Einselection in Action: Decoherence and Pointer States in Open Quantum Dots

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Recent work on the role of decoherence has suggested that the decay of quantum effects is governed by a discrete set of pointer states, which affect the quantum to classical correspondence. We show that the conductance oscillations exhibited by open quantum dots are governed by a discrete set of stable quantum states which have the properties of the pointer states, and which are closely related to trapped classical orbits in the open dot.

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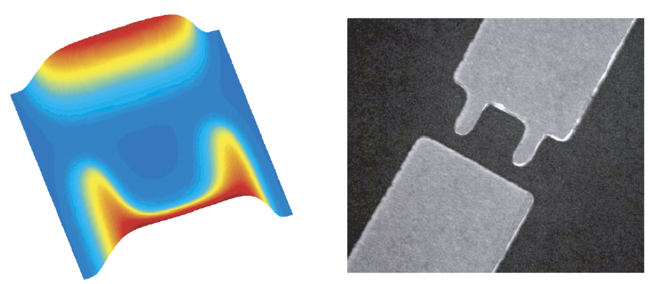
The manner in which quantum states of a system evolve into classical states has been a point of significant discussion in quantum measurement theory for quite some time [1]. In particular, open quantum systems interact with an environment, which may be a bath or reservoir, but also may be the measurement system itself, whose output is presumed to be classical in nature. The manner in which the quantum properties of the system are revealed in the classical results of the measurement, as well as the manner in which these quantum properties evolve into intrinsic classical properties, has been the focus of investigation since the formulation of quantum theory. One interpretation, which explicitly includes the coupled systems, is that of decoherence [2]. Decoherence is thought to be an important part of the measurement process, especially in selecting the classical results, that is, in passing from the quantum states to the measured classical states of a system [3]. However, the description (and interpretation) of the decoherence process has varied widely, but the key is the interaction of the system upon the environment, as well as the interaction of the environment upon the system. Zurek has proposed that the interaction of the system on the environment leads to a preferred, *discrete* set of quantum states, known as *pointer* states, which remain robust, as their superposition with other states, and among themselves, is reduced by the decoherence process [4]. This decoherence-induced selection of the preferred pointer states was termed *einselection* [3]. Recently, it has been argued that the pointer states must be a continuous set of states [5]. In addition to the pointer states, there exists a sea of states that are heavily damped by the decoherence process. If the pointer states constitute a discrete set, then their robustness with respect to decoherence should make it possible to detect them in a measurement process among all the heavily damped states. However, if the pointer states constitute a continuous set, as recently argued in Ref. [5], then not only would their detection in measurement be impossible, but so would any remotely precise measurement on a quantum system with a classical measuring apparatus.

In this report, we discuss a physical system in which we believe the properties of pointer states are observable. Here, we describe the key features of measurements on this system and show how a discrete set of (pointer) states is selected, which provide a measurable conduction oscillation, and which are orthogonal to the majority of quantum states in the system. This system is an open quantum dot, in which the coupling to the environment is mediated by a pair of quantum point contacts [6]. In practice, these dots are realized by applying depletion potentials to lithographically defined gates, which provide lateral confinement of a quasi-two-dimensional electron gas formed at the interface of a GaAs/AlGaAs heterostructure (Fig. 1). This results in the confinement of electrons to a submicron sized ballistic cavity that is coupled to its environment through the quantum point contacts. Conductance through this dot is governed by the transmission and



(a) (b)

FIG. 1 (color online). (a) A perspective view of the confining potential which creates the ballistic quantum dot. The two narrow portions are the quantum point contacts, which are open and pass multiple transverse modes. The central region has a typical dimension that ranges from 0.2 to 1.0 μm. The external environment is an extended quasi–two-dimensional electron gas to which contacts are applied in order to measure the voltage across, and the current through, the quantum dot. (b) A scanning electron micrograph of an actual set of gates. The light colored area is gold metallization to which the voltage bias is applied. The dark area is the surface of the semiconductor layers.

reflection of waves originating in the external environment. Variation of either a normal magnetic field, or the confining potential of the quantum dot itself (by means of gate voltages), produces quasiperiodic conductance oscillations. This coupling of the dot states to the environment is known to produce decoherence within the dot [7,8], which washes out most quantum structure, but a set of states remains robust against this process. Hence, these semiconductor quantum dots are ideally suited for studying the influence of the environment on the energy level spectrum. It is found that the conductance oscillations in these dots arise from a discrete set of stable quantum states, which are only weakly coupled to the environment. These states recur in a nearly periodic manner in the energy spectrum of the dot [9,10]. Moreover, these states are strongly correlated to regular *classical* trajectories in the dot, which lie on an isolated Kolmogorov-Arnold-Moser (KAM) island in the mixed phase space [11]. The spectral width of these states is relatively independent of the environmental coupling strength [12]. Consequently, it seems that these robust states may well be the pointer states in this quantum system.

We have studied a great many such gate-defined quantum dots, with lateral size varying from 0.2 to $> 1.0\ \mu$m, and the results found are quite similar in behavior. As the gate voltage that is used to define the device confining potential is made more negative, the dot is reduced in size and the various energy levels are pushed up through the Fermi energy. This leads to a series of conductance oscillations, which ride on top of a monotonic background. These oscillations become stronger in high quality material and exhibit one, or perhaps two, dominant frequencies that are dot-size dependent. The oscillations disappear for temperatures above a few degrees kelvin. These oscillations should not be confused with universal conductance fluctuations (UCF), which are aperiodic and typically arise in mesoscopic systems due to impurity induced disorder [13]. We have studied these oscillations in surface depletion gate-defined dots [6], etched isolation in-plane gated dots [14], and in etch-defined dots [15], so that the results do not depend upon the relative softness of the potential or the material in which the dot is fabricated. In results in which the magnetic field is varied, the experimental oscillations are characterized by a single dominant frequency, and quantum simulations, as well as classical simulations, yield essentially this same frequency [16], and this frequency is found to scale with the size of the dot [17]. When the gate voltage is varied, these oscillations are also observed, although the actual frequency depends upon both the dot size and the lever arm from the gate voltage to the actual Fermi level motion within the dot [9]. The oscillations often are observed over the entire range of gate voltage and persist to conductance values of 15 e^2/h, which represents a very open dot. Again, the experimental results and quantum simulations (discussed below) yield the same dominant frequency in the dots.

The nature of the quantum states has been investigated through simulation of electron transport through the dots, and the connection of these simulations to atomic force microscope measurements of scarred wave functions in these billiards has recently been demonstrated [18]. These simulations begin by computing the three-dimensional, self-consistent potential profile of the open dot at each gate voltage, from which the conductance is computed using a lattice discretization of the single-particle Schrödinger equation in the effective mass approximation [16]. Here, the open dot is broken into a set of slices across which we translate using a stable, iterative scattering matrix approach. In this way, we can obtain the conductance from the Landauer formula. Finite temperature is included by averaging the conductance traces over an energy range of $k_B T$ with the Fermi function. From these simulations, conductance oscillations are found which agree well with those observed in experiment. In particular, both the number of Fourier peaks which occur in the simulation and their amplitude agree well with the experimental results. From studies of the wave function itself, we find that these peaks correspond to the frequencies at which specific sets of scarred wave functions recur in the dot [16,19]. Decomposition of these scarred wave functions show that they arise from a single eigenstate of the closed dot [20,21]. These particular states are quite stable as the leads are opened to allow stronger coupling to the environment, and in fact seem to be insensitive to this coupling, which agrees with experiments which have demonstrated that the dominant frequency components of the conductance oscillations are extremely stable to variation of the coupling strength over a wide range.

Indeed, we have even observed evidence for these regular oscillations in dots whose leads support as many as 30 propagating modes [22]. In Fig. 2, we show the density of states within a 0.3 μm dot. This is dominated by conductance resonances that move as the bias is varied, which changes the coupling to the environment as well as the dot size. It may be seen that the linewidth does not change significantly as the environmental coupling is increased, even though the resonance is shifted due to the change in the dot size. Indeed, nearby states are completely damped by the environment and uncoupled to the stable state, even though they may be separated by an energy much less than the linewidth (approximately 21 μeV in the figure). For example, the resonance indicated by the arrow in this figure has another closed-dot eigenstate nearby, which is completely damped by its interaction with the environment, so no peak appears in this figure. The wave function of the resonance is shown in inset (b), while the nearby state is shown in inset (a).

We illustrate the lack of coupling to nearby states further in Fig. 3. Here, we expand a portion of Fig. 2, and the darkness of the image relates to the amplitude of

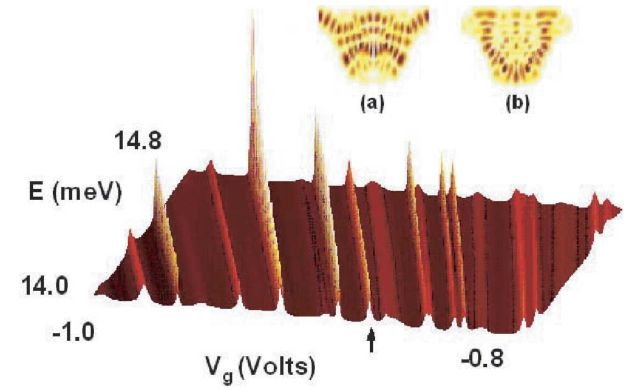


FIG. 2 (color online). The density-of-states peaks, corresponding to conductance resonances, in the quantum dot. The peaks correspond to the stable wave functions in the dot as the gate voltage and Fermi energy are varied. As the gate voltage is varied, the dot becomes more open, but the stable resonances show no increase in width as the coupling to the environment is increased. The arrow indicates a resonance, whose wave function is indicated by inset (b), for which the state of inset (a) is quite near, but is completely damped. The linewidth is about 21 μeV.

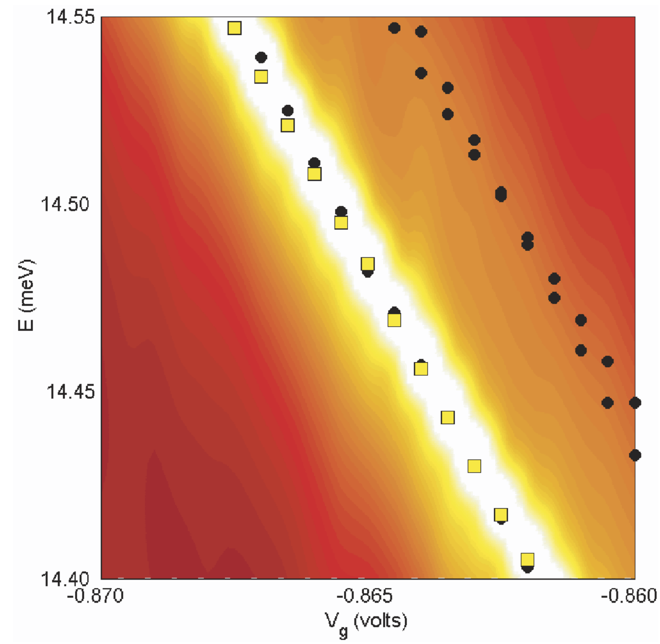


FIG. 3 (color online). An enlargement of a portion of Fig. 1, to show the lack of interaction between the stable wave functions and nearby states. The dark regions are those of lower amplitude in the density of states. The filled (color) squares are the stable resonance indicated by the arrow in Fig. 1 and the wave function of inset (b) to that figure. The black circles are nearby states, which are completely damped by the interaction with the environment.

the density of states. The filled squares are the robust conduction state of Fig. 2(b), while the solid circles are nearby states that are completely damped by their interaction with the environment. While one of these actually crosses the resonant state, there is no interaction as the two wave functions are orthogonal, as may be seen from the wave functions in the insets to Fig. 2. This orthogonality between the pointer state and the nearby state is evident, and presumed to result from the einselection process, where the density matrix becomes diagonal in the pointer states. Decoherence of the other states arises from their strong interaction with the environment, and any excitation of these states results in amplitude leakage to the environment. In a closed system, these background states would also be excited, but they are damped in the open system. We interpret these as contributing to the background conductance, which clearly increases with the degree of opening in the quantum dots, which is further discussed below.

In general, the classical dynamics of these open dots exhibits a mixed phase space behavior [23]. In such studies, a Poincaré section taken normal to the plane of the dot, and passing through the point contacts, exhibits the characteristic sea of chaos and a stable KAM island of orbits which correlate well with the observed gate voltage dependence and with the scarred wave functions [11]. We have argued that the orbits on the KAM island are isolated from the leads and must be coupled to the environment by phase space tunneling [11]. The states on the KAM island exhibit exactly the same periodicity as the stable quantum states discussed above, and these clearly correspond to one another as expected from the einselection theory [2]. Similar observations of the persistence of special states, as the quantum dot is opened, and a strong correlation between these quantum states and classical results, has been seen by Nazmitdinov *et al.* [24] and by Bäcker *et al.*[21]. In fact, we would argue that this result is expected from the einselection theory. Zurek has suggested that "einselected states are predictable: they preserve correlations and hence are effectively classical" [2]. It is this process that takes the quantum states and then correlates them well with what become the classical orbits. On the other hand, the KAM islands are surrounded by a "sea of chaos," which is felt to derive from the background states which are strongly coupled to the environment. More particularly, the occupation of these latter states is lost to the environment as the dot is opened, as they no longer possess any amplitude localized within the dot. The strong decoherence of these states leads to the destruction of their quantum nature and their contribution to the chaotic states yielding the background conductance in the dot. The need to tunnel to the KAM island correlates to the quantum transport process for the stable states, and the resultant Fano lineshape is observed as the conductance oscillation [20]. As discussed above, we recall that, while we measure currents, we physically are measuring the transmission of waves propagating from the environment to the dot, and the dot states modify the reflection and transmission of these waves. Thus, the properties of the dot affect the environment through this modification of the transmission coefficients.

In summary, we find that the conductance oscillations in open quantum dots are related to a set of eigenstates, whose stability is consistent with einselection; i.e., the selection of a set of *discrete pointer states* which are quite stable as the coupling to the environment is increased. The observed pointer states have a narrow line width, and their superposition with nearby quantum states, well coupled to the environment, is heavily damped by decoherence. Moreover, the scarred wave functions of the pointer states strongly resemble the trajectories found in classical simulations of the same self-consistent potential, which suggests these are the route through which the quantum to classical transition occurs.

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