# Photonic tunneling time in frustrated total internal reflection

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Frustrated total internal reflection is considered as the classical analog of quantum-mechanical tunneling. Here the tunneling time in frustrated total internal reflection is discussed. It is shown that the phase time allows for vanishing and negative barrier traversal times. The tunneling time is shown to be dominated by a time scale based on the Goos-Hänchen shift. The role of further nonspecular deformations of the transmitted beam is addressed. The resulting tunneling times are compared with experimental data.

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## INTRODUCTION

The quest for the tunneling time, dating back to the origins of quantum mechanics [1], still awaits its final resolution despite many established devices like the tunneling diode. In the last decade the idea of exploring the tunneling time mystery by analyzing photonic tunneling instead has emerged. This strategy is based on the formal analogy between particle tunneling across square barriers and electromagnetic waves crossing classically forbidden regions in the form of evanescent modes. (The analogy itself holds for frustrated total internal reflection [2,3] and waveguides [4].) The interest in photonic tunneling, which exists in its own right for both fundamental research and technological applications, gained tremendous impetus when superluminal velocities were reported in a series of experiments summarized in recent reviews [5,6].

We discuss here the time scales of photonic tunneling, focusing on the time honored example of frustrated total internal reflection (FTIR) [7]. To be specific, we consider the arrangement depicted in Fig. 1 showing two identical prisms separated by a gap of air representing the barrier.

For small gaps, the total reflection to be expected for an incoming TE- (or TM-) polarized beam hitting the prism-air interface at an angle $\theta$ with $\theta > \theta_c := \arcsin 1/n$ becomes frustrated and photonic tunneling takes place. Previous photonic tunneling time experiments have shown that the phase time [8,9] does describe the barrier traversal time [5,6]. By analogy one would expect the phase time to describe the tunneling time in FTIR also. A transmitted beam, however, experienced apart from the phase shift several nonspecular deformations and shifts [10]. [The Goos-Hänchen shift, probably the most prominent example of these effects, and an angular deviation ($\delta$) are indicated in Fig. 1.] These deformations and shifts all define natural time scales which in principle could contribute to the tunneling time. It has been suggested recently to identify the tunneling time in FTIR as the sum of the barrier traversal time described by the phase time and a contribution from the Goos-Hänchen shift [11]. Following this suggestion, the present study focuses on the actual contributions of the phase time and the time associated with the Goos-Hänchen shift to the tunneling time. Apart from the Goos-Hänchen shift, an incoming beam could experience in FTIR an angular deviation, a beam-waist modification, and a focal shift. Possible contributions of these effects to the tunneling time are checked also. The theoretical tunneling times given below are computed from an explicit form of the phase shift experienced by the transmitted beam in FTIR. This phase shift, in turn, has been derived and verified experimentally [12]. The predictions are compared with experimental data for the phase time [13], the Goos-Hänchen shift and the corresponding tunneling time [14–16], and a tunneling time defined by the angular deviation [15].

The material is organized as follows. In the next section, some basic facts about photonic tunneling in FTIR are recalled before discussing the phase time. It is shown that the phase time allows for positive, vanishing, and unphysical negative tunneling (i.e., barrier traversal) times as a function of the angle of incidence. Since the phase time is a result of boundary effects in regions of real wave number $k$, the origin of this unphysical result is identified in the Goos-Hänchen shift, which is shown to define an experimentally accessible tunneling time in the form of a dwell time. Then further time scales that could be associated with nonvanishing nonspecular deformations of a transmitted beam in FTIR are addressed. The resulting predictions are compared with experimental data. Reasonable agreement in the case of the Goos-Hänchen shift is found for certain ranges of the parameters (angles of incidence, beam width, and polarization). The pa-

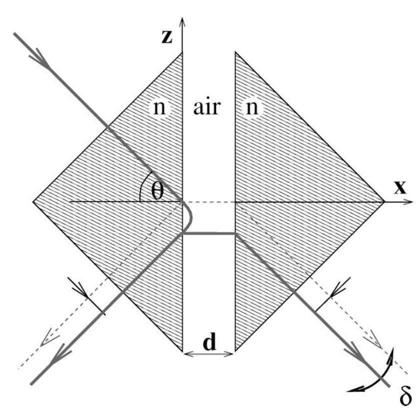


FIG. 1. Photonic tunneling in the double-prism experiment dating back to Newton [7]. The prisms with equal index of refraction ($n$) are separated by a gap of width $d$. The fate of an incoming beam hitting the prism-air interface at an angle $\theta > \theta_c = \arcsin 1/n$ is shown, indicating the Goos-Hänchen shift $D$ (marked by a straight arrow) and an angular deviation $\delta$ as elucidated in the text.

 

per is concluded by a short summary listing some of the open questions arising from the present analysis.

## PHASE TIME IN FTIR

A TE- (or TM-) polarized electromagnetic wave hitting the air gap between the prisms under an angle of incidence $\theta > \theta_c$ is not totally reflected at the interface, but penetrates into the gap as sketched in Fig. 1. The wave in the gap is characterized by the wave numbers

$$k_{\parallel} = \frac{\omega n \sin\theta}{c}, \quad k_{\perp} = \imath \frac{\omega}{c}\sqrt{n^2 \sin^2\theta - 1}, \tag{1}$$

where $k_{\parallel}$ characterizes the motion parallel to the interface and the imaginary $k_{\perp}$ associated with an evanescent wave defines the penetration depth perpendicular to the interface; $c$ is the velocity of light in vacuum, $\omega$ denotes the angular frequency of the beam, and $n$ is the index of refraction. [The wave numbers (1) can actually be measured [17].] The dispersion relation

$$\omega^2 = c^2(k_{\parallel}^2 + k_{\perp}^2) \tag{2}$$

gives for the motions parallel and perpendicular to the interface the group velocities

$$v_{\parallel} = \frac{c}{n \sin\theta}, \quad v_{\perp} = \imath c \sqrt{n^2 \sin^2\theta - 1}, \tag{3}$$

showing that the concept of a group velocity loses its meaning for motion perpendicular to the interface.

When photonic tunneling takes place, the transmitted beam exhibits a phase shift. This phase shift, easily computed by analyzing multiple scattering of the incoming beam in the gap, reads [12]

$$\Phi = \arctan\left(\frac{\tanh \gamma(d)}{\tan\varphi}\right) \tag{4}$$

with

$$\gamma(d) = \frac{d\omega\sqrt{n^2 \sin^2\theta - 1}}{c}; \tag{5}$$

the polarization-dependent phases $\varphi$ read

$$\varphi_{\mathrm{TE}} = \arctan\left(\frac{2n\cos\theta\sqrt{n^2\sin^2\theta - 1}}{n^2\cos 2\theta + 1}\right),$$
$$\varphi_{\mathrm{TM}} = \arctan\left(\frac{2n\cos\theta\sqrt{n^2\sin^2\theta - 1}}{\cos^2\theta - n^2(n^2\sin^2\theta - 1)}\right). \tag{6}$$

The phase shift of the reflected beam is given by $\Phi + \pi/2$.

An evanescent wave cannot accumulate phase in the direction characterized by an imaginary wave number [cf. Eq. (1)] [18]. The phase shift $\Phi$ thus seems to result from the prism-air interfaces representing the entrance and exit of the barrier. (The contribution of the Goos-Hänchen shift is commented on below.) As a consequence, the phase shift should become independent of the barrier thickness in the limit of opaque barriers. This prediction follows from Eqs. (4)–(7) and has indeed be seen in an experiment [12].

Previous studies of photonic tunneling identified the phase time [8,9] to describe the actual tunneling time defined as the barrier traversal time [5,6]. Experiments measuring the phase time are in full agreement with those measuring the group velocity directly [5]. In the present case, the phase shift defined in Eqs. (4)–(7) allows us to compute the phase time [8]

$$\tau_{\Phi} := \left(\frac{d\Phi}{d\omega}\right) \tag{7}$$

explicitly. Insertion of the phase shift $\Phi$ leads to

$$\tau_{\Phi} = \frac{\gamma(d)}{\omega}\,\frac{1}{\tan\varphi}\,\frac{\tan^2\varphi}{\tan^2\varphi\cosh^2\gamma(d) + \sinh^2\gamma(d)} \tag{8}$$

for the transmitted and the reflected beam, where $\gamma(d)$ and $\varphi$ have been defined in Eqs. (5) and (7). This result is plotted in Figs. 2 and 3 as a function of the gap width using the parameters of recent tunneling time experiments in FTIR in the microwave [13] and optical [15] regimes.

The phase time obviously shows the Hartman effect in both cases in agreement with other photonic tunneling time experiments [5,6]; the time saturates to a constant value at $d \sim 5\lambda$ in the optical (Fig. 2) and at $d \sim \lambda$ in the microwave (Fig. 3) regime. More important, however, is the *negative* tunneling time found for the microwaves. This negative time results from the frequency-independent factor $1/\tan\varphi$ in Eq. (8): for $\varphi < \pi/2$, one obtains positive tunneling times decreasing with increasing angle of incidence to $\tau_{\Phi} = 0 \Leftrightarrow \varphi = \pi/2$; for larger angles of incidence, the tunneling time changes its sign. The critical angle for the sign change is given by

$$\theta_s^{\mathrm{TE}} = \arcsin\left(\sqrt{\frac{n^2+1}{2n^2}}\right), \quad \theta_s^{\mathrm{TM}} = \arcsin\left(\sqrt{\frac{n^2+1}{n^4+1}}\right). \tag{9}$$

In the case of the microwave experiment mentioned above [13], this critical angle is $\theta_s^{\mathrm{TE}} = 58.39° < \theta$, while it amounts to $\theta_s^{\mathrm{TE}} = 60.14° > \theta$ in the case of the optical experiment [15], where $\theta$ is the angle of incidence.

The angle-dependent values of the phase time allowing for vanishing as well as negative tunneling times are difficult to interpret. (The same result follows from independent derivations of the phase shift $\Phi$ via stationary phase theory [19] and ray theory [20].) This unphysical result is caused by the Goos-Hänchen shift elucidated in the next section. This shift is a motion parallel to the prism-air interface (cf. Fig. 1) described by a real wave number. In the course of this motion, the wave can accumulate phase before tunneling. The Goos-Hänchen shift thus contributes to the total phase shift $\Phi$ in addition to the contributions from the two interfaces limiting the gap. (This is the main difference from photonic

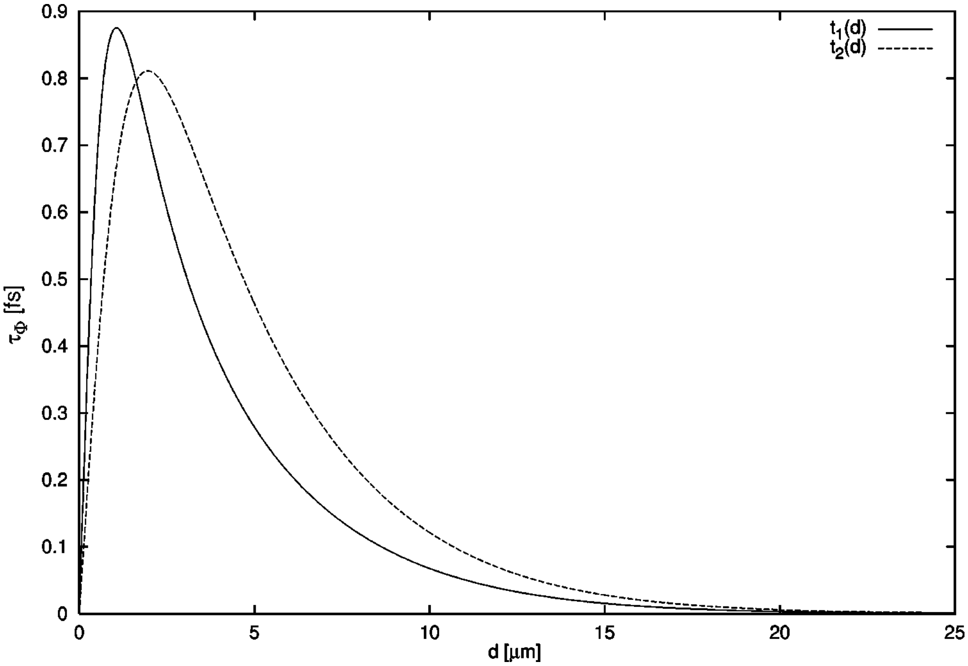


FIG. 2. Phase time predicted by Eq. (8) for an optical tunneling time experiment [15] with $n=1.409$, $\theta=45.5°$, $\lambda=3.39$ $\mu$m (i.e., $\nu=0.884\,956\times10^{14}$ Hz). $t_1(d)$ $[t_2(d)]$ denote TE- [TM-] polarization of the beam. The phase time is given in femtoseconds.

tunneling in undersized waveguides: the phase shift observed there [5] results solely from the entrance and exit of the barrier.) The negative tunneling times show that the phase time approach is not an appropriate tool to determine the tunneling time in FTIR. The phase time does not contribute to the tunneling time, contrary to a recent suggestion [11].

## GOOS-HÄNCHEN SHIFT

In total reflection, the reflected beam is shifted with respect to geometrical optics. This shift, foreseen by Newton [21] and demonstrated for the first time by Goos and Hänchen [22], plays a prominent role in many applications [23].

The Goos-Hänchen shift is given by the relationship

$$D_0 := -\frac{\partial\alpha}{\partial k_\parallel}, \tag{10}$$

where the wave number $k_\parallel$ has been defined in Eq. (1). Upon insertion of $\alpha$, the phase of the Fresnel reflection coefficient, one obtains an explicit form of $D_0$ which has been verified experimentally in the vicinity of the critical angle [14].

In the case of FTIR, nonspecular deformations of electromagnetic beams hitting multilayered media predict equal shifts and deformations in reflection and transmission [10,24]. Applied to the Goos-Hänchen shift, this suggests for the shift of the transmitted beam the ansatz

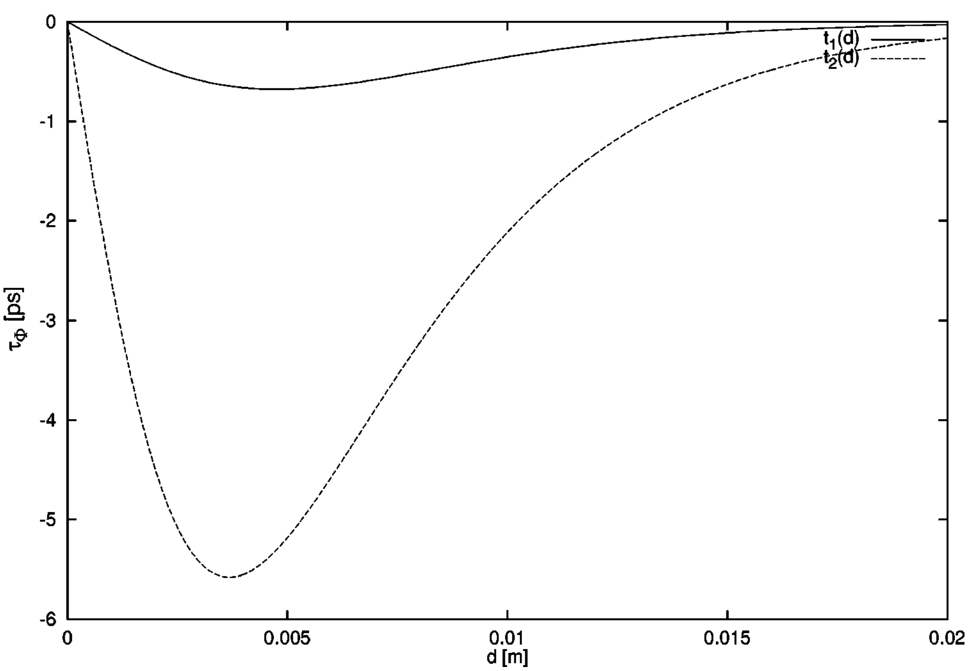


FIG. 3. Phase time predicted by Eq. (8) for a microwave tunneling time experiment [13] with $n=1.49$, $\theta=60°$, $\nu=9.5\times10^9$ Hz. $t_1(d)$ $[t_2(d)]$ denotes TE- [TM-] polarization of the incoming beam. The phase time is given in picoseconds.

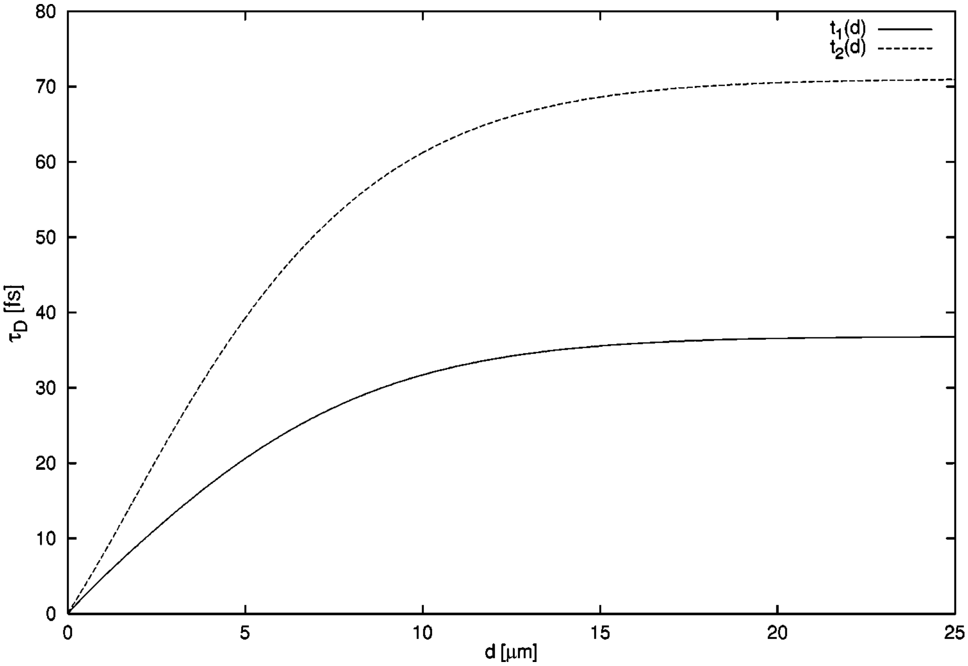


FIG. 4. Tunneling time derived from the Goos-Hänchen shift according to Eq. (13) resulting from the parameters of the optical experiment [15] with $n = 1.409$, $\theta = 45.5°$, $\lambda = 3.39$ $\mu$m. $t_1(d)$ [$t_2(d)$] stand for TE- [TM-] polarization. The dwell time $\tau_D$ is given in femtoseconds.

$$D := -\frac{\partial\Phi}{\partial k_\parallel}, \tag{11}$$

where $k_\parallel$ has been introduced above and $\Phi$ is the phase shift introduced in Eqs. (4)–(7). The explicit forms of $\Phi$ [cf. Eqs. (4)–(7)] and of $k_\parallel$ [cf. Eq. (1)] show that this ansatz does indeed lead to equal shifts of the reflected/transmitted beam. (Derivations of the Goos-Hänchen shift via stationary phase theory [19] or ray theory [20] led to the same result.) The Goos-Hänchen shift $D_0$ introduced in Eq. (10) is recovered in the limit of large air gaps via the relationship

$$\lim_{d\to\infty} D = D_0, \tag{12}$$

which is verified by computing $D$ and $D_0$ defined explicitly in Eqs. (10) and (11).

The actual path of a beam in the air gap shown in Fig. 1 has been overemphasized to honor Newton's foresight of the Goos-Hänchen shift; the vertical path between the prisms symbolizing the tunneling process should not be taken literally since an evanescent wave cannot be observed [25]. (Evanescent photons do not exist *per se*, but should be interpreted as virtual photons [26].)

Since the velocity $v_\parallel$ parallel to the interface is conserved, one can associate a time scale with the Goos-Hänchen shift via

$$\tau_D = \frac{n \sin\theta}{c} D, \tag{13}$$

in accordance with earlier observations of the equivalence between spatial and temporal shifts [27,28]. Strictly speaking, this time should be called a dwell time describing a motion along the boundary of the barrier and not the tunneling time required for crossing the barrier. The dwell times defined in Eq. (13) are plotted in Figs. 4 and 5 using the same parameters as in Figs. 2 and 3 to allow a comparison of the two approaches.

Some results are obvious: (i) the tunneling time defined in Eq. (13) is always positive and saturates to a constant value (Hartman effect); (ii) the tunneling times for TM-polarized beams [$t_2(d)$] are bigger than those for TE-polarized beams [$t_1(d)$] in the optical experiment, while the situation is opposite in the case of microwaves due to the large angle of incidence chosen there; (iii) the recent suggestion to identify the phase time $\tau_\Phi$ defined in Eq. (7) with the dwell time $\tau_D$ defined in Eq. (13) [15] has to be rejected since the two time scales give substantially different results. Unlike the phase time $\tau_\Phi$, the experimentally accessible dwell time $\tau_D$ defines acceptable tunneling times in FTIR for *all* angles of incidence.

The different polarization dependance of the tunneling time in the optical and the microwave experiments noted above results from the polarization dependance of the Goos-Hänchen shift: for an angle of incidence $\theta$ with $\theta < \Theta := \arcsin\sqrt{2/(n^2+1)}$, TM-polarized beams lead to larger shifts than TE-polarized beams; for $\theta > \Theta := \arcsin\sqrt{2/(n^2+1)}$, the situation is opposite. (The angle $\Theta$ evaluates to 54.9° in the optical and 52° in the microwave experiment.) This angle dependence accounts for the different polarization-dependent tunneling times depicted above.

## TIME SCALES OF NONSPECULAR DEFORMATIONS

In reflection at multilayered media, the reflected beam experiences 20 nonspecular deformations and shifts not accounted for by geometrical optics [10,24]. Some of these effects are also seen in total reflection with $\theta > \theta_c$. For symmetry reasons, these shifts can also be expected to be observable in FTIR. (The Goos-Hänchen shift is an example of such a symmetrical shift.) Since these deformations and shifts all take time, they could contribute to the tunneling

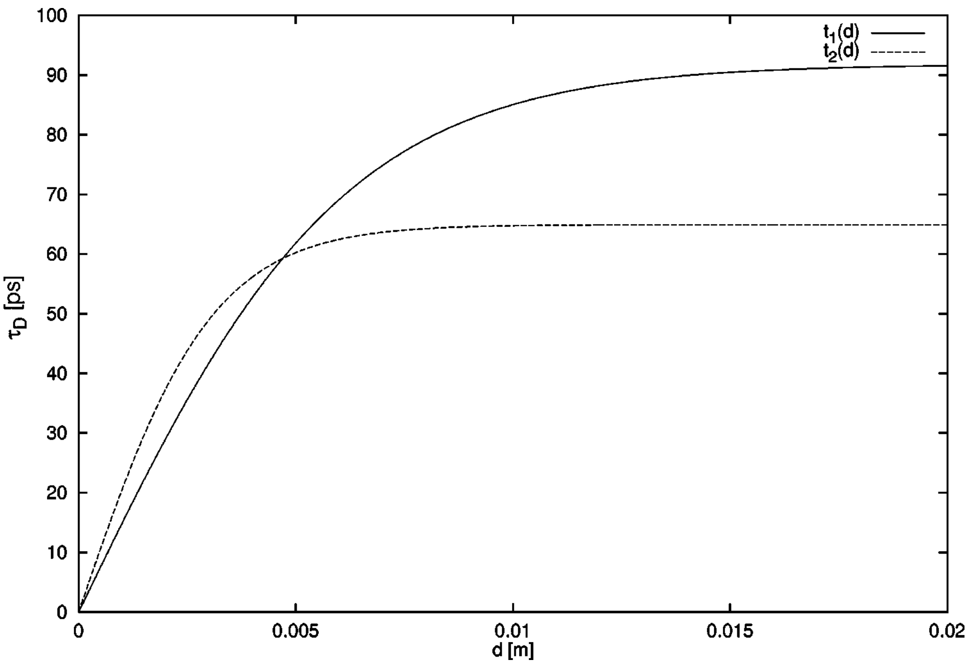


FIG. 5. Tunneling time derived from the Goos-Hänchen shift according to Eq. (13) resulting from the parameters of the microwave experiment [13] with $n = 1.49$, $\theta = 60°$, $\nu = 9.5$ GHz. $t_1(d)$ [$t_2(d)$] stand for TE- [TM-] polarization. The dwell time $\tau_D$ is given in picoseconds.

time like the Goos-Hänchen shift does. The most pronounced effects apart from the Goos-Hänchen shift are the angular deviation, the beam-waist modification, and the focal shift discussed in the following.

In reflection at multilayered media, the plane wave components of a wave packet experience different phase shifts. This results in an angular shift of the beam axis of the reflected beam with respect to geometrical optics. This angular shift is approximately given by [10,24]

$$\delta_\theta = \frac{2}{(kw)^2} \frac{d \ln r(\theta)}{d\theta}, \tag{14}$$

where $r(\theta)$ is the Fresnel reflection coefficient, $w$ is the beam half width at the waist, and $k := 2\pi n/\lambda_0$ is the wave number with the free space wavelength $\lambda_0$. As in the case of the Goos-Hänchen shift, the transmitted beam in FTIR should also experience an angular shift. It is thus natural to associate a time scale with the angular deviation via [15]

$$\tau_\delta = \frac{2w}{nc \sin\theta} \frac{2}{(kw)^2} \frac{d \ln t(\theta)}{d\theta}, \tag{15}$$

with the transmission coefficient $t(\theta)$.

This ansatz, however, bears an intrinsic problem. For the case of total reflection it has been proved that the angular shift vanishes for $\theta > \theta_c$. The symmetry arguments used before in the context of the Goos-Hänchen shift show that the angular shift should vanish in FTIR also [10,24]. The tunneling time of Eq. (15) defined by the angular shift thus should not contribute to the tunneling time.

The so-called beam-waist modification describes an angle-dependent narrowing of the beam width in reflection at a single interface or multilayered media. Like the angular deviation, this deformation vanishes in total reflection with $\theta > \theta_C$. Any contribution from the beam-waist modification to the effective tunneling time in FTIR thus should be negligible also.

A converging Gaussian beam experiences a shift of the focal point in total reflection [10,24]. The magnitude of this shift can be derived from the phase of the reflected beam via

$$F := \frac{1}{k} \frac{d^2\alpha}{d\theta^2}, \tag{16}$$

where $k = 2\pi n/\lambda_0$ and $\alpha$ is the phase of the Fresnel reflection coefficient. Apart from the Goos-Hänchen shift, this is the only nonvanishing nonspecular deformation in the case of total reflection. The focal shift thus should be observable in FTIR also upon replacing the well collimated beam normally used by a focused beam. The magnitude of this shift follows from Eq. (16) upon replacing $\alpha$ by the phase shift $\Phi$ defined in Eqs. (4)–(7). Both shifts, the focal shift and the Goos-Hänchen shift, would then contribute to the total tunneling time in FTIR. Experimental data on the focal shift in FTIR are, however, missing so far, thus leaving an evaluation of the associated tunneling time an open question awaiting experimental clarification.

## COMPARISON WITH EXPERIMENTS

The photonic tunneling time in FTIR has been measured on several occasions; additional values of the tunneling time can easily be derived from experimental data for the Goos-Hänchen shift via Eq. (13). The phase time in FTIR has been measured recently without taking the Goos-Hänchen shift into account [13] and a tunneling time of $\tau_\Phi \sim 5$ ps has been reported. However, an inspection of Figs. 3 and 5 shows that this time is not accounted for by the phase time or the tunneling time based on the Goos-Hänchen shift. This makes an interpretation of the data via the phase time ansatz (7) impossible. The Goos-Hänchen shift, in turn, predicts a tunneling time of the order 70–90 ps in accordance with previous measurements of photonic tunneling times reporting values of $\tau \sim \lambda_0/c$, where $\lambda_0$ is the free space wavelength of the respective experiment [5].

The tunneling time associated with the Goos-Hänchen shift has been measured in an optical experiment [15]. Here, asymptotic constant tunneling times of $\tau_D \sim 40$ fs for TE polarization and $\tau_D \sim 70$ fs for TM polarization have been reported for a gap width of $d=20$ $\mu$m. An inspection of Fig. 4 shows that these experimental data are reproduced by the ansatz (13) when using the same parameters as in the experiment [15]. This time is, however, of the order $\tau_D \sim 5\lambda_0/c$, contrary to previous experimental data. It remains to be seen if this indicates a genuine difference between tunneling times of FTIR in the optical and the microwave regimes.

This ansatz for the tunneling time is far from being complete, however, due to the sensitivity of the Goos-Hänchen shift to several parameters. This shift is an intricate function of the polarization, the angle of incidence, the beam width $w$, and the beam geometry itself [16]. The definition (11) of the Goos-Hänchen shift predicts values for the shift in FTIR that cover experimental data only for angles of incidence near the critical angle [14,15] and for relatively large ratios $w/\lambda_0$ with $w/\lambda_0 = 5-10$. Limiting the value of $w/\lambda_0$ to values $w/\lambda_0 = 0.95$–2 results in values for the Goos-Hänchen shift [16] not covered by any model so far. The experimentally motivated claim that TM-polarized microwave beams always lead to Goos-Hänchen shifts that are bigger than those for TE-polarized beams [14,15] does not hold, as the angle dependence elucidated above, new experimental data [16], and a computation of the Goos-Hänchen shift via Eq. (11) show. The impact of these parameters on the tunneling time (13) deserves further study.

The time scale associated with the angular deviation presented in Eq. (15) has been introduced recently [15] and large tunneling times have been reported [15]. This observation is in conflict with existing models of nonspecular deformation in FTIR as discussed above. A resolution of this conflict cannot be offered here; more experimental data are required to settle this question. A similar statement can be made for the focal shift, which is impossible to observe for well collimated beams. Any measurement of the focal shift in FTIR would show immediately that this effect defines a time scale whose relevance for the photonic tunneling time deserves further study.

## CONCLUSIONS AND OUTLOOK

The time scales of photonic tunneling in FTIR have been discussed. It has been shown that the phase time used in previous studies of photonic tunneling describing the barrier traversal time allows for positive, vanishing, and negative tunneling times as a function of the angle of incidence for given $n$. Since this time thus does not give a unique result for a given barrier, it does not provide a reasonable measure for the barrier traversal time, contrary to a recent suggestion [11]. The unphysical prediction of the phase time is caused by the neglect of the Goos-Hänchen shift, which provides an independent time scale for the tunneling time in the form of a dwell time. A measurement of the Goos-Hänchen shift effectively amounts to measuring the phase shift governing the observable tunneling time in FTIR. Reasonable agreement between theoretical values of $\tau_D$ and experimental data has been found. Discrepancies between theoretical values of the Goos-Hänchen shift based on Eqs. (4)–(7) and (11) and experimental data [16] originate from the sensitivity of this shift to certain parameters not yet adaequately incorporated in any model of this shift. The most pronounced nonspecular deformations in FTIR to be expected by analogy with reflection at multilayered media have been discussed. The focal shift, if measurable in FTIR, can be expected to contribute to the tunneling time. The measurement of the angular deviation reported recently [15] poses a puzzle that can only be resolved by further experiments.

The tunneling time in FTIR thus appears to be governed by several time scales originating from nonspecular deformations, where only the Goos-Hänchen shift has been uniquely identified so far. The barrier traversal time, i.e., the time required for crossing the air gap, is not known despite the long history of this phenomenon.

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