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# The formation of the angular dependences of the inelastically scattered electrons by their quantum transport near the surface of a solid

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**Abstract**

Features of the formation of angular dependences of electrons emitted from a disordered solid and experiencing inelastic scattering have been considered. Such fine details of the dependences are formed by the processes of quantum transport of emitted particles. We took the cases of two-particle and multi-particle inelastic processes. Qualitative and quantitative assessments of the relative contributions of different groups of particles were carried out. The effects related to quantum electron transport were shown to be generally more pronounced in the case of registration of electrons generated inside the solid in the inelastic scattering of particles of the primary beam. This is true both for the electrons generated by ionization processes and Auger electrons. The obtained results point to the possibility of using this effect in applied electron spectroscopy.



*Keywords:* Electron scattering; Quantum transport; Weak localization; Surface of a solid.

## Introduction

Determining the physical causes of the formation of the corrections to the collision term of the Boltzmann kinetic equation that are associated with the phenomenon of quantum interference is one of the most interesting and challenging subjects in the field of particle scattering. This problem has been studied both in its classical wave aspect and from the quantum perspective, especially since the start of the trend to derive the kinetic Boltzmann equation from the quantum equation for the density matrix. As it turns out, describing radiative transfer based on wave equations and based on conventional transport theory does not always yield matching results. This difference is most evident when describing the backscattering of electromagnetic waves from inhomogeneous media [1–6]. An increased probability of such scattering and the manifestation of weak localization of electrons in disordered media have the same physical cause. Explaining these effects from the perspective of the particles is related to their quantum transport.

Quantum transport of electrons means that they experience collisions while moving in a medium, with each subsequent collision starting before the previous one has ended. This motion can occur both under

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the action of an applied external field, and because of the initial kinetic energy stored by the electrons. The aspect of quantum transport associated with the phenomenon of weak localization is universal; it manifests itself in the well-known problems of conductivity theory and in problems on radiation and mass transfer. If the motion of electrons or photons occurs in a disordered medium, such interference leads not only to quantitative corrections to the results obtained with the help of the Boltzmann equation, but to qualitatively new effects. In the best-known case, these effects are related to Anderson localization [7,8].

In recent years, quantum transport and, in particular, weak localization have been heavily studied both theoretically and experimentally. The negative anomalous magnetoresistance in solid state physics and weak localization of light in classical electrodynamics can be considered the two key experimentally observed facts proving the existence of peculiar interference phenomena observed during scattering in disordered media.

Normal weak localization of electrons is caused by their elastic collisions with the scattering centers. Up until now, it has been assumed that inelastic collisions suppress the quantum interference processes related to preserving the phase memory of electrons. Inelastic scattering determines the dissipative processes during the motion of particles in the media. For a long time, these dissipative processes were believed to be the main result of inelastic particle scattering in solids. While this is certainly true of the normal weak Anderson localization, it turns out that inelastic processes can also be a source of new quantum interference phenomena; this indicates that a new type of weak localization could possibly exist.

Electrons with energies ranging from tens of eV to a few keV clearly exhibit a new type of quantum transport, as shown in Refs. [3,9,10]. This is due to the fact that, in contrast to the normal weak localization corresponding to an increase in electron backscattering into a very narrow range of solid angles of about $\lambda\!\!\!^{-}/l$, the preferential scattering of electrons occurs in a wide range of angles: $(\lambda\!\!\!^{-}/l) \cdot (E/\hbar\omega)$. Here $\lambda\!\!\!^{-}$ is the de Broglie wavelength, $l$ is the electron mean free path, $E$ is the electron energy, $\hbar\omega$ is the energy lost by the electron.

The possibility of observing a new type of quantum transport in an inelastic channel was predicted on the assumption that the motion of electrons occurs in such a manner that in addition to inelastic scattering, the electrons experience single scattering through a large angle. Later it was revealed that the new type of weak localization is also preserved under multiple elastic scattering through arbitrary angles [3]. It was also established that the role of the surface in the theory on the new type of quantum transport is not destructive, and may even in some cases be determining. This preserved localization and the role of the surface are the key factors regarding the manifestations of the new type of weak localization in natural processes, as well as in the possibility of directly observing the effect.

It was previously demonstrated that it was possible to observe the effect described when detecting the electrons emerging from a solid irradiated by a beam of primary electrons of intermediate energies (from tens of eV to tens of keV).

When discussing the quantum transport effects that interest us, we are going to focus on two types of particles emerging from a solid into a vacuum.

The first type is the electrons in the primary beam, which can scatter in a crystal both elastically and inelastically (the latter kind of scattering can be single), and then exit the medium.

The second type is the electrons generated by the primary beam within a solid, then experiencing elastic and inelastic collisions during the motion towards the surface. The difference between the secondary-emission electrons emerging from the solid body and experiencing the new type of weak localization, and the electrons of the first type with respect to quantum transport processes is in the different influence of the surface and the near-surface area of the solid on the formation of the angular dependences of particles. The performed analysis of quantum transport in these two types of particles allowed to investigate in detail the role of the solid's surface in the new type of weak localization processes.

## New type of weak localization in surface electron emission

In order to better identify the influence of the effect on particle scattering, let us consider the two described types of electrons with approximately the same energies. This will, wherever possible, eliminate the nonessential energy differences in the quantitative characteristics of surface influence on the scattering processes.

A particle passes directly near the surface twice before exiting the medium; the surface of the sample should then have a significant effect on the scattering of the primary beam electrons experiencing both elastic and inelastic scattering when interacting with the