# A PRECISION TEST OF DECOHERENCE

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ABSTRACT: The motion of a charged particle over a conducting plate is damped by Ohmic resistance to image currents. This interaction between the particle and the plate must also produce decoherence, which can be detected by examining interference patterns made by diffracted particle beams which have passed over the plate. Because the current densities within the plate decay rapidly with the height of the particle beam above it, the strength of decoherence should be adjustable across a wide range, allowing one to probe the full range of quantum through classical behaviour.

## Introduction

Charged particles passing close to conducting surfaces have been investigated in tests of the Ahoronov-Bohm effect [1]) and the equivalence principle [2]). The phenomenon of dissipation due to electrical resistance to image currents in the conductors has been investigated extensively, but the effects on the particles of the concomitant resistor noise have been discounted [3]). Among these effects will be decoherence[4]). We propose that the strong dependence of the image current densities to the easily varied parameter of trajectory height makes the motion of a charged particle over a conducting plate an excellent precision test for our understanding of decoherence.

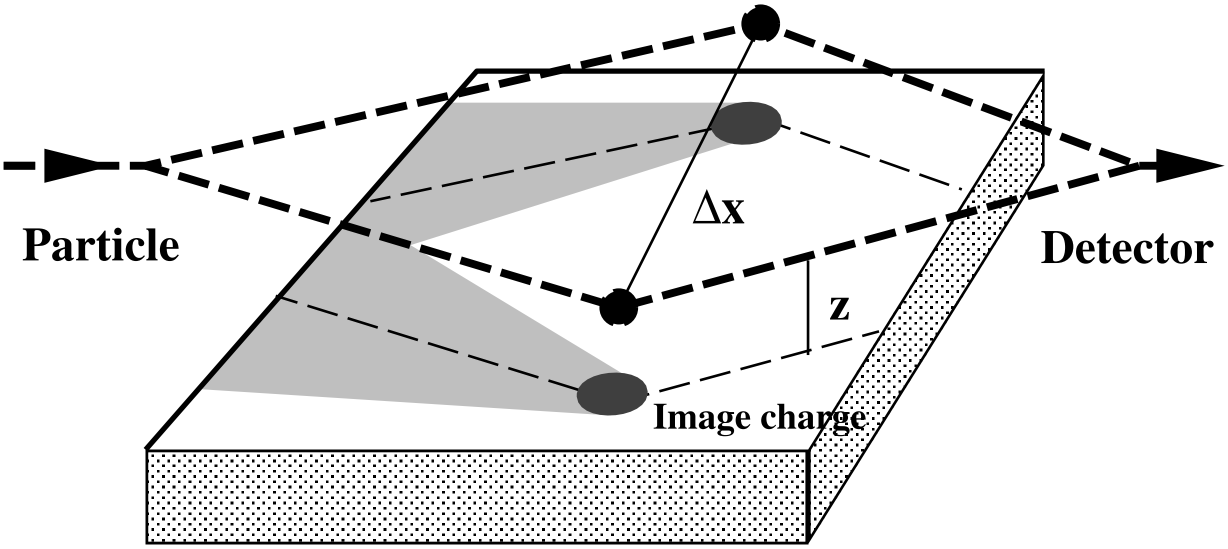


**Figure 1:** Sketch of proposed system. The heavy dashed lines indicate two trajectories of the particle over the conducting plate. The large shaded regions represent the disturbance in the electron gas inside the plate.

## Decoherence

If a charged particle passes over a conducting plate along some trajectory, it induces an image charge on the surface of the conductor, which moves with the particle by inducing bulk currents within the body of the conductor [5]. These bulk currents encounter Ohmic resistance, which is primarily due in metals at room temperature to the scattering of coherent electron flow by thermal phonons. The passage of the charged particle along a trajectory over the conductor thus leaves a wake of disturbance in the electron and phonon gas beneath it.

After the charge has crossed the plate (and continued on its flight towards a detector), the disturbed state of the conductor remains as a record of the charge's passage (and in fact, of the particular path that it took). Quantum mechanically, this means that the state of the electron gas and of the charged particle must be described together by a joint wave function. The contribution to this wave function from a single trajectory $\mathcal{T}$, at the end of which the particle is at position $Q$, can be written as

$$|\Psi_{\mathcal{T}}\rangle = |Q\rangle\,|\psi_E[\mathcal{T}]\rangle\ .$$

According to Feynman's picture of quantum evolution, the final state of the system is found by a weighted sum of such states $|\Psi_{\mathcal{T}}\rangle$ over all trajectories $\mathcal{T}$ which the particle may have taken. Quantum mechanics then predicts the probability of finally observing the particle at a given position $Q$ (without measuring any properties of the conducting plate) to be

$$\begin{aligned} P(Q) = &\sum_{Q_i,Q_i'} \phi(Q_i)\phi^*(Q_i') \\ &\quad\times \sum_{\mathcal{T}}\sum_{\mathcal{T}'} e^{\frac{i}{\hbar}(S[\mathcal{T}]-S[\mathcal{T}'])}\langle\psi_E[\mathcal{T}']|\psi_E[\mathcal{T}]\rangle\ , \end{aligned}$$

where the sums are over trajectories $\mathcal{T}$ or $\mathcal{T}'$ in which the particle begins at $Q_i$ or $Q_i'$ and ends up at $Q$, and $\phi(Q_i)$ is the wave function describing the initial state of the particle.

If this initial state is a superposition of two distinct localized states, such as is produced by a double slit, cross terms in (99) can produce a probability distribution $P(Q)$ which is not the classical "two lumps", but an interference pattern characteristic of wave mechanics. The familiar textbook case in which this possibility is fully realized occurs only when $\langle\psi_E[\mathcal{T}']|\psi_E[\mathcal{T}]\rangle \rightarrow 1$, so that the conducting plate does not effectively distinguish between different particle trajectories. In general, though, this inner product is *not* unity, and trajectories that are far apart may disturb the plate's electron gas in such different places that the inner product of the electron states will be negligible. Interference between these trajectories will therefore be suppressed, and the final probability distribution of the particle will thus be altered towards the classical limit.

This phenomenon is an example of the process known as *decoherence*[4]), which is believed to play a crucial role in enforcing the effective classicality of macroscopic physics, and is thought to be the greatest challenge facing such hypothetical advanced technologies as quantum computing[6]). A precision test of decoherence is thus highly desirable.

## Precision Test of Decoherence

The system of charged particle and conducting plate is suitable for a precision test of decoherence, because the strength of their interaction is adjustable over a wide range. Calculations using classical electromagnetism, for a charge $Q$ moving over the plate at a height $z$ and constant velocity $v$ show a rate of Joule heating in the conductor which is

$$P_C = \frac{Q^2 \rho v^2}{16\pi z^3} \ ,$$

where $\rho$ is the specific resistivity of the plate. This implies an Ohmic dissipation rate proportional to $d^{-3}$: we can compute the relaxation time $\tau_r$ to be

$$\tau_r = \frac{v}{\dot{v}} \sim \left(\frac{z}{10^{-4}\mathrm{m}}\right)^3 \times \begin{cases} 2 \times 10^3 \mathrm{s} & \text{electron} \\ 3\frac{M}{Q^2} \times 10^6 \mathrm{s} & \text{ion} \end{cases}$$

where $M$ is the ion mass in units of proton mass, and we take the resistivity $\rho$ to be on the order of $10^{-6}\Omega$m. (This rather high resistivity is possessed by manganese at room temperature; since a resistivity a few orders of magnitude higher still could be even more convenient, alloys or semi-conductors might be contemplated instead of a pure metal.)

(Note that adding a thin layer of insulator on top of the conducting plate will actually produce dissipation proportional to the inverse *fourth* power of $z$ [2,5]). The sensitivity to $z$ that we are considering can thus be made even greater; but we will not discuss this option here in detail.)

These calculations are classical, and a proper quantum treatment is certainly required to make serious theoretical predictions concerning decoherence in this system. We must consider the unitary evolution of phonons and a nearly free electron gas as a charge passes over the plate on an arbitrary trajectory. The electromagnetic field may presumably be treated classically, and for sufficiently slow particles an adiabatic expansion to first order in the particle speed will probably suffice. After the charge has crossed the plate, the direct perturbation of the conductor by the charge will cease, but the resistive interactions among the conductor's constituents that were driven by the charge, as it dragged an image current of electrons through the mill of thermal nuclei, will have brought the conductor into a final quantum state that depends on the particle's trajectory. The inner product between two such states must then be computed.

For the present brief communication, we merely suppose that the full quantum calculation will recover both the classical dissipation rate, and the result (typical in linear systems) that decoherence rates are proportional to it. As a zeroth order approximation that should be reasonable at room temperature, we will assume that the decoherence time scale $\tau_d$ is given by the formula for a completely linear model at high temperature[7]),

$$\tau_d = \tau_r \left(\frac{\lambda_{dB}}{\Delta x}\right)^2 ,$$

where $\lambda_{dB} \equiv h/\sqrt{2mk_BT}$ is the thermal de Broglie wavelength, and $\Delta x$ is a length scale characterizing the difference between the two quantum states that are to decohere. In our case, we will take this scale to be the distance between Feynman trajectories across the plate, which could perhaps be of order $10^{-4}$m.

Since $\tau_r$ is proportional to the particle mass, we therefore estimate the same decoherence time for singly charged ions and electrons:

$$\tau_d \sim \left(\frac{z}{10^{-4}\mathrm{m}}\right)^3 \times 10^{-5}\mathrm{s} .$$

If we assume that our charged particles will traverse a conducting plate that measures a centimeter across, flying at a speed on the order of a kilometers per second, the decoherence time will be on the order of the time of flight for $z \sim 0.1$ mm. By varying the trajectory height $z$ we should therefore indeed be able to probe the full range from negligible to strong decoherence.

## Conclusion

There are a number of aspects of decoherence which one would like to have clarified by a precision experiment. One of the most interesting is the dependence of the decoherence of two trajectories on the spatial distance between them. In simple linear models, decoherence has a Gaussian profile with distance, but in general we expect that this profile will instead approach some non-zero constant value at large distances [8,9]). In the particle and conductor system, we expect the length scale at which this saturation occurs to be set by the correlation length in the electron gas.

By varying the separation between the two slits through which the particle is coherently passed before crossing the plate (or using different crystal lattices for diffraction, if a low intensity electron beam is used instead of a stream of ions), one can vary the distances over which quantum interference of trajectories is important in determining the final $P(Q)$. This should allow one to probe the dependence of decoherence on spatial separation. By also varying the overall strength of decoherence, through the trajectory height $d$, we can investigate decoherence in a two dimensional parameter space, and provide a stringent test of decoherence in a system which is theoretically non-trivial. Unlike set-ups deliberately designed to mimic simple theoretical models for decoherence, the particle crossing a conducting plate will thus be able to stretch our theory: it is a real precision test of decoherence.

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French title and abstract:

UN TEST PRÉCIS DE DÉCOHÉRENCE

Le mouvement d'une particule chargée au dessus d'un un conducteur plat est dissipée par la résistance Ohmique due aux courants images. Cette interaction entre la particule et le conducteur produit aussi de la décohérence, qu'on peut détecter dans les franges d'interférence formées par des faisceaux de particules qui ont traversé le conducteur. Puisque la densité de courant dans le conducteur est très sensible à la hauteur de la particule, on peut controller le degrée de décohérence, et à cette façon étudier le phénomène de décohérence du domaine quantique jusqu'à celui classique.