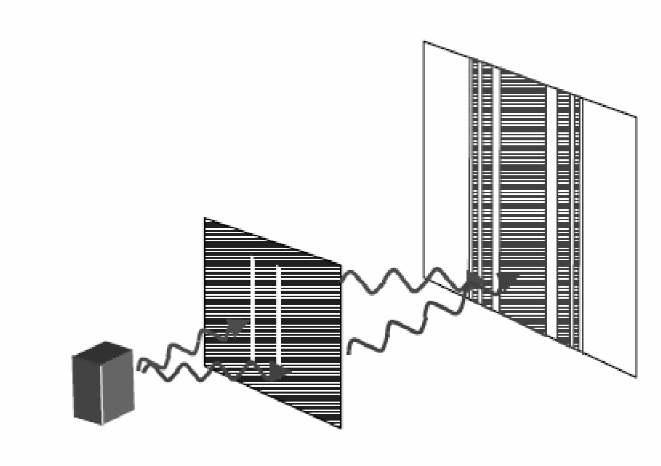
Quantum Coherence

10/06/2005

Heinzel, Ch 5, 8

Quantum coherence, tightly related to quantum interference

Prototypical quantum coherent system: two-slit interference experiment.



Amplitude for path A = ϕ_A

Amplitude for path B = ϕ_B

Probability = $| \phi_A + \phi_B |^2$

$= \underbrace{| \phi_A |^2 + | \phi_B |^2}_{\text{Classical result}} + 2 \, \mathrm{Re} \, \phi_A^* \phi_B$

- Electron beam traveling in isolation, in vacuum.
- Elastic scattering (diffraction) of electrons off slits.
- Coherence seen over large length scale….

A system is said to be quantum coherent if, to calculate probabilities of processes, one must include interference terms.

Coherence time / length

No interference pattern is observed if the phase between waves through the two slits is random in time; decoherence sometimes known as *dephasing*.

Consider dropping an electron into a solid, where at some rate it undergoes inelastic interactions with the environment (other electrons, phonons, magnetic impurities). Equivalently, since *inelastic scattering disturbs the environment (information is given to the environment)*, quantum coherence will be lost. (eg, if you add an photon counter at one of the slits, no interference pattern will be observed.)

Note: *elastic scattering* off disorder or edges does ***not*** cause decoherence – added a *fixed* phase to the system.

On some time scale τ_ϕ, the phase of the electron becomes essentially uncorrelated with its initial phase. Result: washing out of interference effects.

Distance the electron moves in this time in a diffusive system:
$l_\phi = (D\,\tau_\phi)^{1/2}$ = coherence length.

Length scales

As inelastic processes freeze out, τ_f is expected to **diverge**, with power law exponent set by dimensionality and inelastic mechanism:

electron phonon :$\tau_\phi \sim T^{-3}$

electron-electron:$\tau_\phi \sim T^{2/(d-4)}$

Phase coherence length $l_\phi = (D\,\tau_\phi)^{1/2}$ ↑ as T ↓

Mean free path $l_e = v_F \tau$ dominated by elastic scattering (impurities, roughness) and is stays constant

mesoscopic physics regime

Sample channel length L

$L < l_e$, ballistic, $L > l_e$, diffusive

$L < l_\phi$, phase coherent, $L > l_\phi$, incoherent

$l_\phi > l_e$ at low temperatures, and lots of interesting phenomena observed when $l_e < L < l_\phi$

Quantum coherence: Aharonov-Bohm effect

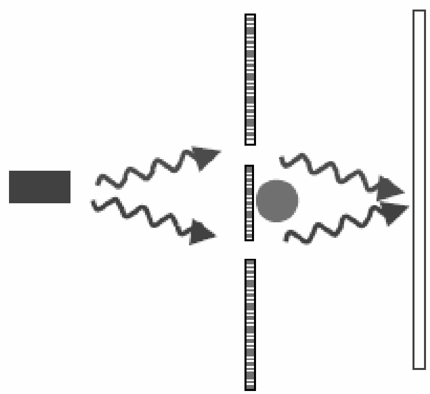
In magnetic field, $\hbar\mathbf{k} \rightarrow \hbar\mathbf{k} + q\mathbf{A}$ phase= k*r

the vector potential $\nabla \times \mathbf{A} = \mathbf{B},$

$$\oint \mathbf{A} \cdot d\mathbf{r} = \Phi$$

Presence of A leads to particles moving along a trajectory picking up an additional quantum mechanical phase:

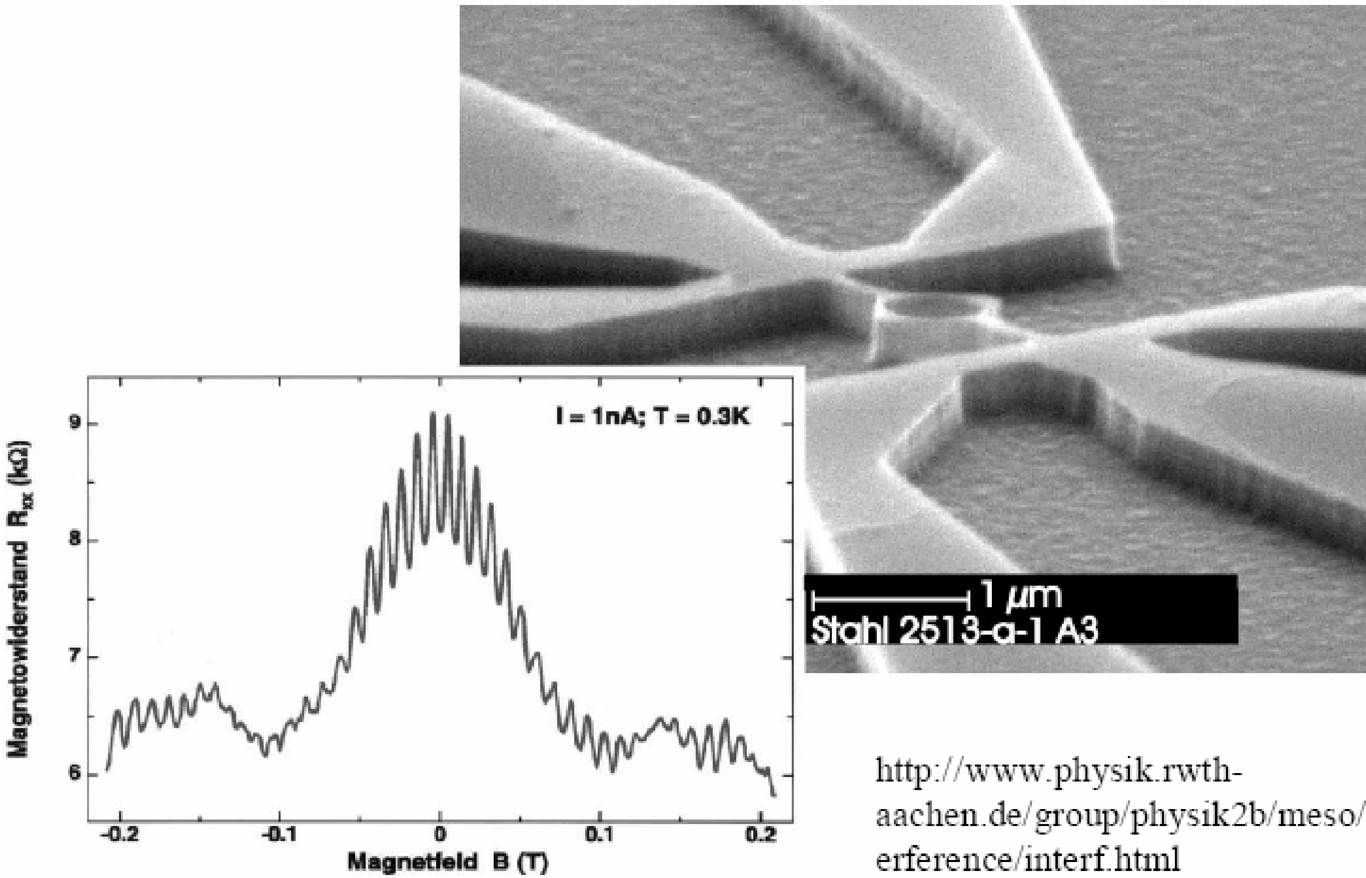
$$\psi \rightarrow \psi \exp\left(i \frac{\oint e\mathbf{A} \cdot d\mathbf{r}}{\hbar} \right)$$



- Interference fringes shift as current through solenoid is varied.
- Complete shift of 2π when flux enclosed = 1 flux quantum, h/e.

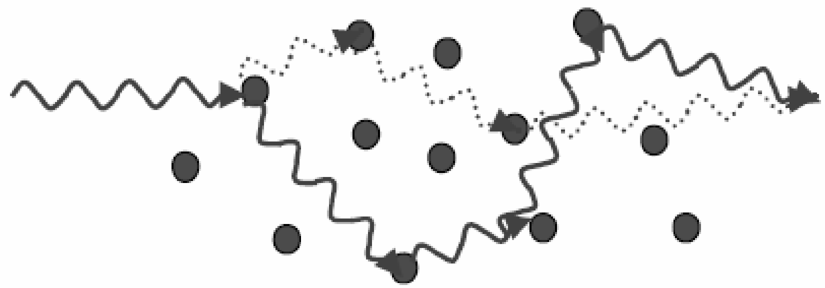
Quantum coherence: Aharonov-Bohm effect

- can see Aharonov-Bohm effect in solids if ring circumference is <~ coherence length!



http://www.physik.rwth-aachen.de/group/physik2b/meso/interference/interf.html

Quantum coherence: conductance fluctuations

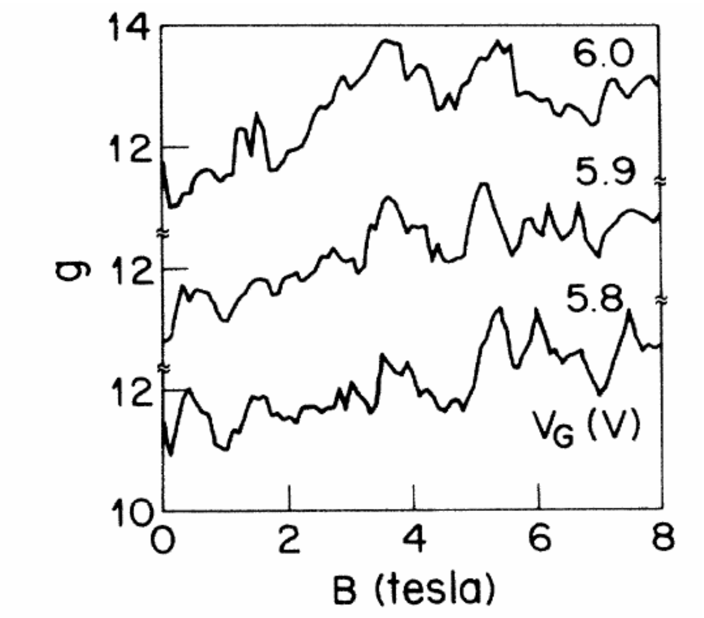


- In fully coherent region, conductance involves adding amplitudes from all possible trajectories, where phases are distributed *randomly*.
- Analogous to diffraction off array of randomly placed slits.
- Interference pattern on a screen would be random bright and dark regions - “speckles”.
- Shifting the relative phases of the waves would move the speckles randomly yet deterministically.

Quantum coherence: *universal conductance fluctuations*

One way of shifting relative trajectory phases: magnetic field.

Result: applying a magnetic field leads to fluctuations in sample conductance $\delta G(B)$ that depend on exact configuration of scatterers in that sample.



Skocpol et al., PRL **56**, 2865 (1986).

- In coherent volume, rms $\delta G \sim e^2/h$
Independent of the sample!

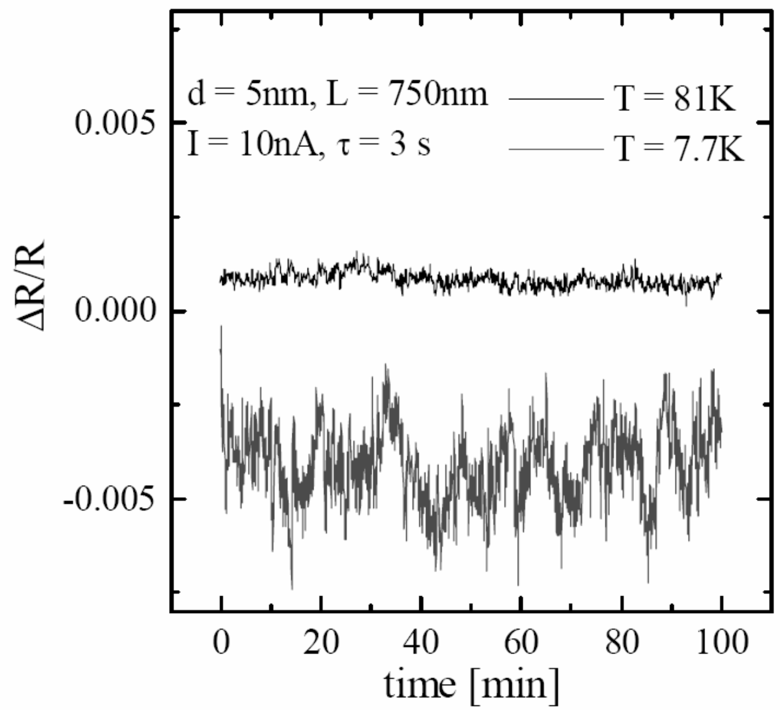
- Field scale $B_c \sim 1$ flux quantum through a typical coherent area, L_ϕ^2.

$l_e < L < l_\phi$

Quantum coherence: *conductance fluctuations*

Changes in defects' positions as a function of time that alter the phases of interfering trajectories

Resistance fluctuates as a function of time.
Result = (quantum) noise!



Conductance fluctuations and ensemble averaging

Why don't we see quantum CF all the time?

- Fluctuations are *not correlated* from coherent volume to coherent volume - they average away to zero when $L >> L_{\phi}$.

- For N coherent volumes in series, the size of fluctuations, δG is down by factor of $1/N^{1/2}$.

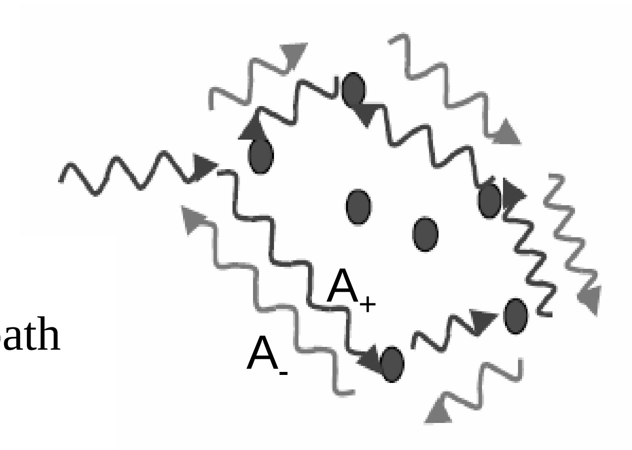
- A correlation energy scale also exists for coherence phenomena: $E_{\varphi} = \frac{\hbar D}{L_{\phi}^2}$

- Thermal smearing ($k_B T > E_{\phi}$) suppresses fluctuations by similar factor.

- Large voltage drops can also suppress fluctuations ($eV > E_{\phi}$)

- Noise in real devices at room temp. may still have a contribution from these effects.

Quantum coherence: weak localization



Time-reversed path
$A_+=A_-$

$l_e<L<l_\phi$

Coherent backscattering.

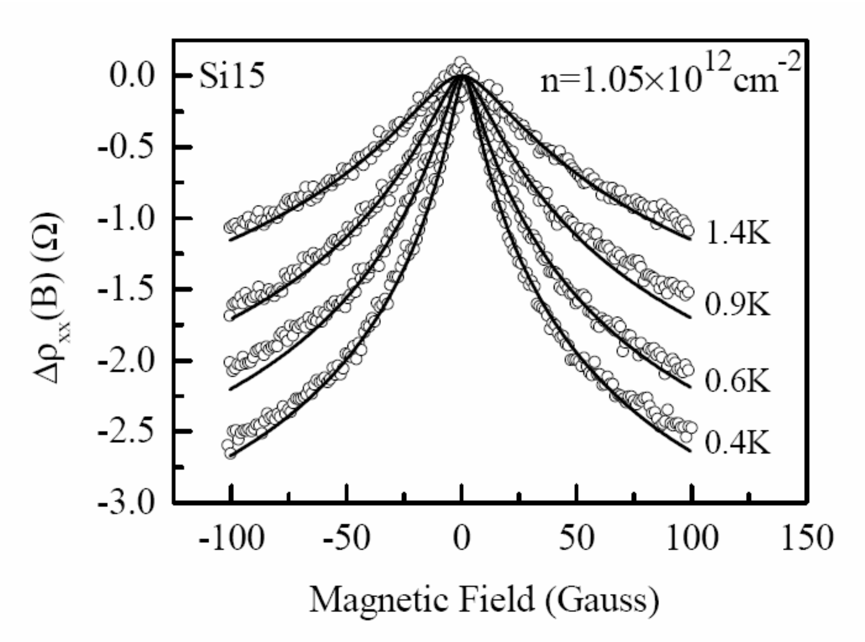
Probably for the particle being scattered back to its origion
$|A_++A_-|^2=4A_+^2$, instead of $|A_+|^2+|A_-|^2=2A_+^2$

$l_\phi\uparrow$ as $T\downarrow$ All diffusive 1D and 2D samples become insulating as T->0!

still under debate

Quantum coherence: weak localization

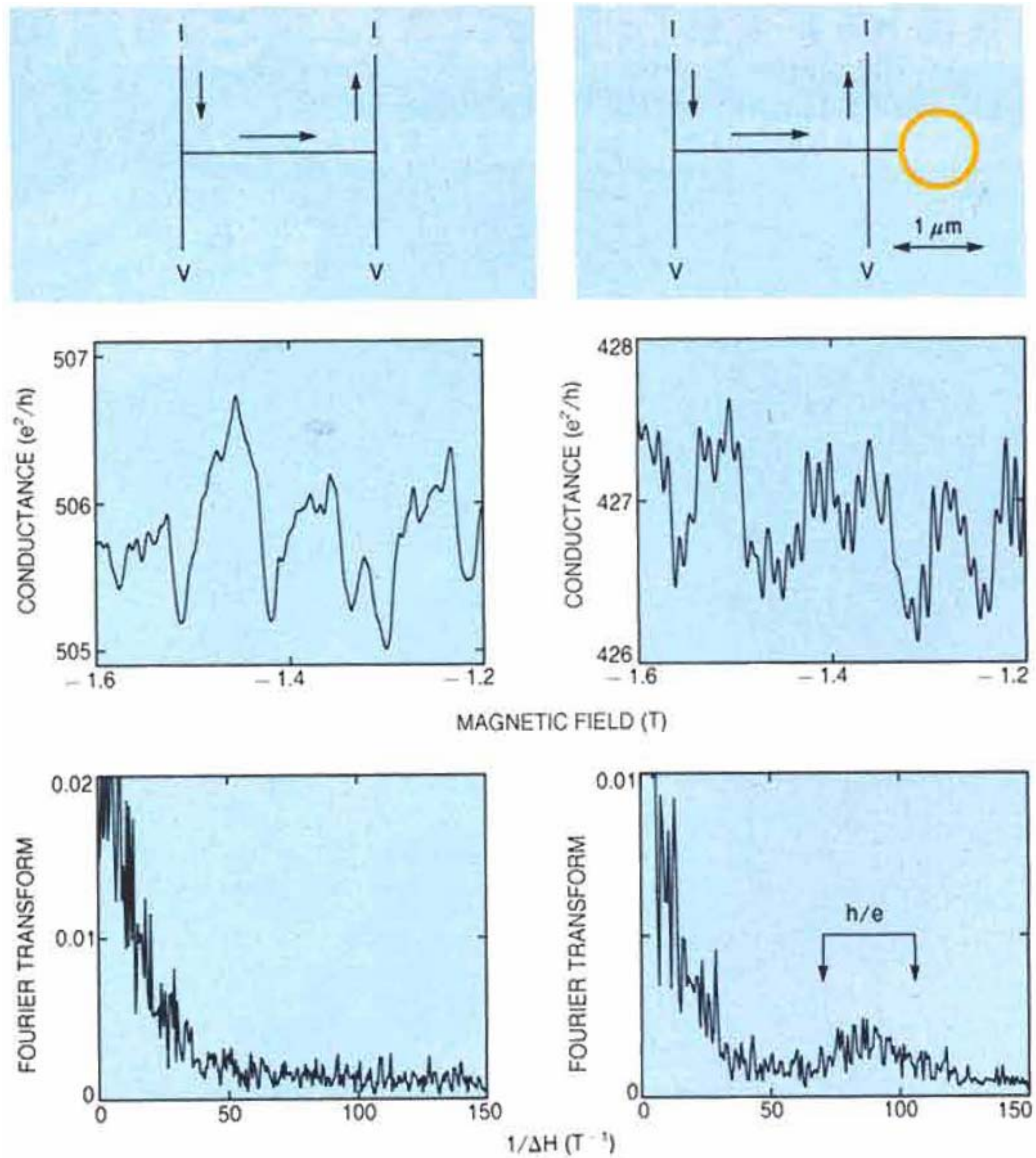
• One flux quantum through typical trajectory suppresses this effect due to Aharonov-Bohm phase.
• Result: a magnetoresistance with a size and field scale set by τ_ϕ and conductor properties (dimensionality, *D*, etc.). Used to calculate τ_ϕ



Weak-localization on Si MOFET sample

Brunthaler et al., cond-mat/9911011

Non-local resistance



Length scale defined by l_ϕ, rather than the voltage probes!

Physics Today, Dec, 1988

How relevant is quantum coherence to technology?

Right now, not very, except in specialized cases like the noisedescribed earlier.

In the future, however:

• Quantum interference effects essential to understanding conductance of very small systems, like single molecules.

• Coherence times for *spins* are much longer than for orbital wavefunctions: possibility of using spin-based properties for novel devices.

• Coherence lengths at room temperature are often very short (few atoms), but not inaccessible any more….