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Notes on decoherence at absolute zero

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Abstract

The problem of electron decoherence at low-temperature is analyzed from the perspective of recent experiments on decoherence rate measurement and on related localization phenomena in low-dimensional systems. The importance of decoherence at zero temperature, perhaps induced by quantum fluctuations, is put in a broader context. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Decoherence is the process which — through the interaction of the system with external degrees of freedom referred to as an environment — sustains a loss of quantum coherence in a system. It defines the transition from quantum behavior of a closed system, which thus possesses unitarity or time reversibility and displays interference due to the superposition of its wave function, to the classical behavior of the same as an open system; the loss of unitarity or time-reversal symmetry leads to a loss of interference [1]. This openness comes from the coupling of the quantum system to an environment or a bath [2,3]. A closed system, on the other hand, does not undergo decoherence. The quantum system in question could be an electron whereas the environment could be thermal phonons or photons, and even other electrons whose properties are not measured. The coarse-graining of the irrelevant degrees of freedom defining the environment, which are not of interest to the measurement, generates both dissipation and decoherence: the latter formally related to the decay of the off-diagonal terms of the reduced density matrix operator denoting the quantum system.

The interpretational problem with decoherence, and in fact the notion of decoherence itself, vanishes when one treats the system-environment combination as one indivisible quantum object. The combination is closed and evolves unitarily according to the laws of quantum mechanics transforming pure states into pure states, hence there is no decoherence. The problem only arises in the splitting of the whole as "a system of interest" to the observer or the experiment, and the remaining degrees of freedom as "the environment". This split is necessary and must be acknowledged from the observer's or experiment's perspective. Interestingly, a pure state of the closed combination is compatible with each part being in mixed states. Decoherence is obtained by considering the density matrix operator for the combination and partially tracing out the irrelevant degrees of freedom, namely those of the environment. The reduced density matrix operator then represents the "effective" system alone as a statistical mixture, which is of interest to a measurement in an experiment. An initially isolated system inevitably loses quantum coherence due to its coupling to a complex or a "large" environment with very many degrees of freedom. When both the system and the environment are treated quantum mechanically, the quantum entanglement becomes an important concern for the loss of coherence.

The loss of coherence of an electron inside a disordered conductor occurs due to the interaction with environments: its coupling to localized spins-pseudo or magnetic, electron–phonon interactions and electron–electron interactions, the latter being dominant at low-temperature. Conventional theories [4] decree that the suppresion of coherence, characterized by a decoherence

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rate $1/\tau_\phi$ vanish with decreasing temperature, ultimately giving a Fermi-liquid ground state. However, in experiments a finite decoherence rate is observed at low-temperatures [5], which perhaps persists down to $T = 0$. Considering the consequences of such an observation, to be discussed in Sections 3 and 4, it is imperative to put the experimental observation on firm ground. Towards that end, our experimental observation of τ_ϕ saturation has undergone extensive experimental checks detailed in Section 2. Corroborative problems in mesoscopics denoting severe discrepancies between experiments and the conventional theories are outlined in Section 3, a connection between these discrepancies and τ_ϕ saturation is made. In the final section, zero temperature decoherence and the role of quantum fluctuations of the environment is put in a broader perspective.

It is argued that zero temperature decoherence observed in low-dimensional electronic systems is important in understanding various low-temperature properties of metals, acceptance of which as an intrinsic effect appears imminent.

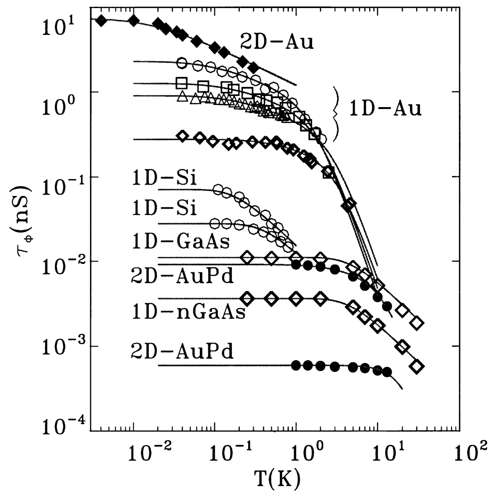

Fig. 1. Measured decoherence time in various mesoscopic systems.

2. Electron and its environments: Measurement of electron decoherence rate

Inside a disordered conductor, an electron undergoes various kinds of interference. The interference of two paths in a doubly connected regime gives an Aharonov–Bohm correction to the electron conductance, which can be modulated periodically as a function of the applied field. Similarly, interference correction arising from paths inside a conductor in a singly connected regime gives reproducible conductance fluctuations. If the interferring paths are a time-reversed pair, then the correction to the conductance gives weak localization which can be suppressed by the application of a magnetic field. Persistent current is also observed due to interference in isolated metal rings.

Interference due to phase coherence in the electron wave function can be studied using any of these effects if the exact dependence of the measured quantity can be explicitly expressed in terms of a decoherence rate $1/\tau_\phi$. Weak localization correction, though the least exotic of the effects mentioned above, gives a single-parameter estimate of decoherence rate $1/\tau_\phi$ without any further assumption regarding the effect. Physically, it is meaningful then to imagine the breaking of time-reversal symmetry and the emergence of non-unitarity as the suppression of interference between the time-reversed paths by an applied magnetic field.

Fig. 1 displays a small representative of a vast body of data available in the literature. What is observed in the experiments is the following: (a) At high-temperatures the decoherence rate $1/\tau_\phi$ is temperature-dependent due to various mechanisms such as electron–phonon and electron–electron interactions, but at low-temperatures the rate inevitably saturates, suggesting the onset of a temperature-independent mechanism. (b) The limiting rate $1/\tau_0$ and the temperature at which it dominates vary over a wide range depending on the system, though a one-to-one correlation with the sample parameters such as the diffusion constant D, or resistance per unit length R/L can be made very accurately [5–8].

A compilation of some saturation data in various systems is contained in Refs. [5,7,8]. In view of these experiments it seems plausible that the observed saturation could be a real effect. Such a hypothesis must be thoroghly investigated, since the saturation of decoherence rate suggesting an intrinsic decoherence is known to have serious consequences. To that end, we have performed various control experiments which suggest that this limiting mechanism is not due to any artifacts and is intrinsic. Extensive checks for the role of various artifacts include the following:

2.1. Heating of the system

Loss of thermal contact of the electron in the sample with the cryostat would imply that the temperature of the sample is locked at the apparent saturation temperature T_0. In the experiment, the electron temperature was determined by measuring the electron–electron interaction (EEI) correction to the conductivity [4] at a magnetic field strong enough to quench weak localization. Electron temperature was found to be in equilibrium with the cryostat to within a temperature [5] of an order of magnitude less than T_0.

2.2. Magnetic impurities

Magnetic impurities such as iron(Fe) in a host metal of gold(Au) were shown not to cause saturation [5], contrary to an earlier notion and consistent with other experiments [9,10]. A detailed study [11] revealed interesting properties of Kondo systems in quasi-1D systems, different from the anticipated behavior for the bulk Kondo systems.

2.3. External high-frequency noise

Initial checks [5], confirmed by subsequent controlled experiments, showed that externally generated high-frequency (HF) noise [12] did not cause dephasing before heating the sample [13] to a substantially higher temperature. A similar control experiment on the saturation of $1/\tau_\phi$ in quantum dots reached the same conclusion [14].

2.4. Two-level systems

Recently, an argument [15] was made that nonmagnetic impurities, which in principle give rise to a dynamic or time-dependent disorder, could be responsible for the observed saturation; such defects, usually modeled as two-level systems (TLS), result in the usual low-frequency $1/f$ noise in conductors. For the following reasons, TLS can be ruled out as the effective environment in our experiments: (a) A typical level of noise power of 10^{-15} W at ~ 1 GHz ($\omega \sim \tau_0^{-1}$), required for dephasing [10,11], would suggest a power level of 1 μW or higher at low-frequencies (1 mHz–10 Hz). At such high-power levels one would anticipate the observation of low-frequency switching or hysteresis. Neither phenomenon was observed in our experiment on timescales of months. (b) Another reason for the TLS to be ineffective in our gold samples is the signature of mesoscopic dimensions in the temperature dependence, contrary to an expected bulk dependence as in any "Kondo-like" theory. (c) In the model [15], $\tau_\phi \propto T^{-1}$ in the temperature-dependent regime, whereas in the experiment $1/\sqrt{T}$ dependence was observed [5] for most of the metallic samples.

Another construct based on the presence of dynamical nonmagnetic impurities or TLS [16] suggests that the coupling between the TLS and the electron in a metal could give finite scattering even at $T = 0$ in the non-Fermi-liquid regime, i.e. below the corresponding Kondo temperature T_K. In this clever construct it is expected, above and beyond the anticipated behavior of TLS discussed earlier, the observed saturation rate will be non-unique and history dependent. But no dependence on history or on annealing was observed over a period of months in our experiments. For these reasons two-level systems are not thought to be relevant to our observed saturation.

2.5. Openness to external phonons in the leads

This nonequilibrium effect arises because of the contact leads to the sample, necessary for measurement. It has been suggested [17], based on earlier arguments [18,19], that due to electron–phonon coupling phonons in the leads exist as an inevitable extrinsic environment. The associated phonon emission process gives an effective lifetime to the electron. It is argued that low-temperature saturation is determined by the contact geometry and configurations, and the dependence at high-temperature is determined by material properties. First, in our experiments, in anticipation of such a possibility, the 2D contact pads were fabricated at least a length of 3–5L_ϕ away from the four-probe part of the sample. Leads to the 2D pads of this length had the same geometry as the sample itself. The effect of 2D pads in the weak localization traces was not detected, and the traces were very different from the 2D weak localization functional form.

For the high-temperature part, a large body of data compiled in Refs. [5,7,8] shows the lack of material dependence of τ_ϕ. The dependence [17] is due to very different diffusion constants and other sample parameters in the systems compared. Finally, description of the saturation value in terms of only intrinsic parameters of the sample [5–8] argues against the effectiveness of the proposed mechanism in our experiments.

2.6. Other artifactual environments

There are suggestions that gravity [20] is an inevitable environment, making every system essentially open. It has also been argued that the nuclear magnetic moment of gold — representing nuclear degrees of freedom — may provide an effective environment for temperature-independent decoherence. The last two suggested mechanisms have been ruled out by incorporating experiments on different materials, and by the observation of the obvious parametric size dependence in the same material (Au) [5].

After considering most of the extraneous effects it was concluded that the observed saturation of τ_ϕ in our experiments is an intrinsic effect.

3. Manifestation of zero temperature decoherence in mesoscopic physics

If the premise is assumed, for the sake of arguments in this section, that the temperature-independent dephasing of electrons is intrinsic, then the saturation of τ_ϕ must manifest itself ubiquitously in low-dimensional electron systems by behavior including but not limited to low-temperature saturation of the appropriate physical quantity.

3.1. Saturation of τ_ϕ in all dimensions

The data in Fig. 1 show saturation of τ_ϕ in quasi-1D and 2D disordered conductors. Recent experiments report the observation of saturation in τ_ϕ in open ballistic quantum dots, representing 0D systems, below a temperature of 100 mK in one set of experiments [14], and below 1 K in another set of experiments [21]. τ_ϕ in 3D amorphous Ca–Al–X (X = Au,Ag) alloys also saturates below 4 K [22].

3.2. Other manifestations in quasi-1D: persistent current and e–e interaction

It is understood that the saturation of τ_ϕ would imply a similar saturation in the electron–electron interaction (EEI) correction [23] to the conductivity, measured at a finite field with the weak localization contribution quenched. The saturation temperature for EEI correction should be lower, and comparable to $\hbar/\tau_0$. Experiments [24] do show such a saturation and a strong correlation between the EEI saturation temperature and τ_0.

Saturation of τ_ϕ also offers solution to the problem of persistent current in normal metals [25], namely that the observed current is too large and diamagnetic. In experiments, the range of temperature in which a persistent current is measured is indeed the same where τ_ϕ is saturated. Intrinsic high-frequency fluctuations – responsible for τ_ϕ saturation – will imply the presence of a non-decaying diffusion current, corresponding to the persistent current with a size comparable to $e/\tau_D \equiv eD/L^2$.

3.3. Transition from weak-to-strong localization in quasi-1D conductors

A finite decoherence rate at zero temperature is expected to stop the Thouless transition [26] from weakly to strongly localized states. This disorder-driven transition to localized states in quasi-1D, with the characteristic length scale of ξ has two possible courses depending on the competing length scale of diffusion characterized by L_ϕ at $T = 0$: (i) Complete suppression (no transition at all, $L_0 \ll \xi$); (ii) Inihibition (activation with decreasing temperature — denoting a transition to a strongly localized state — inevitably saturates: $L_0 \sim \xi$ in the experimental range). Both aspects have been well documented in experiments on δ-doped GaAs wires [27] and GaAs–Si wires [28].

3.4. Lack of one-parameter scaling

One-parameter scaling theory of localization [29], the foundation for the theory of low-dimensional conductors, requires phase coherence length to diverge as a negative power of T: $L_\phi \propto T^{-p/2}$. A finite temperature-independent decoherence length L_0 immediately suggests breakdown of the one-parameter scaling theory. Experiments on Si–MOS systems have convincingly shown [30] the lack of one-parameter scaling.

3.5. Metallic behavior in 2D systems

In contrast to the conventional theory of metals [29] which purports that 2D systems at $T = 0$ become insulators with zero conductivity, recent experiments [31] find metallic behavior at low-temperatures. Furthermore, at low-temperatures the conductivity of the metallic state is observed to saturate with a finite value [32]. However, a nonvanishing decoherence of the electron would suggest finite diffusion of the electron, and hence no Fermi-liquid ground state or insulating state with zero conductivity at $T = 0$. With decreasing temperature, localization driven by disorder is suppressed, sometimes even before the onset by zero temperature dephasing depending on the competition.

Formation of insulating states is inhibited by diffusion induced by the zero temperature decoherence, irrespective of the initial states. The quantum-hall-to-insulator transition is in some sense similar to the transition in quasi-1D or 2D conducting systems. A quantum-hall system beyond a critical field B_c becomes insulating with a diverging ρ_{xx} as T is reduced [33]. However, formation of this insulating state is expected to be inhibited with a low-T saturation of the increasing ρ_{xx}. Such a saturation has been observed [34], and, on the basis of a recent theory [35], it is related to a finite dephasing length at low-T. This may perhaps be the size of the puddle in the quantum-Hall liquid. Likewise in superconductor-to-insulator transition in 2D a-MoGe films a similar leveling of the resistance was observed [36] with the conclusion that the saturation is due to the coupling to a low-temperature dissipative environment [37].

4. Counterpoint to conventional theories

The conventional theory of metals, specifically in low dimensions, is based on the scaling laws of localization [29] augmented by the perturbative treatment of interaction [4]. The very nature of these theories requires that the phase coherence length diverge with decreasing temperature according to a power law, $L_\phi \propto T^{-p/2}$, for some positive p. The early phenomenological motivation of such a diverging form at low-T was formalized in a perturbative calculation of dephasing length [38,4]. The structure of the Fermi-liquid picture, that the electron interaction can be treated as low-lying excitations of a non-interacting system while maintaining the Fermi-liquid ground state at $T = 0$, is fully retained even in the presence of disorder at low dimensions.

Our experimental observation of τ_ϕ, or equivalently L_ϕ, saturation argues against the premise of the conventional theory, and it contradicts the supporting theory [38] of electron dephasing in low dimensions. In the last two sections, a phenomenological case is made against the premise of the conventional theory. In the following, we briefly discuss the lack of validity of these theories at low-temperatures.

Let us just consider the electron–phonon interaction for the sake of the argument. In a conductivity experiment only the scattering rate of the electron is measured, which includes electron–phonon scattering. Traditionally, the relevant phonon states available for an electron to scatter off depends on temperature T via thermal population. As $T \to 0$, this population shrinks to zero, making the scattering rate of the electron vanish. By this argument most scattering mechanisms yield vanishing scattering rate at $T = 0$, where the states to be scattered off are thermally populated. Non-thermal scattering processes obviously do not have to vanish at $T = 0$. The phase shift in the electron wave function $\delta\phi$ arising out of electron scattering, say off the phonons in a phonon bath, is random ($\langle \delta\phi \rangle = 0$) and on averaging it produces a dephasing effect as a suppression of the interference term by a factor $e^{-t/\tau_\phi} \equiv \langle e^{i\delta\phi} \rangle$. This indicates that (a) phase shifts arise only in presence of a thermal population, and (b) the bath of phonons itself does not undergo any change which might have an effect or back reaction on the electron; in other words, there is no entanglement between the electron and the bath. The last two statements are often phrased differently: the electron acquires phase shifts due to its coupling to equilibrium fluctuations of the bath, and the vanishing population through which T enters in the equation has to satisfy the law of detailed balance.

This is a point of view, and a limited one at best, for the following reason. If one starts with a ground state of the electron and the ground state of the environment and the coupling is turned on, then the product state evolves in such a way, even at zero temperature, that after a certain time the electron is no more in its ground state entirely; there is a fractional probability of finding the electron in its ground state. In other words, the electron can be described only by a mixed state of both the environmental variables and the electron variables. The electron can be measured only after the integration of the irrelevant environmental variables, the very process that introduces decoherence.

What is measured in above-mentioned experiments is not a property of the combined system of the electron and environment. In the measurement process the environmental degrees of freedom are averaged out, the effect of averaging is still retained in the measured quantity. Thus, the electron cannot be considered to be a closed system, and the notion of a unique ground state in such a case is meaningless.

An electron must exhibit zero temperature decoherence if it is coupled to a phonon bath; the problem is isomorphic to the Caldeira–Leggett model which does indeed show zero temperature decoherence. The same is true for an electron coupled to a fluctuating electromagnetic field, representing electron–electron interaction, in spite of complications due to the Pauli exclusion principle. To summarize the case against conventional theories, (a) experimental evidence is overwhelmingly against, (b) a quantum mechanical treatment of the problem does give agreeable results, (c) certain other outstanding problems can be understood with the notion of zero temperature decoherence, and finally (d) the basic theory of decoherence in an exactly solvable model of Caldeira–Leggett is contrary to the conclusions of these theories [39].

5. Endnotes: quantum fluctuations and decoherence

To explain the results of the experiments [5], it was suggested [6] that high-frequency fluctuations of quantum origin could indeed cause the saturation. Following the well-established concept [38], of dephasing of an electron by "classical" electromagnetic field fluctuations, it is reasonable to consider decoherence due to the coupling of the electron to quantum fluctuations of the field. Such an extension is not new, and is well known in quantum Brownian motion [2]. A particle coupled linearly to a bath of oscillators, all in their individual ground states, with a linear coupling, shifts the equlibrium position of individual oscillators without exciting them. The resulting back reaction on the particle causes both dissipation and decoherence even at absolute zero, the latter quantified by the decay of off-diagonal elements of the reduced density matrix in the long time limit [2,40–45]. A similar construct has been made earlier [42] in the mesoscopic context. The cut-off dependent result is universal in the mesoscopic models as well as in quantum brownian motion models.

The initial back-of-the-envelope calculation [6] surprisingly described the saturation rate observed in many experiments. The rigorous and commendable calculations [7] which verified the notion have been severely criticized [46,47]. Though the latter calculations are self-consistent [46], the theories fail at the starting point. A pedestrian argument against the use of the "law of detailed balance" [46,15] is that it describes only thermal transitions. To understand zero temperature effects one must add a non-thermal part, put in by hand, as is normally done for spontaneous emission in the Einstein rate equation for a laser.

As mentioned in the Introduction, it is the entanglement of the environment with the electron that contributes to the decoherence even though energy exchange is not allowed between the individual non-interacting parts, i.e. the electron and the electromagnetic field modes. The combination is a closed system and does evolve unitarily without decoherence, but the individual parts can remain in mixed states at the same time. In terms of photons, one can imagine exchange of virtual pairs of photons with the field by the electron along two different interferring paths. Such an interpretation is often misunderstood as dressing of an electron or an atom by vacuum fluctuations, and is often a source of confusing debate.

There have been a few parallel developments surrounding the question — whether or not quantum fluctuations can cause decoherence. The role of vacuum fluctuations in decohering atomic coherence has been discussed recently [48]. The decoherence of an electron due to its coupling to vacuum fluctuations has also been previously considered [49–52] with an affirmative conclusion. There was another interesting development on the problem of a quantum limit of information processing pertaining to computation. Starting from a well-known result from black hole entropy theory, a proposal was made suggesting quantum-limited information loss [53], quantified by entropy. This was severely criticized [54] again with the argument that zero-point energy cannot be dissipated as "heat". Though the debate was unresolved [55], since then it is known in the refined description of decoherence [56–59] that a part of the entropy can reside in the correlation. The sum total of entropy of a system, bath and that contained in the correlation is equal to the entropy of the combination. This is a different way of saying that a pure state of the combination is consistent with partial mixed states. All these above-mentioned debates were not settled due to the lack of any experiments. Fortunately, our problem starts from experimental results.

In conclusion, our experiments along with almost all existing experiments on the direct or indirect measurement of decoherence rate are more than suggestive of a non-thermal mechanism, which is in all probability intrinsic. Existence of field fluctuations at frequencies higher than the temperature, irrespective of their origin, can explain various discrepancies in mesoscopic physics. In this paper we briefly discussed how persistent current and electron–electron interaction correction may be affected by the saturation of decoherence rate. Following similar arguments, the experimentally observed formation of metallic states in 2D, lack of universal one-parameter scaling, suppression or saturation of strong localization, and suppression of quantum-hall-insulator transition can be understood. In mesoscopic physics alone, the fundamental role of low-temperature behavior of electron decoherence cannot be overemphasized.

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