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Short Communication

Response to "The Büttiker–Landauer Model Generalized"

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Støvneng and Hauge have criticized our interpretation of what we have called the traversal time for tunneling. This is a brief rebuttal.

KEY WORDS: Tunneling; traversal time; modulated barrier.

Støvneng and Hauge,[1] in their discussion of traversal time in tunneling, have confirmed some technical details in our work,[2,3] but disagree with our interpretation. Similar points are made by Hauge and Støvneng in ref. 4. We first of all express our surprise that a discussion of this supposedly subtle and controversial question should ignore the growing experimental evidence.[5] We also note, as indicated in ref. 3 and in our earlier publications, that there are by now a large number of contributors whose viewpoints may differ from ours, but not nearly to the extent that is characteristic of ref. 1. The work of Leavens and Aers[6] which generalizes and extends our work particularly deserves to be mentioned in that regard.

The basic motivation for our discussion of a time-modulated barrier is very simple. If a particle spends time interacting with a barrier through which it tunnels, then if the parameters of the barrier are varied slowly

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compared to that time, the tunneling particle should see the instantaneous value of the modulated parameter. If we increase the frequency with which the barrier parameters are modulated, then the particle should make a transition to more complex behavior when, in the time of its interaction with the barrier, it no longer sees only a small fraction of the modulation cycle. We ask at what frequency does this change occur. The result, of course, does not define a precise time, only a magnitude.

Our approach in its original form and its extension in ref. 7, and in the closely related work by Leavens and Aers, emphasizes the barrier height dependence of the *complex* transmission amplitude, including both phase changes and amplitude changes. Our most general result for the traversal time through a single rectangular barrier, obtained in ref. 7, is as follows. In terms of the transmission amplitude $T^{1/2}e^{i\Delta\phi}$, where T is the transmission probability and $\Delta\phi$ is the phase change in transmission through the barrier, the traversal time can be expressed in the form [see Eq. (2.18c) of ref. 7]

$$\tau_T = \hbar[(\partial \ln T^{1/2}/\partial V)^2 + (\partial \Delta\phi/\partial V)^2]^{1/2} \tag{1}$$

It is the sensitivity of the transmission probability as well as that of the phase with respect to a small change in the barrier height V that counts. For energies well above the barrier peak, Eq. (1) tends to the time of classical motion over the barrier. Thus, the extension of our original work in ref. 7, and by Leavens and Aers,[6] has provided a single formalism, applicable to all energies.

A number of authors, including Støvneng and Hauge, still show an affinity for a traversal time which relates *only* to the change in phase, and can be related to the delay of the peak, or delay of the center of gravity, of a wave packet. As stated by us, on a number of occasions: Incoming peaks do not, in any simple physical way, turn into outgoing peaks; similarly for the center of gravity. The advocates of characteristic tunneling times based exclusively on phase have provided no indication that these relate to actual measurements. Instead, the growing experimental literature[5] clearly points to the use of a "clock," in the form of some additional degree or degrees of freedom coupled to the tunneling particle, and the ability of the additional degrees of freedom to adjust to the progress of tunneling. That is more clearly related to our modulated barrier scheme than to something than can be deduced from the one-dimensional wave equation for a time-independent potential.

A critique of our viewpoint can be based on disagreement with our argument about the physical significance of the frequency at which tunneling can no longer be calculated from a quasistatic approximation. The authors of ref. 1 present no discussion of that kind; indeed, their paper depends entirely on formal manipulations. They have applied our techniques to ranges outside of the limitations stated in our papers. Any approach can be made to look silly if it is applied beyond its stated limit of applicability.

A separate paper[8] will discuss the analytical details ignored here, and also will rebut the criticism in ref. 1 of the Larmor clock approach[7] to traversal time and to other times asscoiated with tunneling.

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