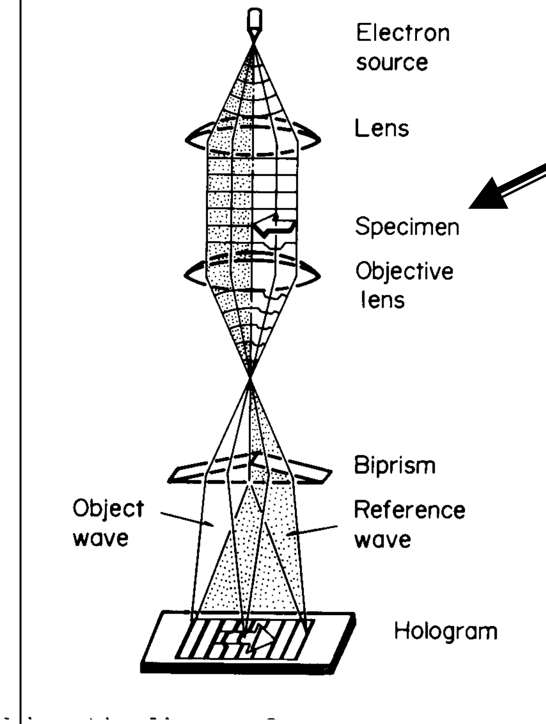
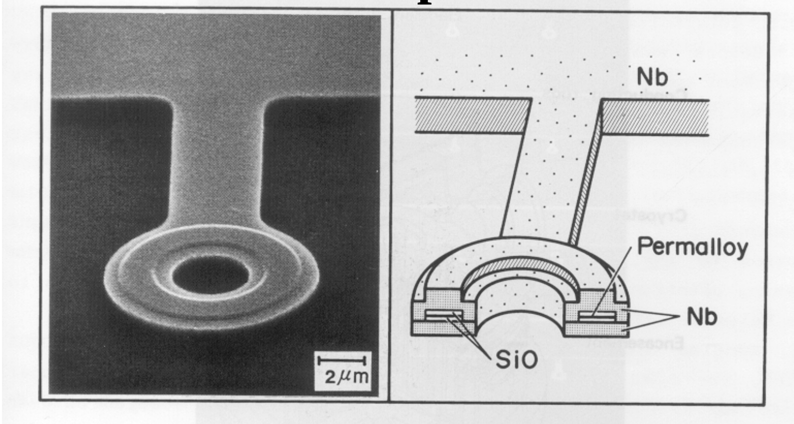
Aharonov-Bohm effect

The vector potential can affect the quantum behavior of a charged particle that does not encounter an electromagnetic field (in classical dynamics, potentials have no influence on the fields)

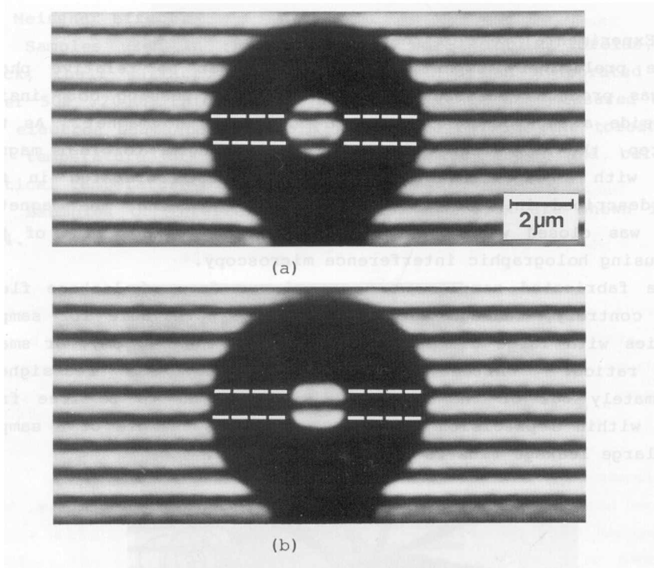
holography with electrons



sample



result measurements



<u>Theory</u>: Aharonov and Bohm (1959)
(see also Griffiths, Introduction to Quantum Mechanics 10.2.4)
<u>Measurement</u>: Tonomura et al. PRL 56 (1986) 792

The Aaronov–Bohm effect in disordered conductors

B. L. Al'tshuler, A. G. Aronov, and B. Z. Spivak
B. P. Konstantinov Institute of Nuclear Physics, USSR Academy of Sciences

(Submitted 18 November 1980)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 2, 101–103 (20 January 1981)

It is shown that the Aaronov-Bohm effect, which is manifested in the oscillations of the kinetic coefficients as a function of the magnetic flux that penetrates the sample, must exist in disordered normal conductors. The period of these oscillations is $\Phi_0 = bc/2e$, i.e., it is half as large as in the ordinary Aaronov-Bohm effect.

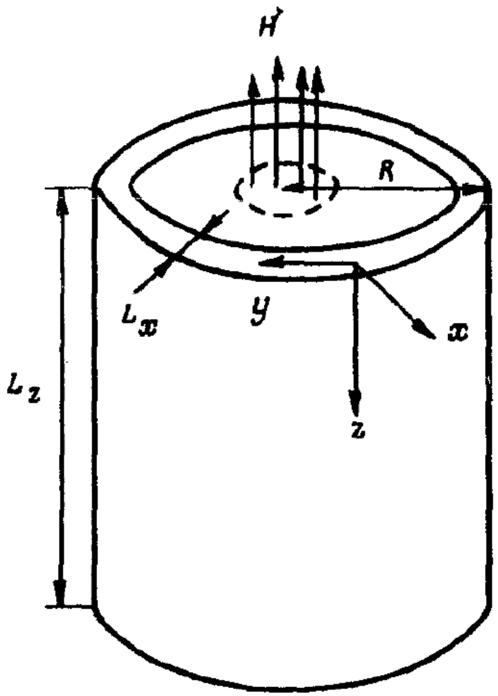
Observation of the Aaronov-Bohm effect in hollow metal cylinders

B. L. Al'tshuler, A. G. Aronov, B. Z. Spivak, D. Yu. Sharvin, and Yu. V. Sharvin
B. P. Konstantinov Institute of Nuclear Physics, Academy of Sciences of the USSR and Institute of Solid State Physics, Academy of Sciences of the USSR and Institute of Physical Problems, Academy of Sciences of the USSR

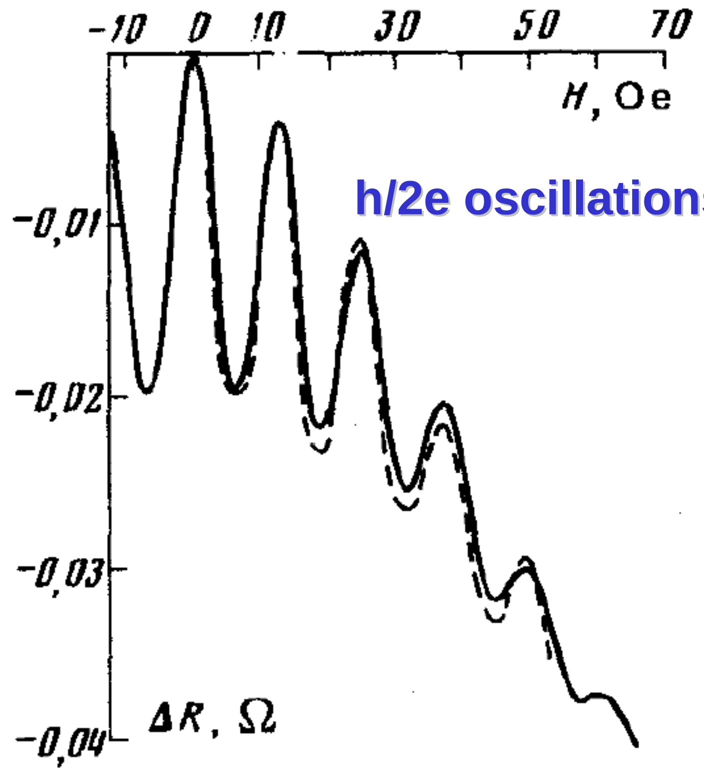
(Submitted 22 April 1982)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 11, 476–478 (5 June 1982)

The oscillatory dependence of the resistance on the magnitude of the magnetic flux in the cross section of a specimen with period $hc/2e$ and negative longitudinal magnetoresistance are observed in cylindrical lithium films at helium temperatures. The phase of the oscillations and the sign of the magnetoresistance are opposite to those observed for magnesium,[4] which is attributed to the smallness of the spin-orbital interaction in lithium. The results agree well with the theoretical predictions.

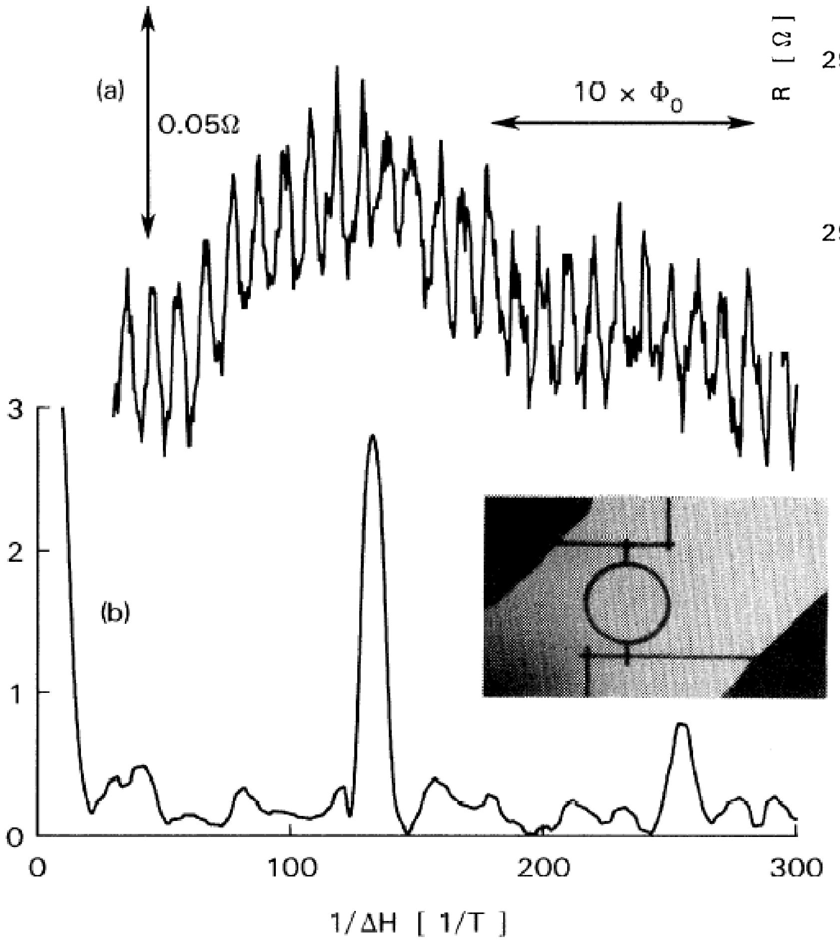


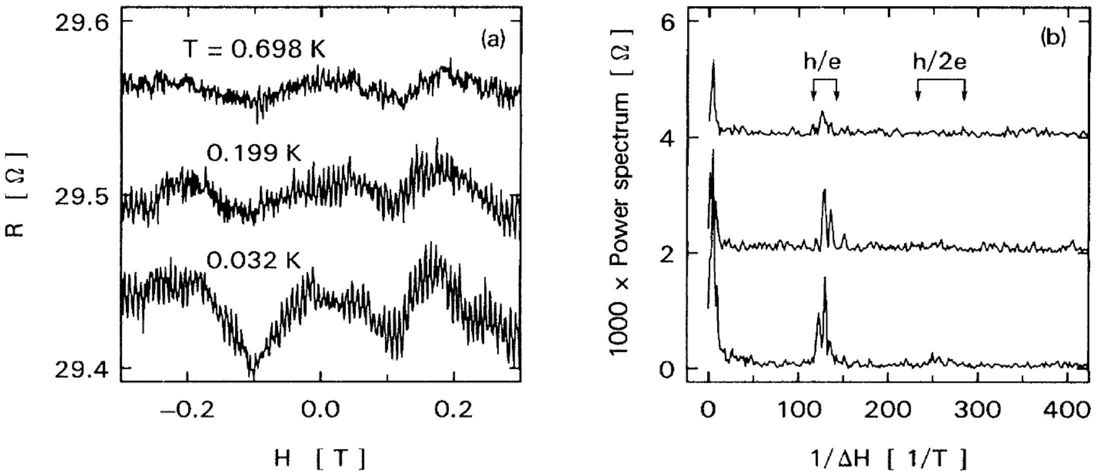
Lithium film evaporated on a quartz filament
ℓ_ϕ = 2.3 μm
L_z = 1 cm
N = 10.000/2.3 = 4348
Diameter: 1.1 μm
Film thickness: 0.12 μm



h/2e oscillations

Aharonov-Bohm (AB) effect in a normal metal ring: h/e oscillations



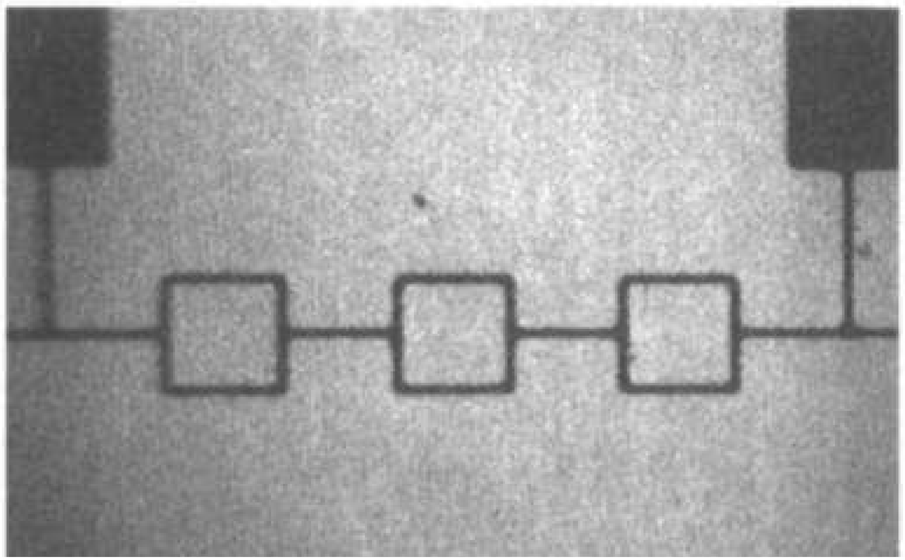


polycrystalline gold film
mean-free path: 10 nm
ρ = 5 μΩcm (4K)
d_{in} = 784 nm; w = 41 nm

An important conclusion drawn from this experiment is that the electron phase is not randomized by elastic scattering events (electrons traversing the ring undergo thousands of such events); inelastic scattering destroys phase coherence.

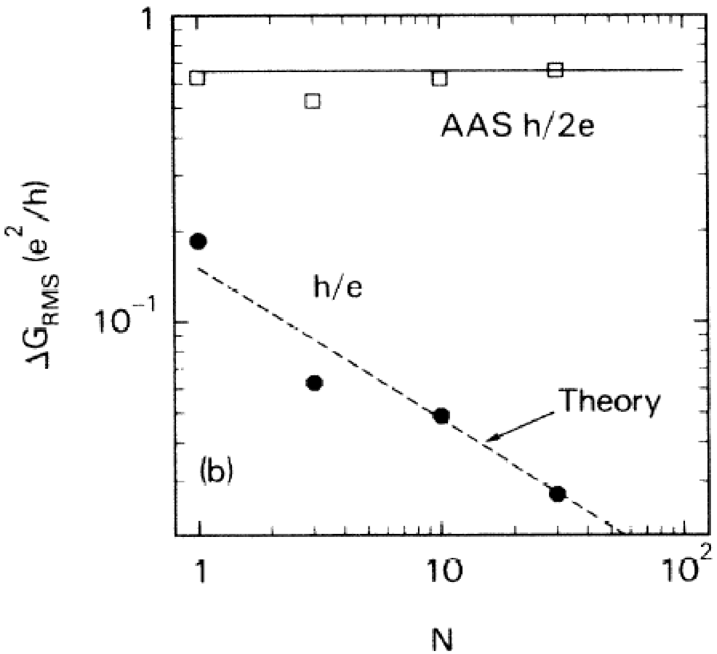
R.A. Webb *et al*.
Phys. Rev. Lett. 54 (1985) 2696

averaging over rings: AAS oscillations



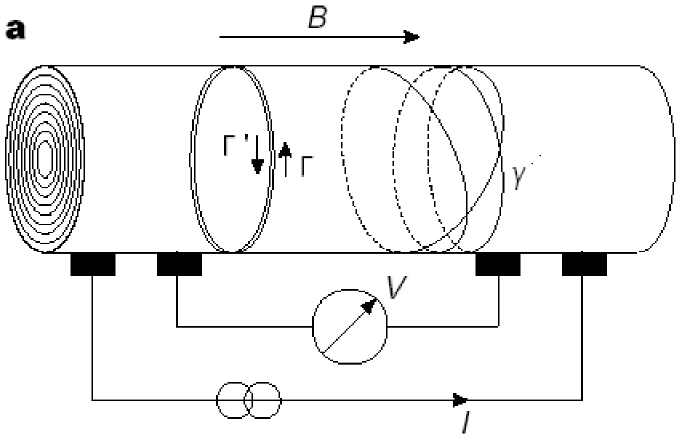
- **Altshuler-Aronov-Spivak (AAS) oscillations**
- **period: h/2e**
- **AAS oscillations remain visible after averaging: why?**
- **Why do the AB oscillations die out?**

tion, the rms oscillation size is $\Delta G = \Delta R / N R_L^2$, where ΔR is the rms value of the resistance change of the sample, and R_L is the resistance of one loop *without leads*. Two observations are immediately made. First, the AAS oscillations are *not* affected by the averaging of uncorrelated regions. This was expected[9, 11] since these oscillations exist in very large samples.[1–3] Second, the h/e oscillations die out as the square root of the number of loops. With extrapolation to very large arrays, such as those studied previously,[2, 3] they would be buried in the noise.

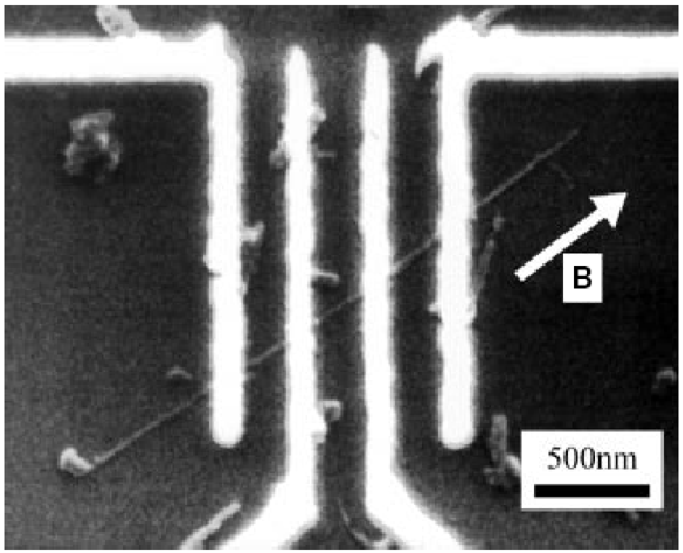


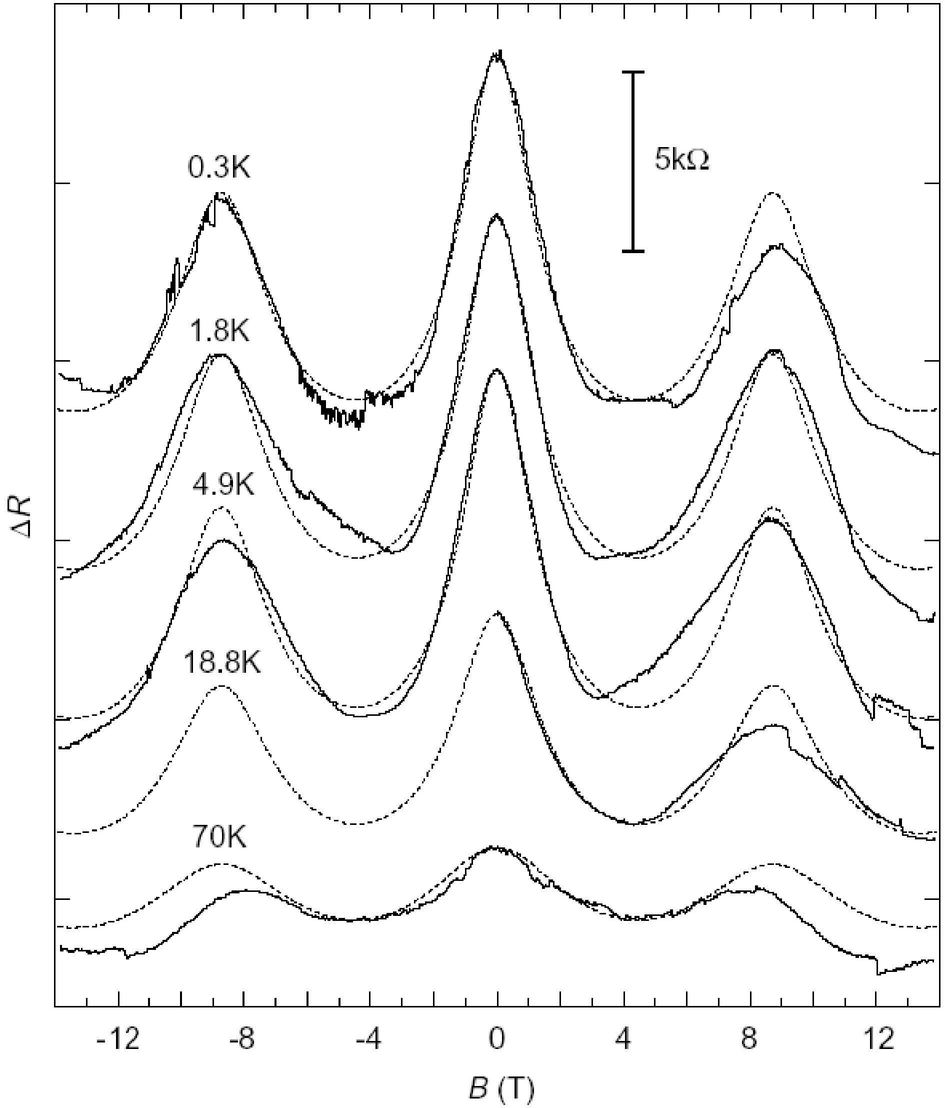
C.P. Umbach et al. *et al*.
Phys. Rev. Lett. 56 (1986) 386

AAS oscillations in a multi-wall carbon nanotube



ℓ_ϕ = 50 nm; L_z = 170 nm
diameter: 6 nm



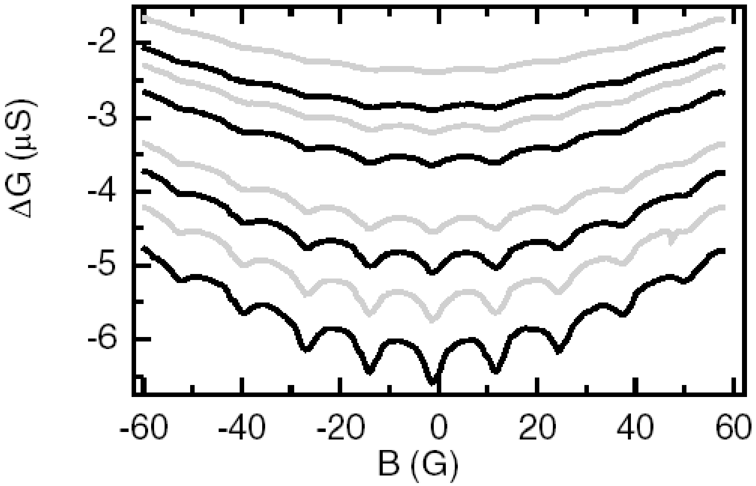


A. Bachtold *et al*.
Nature 397 (1999) 673

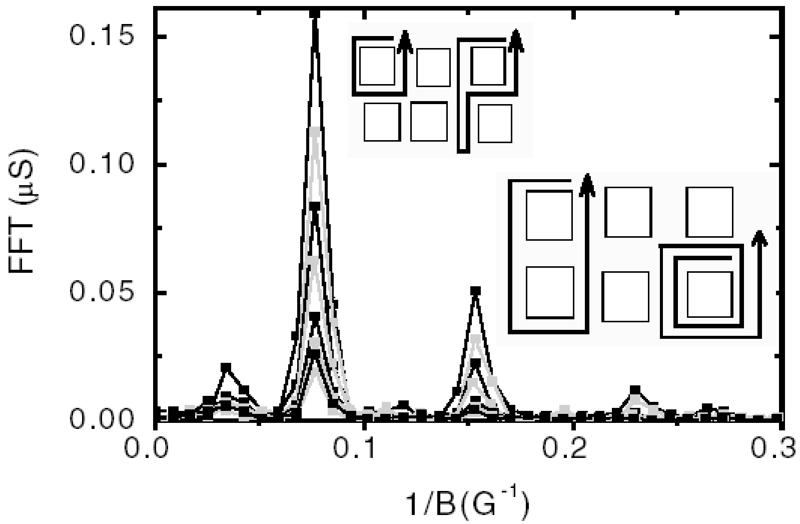
PRL **93,** 246804 (2004) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2004

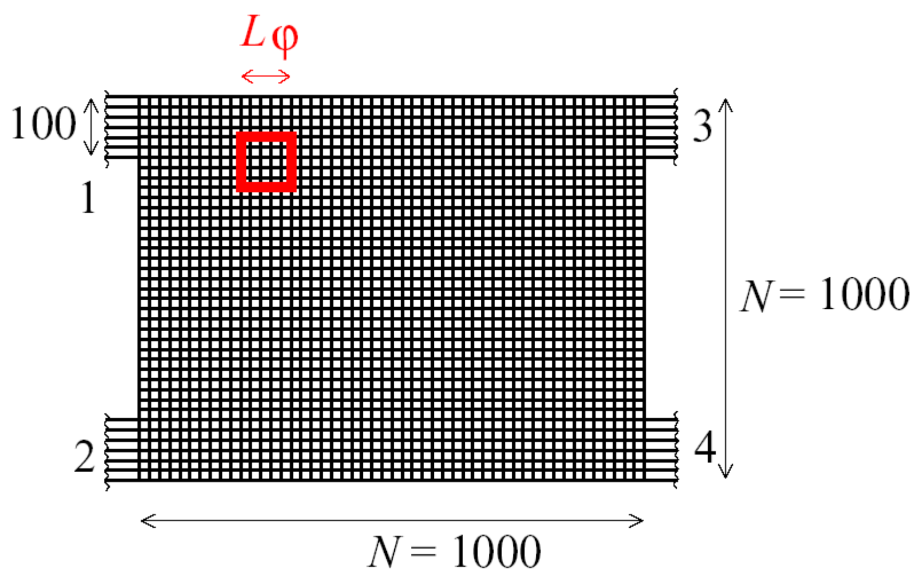
Direct Measurement of the Phase-Coherence Length in a GaAs/GaAlAs Square Network

M. Ferrier,[1] L. Angers,[1] A. C. H. Rowe,[1] S. Guéron,[1] H. Bouchiat,[1] C. Texier,[2,1] G. Montambaux,[1] and D. Mailly[3]



The low temperature magnetoconductance of a large array of quantum coherent loops exhibits Altshuler-Aronov-Spivak oscillations with a periodicity corresponding to 1/2 flux quantum per loop. We show that the measurement of the harmonics content provides an accurate way to determine the electron phase-coherence length L_φ in units of the lattice length with no adjustable parameters. We use this method to determine L_φ in a square network realized from a 2D electron gas in a GaAs/GaAlAs heterojunction, with only a few conducting channels. The temperature dependence follows a power law $T^{-1/3}$ from 1.3 K to 25 mK with no saturation, as expected for 1D diffusive electronic motion and electron-electron scattering as the main decoherence mechanism.





10^6 cells etched in 2DEG

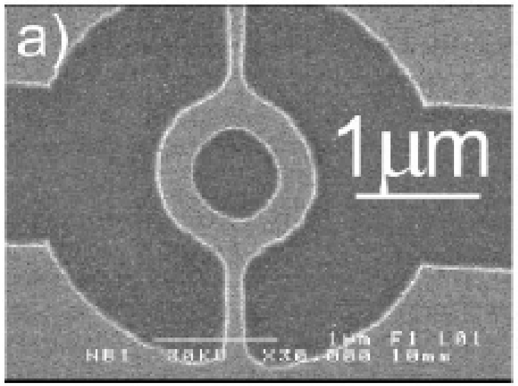
with $a = 1\ \mu m$

PHYSICAL REVIEW B, VOLUME 64, 045327 2001

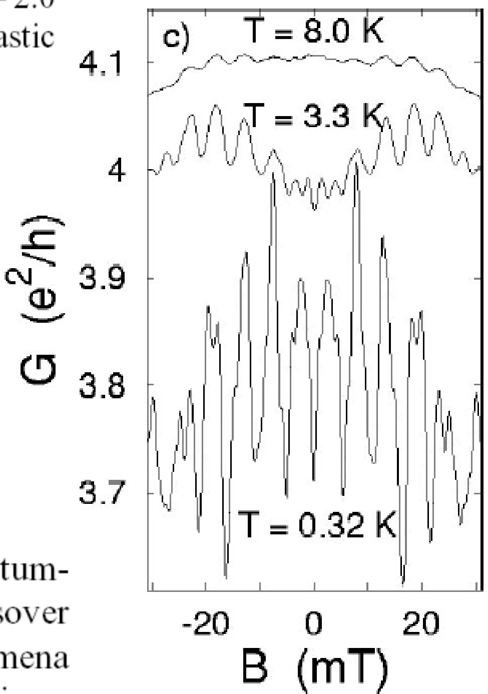
Mesoscopic decoherence in Aharonov-Bohm rings

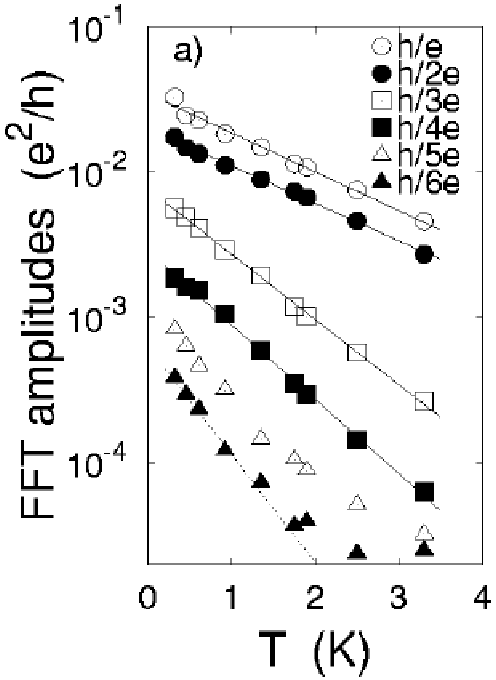
A. E. Hansen,* A. Kristensen,† S. Pedersen,‡ C. B. Sørensen, and P. E. Lindelof

$GaAs/Ga_xAl_{1-x}As$ heterostructure. At liquid He temperatures, the unpatterned 2DEG density and mobility is $n = 2.0 \times 10^{15}$ m^{-2} and $\mu = 80$ $m^2/V\,s$, corresponding to an elastic mean free path $l_e = 6$ μm.



The understanding of decoherence in quantum-mechanical systems gives valuable insight into the crossover from quantum to classical behavior. Quantum phenomena like weak localization, universal conductance fluctuations, and the Aharonov-Bohm effect, that are observed in mesoscopic electronic systems, make these systems well suited for studying decoherence. The loss of electron phase coherence is interesting in its own right, because it reveals information about the fundamental physics of the electron-scattering mechanisms. Moreover, from the perspective of possible phase-coherent mesoscopic electronic devices,[1] a knowledge of phase-breaking length and time scales is crucial.





We find the phase coherence length $L_\phi \propto T^{-1}$.

phase-coherent transport

- **Weak localization:** coherent back scattering of electron waves giving rise to an enhanced resistance around zero magnetic field. Observed in diffusive samples of (almost) any shape; observed at low temperatures and in samples with a relatively large resistance. Measurements allow for the determination of the phase-coherence length.

- **Weak anti-localization:** spin-flip processes kill coherent backscattering and lead to a decrease of the resistance around zero magnetic field.

- **Universal Conductance fluctuations (UCF):** the fluctuations are of the order of e^2/h, regardless of the sample size and the degree of disorder. UCF result from a change in electron interference paths due to a change in the enclosed magnetic flux (but also a change in the chemical potential (gate) or the impurity configuration). Averages out when many ensembles are considered leaving only the weak localization signal.

- **AAS oscillations:** coherent-backscattering in ring structures of sizes smaller than the phase-coherent length; effect persists for an ensemble of rings. Periodicity: h/2e.

- **AB oscillations:** quantum interference of two electron waves coming from the two arms in ring structures of sizes smaller than the phase-coherent length; effect is most pronounced for a single ring (effect averages out for an ensemble of rings). Periodicity: h/e.

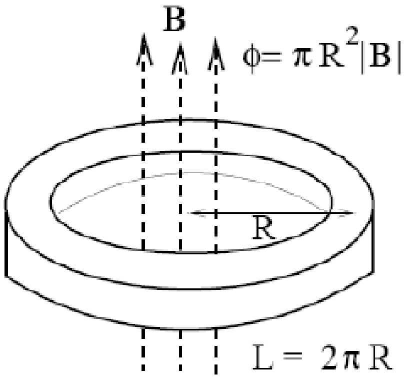
Which two effects have the same origin?

the four questions on phase-coherent transport

- Why do AAS oscillations remain visible after averaging? Why do AB oscillations die out?
- What is the role of the Fermi wave length?
- How large of an magnetic field is needed to see one full period of an AB oscillation for a nanotube with a diameter of 1 nm?
- What is the typical energy scale in phase-coherent transport?

persistent currents

Mesoscopic normal-metal ring



$$\psi_n(x+L) = e^{i2\pi\phi/\phi_0}\,\psi_n(x)$$

- magnetic flux breaks time-reversal symmetry

- current-carrying electronic ground state: current can*not* decay

- gauge invariance: current is periodic in flux with period $\phi_0 = h/e$

- sizeable current requires phase coherence around ring

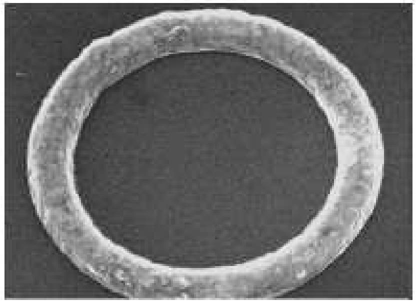
An electrical current induced in a resistive circuit will rapidly decay in the absence of an applied voltage. This decay reflects the tendency of the circuit's electrons to dissipate energy and relax to their ground state. However, quantum mechanics predicts that the electrons' many-body ground state (and, at finite temperature, their thermal equilibrium state) may contain a persistent current (PC), which flows through the resistive circuit without dissipating energy or decaying. A dissipationless equilibrium current flowing through a resistive circuit is counterintuitive, but it has a familiar analog in atomic physics: Some atomic species' electronic ground states possess nonzero orbital angular momentum, which is equivalent to a current circulating around the atom.

Buttiker, Imry & Landauer (Phys. Lett. 1983):

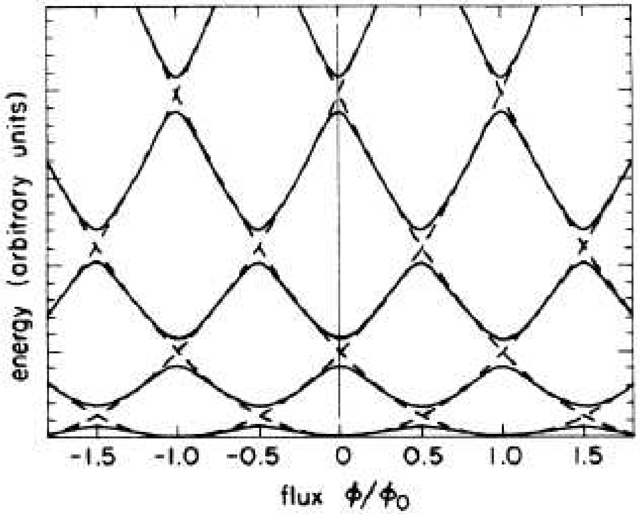
- mesoscopic persistent current survives in the presence of disorder, i.e., in samples with finite resistivity

- current is sample specific and changes sign as function of disorder configuration, number of electrons, …

the one-dimensional ring



flux-dependent
spectrum



$$I = -\frac{\partial E}{\partial \phi}$$

- eigenfunctions

$$\psi_n(x) = \frac{1}{\sqrt{L}} e^{ik_n x}$$

- spectrum

$$\epsilon_n = \frac{\hbar^2 k_n^2}{2m} \; ; \; k_n = \frac{2\pi}{L}\left(n - \frac{\phi}{\phi_0}\right)$$

- sign change with every additional electron

- sample specific: dominated by variance across ensemble

- magnitude $I \sim e v_F / L$

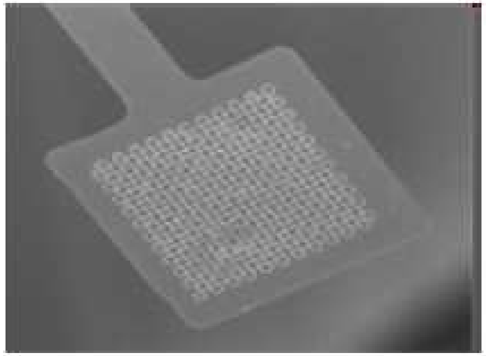
$$I \sim e/\tau_D$$

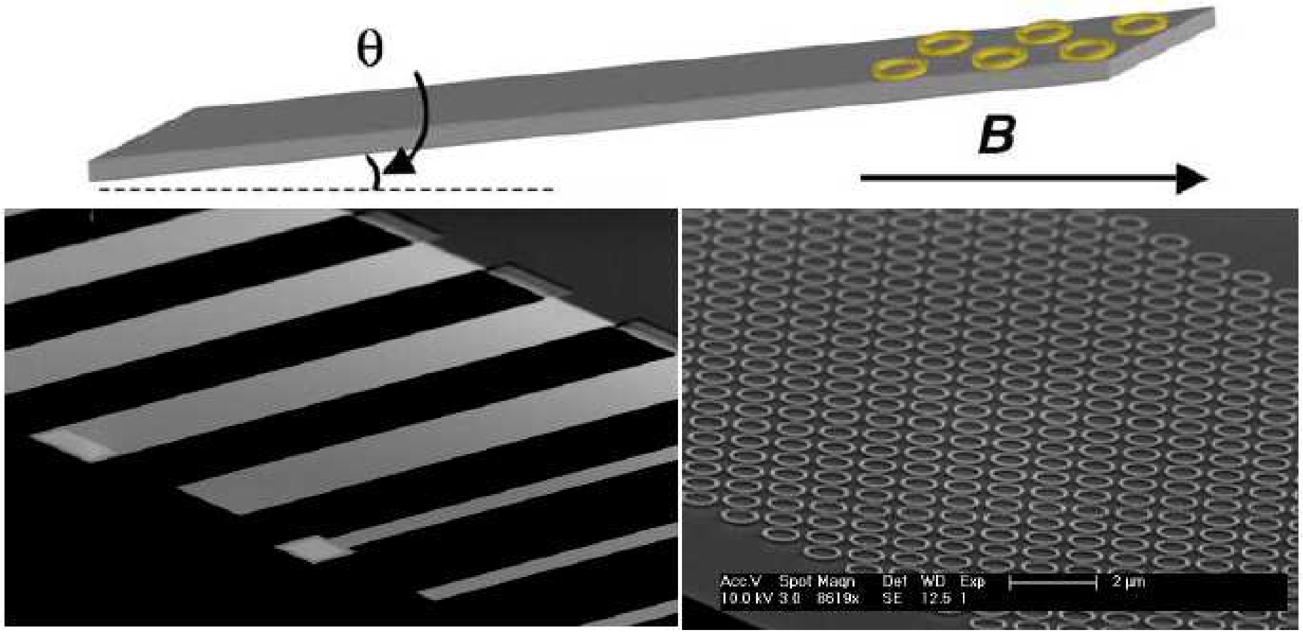
What is τ_D? And how is the energy $\hbar/\tau_D$ called?

Persistent Currents in Normal Metal Rings

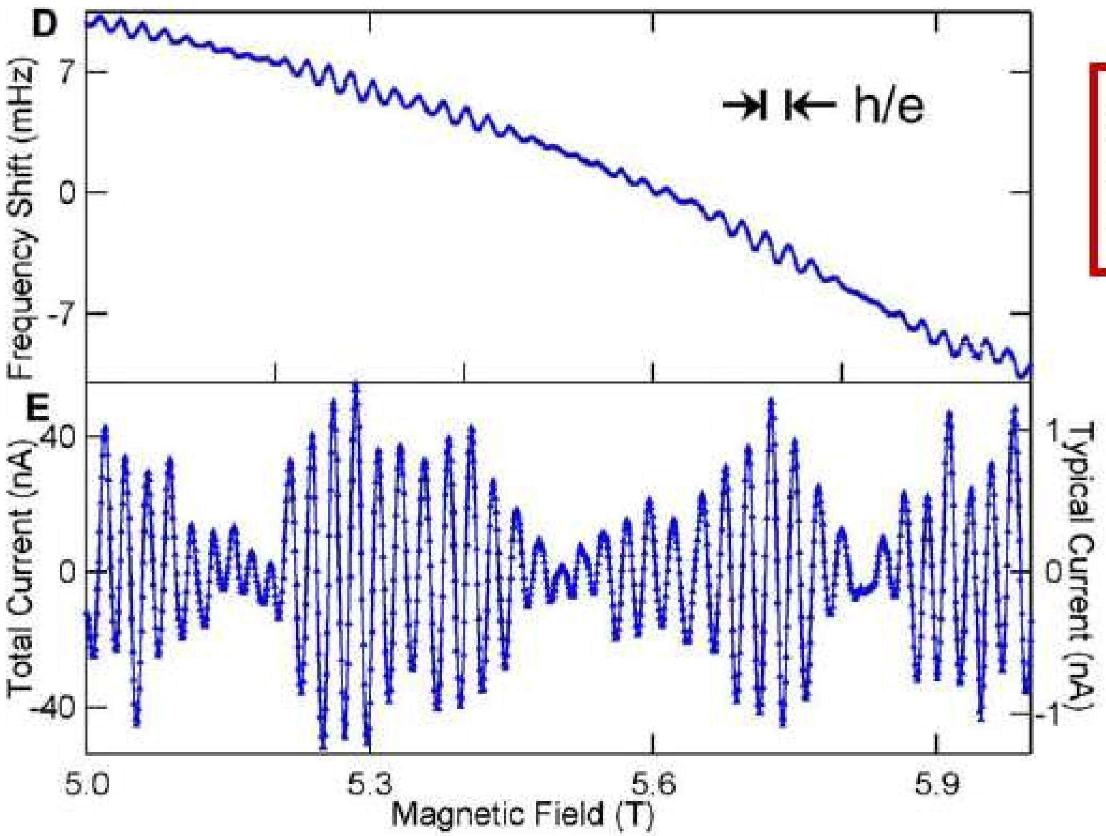
A. C. Bleszynski-Jayich,[1] W. E. Shanks,[1] B. Peaudecerf,[1] E. Ginossar,[1] F. von Oppen,[2]
L. Glazman,[1,3] J. G. E. Harris[1,3]

Quantum mechanics predicts that the equilibrium state of a resistive metal ring will contain a dissipationless current. This persistent current has been the focus of considerable theoretical and experimental work, but its basic properties remain a topic of controversy. The main experimental challenges in studying persistent currents have been the small signals they produce and their exceptional sensitivity to their environment. We have developed a technique for detecting persistent currents that allows us to measure the persistent current in metal rings over a wide range of temperatures, ring sizes, and magnetic fields. Measurements of both a single ring and arrays of rings agree well with calculations based on a model of non-interacting electrons.





frequency shifts and current

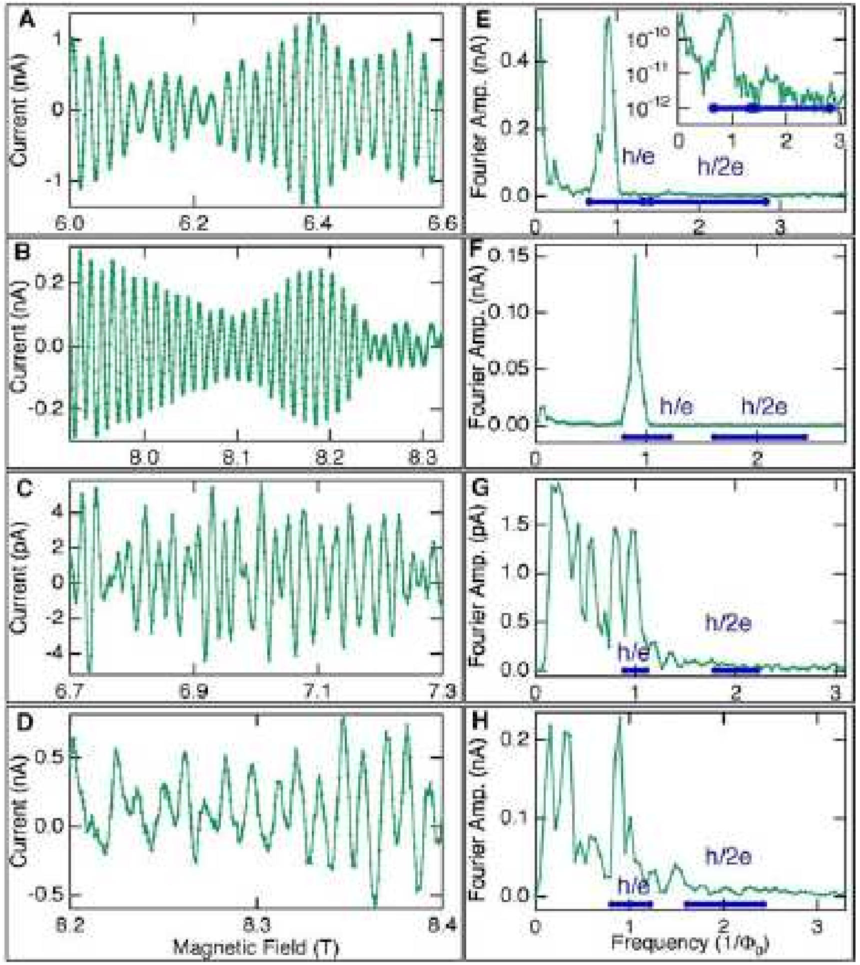


1680 rings
r = 308 nm
T = 365 mK

$I_\Sigma/\sqrt{N}$

In the presence of a magnetic field $\vec{B}$, each ring's current I produces a torque on the cantilever $\vec{\tau} = \vec{\mu} \times \vec{B}$ as well as a shift $\delta\nu$ in the cantilever's resonant frequency ν. Here $\vec{\mu} = \pi r^2 I \hat{n}$ is the magnetic moment of the PC, r is the ring radius, and $\hat{n}$ is the unit vector normal to the ring. We infer $I(B)$ from measurements of $\delta\nu(B)$; the conversion between $\delta\nu(B)$ and $I(B)$ is described in the supporting online material (SOM) text.

different devices



r=308nm; N=1680

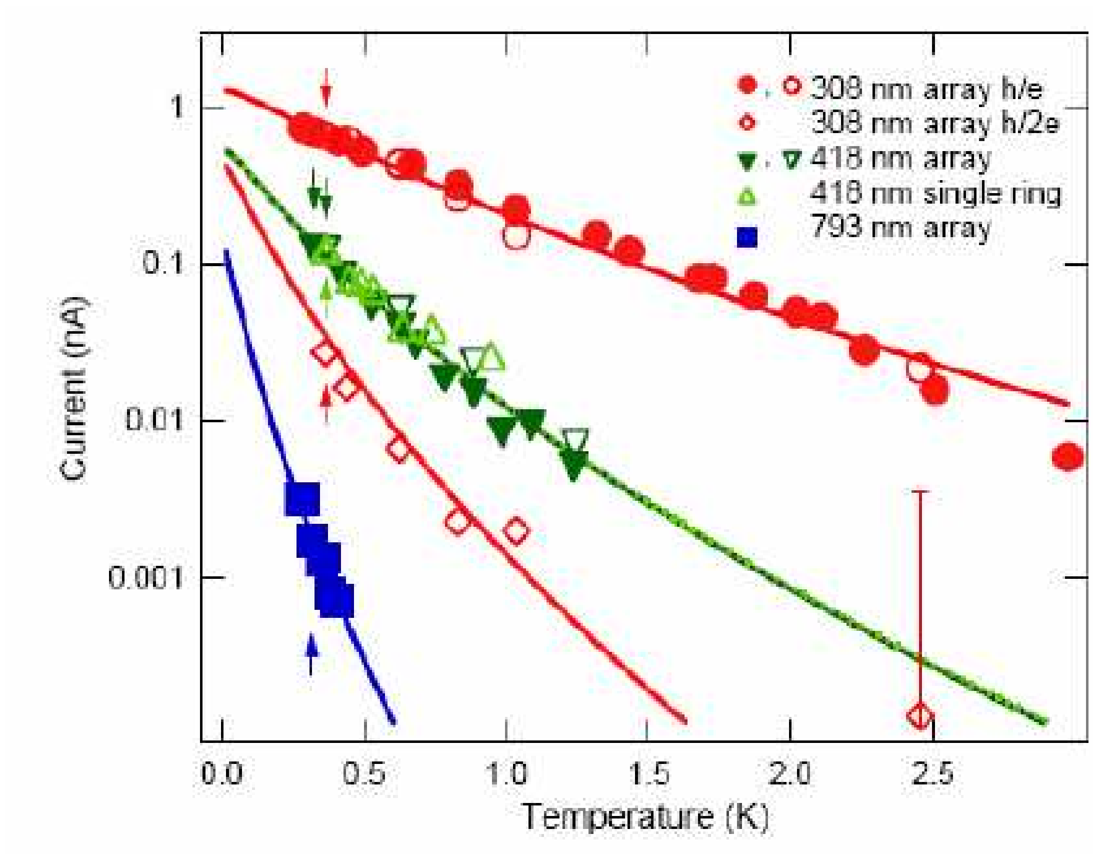
r=418nm; N=990

r=793nm; N=242

r=418nm; N=1

Sample	r (nm)	w (nm)	d (nm)	N	D (cm^2/s)
308-nm array	308	115	90	1680	271 ± 2.6
418-nm array	418	85	90	990	214 ± 3.3
793-nm array	793	85	90	242	205 ± 6.5
418-nm ring	418	85	90	1	215 ± 4.6
Wire (see SOM text)	289,000 (length)	115	90	1	260 ± 12

temperature dependence: Thouless energy



$$\left\langle I^2_{h/pe}(T)\right\rangle = g\left(p^2\frac{T}{T_{\mathrm{T}}}\right)\left\langle I^2_{h/pe}(0)\right\rangle \qquad (2)$$

where $g(x) = \frac{\pi^6}{3}x^2\sum_{n=1}^{\infty} n\ \exp[-(2\pi^3 nx)^{1/2}]$,

$\langle I^2_{h/pe}(0)\rangle^{1/2} = 0.37p^{-3/2}\frac{3eD}{(2\pi r)^2}$, and $T_{\mathrm{T}} = \frac{\hbar\pi^2 D}{k_{\mathrm{B}}(2\pi r)^2}$.

amplitude & temperature scale depend on diffusion constant *D* (via Thouless energy $\hbar/\tau_D$)