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Time in dissipative tunneling: Subtleties and applications

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HIGHLIGHTS

- Dissipative tunneling through a rectangular barrier is studied.
- Dissipation is treated semiclassically with a frictional force.
- The transmission dwell time of electrons in an $Al/Al_2O_3/Al$ junction is evaluated.
- Temperature dependence of the friction coefficient for Al_2O_3 is provided.

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ABSTRACT

Characteristic features of tunneling times for dissipative tunneling of a particle through a rectangular barrier are studied within a semiclassical model involving dissipation in the form of a velocity dependent frictional force. The average dwell time and traversal time with dissipation are found to be less than those without dissipation. This counter-intuitive behavior is reversed if one evaluates the physically relevant transmission dwell time. Apart from these observations, we find that the percentage of energy lost by the tunneling particle is higher for smaller energies. The above observations are tested and confirmed in a realistic case by applying the dissipation model to study the current–voltage data in a $Al/Al_2O_3/Al$ solid state junction at various temperatures. The friction coefficient for Al_2O_3 as a function of temperature is presented. It is found to decrease with increasing temperature.

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1. A brief history of tunneling time

Quantum tunneling was one of the first bizarre implications of quantum mechanics which at first found its application in the study of alpha decay of radioactive nuclei [1]. It was however soon realized that this phenomenon was not restricted to nuclear physics but was rather a general result of quantum mechanics which is now often used in atomic physics [2], solid state physics [3], chaotic scattering [4], in constructing electron tunneling microscopes and even in branches of science other than physics. Though we are a long way from 1928 when Gamow published his pioneering work [1] and tunneling seems to be a well understood phenomenon with ramifications in many branches of physics, there still exist paradoxes and unanswered questions in this field. For example, the time spent by a particle tunneling a barrier has been a topic of much debate with many different definitions of tunneling times in literature [5–8]. In [6] the authors discussed several time concepts such as the dwell time [9], traversal time [10], phase time [11] and even complex times. Ref. [12] discusses the tunneling of composite particles, resonant tunneling and how the coupling between intrinsic and external degrees of freedom can affect tunneling probabilities. The dwell time formalism for the transition from a quasilevel to a continuum of states was discussed in the context of electron and alpha particle tunneling in [13]. Over the years, many of the time concepts have been put to test in physical situations and the transmission dwell time seems to emerge as the concept with a physical meaning [3,14,15] as well as free of paradoxes [16] and singularities such as those found in the phase time [17].

Dissipative tunneling times have however been explored to a lesser extent historically. In recent years, the authors in [18] have studied the phase and dwell times with dissipation in different contexts [19]. In [18], studying the dissipative tunneling through an inverted harmonic oscillator in context with ion transport at nanoscale, the authors showed that the phase time delay can be estimated directly in terms of a frictional coefficient. The average dwell time, τ_D, through a rectangular potential barrier using a path decomposition technique was investigated in [20] leading to the counter-intuitive result that τ_D in the presence of dissipation becomes smaller than that in a non-dissipative case. The traversal time behavior for a rectangular barrier with energy losses included was described in [21] within a semiclassical approach with dissipation included in the form of a frictional force. Using a somewhat similar approach for dissipation with the latter given by a frictional force as in [10], in the present work we shall show that the counter-intuitive result found in [20] can indeed be explained.

An understanding of the tunneling times with dissipation can prove important for studying the characteristics of solid state tunnel junctions. The importance of the tunneling times in this context was realized in [22] where the author noticed that "the image force acting on an electron tunneling through a dielectric film enclosed by metal electrodes depends on the dielectric constant of the film and the charge build-up in the electrodes which in turn are both dependent on the duration of the tunneling process". In what follows, we shall present the expressions for the dwell and traversal times with dissipation for tunneling through a rectangular barrier. Calculations using these expressions are done in context with an experiment [3] reported in an earlier work by two authors of the present work. Ref. [3] presented a method to extract the average dwell times from tunneling experiments in solid state junctions. The current–voltage (I–V) characteristics reported there are now used in a model that includes the effects of dissipation on tunneling times. Furthermore, the new fits to these data allow us to determine the frictional coefficient for Al_2O_3 from 3.5 to 300 K.

2. Semiclassical dwell and traversal times

The concept of an average dwell time was first introduced in the form of a collision time by Smith [9]. Calling it as the time of residence in a region and using steady state wave functions he defined it as the integrated density divided by the flux in (or out). The lifetime of an unstable state was thereby given as the difference between the residence time with and without interaction. This difference was essentially the time delay introduced due to the formation, propagation and decay of the unstable state. Using the residence or dwell time delay, he went on further to construct a lifetime matrix, $\mathbf{Q}$, which was Hermitian and the diagonal elements q_{ii} gave the lifetimes of unstable