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On time and space in potential barriers

Günter Nimtz and Horst Aichmann*
II. Physikalisches Institut, Universität zu Köln,
**Zur Bitz 1, Bad Nauheim/Germany*

Abstract
The energy of a wave packet tunneling a barrier is negative and its wavenumber is imaginary. What happens with time and locality? Several studies have been published resulting in a real time. However, previous theories and recent experiments revealed that the time spent inside a barrier has no finite value but is zero. A "zero time" observation was found in different experiments and fields. In 1953 Brillouin conjectured that wave mechanics holds for all fields including elastic, electromagnetic and Schrödinger waves and possibly other areas such as neuroscience. Our report addresses both, time and space.

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I. Introduction

In 1991 Applied Physics Letter published an important and internationally controversial discussed report on the analog tunneling time of microwaves [1]. This study compared experiments with theories. The authors concluded that the tunneling wave travelled at a subluminal velocity. Incidentally, the reproduction of the experiment resulted in superluminal speed. Today several theoreticians are almost certain that space and time are illusions, for instance N. Seiberg [2]. We present experimental data, namely tunneling, a process where this illusion becomes reality. Finite time experiments were conducted in Refs. e.g. [3 - 6] but in several studies the dwell time inside a barrier was found to be zero [7, 8, 9, 20 - 22]. Several theoretical calculations have been used to predict this phenomenon [7, 11 - 13]. It is difficult to determine the time at which a wave packet dwells inside a tunnel. The wave packets of various fields spent inside a tunneling barrier time is often called dwell time. Usually, the published data on tunneling time are the measurement results of the interaction time at the barrier entrance and its exit. This time is often misleadingly proclaimed as tunneling time. However the tunneling dwell time is zero and space is not localized in a potential barrier. A simple but reliable method is to measure the phase change of electromagnetic waves passing through a tunnel according to the relationship:

$$t_\Phi = d\Phi / d\omega \qquad (1)$$

where t_Φ is the measured tunneling time, $d\Phi$ is the observed phase derivation between the tunnel input and output, ω is the angular frequency of the wave packets.

Another simple method discussed by Sommerfeld is the double prisms methods. The experimental setup is illustrated in Fig 1.

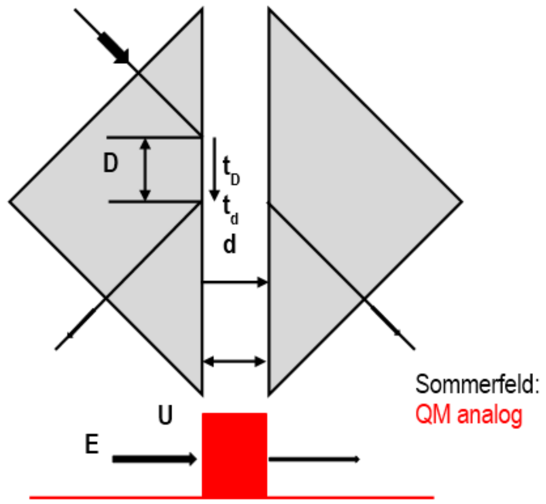

Fig.1 The double prisms as tunneling analog, introduced by Sommerfeld [14].

U is the potential height, E the energy of the incoming wave packets, d the distance between the prisms, t_d the corresponding dwell time, D the Goos-Hänchen shift with the corresponding time t_D [15].
In 1971 Carniglia and Mandel [16]showedin an optical set up that evanescent (tunneling) waves have a constant phase independent of frequency and distance. According to the phase time relation (**1)** the theoretical and experimental results point to a zero time for the evanescent waves. The same result, that is no phase shift of microwaves in a tunneling experiment was observed by Enders and Nimtz 1992 [7, 10]. However, since the time delay at the potential barrier front has been included in all the published data, the "zero time" inside the tunneling distance could produce a seemingly superluminal velocity of the wave packet [7]. This superluminal phenomenon provoked much in relativistic physics, e.g. [7, 18]. Incidentally, readers are told that Einstein has shown that there is no superluminal – faster than light –velocity possible. However, there are several velocities for defined information - transport defined. The basic information was calculated by Sommerfeld and Brillouin with an infinite frequency band width [17, 19].

Wave propagation and group velocity
However, in reality all signals are frequency band limited and all the consequences of this property were additionally calculated by Sommerfeld and Brillouin [19, 20]. A special theory of relativity is relevant only for such information or waves. As mentioned above, the superluminal phenomenon provoked much ado in relativistic physics, e.g. [7, 15, 17, 18]. In the famous book of Brillouin on ***wave propagation and group velocity*** Brillouin and Sommerfeld clarified and defined the different velocities.
Hartman calculated the tunneling time according to the phase time and the Schrödinger equation for Gaussian wave packets [12].The added microwave data [16] displayed in Fig. 2 shows the results for different tunnel length. These theoretical and experimental values revealed zero tunneling time a long time ago.

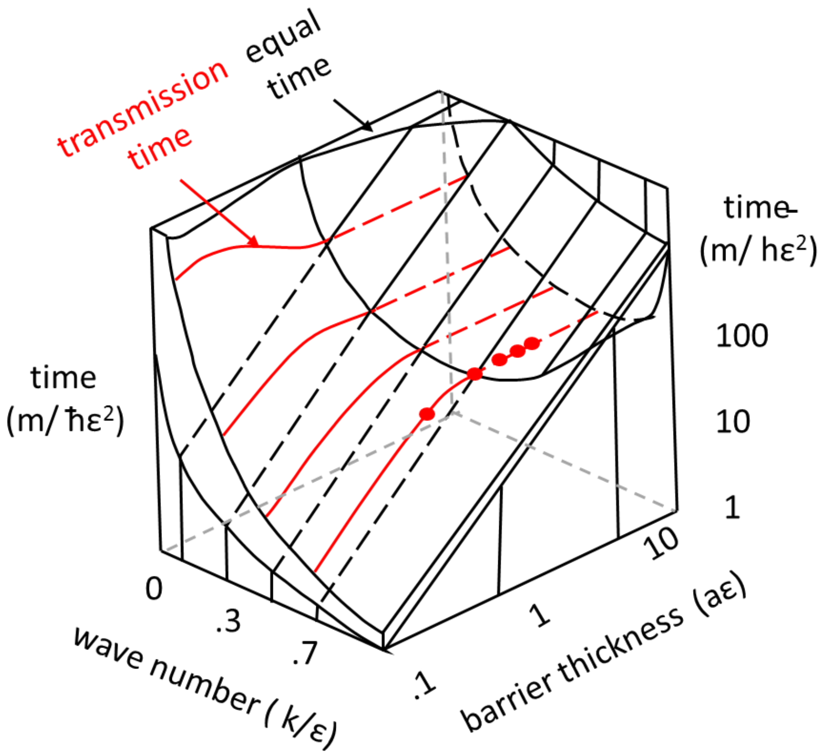

Fig.2

Graph of the calculated particle transmission time as a function of barrier thickness [7], where m is the particle mass, ħ the Planck constant and k/ε is the incident wave number normalized to ε, the wave number equivalent to the potential barrier height. The dots represent the appropriately scaled experimental data of transmission time for evanescent electromagnetic waves [17]**.** Experimental parameters are as follows: center frequency of the Gaussian-like wave packet **ν** = 8,7 GHz**,** a = 10, 40, 60, 80 and 100mm; for more details see Ref.[17].

The Fourier analysis of the phase time f(t) is given by 2 for signals with infinite and limited frequency bands, where x is the distance travelled (3) [19].

$$f(t) = \frac{1}{2\pi} \mathrm{Re} \int_{-x}^{+x} \left[e^{i\omega(t-T)} - e^{i\omega t}\right] \frac{d\omega}{\omega-\omega o} \qquad (2)$$

If this signal traverses a distance x, each frequency ω propagates with its phase velocity $v_{ph}(\omega)$

If we do not deal with such signals with a fast rise and fall time (the realistic and the only procedure signals and reactions are mediated) we can suppress frequencies very different from ω_0 by expansion of the exponents [19] and the formula becomes

$$f(t,z) = \frac{1}{2\pi} e^{-kz} \mathrm{Re}\{e^{i\omega_0} \int_{\omega-\omega_0}^{\omega+\omega_0} \left[e^{i(\omega-\omega_0)(t-T)} - e^{i(\omega-\omega_0)t}\right] \frac{d\omega}{\omega-\omega o}\} \qquad (3)$$

General result

Assuming that the signal has only imaginary wave numbers there is no time spent crossing the tunnel barrier. In the following we cite some theoretically obtained zero time tunneling data as well as recently measured data.

As shown in table 1 the data observed barrier tunneling time $t_d = 0$.

Microwave double prisms gap [15]
Electron [9]
Ammonia [24]
Atom Rb [8, 22]

Table 1: data of observed barrier tunneling time $t_d = 0$ [8, 9, 22].

In Refs. (7, 8) the "zero tunneling time" of Schrödinger wave packets have been deduced: Rb atoms are tunneling out of a Bose-Einstein-Condensate in (7, 21), and electron tunneling was studied in Refs. (8, 21, 23).

Itis remarkable that in Brillouin's fundamental text book from 1960 the zero time for tunneling was forecasted [18].

The situation also applies for the three space coordinates, and thus less spectacular investigation than photonic tunneling. Aichmann et al. [21] recently demonstrated an evanescent tunneling analog with microwaves. The non-locality of evanescent tunneling waves was proved at microwave frequencies in all three dimensions of space that is in all three dimensions of the waveguide barrier. Even with rather simple measurement techniques such as return loss and power the results again show that the macroscopic behavior of wave packets corresponds to the microscopic behavior.

II. Discussion

The behavior of non-located particles in the tunneling process was shown e.g. by Merzbacher in his textbook 1970 [11]. A microwave tunneling experiment revealed that in barriers the space-time with all four dimensions is zero [21]. This phenomenon is observed in microscopic and in macroscopic systems and presumably is valid in all fields [10, 22, 23] and in neuroscience.

The zero time takes place only by tunneling potentials with no imaginary i.e. no absorbing component [25]. Remarkably a non-localized wave packet does not change any properties during the tunneling process.

Looking from our outside " live world " into the " tunneling world " we see a room with no time and with no volume.

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