CHAPTER 1

ELECTRON COHERENCE AND DEPHASING IN METAL FILMS, WIRES AND RINGS

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The fields of weak localization, quantum interference and dephasing in disordered metal microstructures underwent dramatic advances in the past three decades. We describe the earlier advances, focusing on those at Yale in which Prof. Imry had significant input. We also present a novel physical picture to understand the essential mechanics of dephasing by Nyquist noise.

1.1. Introduction

In the late 1970s and early 1980s, the understanding of electron transport in disordered metal microstructures advanced dramatically. Electron interference effects were predicted and observed. These initially provided theoretical challenges, and also challenged our intuition regarding dissipation and conduction processes. The theoretical understanding developed at that time[1] is quite complete. The early experiments benefitted significantly from discussions between theorists and experimentalists. Much of the initial theory was done in the USSR, and therefore the discussions were not as rapid and personal as in modern times. Professor Imry, then at Tel Aviv University and at IBM, had a significant hand in guiding some of our ideas at Yale University. We therefore present here a brief review of some of that early work. This may also serve as a brief introduction for beginning students.

1.2. Weak Localization and the Aharonov-Bohm Effect

Weak localization is an effect that was first associated with one-dimensional (1d) wires. The prediction by D. Thouless[2] in 1977 that 1d metal wires would all be insulators at a sufficiently low temperature shocked some of us, and stimulated experiments. The first such experiments were published in 1979[3,4] and showed that 1d effects definitely occurred in wires approximately ≤100 nm in diameter,[3] but that 2d weak localization (WL) occurred in wider wires, of order a micron in width.[4] Weak localization is the high temperature precursor of the insulating state predicted for T = 0. WL arises from electron partial waves which can backscatter and travel along time-reversed paths to return to the point of origin, where they interfere constructively (in the simplest case) - see Fig. 1b. Since the pathlengths are identical for the time-reversed pairs, the interference is constructive.

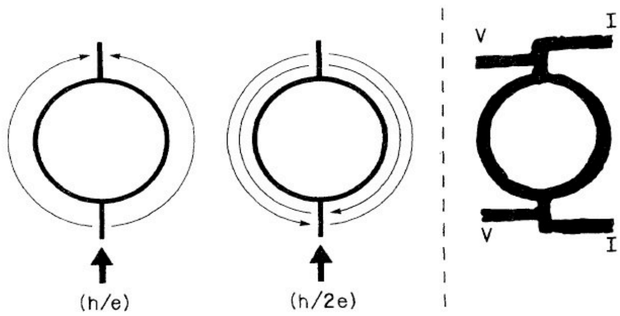

Fig. 1. Paths for h/e and h/2e AB interference effects in metal rings; micrograph of a ring; from Ref. 10.

The likelihood of returning to the origin is higher in this coherent case than for the case of classical diffusion, where there is no phase present. Thus, in this quantum coherent case, the electron in Fig. 1b gets somewhat stuck at the point of origin. It is weakly 'localized'. A magnetic field couples to and increments the phases of the electron waves, through the magnetic vector potential. For a ring, this gives the Aharonov-Bohm (AB) effect. Subsequent studies of the magnetoresistance of wires[5,6] related more explicitly the effects due to weak localization to the processes by which the waves lose their phase, called dephasing.

The physical understanding of the weak localization mechanism was advanced by the experimental work of Sharvin and Sharvin.[7] They observed the Aharonov-Bohm interference effect in a metal cylinder with thin walls, with a magnetic field oriented along the length of the cylinder. This striking result made clear that electron interference was directly observable, and this led to the search for interference effects in single rings, of diameter order of 1 μm. The AB interference they observed had a magnetoresistance which oscillated with field, with a flux period of $\Delta\phi = h/2e$, with h Planck's constant; this oscillation with field is due to a backscattering process, Fig. 1b, where the magnetic flux is encircled twice by the two partial waves.

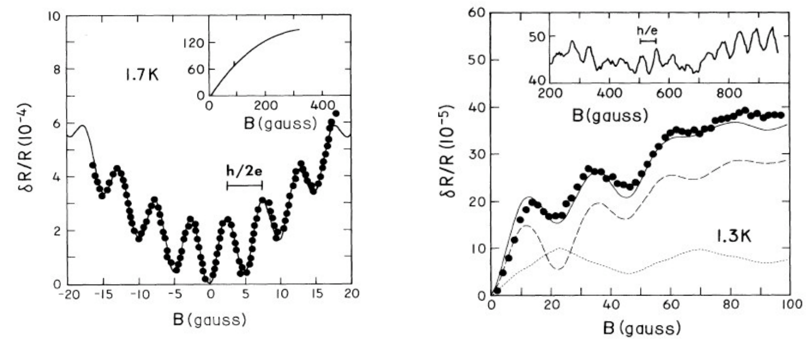

Fig. 2. Left: Magnetoresistance (MR) of Al ring showing interference effect with flux period h/2e; inset: high field MR with different scales; Right: MR of Ag ring, at low and high field. At low field, the dashed line is the contribution due to h/2e interference, and the light dotted line that due to h/e AB effect; inset: at high field, only the h/e effect is observed; from Ref. 10.

In 1985 Webb et al. observed interference in a single ring that corresponded to the forward-scattering interference effect.[8] The conductance varied in a periodic fashion with magnetic flux, with a flux period $\Delta\phi = h/e$; see Fig. 1a. This effect is analogous to the 'universal conductance fluctuations' [9] also seen at low temperatures, in short metal wires. In the wires, the forward scattering effect is present, but there is no single area, as in the ring, which defines a unique flux period for the magnetoresistance. This forward scattering effect is different from the interference effect that gives backscattering and which gives rise to weak localization. This is because for the forward scattering effect, the two waves never travel on paths that are identical.

Research at Yale in 1985 on micron-size rings[10] demonstrated both the h/e effect and the backscattering effect that is involved in weak localization, shown in Fig. 1b, with magnetic flux period $\Delta\phi = h/2e$. In Fig. 1a, many pairs of paths add up incoherently (they have random phases) to give the forward-scattering effect. In Fig. 1b, only the few special, time-reversed pairs of paths add, but these add coherently, having the same phase vs. magnetic field, because the path lengths of the two time-reversed paths are the same. The data for these rings is shown in Fig. 2. The h/e effect is dominant only at high field; at low field, the h/2e interference due to backscattering is dominant. The relative magnitudes depend on the temperature as well as the field.

1.3. Dephasing mechanisms in 1d and 2d metallic systems

The size scale of the rings studied[8,10] was set by the electron phase-coherence length. At *very* low temperatures and energies, the electron wave propagates diffusively due to elastic (impurity) scattering, staying in a state of constant energy. However, at finite temperature, interactions with other electrons and with the lattice lead to loss of phase memory, with a temperature-dependent time scale τ_φ and a length scale $(D\tau_\varphi)^{1/2}$; D is the diffusion constant. Phonon scattering and electron-electron scattering both contribute to the dephasing rate τ_ϕ^{-1}. Dephasing occurs when the pairs of paths that give interference (see Fig. 1) either lose their individual phase memories, or the different pairs of paths change their relative phase relations as a function of time (pairs relative to one another), so that dc interference no longer is observed. Research at Yale established that the dephasing rate in the 2d metal films[11] and 1d wires[12] is given by the sum of the electron-phonon (el-ph) process and the electron-electron (el-el) process,

$$\tau_\varphi^{-1} = \tau_{\varphi,\text{el-ph}}^{-1} + \tau_{\varphi,\text{el-el}}^{-1}. \qquad (1)$$

The electron-electron inelastic scattering that gives dephasing is due to a new mechanism, Nyquist noise. This is different from the inelastic electron-electron scattering with *large* energy exchanges, which in clean metals has a temperature dependent rate $\approx T^2$ with exchanges of energy of order k_BT. Nyquist noise dephasing is much stronger in dirty (diffusive) metals than the dephasing due to electron-electron scattering with large energy exchange.

The ideas on dephasing mechanisms grew out of theory developed to understand weak localization. The mechanisms of dephasing described here are indeed all due to inelastic processes. However, the inelastic time is the characteristic time for an electron to lose energy (equal to k_BT). The inelastic time is, in general, different from the dephasing time.[1]

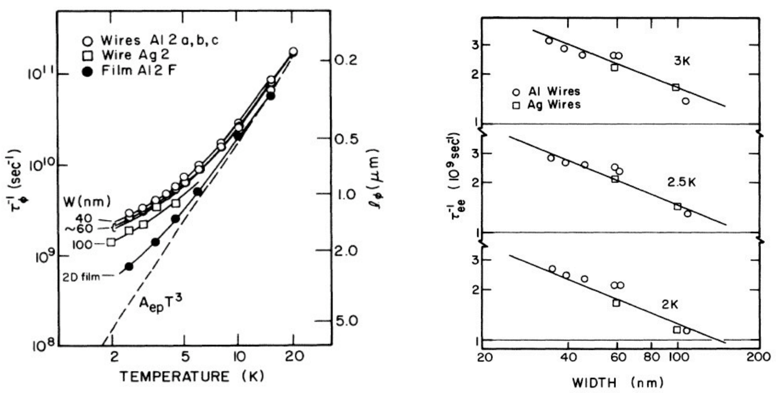

Fig. 3. Left: Phase-breaking rate vs. temperature; the electron-phonon contribution, with rate $\approx T^3$, is shown as a dashed line. The electron-electron contribution to the total dephasing rate, $\tau_{\varphi,\text{el-el}}^{-1}$, is shown on the right. Solid lines are theory;[1] from Ref. 12.

We also investigated at Yale the new mechanisms causing dephasing. We therefore measured[12] the weak-localization magnetoresistance of Ag and Al wires vs. temperature, for wires of various widths. The magnetoresistance was analyzed to deduce τ_φ. We extracted $\tau_{\varphi,\text{el-ph}}$

from the data for wide wires at high temperatures. Using Eq. 1, we obtained $\tau_{\varphi,el\text{-}el}$. The results are plotted in Fig. 3. The fit to the theory predictions is excellent, for both the magnitude and for the dependence on temperature and wire width.

Recent research in this field has characterized the persistent currents that flow in individual rings at very low temperatures. These persistent currents were first seen in individual rings by Chandrasekhar et al. at IBM,[13] but the magnitude has remained puzzling. Recent work at Stanford[14] and Yale[15] has advanced the understanding, and recent theory[16] points to possible resolution of the puzzling magnitude of the observed effect. Small quantities of magnetic scatterers may play an important role in the experiments. Challenges remain open for future experiments, and this field continues to pose interesting questions.

1.4. Dephasing - a Simple Pedagogical Model

Dephasing of electron waves in metals was not a significant research topic prior to the concepts of weak localization and associated interference effects. Measurements at Yale have confirmed in detail the novel theoretical predictions for electron-electron dephasing in 2d films and 1d wires, discussed above. These experiments demonstrate that at low temperatures, electron-electron dephasing (by Nyquist-Johnson noise) dominates. At higher temperatures, typically above a few K, electron-phonon inelastic scattering dominates. We present below a physical picture that argues for the *plausibility* of the dephasing due to Nyquist noise, which causes a fluctuating electric field **E** in the metal. Our argument is not intended to make a quantitative prediction. Rather, it is intended to be a pedagogical introduction to the rationale for dephasing, and to explain how finite-frequency noise can cause dephasing.

Dephasing is caused by energy exchange with the environment that is different for the two partial waves. We consider the simplest case of a metal film. We draw in Fig. 4 the paths of the two electron partial waves, paths 1 and 2, as direct, with one scattering event along each path. Even though the real motion is diffusive, this simplification still captures the essential ideas. The two partial waves originate (split apart) at point A. The energy on path 1 is given by $E_1 = hf_1$. If there is no change in the energies of the two partial waves when they travel to point B where they recombine, they will interfere at this exit point, B. For a given pair of paths the interference can have any phase, but that phase will be constant in time. However, if E_1 changes during propagation from point A to point B, and E_2 is constant, then the two partial waves 1 and 2 arrive at point B having different frequencies, and cannot have dc interference at point B. Dephasing has occurred due to the change of energy E_1 (and frequency f_1).

If the two waves in Fig. 4 accumulate a significantly phase difference along the two paths, dephasing will occur. The typical time to traverse from A to B is τ_φ. The phase difference, for a frequency difference of Δf, is $\Delta\varphi \approx (\Delta f\ \tau_\varphi)$. A phase difference of $\Delta\varphi = \pi$ is significant for dephasing. This amount $\Delta\varphi = \pi$ would be accumulated if the two energies differ only by the small amount $\Delta E = h\,\Delta f \approx \pi\, h\, \tau_\varphi^{-1} << k_B T$. The actual phase difference changes vs. time, since we will find below that ΔE varies in time. Thus, dc interference is destroyed. The inequality $\Delta E << k_B T$ in this result means that *small* energy exchanges, $<< k_B T$, can fully dephase the two partial waves; large energy exchanges ($\approx k_b T$) are not necessary to cause dephasing. Multiple small energy exchanges of even smaller energies also dephase.

Energy exchange can occur due to phonon emission or absorption, typically of large energy $\approx k_B T$. But fluctuating electric fields can also dephase the electron waves. Consider a time dependent **E** field in the direction shown in Fig. 4, with a single oscillation during the time to propagate from A to B. (Typically, the relevant time scale is the dephasing time, τ_φ, determined self-consistently.) On path 2, the energy E_2 is decreased (compared to zero electric field) since **E** and the velocity $\mathbf{v_2}$ are in the same direction during the first half of the cycle, when $\mathbf{v_2}$ is parallel to **E.** (This causes a **de**crease of energy because the charge is negative.). During the second part of the cycle, in contrast, $\mathbf{v_2}$ is orthogonal to **E**; no energy is added to the wave. On path 1, the energy

E_1 is increased, since **E** and $\mathbf{v_1}$ are in opposite directions during the second part of the cycle, and the charge is negative. During the first half of the cycle, no energy is added to that wave. Thus, a significant ΔE and frequency difference, Δf, can occur between the two waves. Because **E** fluctuates in time, the phase difference will also fluctuate for those two paths. The time-dependent **E** field waveform shown will thus dephase the two electron partial waves. A dc electric field will not dephase, by the same argument. Nyquist noise contains components at all frequencies. The most effective frequencies are $f \approx \tau_\varphi^{-1}$.

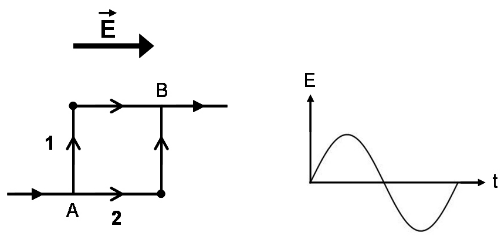

Fig. 4. Model of dephasing by a time-varying electric field **E.** An electron enters from left, and two partial waves split apart at point A. These two waves traverse the paths 1 and 2, and then recombine at point B. Dc interference can occur if the two frequencies are the same. The time-varying **E** field shown will cause a time varying phase shift between the two paths. The overall conductance is due to many such pairs of interfering paths, and the **E** field shown will cause different phase shifts for the *different* pairs of paths, leading to loss of dc interference.

1.5. Conclusions

Experiments and theory for electron transport in disordered metal films, wires, and rings have led to a deep understanding of issues of coherence and dissipation in disordered conductors, and revealed new and unexpected interference effects.[17] Dephasing by Nyquist noise was one of the new effects, and plays a key role in all the experiments. We have presented a 'toy' model of this effect which captures the essence of Nyquist dephasing. It does not predict the temperature dependence of the dephasing rate, nor how this rate depends on sample dimension and material parameters. Happily, the full quantitative theory[1] is available to predict all these. The predictions have been carefully tested in our experiments, with very satisfying confirmation of this novel and important theory. Significant further development, and the establishment of mesoscopic physics as an important area of research and understanding, has occurred in the subsequent decades.[17]

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