Electron decoherence at zero temperature
The phenomenology and associated difficulties

P. Mohanty
Condensed Matter Physics, California Institute of Technology, 114-36, Pasadena, CA 91125

Key words: decoherence, dephasing, Fermi liquid, Anderson localization, scaling theory, linear response, mesoscopic conductors, zero temperature

Abstract:

The concept of decoherence at zero temperature is fundamental to many areas of physics including condensed matter physics. Recent experiments invariably show that electron decoherence in mesoscopic conductors is dominated by a temperature independent mechanism at low temperatures, which suggests decoherence even at zero temperature contrary to the expectations in conventional theories. Electron decoherence and other related phenomena are reviewed in light of this discrepancy. Various aspects of disordered electronic systems fundamental to the understanding of the problem are briefly examined.

1. WHY IS IT IMPORTANT?

The problem of low temperature decoherence of an electron inside a disordered conductor is extremely important in many areas of physics. For instance, to verify predictions of the quantum theory, measurements have to be made. However, one prevalent interpretation requires the explicit existence of a classical apparatus for measurement. The necessity of classical mechanics to interpret quantum theory of which it should be a limiting case creates the so-called quantum measurement problem in addition to the fact that the measurement process itself is not described by quantum mechanics. The idea of decoherence or loss of quantum coherence—signifying transition
from the quantum to the classical realm by the coupling to an environment—
within the quantum mechanical framework at zero temperature is thus
extremely fundamental. Despite its glaring necessity, most studies of
decoherence are done in the high temperature (classical) limit for the
environment. Any phenomenology which depicts zero temperature
decoherence is thus essential to foundational problems\(^2\) of quantum theory.

In condensed matter physics, metals are usually understood as Fermi
liquids\(^3\). In this picture, there is a unique many-body ground state at T=0 in
which electrons occupy all levels up to the Fermi surface according to
exclusion statistics. The low-lying excitations from this ground state are
understood in terms of quasi-particles with long lifetimes. These quasi-
particles are thought to be free with only a few effective parameters entering
various equilibrium physical quantities such as thermodynamic density of
states, spin susceptibility and specific heat, given in terms of their free-
electron expression and the Landau parameters. An effective Landau theory
of disordered interacting electron systems is obtained\(^4\) by modified Landau
expressions in terms of new renormalization parameters of the interaction
effective coupling which also contain the diffusion constant, appearing in the
propagator of the diffusion mode. This formalism was successful in
explaining various experimentally observed physical properties.

The concept of localization of electrons in a random potential or
Anderson localization\(^5\), based on a single-electron picture, forms the
microscopic foundation of disordered metals and insulators. With a given
degree of disorder, the system is described in terms of an effective coupling
identified with the inverse conductance. The conductivity or diffusion
constant is renormalized, and, in strong disorder, the system evolves towards
an insulating state, becoming an Anderson insulator at T=0. Inclusion of
electron-electron interaction\(^6\) completes\(^4\) and modifies Anderson localization
in an apparently rich framework of renormalized perturbation theory.

The above Fermi-liquid description\(^4\) starts from the unique many-body
ground state at T=0, which forbids the scattering of the electron as all
available states are filled up. The inelastic scattering rate\(^7\) or even dephasing
rate\(^8\) 1/\(\tau_0\) must vanish as T \(\rightarrow\) 0 due to the lack of any phase space for
scattering. Understanding of the quantum localization effects in low
dimensional disordered conductors, usually described by the scaling theory\(^4\),
relies additionally on this aspect for a power-law dependence: \(L_0 = (D\tau_0)^{1/2}\)
\(\sim T^\phi\) or 1/\(\tau_0 \rightarrow 0\) as T \(\rightarrow\) 0. A power law divergence of 1/\(\tau_0\) at T=0 is
confirmed by the perturbative calculation of 1/\(\tau_0\) due to the electron-electron
interaction\(^6\). If there is a finite electron decoherence rate 1/\(\tau_0\) at zero
temperature, then there will be diffusion or spreading of the wave packet
associated with the decoherence of the constituting electron wave functions.
This will preclude quantum localization in spite of the strong disorder\(^5\).
In a broader perspective, the quantum-limited decoherence is relevant to many other fundamental problems, including quantum computation, the problem of particle production in the early universe in cosmology, the black-hole entropy problem, and even perhaps the unified theory of interaction.

2. EXPERIMENTS

Experimental determination of the electron decoherence time involves the measurement of interference effects such as the Aharonov-Bohm effect, conductance fluctuations or weak localization. From the size of the correction to the resistance it is possible to quantify $\tau_\phi$. Weak localization, the quantum correction to conductance arising from the interference between pairs of time-reversed paths, is the most reliable technique for many reasons. In quasi-1D conductors, the size of the magnetoresistance from weak localization near zero field is roughly proportional to the decoherence length $L_\phi$. The dimensionality is defined by $L_\phi$ and $L_T = (\hbar D/k_B T)^{1/2}$ the thermal diffusion length. In quasi-1D conductors, the transverse dimensions, width $w$ and thickness $t$, are much smaller than these length scales.

The magnetoresistance correction to the classical resistance $R$ is given by $\Delta R/R = -(e^2/h) (R/L) [L_\phi^{-2} + L_B^{-2}]^{-1/2}$, where $L_B = (3^{1/2}\hbar ewB)$ is the magnetic phase breaking length. The net change of resistance at $B=0$ is given by $\Delta R/R = - (R/R_q) L_\phi/L$. The weak localization correction can be conveniently described as the ratio of the resistance in the units of resistance quantum $R_q = h/e^2 = 25812 \Omega$ and the length in the units of $L_\phi$. Thus $L_\phi$ or $\tau_\phi$ can be determined by fitting the magnetoresistance to the above-mentioned form with no other free parameter. The temperature dependence of $\tau_\phi$ in quasi-1D gold (Au) wires for four representative samples is shown in Fig. 2. At low temperatures all the samples invariably show a weak dependence or saturation of $\tau_\phi$ rather than the $T^{-2/3}$ dependence expected from the conventional theory of electron-electron interaction.

Low temperature saturation of $\tau_\phi$ has been observed in many experiments on a wide range of mesoscopic systems. These include quasi-1D and 2D films of Au, AuPd, Cu, and molecular AuPd wires and semiconducting Si inversion layers, doped and undoped GaAs structures, 0- dimensional open GaAs quantum dots, and various 3D alloys. Measurements on multi-walled carbon nanotubes also display the saturation of the weak localization correction. $\tau_\phi$ extracted from the Aharonov-Bohm correction or conductance fluctuations shows the saturation as well.

Furthermore, the range of the saturation time $\tau_0$ extends over four decades, from few picoseconds to tens of nanoseconds. The temperature range of saturation in these experiments extends over three decades, from
Figure 1. The magnetoresistance of a typical quasi-1D Au wire. Because of the strong spin-orbit scattering in Au, weak anti-localization is observed instead of the standard weak localization. The size of the magnetoresistance dip near zero field is roughly proportional to the phase decoherence length \( L_\phi \). Note that the data is vertically offset for clarity.

20 K down to 20 mK. Controlled experiments show a clear trend between \( \tau_0 \) or \( T_0 \) and the sample parameters. In other words, with the appropriate choice of the sample parameters such as the resistance per unit length \( R/L \), width \( w \), and diffusion constant \( D \), it is possible to tune \( \tau_0 \) and \( T_0 \). In a certain parameter range, \( T_0 \) can even be made lower than the lowest temperature of measurement. Though consistent with this trend, the recent measurement on quasi-1D Ag wires\(^{24}\) shows a continuous temperature dependence of \( \tau_\phi \) down to 50 mK with a value of ~ 10 ns at the lowest temperature; the saturation is expected at a much lower temperature. As a matter of fact, by changing the diffusion constant \( D \) from 0.00008 m\(^2\)/s to 0.0135 m\(^2\)/s, \( \tau_\phi \) could be changed from 50 ps to ~ 60 ns in 2D films\(^{25}\) and \( T_0 \) could be changed from ~ 1 K to much below 20 mK. Thus a clear demonstration of saturation in quasi-1D Ag wires requires detailed measurement on a set of samples with varying \( D \), \( R/L \) or \( w \), similar to the recent experiments on AuPd wires and films\(^{15}\).

In spite of the strong evidence for the saturation of \( \tau_\phi \), its ubiquity and universality, it is necessary to ensure that the effect is not due to artifacts. Recently, various extrinsic mechanisms contributing to the observed saturation have been proposed. The proposed artifacts behaving as effective environments are (a) two-level systems (TLS) operating as a source for 1/f-noise\(^{26}\), (b) TLS as two-channel Kondo scatterers\(^{27}\), (c) external high frequency (HF) noise\(^{28}\), (d) nuclear spins\(^{29}\), and (e) external phonons in the leads\(^{30}\), (f) magnetic impurities\(^{31}\), (g) local spin droplets\(^{32}\), and (h) gravity.
among other external sources\textsuperscript{12}. A systematic study\textsuperscript{12} asserts that the observed saturation in Au wires and in many other systems could not be due to the presence of TLS or HF noise\textsuperscript{33}. Recent experiments on 3D samples made from various materials\textsuperscript{23} show the material independent but the sample-parameter dependent saturation. Experiments on AuPd samples\textsuperscript{15} in a wide range of width also find the dependence of saturation on the sample parameters and the lack of a dominant contribution from a random mechanism, consistent with the experiments on Au wires\textsuperscript{1}. These experiments reinforce the earlier conclusion that the saturation is a real effect, most likely arising from electron-electron interaction\textsuperscript{34}.

3. RELATED PHENOMENA: CONSEQUENCES OF DECOHERENCE RATE SATURATION

3.1 Anomalies in various localization phenomena

Absence of electron decoherence at T=0 is fundamental to the realization of certain localizing transitions from metallic to insulating states\textsuperscript{4} and the lack of such transitions in 2D systems in the scaling theory. Decoherence at T=0 would therefore naturally suggest various anomalies in the transport and thermodynamic properties of disordered conductors at low temperatures. As
discussed in an earlier paper\textsuperscript{12}, there is growing experimental evidence of low temperature anomalies in various localizing transitions. For example, the Thouless crossover\textsuperscript{35} from weak to strong localization in quasi-1D conductors is found to be inhibited\textsuperscript{36} by the zero temperature decoherence depending on the relative size of $\xi_{\text{loc}}$ and $L_0$. In the temperature range of observation if $\xi_{\text{loc}} \ll L_0$, the T-independent decoherence length, then a transition is observed. However, the crossover is going to be cutoff ultimately at lower temperature. If $\xi_{\text{loc}} \gg L_0$, then the crossover will not be observed. Finite decoherence cuts off the crossover with a saturation of the resistance, preventing any further increase of resistance toward an insulating state. Similar arguments suggest that the recent observation of metallic behavior in 2D systems\textsuperscript{37} may be a quantum effect, arising perhaps due to the two competing mechanisms. The saturation of quantum-hall to insulating transition observed in experiments\textsuperscript{38} has also been explained on the assumption of a T-independent decoherence mechanism\textsuperscript{39}.

3.2 Anomalously large persistent current in metals

The intrinsic mechanism, which gives rise to the saturation of $\tau_0$, naturally results in other novel effects\textsuperscript{40}. The time-dependent fluctuations that induce decoherence, a destructive and randomising process, are expected to suppress any quantum coherent effect, an example being the persistent current, a ground state property in equilibrium. Detailed analysis of a mesoscopic ring with an embedded high frequency source indeed finds such a suppression of the persistent current in a ballistic normal metal ring\textsuperscript{41}.

Counterintuitive as it may sound, the very fluctuations resulting in an apparent destructive effect of decoherence can actually give rise to constructive phase coherent effects\textsuperscript{40}. One such example is the generation of a non-decaying dc current due to the rectification of the high frequency fluctuations\textsuperscript{42} (typically in the range of GHz $\sim 1/\tau_0$). A disordered mesoscopic ring does not possess reflection inversion symmetry. The Aharonov-Bohm phase, acquired by an electron over its trip around the ring is an odd function under spatial inversion: $x \to -x$, $\phi \to -\phi$. This asymmetry of the phase under spatial inversion is the crucial reason for the rectification of high frequency fluctuations into a dc current. What is rather interesting though not surprising is that disorder, itself a random effect, in collaboration with another randomising effect could result in a periodic persistent current.

Following the suggestion\textsuperscript{40} that the two phenomena may indeed be connected, recent calculations of non-equilibrium-noise-induced current\textsuperscript{43} found an universal expression relating the generated persistent current to the saturated decoherence rate: $I(T=0) \sim C \tau_0$, where $C$ is a constant of the order unity. This could explain the large size of the experimentally observed
persistent current\textsuperscript{44} surprisingly well, within a factor of 2. Recently, it has been argued that even equilibrium intrinsic noise, for example from a bath of TLS, can give rise to a finite current\textsuperscript{45}. It’s important to find out how and if the electron-electron interaction\textsuperscript{46} can also produce a large persistent current. Of particular interest is how this calculation will relate to the perturbative calculation of the persistent current due to interaction\textsuperscript{47}.

3.3 Anomalous conductance through N/S junction

Another unusual manifestation of electron interference is in the transport across the interface between a normal metal (N) and a superconductor (S). Two processes dominate the transport through such an N/S junction: single-particle tunnelling, and two-particle Andreev tunnelling. Depending on the transmission coefficient of the N/S junction, the ratio of the interface resistance $R_0^N$ and $R_0^S$ in the normal and superconducting states at zero voltage can be small, $R_0^N/R_0^S \ll 1$ (imperfect interface), or it can reach a maximum value of 2 for a perfect interface. The traditional theory\textsuperscript{48} obtains a resistance-voltage curve for the tunnelling with characteristic double dips at $V=\pm \Delta$, the superconducting gap, and a peak at zero bias. An electron from the normal conductor with an energy below the gap cannot enter the superconductor, and is therefore retro-reflected as a hole, tracing exactly the same trajectory. Interference between these two trajectories in the presence of disorder gives rise to an excess differential conductance at zero bias\textsuperscript{49}. As an interference effect, this zero-bias anomaly is sensitive to magnetic field and temperature (or voltage). Magnetic field necessary to suppress the anomaly corresponds to one flux quantum through the normal-metal area.

Interference in the N/S junction provides a novel method of extracting electron decoherence rate\textsuperscript{50}. If $L_\phi \ll L$, the size of the normal metal, then $L_\phi$ plays the role of an effective length of the sample. Since $L_\phi$ is directly related to the interference enhancement of conductance, a saturation of $L_\phi$ will be reflected in the saturation of resistance ratio $R_0^N/R_0^S$ at low temperatures. Recently, experiments on N/S and N/I/S hybrid junctions found the saturation\textsuperscript{51} of $R_0^N/R_0^S$, consistent with the observation of the $\tau_0$ saturation. More experimental analysis\textsuperscript{52} needs to be done to understand the role of interaction in decoherence of the electron-hole pair.

3.4 Anomalous energy relaxation

Electron decoherence at T=0 forces the concept of a unique many-body ground state with a sharp excitation spectrum in metals to be merely an idealization. The saturation value of the rate determines in essence the smearing of the Fermi surface. Inside this smeared regime, i.e. $E < \gamma/\tau_0$, the
energy relaxation rates of the excited states will be larger than what would be expected from the Fermi-liquid theory. Thus the connection between the lack of complete coherence at $T=0$ and an enhanced energy relaxation rate is not at all surprising. Experimental observation of the enhancement, related to the $\tau_\phi$ saturation puts itself farther from the quasi-particle description of disordered metals in the Fermi-liquid framework. Recently, the shape of the electron excitation spectrum was probed by measuring the distribution function in an out-of-equilibrium configuration in Cu and Au wires. The observed excess relaxation was found to be correlated to the saturation of $\tau_\phi$. The enhancement of relaxation was not as pronounced in the Ag wire, which did not show saturation (as it might still be in the high temperature limit). Similar to the persistent current problem, the existence of saturation of $\tau_\phi$, irrespective of its origin, will always imply an excess relaxation. Thus the experimental observation of the latter as well as the correlation is consistent with one of the anticipated consequences.

4. CONCEPTUAL DIFFICULTIES

Interestingly, the reason for which the observed saturation effect is extremely important—it goes contrary to the conventional wisdom—is the same reason why it’s natural to have conceptual difficulties with it and other associated phenomena. The approach of starting from a ground state at $T=0$, even in the presence of disorder and electron interaction, and describing various low-energy properties of metals by low-lying excitations close to this ground state has crippled any conceptual progress beyond which it suffices to treat interaction perturbatively. A mixed state at $T=0$ instead of an idealized many-body pure state is suggested by the observation of temperature independent decoherence. Various related anomalies at low temperatures discussed in the earlier section point to the same problem with the perturbative approach. Even though the necessity of addressing this inadequacy couldn’t be more imminent, there are numerous conceptual hurdles along the way, some of which are enumerated below.

First, the notion of dephasing in mesoscopic physics needs to be re-examined. Traditionally, one assumes a well-defined phase for the electron wave function, which then acquires small phase shifts ($<< 2\pi$) due to its coupling to an environment. Averaging over randomness such as the thermal fluctuations results in the dephasing rate. This prescription is valid for small phase shifts, or when the electron is weakly coupled to the environment, consistent with a perturbative analysis. However, in the strong coupling regime the determination of dephasing rate without the inclusion of the environmental dynamics may be inappropriate as it loses a lot of important
Electron decoherence at zero temperature

physics such as back reaction\textsuperscript{56}. Furthermore, it is well known, in the quantum-brownian-motion models of decoherence\textsuperscript{4} that factorization of the initial density matrix into the system (electron) and the environment parts introduces non-unitarity\textsuperscript{56}. Considering these conceptual problems, it may be proper to replace the notion of dephasing by that of decoherence\textsuperscript{55}, formally described as the decay of off-diagonal terms of the reduced density matrix.

Even though zero temperature decoherence is expected in most models, decoherence of an electron from an electron bath is rather peculiar\textsuperscript{57}. Since electrons are fermions, Pauli exclusion puts a further constraint on the many-body combination of the interfering electron and the electron bath. Scattering of a single electron is prohibited as Pauli exclusion prevents the change of its state or wave function. This gives rise to the much debated\textsuperscript{58} tanh term\textsuperscript{7} in the coth-tanh term for the density of final states for scattering. First, in accord with the points made in the previous paragraph, scattering (in the perturbative sense a la Fermi’s golden rule) and dephasing\textsuperscript{4} or decoherence\textsuperscript{46} are different. Second, the local breathing of the Fermi surface may allow scattering of the electron. Third, if at T=0 there is no ground state with a filled Fermi surface—and it’s not yet clear if that is the case in presence of interaction and disorder, then the issue becomes irrelevant. At the start, a finite smearing of the Fermi sea at T=0 (perhaps due to interaction) would imply a number of unoccupied states available for scattering.

There are other important concerns regarding electron decoherence at T=0 in a metal. Another notion that needs examining is the law of detailed balance at T=0, usually thought of as a mere thermal population expressed in terms of a Boltzmann factor. This however does not include population due to quantum effects. In a related context, even the notion of equilibrium in mesoscopic electron systems needs to be explored in light of recent developments in the studies of spin glasses concerning the violation of the fluctuation-dissipation relation and the emergence of an effective temperature\textsuperscript{59}. Measurements of Johnson noise at low and high frequencies can be useful in connecting the decoherence problem to even the notion of temperature in mesoscopic systems\textsuperscript{60}. The concept of linear response, which forms the basis for defining conductivity needs clarification in this context\textsuperscript{61}. The problem is that the applied bias eV should be much less than k\textsubscript{B}T, for the measurement of conductivity, which implies that the meaning of linear response itself at T=0 is puzzling\textsuperscript{62}. In overall totality, the immediate difficulty that needs to be sufficiently addressed is the unambiguous discrepancy between the perturbative diagrammatic analysis\textsuperscript{58} and the density-matrix path-integral approach based on the quantum-brownian-motion models\textsuperscript{57}.

I thank Prof. Richard Webb for collaboration and ongoing discussions.
10. E. Witten, Colloquium, California Institute of Technology (2000).
32. B.W. Narozhny, L.L. Aleiner, and A.I. Larkin, cond-mat/0005267.
Electron decoherence at zero temperature

45 P. Schwab, cond-mat/0005525.
60 R.A. Webb, private communication.