Dual Optical Tunneling Times in Frustrated Total Internal Reflection

Ph. Balcou and L. Dutriaux*
Laboratoire d'Electronique Quantique—Physique des Lasers, Unité Mixte de Recherche 6627, Centre National de la Recherche Scientifique, Université de Rennes I, F-35042 Rennes Cedex, France
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We investigate experimentally the optical tunneling times associated with frustrated total internal reflection of a light beam. Using as physical clocks the lateral shifts and angular deviations suffered by the transmitted and reflected beams, we measure both components of a complex tunneling time: the phase time and a semiclassical time. The phase time is shown to imply superluminal velocities and to depend strongly on boundary conditions not linked to the tunneling process. By contrast, the semiclassical time yields subluminal velocities and is related solely to tunneling. [S0031-9007(96)02276-4]

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The tunnel effect is a cornerstone of both quantum mechanics and classical electromagnetism, and presents intriguing features that stimulate an ongoing interest. In particular, how to define the time taken by the very process of tunneling has recently attracted a lot of attention for both fundamental and technological reasons. Perhaps the simplest approach is to follow in time the peak of wave-packet tunneling through a barrier. However, the result, known as the phase time [1], happens to saturate to a constant value for opaque barriers [2] so that the apparent velocity of the tunneling particle may be larger than the velocity of light. This superluminal propagation stimulated a lively theoretical debate (see [3,4] for reviews). Other characteristic times for tunneling were then introduced, the most prominent being the "semiclassical time" mostly advocated by Büttiker and Landauer [5]. It yields subluminal velocities so that the causality principle is explicitly obeyed. Other definitions lead to complex time values τ_c [6]. For simplicity, we introduce only that proposed by Pollak and Miller [7]:

$$\tau_c = \tau_\Phi + i\tau_L = -i\,\frac{\partial \ln t}{\partial \omega}\,, \qquad (1)$$

where $t = |t|\exp(i\Phi)$ is the complex transmission coefficient of the wave amplitude and ω the angular frequency of the incoming wave. The real part of τ_c is just the phase time: $\tau_\Phi = \partial\Phi/\partial\omega$, while its imaginary part $\tau_L = -\partial \ln|t|/\partial\omega$ (which we will call the loss time in the following [8]) is essentially equivalent to the semiclassical time in the opaque barrier limit [3,4]. Which of the two time scales, τ_Φ and τ_L, is best suited to characterize tunneling is still very controversial.

Some experiments have been carried out to test the different theoretical predictions. Early results by Guéret *et al.* [9] on quasielectrons tunneling through heterostructures, and by Esteve *et al.* [10] on a Josephson junction yielded each one time value consistent with the semiclassical time. By contrast, other experiments have since demonstrated data consistent with phase times, and implying superluminal velocities [11,12]. In spite of one recent unsuccessful attempt [13], no experimental work has succeeded so far in exploring both time scales, and the need remains to make clear the experimental conditions for which either of these times will be observed.

In this Letter we distinguish and investigate experimentally the two time scales associated to the oldest example of tunneling discovered in physics: frustrated total internal reflection (FTIR) of light. Theoretical studies have shown indeed that the physics of tunneling is essentially identical for classical light waves and quantum mechanical wave functions [14,15]. In particular, Steinberg and Chiao have recently studied systematically the equivalence between the FTIR equation and the Schrödinger one [16]. This opened up the opportunity to perform experiments with light beams, easier to perform and interpret than those with electron waves. Indeed, optical tunneling requires micrometer—rather than nanometer—sized barriers, and is not complicated by such side effects as electron-electron couplings [9,14].

Figure 1 presents the scheme of our optical tunneling experiment. A light beam impinges from a dielectric medium (index $n > 1$) onto an air slab (index 1, width e). For incidence angles i greater than the critical angle

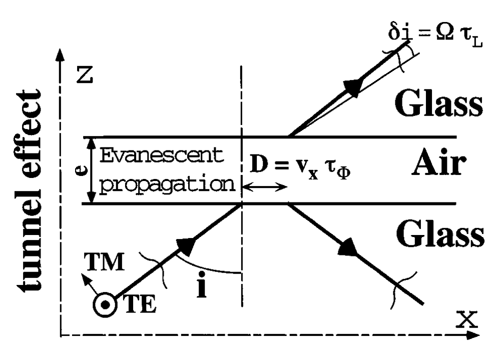

FIG. 1. Measurement principle of tunneling times. While tunneling, the beam proceeds along x with a velocity $v_x = (c/n\sin i)$ and rotates with an effective angular frequency $\Omega = nc/2w_R\csc(2i)$.

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$i_c = \sin^{-1}(1/n)$ of total internal reflection, most of the beam is reflected, and part of it tunnels through the slab. Let us now consider an incident wave packet and follow the motion of its peak. FTIR is a two-dimensional process: Tunneling occurs in the z direction, while the wave packet goes on propagating in the x direction. As its peak emerges from the second interface, it has thus undergone both a temporal shift τ_Φ and a spatial shift D along x. If we assume than the propagation velocity along x is uniform during tunneling, then D and τ_Φ are proportional, so that the phase time can be obtained very simply by measuring D.

This heuristic argument can be fully justified analytically. If $\mathrm{k} = (k_x, k_z)$ is the incident wave vector, then stationary phase analyses [17,18] show that $D = (\partial\Phi/\partial k_x)_\omega$, while $\tau_\Phi = (\partial\Phi/\partial\omega)_{k_x}$. Assuming a $\exp(-i\omega t)$ time dependence, the phase Φ in transverse electric (TE) polarization reads [18]

$$\Phi = \frac{\pi}{2} - \tan^{-1}\left[\frac{2k_z K}{k_z^2 - K^2}\coth(Ke)\right], \qquad (2)$$

where K is the modulus of the evanescent-wave wave vector. Inserting Eq. (2) into the expressions of D and τ_Φ leads to

$$\tau_\Phi = (c/n \sin i)D\,, \qquad (3)$$

provided $\sinh(2Ke)/2Ke \gg 1$, which is valid for barrier widths larger than one wavelength [19]. The same result is obtained in transverse magnetic (TM) polarization. In the well-known Larmor clock theoretical approach, spin-polarized electrons are submitted to a magnetic field while tunneling under the barrier. The resulting spin precession then provides a measure of the traversal time. The basic idea is the same here: An additional degree of freedom, the lateral displacement, is used as a clock to measure the traversal time. Note that this displacement is just the Goos-Hänchen shift, usually observed upon total internal reflection [20]. In that context Kogelnik and Weber [21] have already emphasized the equivalence between temporal and spatial shifts.

As noticed by Hartman [2], tunneling also imposes a change in the mean energy, or wave vector, of a wave packet. This can be easily understood for FTIR, as plane wave components with smaller incidence angle are better transmitted than those with larger incidence angles, so that the emerging beam suffers an angular deviation δi, that can be shown to read

$$\delta i = \frac{1}{kw_R}\left(\frac{\partial \ln|t|}{\partial i}\right)_\omega = \frac{1}{2w_R \cos i}\left(\frac{\partial \ln|t|}{\partial k_x}\right)_\omega, \qquad (4)$$

where w_R is the beam Rayleigh length, that characterizes its divergence. Calculations similar to those mentioned above show that δi is related to the loss time $\tau_L = (\partial \ln|t|/\partial\omega)_{k_x}$ by

$$\tau_L = [2w_R \csc(2i)/nc]\delta i\,, \qquad (5)$$

provided $|i - i_c| \ll \pi/2$. Because of differential losses, the beam mean direction thus rotates during tunneling, which provides a second clock that allows one to measure the loss time. This duality of clocks is very analogous to that demonstrated by Büttiker's analysis of the Larmor Clock [22]. Finally, the same analysis can be performed for both the lateral shift and angular deviation of the partially reflected beam, so that phase and loss times associated with reflection on the barrier can also be measured in principle.

A specific property of FTIR is the existence of two polarization states, TE and TM. The propagation equation in the z direction was shown to be equivalent to the Schrödinger equation in TE polarization [16]. However, FTIR in TM polarization is also a tunnel effect, but with different boundary conditions. This will thus allow us to investigate the influence of the latter on tunneling times.

Our experimental setup is presented in Fig. 2. We direct a lowest-order (TEM_{00}) Gaussian laser beam of wavelength 3.39 μm onto two right-angle prisms P_1 and P_2, facing one another by their hypotenuses. P_2 can be displaced with respect to P_1 by means of a piezoelectric transducer PZT. The parallelism and spacing e between the prisms are controlled by an interferometric method described in Ref. [23], with an accuracy on e of the order of 50 nm. The fused silica prisms have a refractive index $n = 1.409$, so that the critical angle is $i_c = 45.21°$. We have chosen an incidence angle $i = 45.5°$ close to i_c to optimize the lateral shift. However, $i - i_c$ is much larger than the divergence of the laser beam (about 0.01°), so that all the beam components are well into the tunneling regime. The laser beam is either TE or TM polarized, and has a Rayleigh length $w_R = 75$ cm inside the glass.

In a first set of experiments, we measure the tunneled beam displacement $D_\perp$ perpendicular to the incident beam axis, as a function of prism spacing e. As the beam shift is of a few wavelengths only, we use the sensitive detection technique proposed by Emile *et al.* [24]. The beam is sent through a diaphragm $\mathrm{D}_\varnothing$ mounted on a calibrated piezoelectric transducer PZT, and the apertured-beam intensity is detected by a photodiode PD. We impart a sinusoidal horizontal displacement to the diaphragm perpendicularly to the beam axis, at a frequency $f = 90$ Hz. Because of the beam profile symmetry, the intensity signal is periodic at frequency $2f$ if the mean position of the diaphragm is centered on the beam. Any deviation from beam center

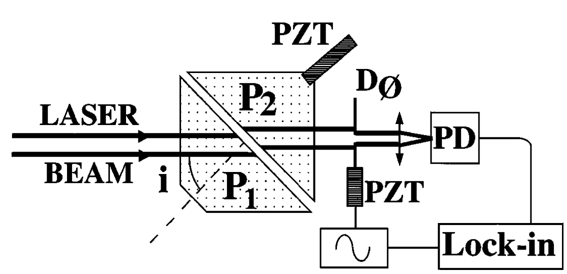

FIG. 2. Experimental setup. P_1, P_2, prisms, i incidence angle, $\mathrm{D}_\varnothing$ diaphragm, PZT piezotranslators, and PD photodiode.

induces a component at frequency f in the signal, whose amplitude is proportional to the deviation to first order. This component can easily be demodulated by a lock-in amplifier. By displacing the aperture by a known amount, we obtain a step function in the demodulated signal that is used to calibrate the data. To obtain the phase time value, we take into account the setup geometry, and in particular the displacement of P_2. Taking advantage of the nearly normal incidence of the laser beam on P_1 (due to $i \simeq 45°$, see Fig. 2), we obtain

$$\tau_\Phi(e) = \left(\frac{n \sin i}{c}\right)\left[\frac{D_\perp(e)}{\cos i} - e\cos(45°)\right]. \quad (6)$$

The same setup can also be installed on the reflected beam to measure the reflection phase time.

In a second set of experiments, we measure the angular deviation in air of the transmitted beam, as a function of e. We simply insert a lens L of focal length $L_f = 24$ cm in the transmitted beam. An angular deviation results in a shift D_ι of the laser spot in the focal plane of L, with $D_\iota = L_f \delta i_{\mathrm{air}}$. D_ι is then measured by the same method as before. From Eq. (5) and $\delta i_{\mathrm{air}} = n\delta i$, the loss time is obtained as $\tau_L(e) = 2\csc(2i) w_R D_\iota(e)/L_f n^2 c$.

The square dots in Fig. 3 show the results for transmission phase times [(a) and (b)], reflection phase times [(c) and (d)], and transmission loss times [(e) and (f)], as a function of e, in TE (a), (c), (e) and TM (b), (d), (f) polarization. The data are averaged over several runs, and the error bars are indicative of statistical uncertainties. Measurements were stopped about $e = 25$ μm, as the transmitted intensity becomes too low for thicker barriers. The corresponding theoretical curves, obtained from Eqs. (1) and (2) and averaging over the wave vector distribution, are displayed as solid lines for comparison.

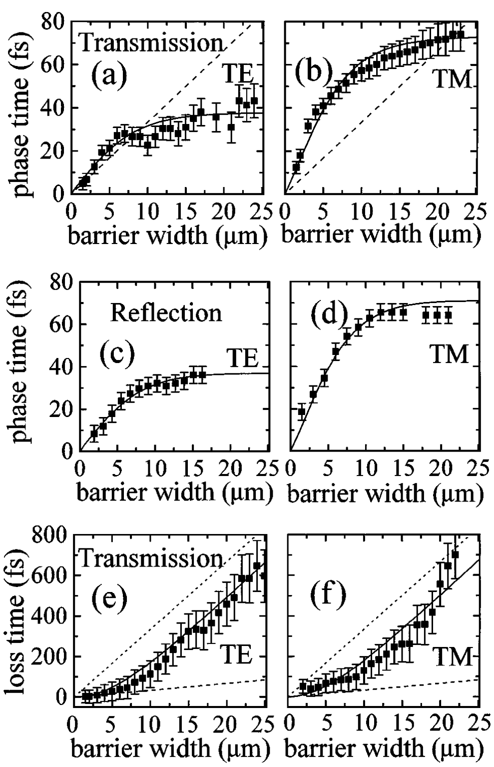

FIG. 3. Experimental (square dots) and computed (solid lines) tunneling times. (a)–(b): transmission phase times; (c)–(d): reflection phase times; (e)–(f): transmission loss times, in TE and TM polarization, respectively. The dashed lines indicate the time to cross e at light velocity. The dotted line shows the predicted semiclassical time.

The transmission phase times first increase linearly and then saturate to an almost constant value. This confirms the so-called Hartman effect: The phase time is independent of barrier thickness in the opaque barrier limit [2]. This remarkable property has been noticed before by Spielmann *et al.* [12] in the context of transmission though multistack dielectric coatings. To illustrate the resulting superluminal propagation, a dashed line represents the light-velocity limit e/c: All points below that line correspond to superluminal velocities. In TE polarization, this is the case for all experimental points for barrier widths larger than 8 μm. By contrast, the loss time variation is about flat for thin barriers, and then increases quasilinearly. All points lie above the light velocity limit, or are consistent with it within the experimental error bars. The data points are actually parallel to the prediction of the semiclassical time $(\hbar\omega/c^2)(e/\hbar K)$ [5,16], displayed as a dotted line. The effective velocity therefore tends to a constant value, as given by Büttiker and Landauer's theory. There is, however, a clear discrepancy, as the measured and computed loss times turn out to be smaller than the semiclassical time by a fixed time lag, about 200 fs here. Finally, one may notice that the loss time becomes much larger than the phase time for opaque barriers: At $e = 20$ μm, we have $\tau_L = 500$ fs, while $\tau_\Phi = 40$ fs only in TE polarization. The complex tunneling time is hence dominated by its imaginary part.

Several authors have predicted that transmission and reflection phase times should be equal [3,16]. Our data clearly demonstrate this point, as can be seen by comparing Figs. 3(a) to 3(c), and 3(b) to 3(d). This equality is not predicted to hold for the loss times: The reflection loss time τ_L^R should be related to the transmission loss time by $\tau_L^R = (T/R)\tau_L$, where T and R are the transmission and reflection intensity coefficients [22]. As T decays to zero very quickly, the reflection loss times are extremely small, of the order of a few femtoseconds at most, which is less than the sensitivity threshold of the experiment. Indeed, our attempts to measure the reflection loss times yielded results consistent with zero.

The polarization dependence of the data is especially noteworthy. As stressed before, TE and TM evanescent waves have the same functional dependence $\exp(-Kz)$, but differ by their boundary conditions. The TM phase times turn out to be larger than the TE ones by almost a factor of 2, while the TE and TM loss times are nearly equal. This shows that the phase times depend strongly on the boundary conditions, which are not really part of tunneling. By contrast, the loss time (or semiclassical time) depends very little on the boundary conditions, but only on the tunneling process itself.

In summary, we have investigated the tunneling times associated with frustrated total internal reflection of light. We have shown that the additional degree of freedom associated with beam propagation along the interface provides a clock, similar to the well-known Larmor clock. The real and imaginary parts of the complex tunneling time correspond, respectively, to the spatial and angular shifts of the beam, and can thus be measured in a stationary experiment. This method differs therefore from the pulsed experiments of Steinberg *et al.* [11] and Spielmann *et al.* [12].

Our experimental results demonstrate the equality between phase times upon reflection and transmission, and that the loss times upon reflection are much smaller than those upon transmission. As predicted by Hartman, the phase time tends to a constant in a deep tunneling regime, while the transmission loss time increases linearly, in parallel with the semiclassical time, the effective velocity being subluminal. Incidentally, the very demonstration of the angular shift suffered by the tunneling beam is also the first observation of a nonspecular effect on a Gaussian beam distinct from a beam displacement, to the best of our knowledge. Finally, the phase time was shown to depend on the TE or TM boundary conditions, in contrast with the loss time.

In most technological applications, how long the tunneling wave or quantum particle couples to other degrees of freedom *inside* the barrier is the most important question. A time value that depends strongly on boundary conditions is clearly not adequate. To that extent, our results substantiate the semiclassical time as the most relevant to describe the physics of tunneling.

*Also with: Lycée Joliot-Curie, 144 Boulevard de Vitré, F-35700 Rennes Cedex, France.

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