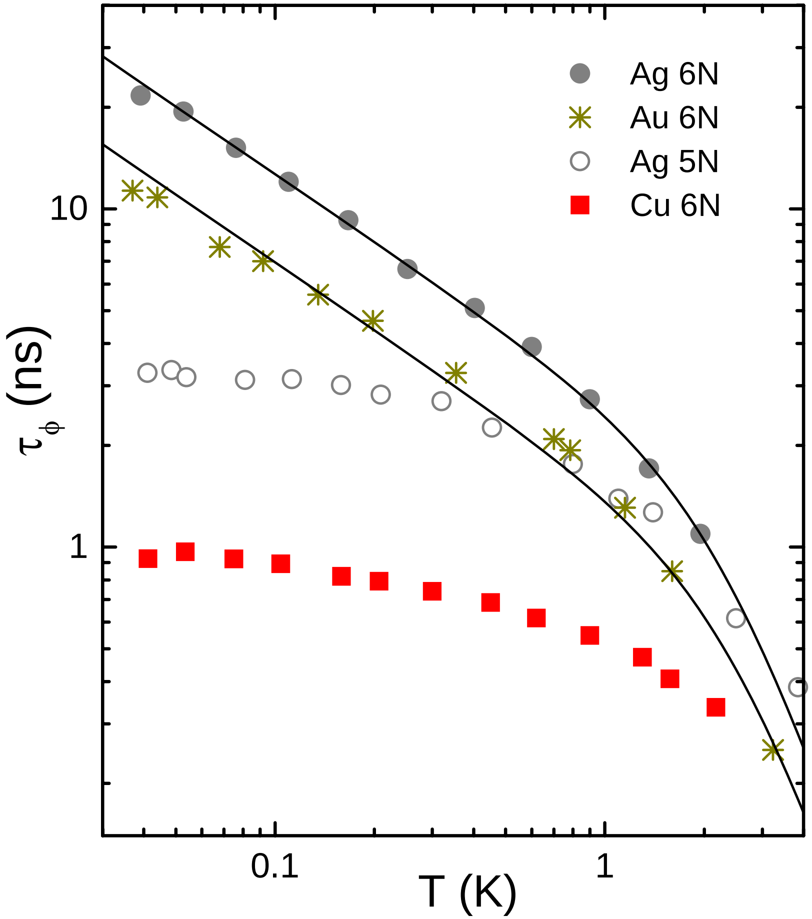


1 ppm :

100 atoms ~ 25 nm

In the wire, 0.01 ppm = 3 impurities/µm

Conclusions



Moral of the story: even at concentrations as low as 1 ppm and below, magnetic impurities dominate electron decoherence in metals at low temperature.

Compare τ_ϕ data with AAK and GZS theories