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Quantum decoherence of interacting electrons in arrays of quantum dots and diffusive conductors

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Abstract

We develop a new unified theoretical approach enabling us to non-perturbatively study the effect of electron–electron interactions on weak localization in arbitrary arrays of quantum dots. Our model embraces (i) weakly disordered conductors (ii) strongly disordered conductors and (iii) metallic quantum dots. In all these cases at $T \to 0$ the electron decoherence time is determined by the universal formula $\tau_{\varphi 0} \sim g\tau_{\mathrm{D}}/\ln(E_C/\delta)$, where g, τ_{D}, E_C and δ are, respectively, dimensionless conductance, dwell time, charging energy and level spacing of a single dot. In the case (i) this formula yields $\tau_{\varphi 0} \propto D^3/\ln D$ (where D is diffusion coefficient) and matches with our previous quasiclassical results [D.S. Golubev, A.D. Zaikin, Phys. Rev. Lett. 81 (1998) 1074], while in the cases (ii) and (iii) it illustrates new physics not explored earlier. A detailed comparison between our theory and numerous experiments provides overwhelming evidence that zero temperature electron decoherence in disordered conductors is universally caused by electron–electron interactions rather than by magnetic impurities.

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1. Introduction

Quantum interference of electrons in mesoscopic conductors manifests itself in a number of fundamentally important phenomena which can be directly observed in modern experiments. One of them is the phenomenon of weak localization (WL) [1–3]. In the absence of interactions electron wave functions preserve their coherence and, hence, quantum interference remains efficient throughout a large part of the sample making WL a pronounced effect. Interactions between electrons and with other degrees of freedom may limit phase coherence thereby making quantum interference of electrons possible only within a finite length scale L_φ. This so-called electron decoherence length as well as directly related to it decoherence time $\tau_\varphi = L_\varphi^2/D$ (where D is diffusion coefficient) are crucial parameters indicating importance of quantum effects in the system under consideration.

At sufficiently high temperatures quantum behavior of electrons in disordered conductors is usually suppressed due to various types of interactions. However, as temperature gets lower, certain interaction mechanisms either "freeze out" or become less efficient in destroying quantum coherence. As a result, both L_φ and τ_φ usually grow with decreasing temperature and quantum effects become progressively more important.

Should one expect L_φ and τ_φ to diverge in the limit $T \to 0$? While some authors tend to give a positive answer to this question, numerous experiments performed on virtually all kinds of disordered conductors and in all dimensions demonstrate just the opposite, i.e. that at low enough T both decoherence length and time *saturate* to a constant and do not anymore grow if temperature decreases further. The list of corresponding structures and experiments, by far incomplete, includes quasi-1D metallic wires [4–16], quasi-1D semiconductors [17–19],

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carbon nanotubes [20–22], 2D metallic [5,6,23–27] and semiconductor [28–30] films, various 3D disordered metals [26,27,31] and (0D) quantum dots [32–36]. Though dimensions and parameters of these systems are different, the low temperature saturation of τ_φ remains the common feature of all these observations.

Is this ubiquitous saturation of τ_φ an *intrinsic* or *extrinsic* effect? If intrinsic, decoherence of electrons at $T = 0$ would be a fundamentally important conclusion which would shed a new light on the physical nature of the ground state of disordered conductors as well as on their low temperature transport properties. While extrinsic saturation of τ_φ could be caused by a variety of reasons, the choice of intrinsic dephasing mechanisms is, in fact, much more restricted. There exists, however, at least one mechanism, electron–electron interactions, which remains important down to lowest temperatures and may destroy quantum interference of electrons even at $T = 0$ [4,37].

In a series of papers [37–40] we offered a theoretical approach that allows to describe electron interference effects in the presence of disorder and electron–electron interactions at any temperature including the most interesting limit $T \to 0$. This formalism extends Chakravarty–Schmid description [3] of WL and generalizes Feynman–Vernon–Caldeira–Leggett path integral influence functional technique [41–44] to fermionic systems with disorder and interactions. With the aid of our approach we have evaluated WL correction to conductance and electron decoherence time in the limit $T \to 0$ and demonstrated that low temperature saturation of τ_φ can indeed be caused by electron–electron interactions. Our results allowed for a direct comparison with experiments and a good agreement between our theory and numerous experimental data for τ_φ in the low temperature limit was found [37,38,45,46]. In particular, for quasi-1D wires with thicknesses exceeding the elastic electron mean free path l at $T \to 0$ our theory predicts $\tau_\varphi \propto D^3$, where D is the diffusion coefficient. This scaling is indeed observed in experiments for not very strongly disordered wires typically with $D \gtrsim 10\,\mathrm{cm}^2/\mathrm{s}$ (see Section 6 for more details).

On the other hand, for strongly disordered structures with smaller values of D this scaling is not anymore fulfilled and, moreover, an opposite trend is observed: τ_φ was found *to increase* with decreasing D [27,31,47]. This trend is *not* described by our expressions for τ_φ [37,38]. Another interesting scaling was observed in quantum dots: saturated values τ_φ were argued [36] to scale with the dot dwell times τ_D as $\tau_\varphi \approx \tau_\mathrm{D}$. Our theory [37,38] cannot be directly used in order to explain the latter scaling either.

In order to attempt to reconcile all these observations within one approach it is necessary to develop a unified theoretical description which would cover essentially all types of disordered conductors. It is worth pointing out that the technique [38–40] is formally an exact procedure which should cover all situations. However, for some structures, such as, e.g., quantum dots and granular metals, it can be rather difficult to directly evaluate the WL correction within this technique for the following reasons.

First of all, our description in terms of quasiclassical electron trajectories may become insufficient in the above cases, and electron scattering on disorder should be treated on more general footing. Another—purely technical—point is averaging over disorder. In our approach [37–40] it is convenient to postpone disorder averaging until the last stage of the calculation. In some cases—like ones studied below—it might be, on the contrary, more appropriate to perform disorder averaging already in the beginning of the whole consideration. In addition, it is desirable to deal with the model which would embrace various types of conductors with well defined properties both in the long and short wavelength limits. This feature will help to construct a fully self-contained theory free of any divergencies and cutoff parameters.

Recently [48] we made a first step towards this unified theory. Namely, we adopted a model for a disordered conductor consisting of an array of (metallic) quantum dots connected via junctions (scatterers) with arbitrary transmission distribution of their conducting channels. This model allows to easily crossover between the limits of a granular metal and that with point-like impurities and to treat spatially restricted and spatially extended conductors within the same theoretical framework, as desired. Within this model in Ref. [48] we analyzed WL corrections to conductance merely for non-interacting electrons and included interaction effects by introducing the electron dephasing time τ_φ just as a phenomenological parameter. Systematic analysis of the effect of electron–electron interactions on weak localization within this formalism will be developed in this paper. This approach will allow to microscopically evaluate τ_φ for all types of disordered conductors under consideration.

The structure of our paper is as follows. In Section 2 we will discuss qualitative arguments illustrating the role of scattering and interactions in electron dephasing. In Section 3 we introduce our model of an array of quantum dots and outline a general theoretical framework which is then employed in Sections 4 and 5 for rigorous calculations of WL correction to conductance and electron decoherence time in the presence of electron–electron interactions. A detailed comparison of our results with numerous experiments performed in various disordered conductors is carried out in Section 6. A brief summary of our main results and conclusions is presented in Section 7.

2. Qualitative arguments

Before turning to a detailed calculation it is instructive to discuss a simple qualitative picture demonstrating under which conditions electron dephasing by interaction is expected to occur.

Consider first the simplest system of two scatterers separated by a cavity (quantum dot, Fig. 1) The WL