On the possibility of measuring the Unruh effect

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Abstract There is a persistent state of confusion regarding the nature of the Unruh effect. We will argue that, in contrast to some interpretations thereof, the effect does not represent any novel physics and that, by its very nature, the effect is fundamentally unmeasurable in all experiments of the kind that have been contemplated until now. Also, we discuss what aspects connected with this effect one might consider as possibilities to be explored empirically and what their precise meaning may be regarding the issue at hand.

Keywords quantum field theory in curved spacetime · Unruh effect · quantum electrodynamics · accelerated frames

1 Introduction

One of the most surprising outcomes of the development of the quantum field theory in curved space-time pertains, paradoxically, to the flat space-time realm: the so called Unruh effect [1], which establishes that, as seen from the point of view of accelerated observers, the ordinary Minkowski vacuum state for a free quantum field, corresponds to a thermal state with an indefinite number of particles. The mathematical analysis of this effect is closely related to the Hawking radiation by black holes, and perhaps for this reason it has
attracted a lot of attention among theoretical physicists. It has attracted much less attention on the part of the experimental physics community, probably because back-of-the-envelope calculations indicate that its magnitude is very small under normal circumstances. This situation appears to be changing with the availability of very high energy particle accelerators, and the increase in the precision of some of the experimental devices. In fact, there is now a funded proposal to engage precisely in the experimental search for this intriguing effect [2].

The objective of this paper is to address a severe misunderstanding that seems to lie behind such proposals and that, as we will see, completely dooms essentially any project along these lines. As we will discuss, the Unruh effect is, by its very nature, unobservable by inertial observers, and any identification of a signature of this effect that might be thought to be uncovered in the experimental searches will only be due to the failure to take into account some effect of standard QED. In other words, if any positive signal is observed in such experiments it would represent novel physics unrelated to the Unruh effect, in essence, an unexpected departure from QED due to novel physics.

This claim seems very strong but, as we will see, it is the inescapable consequence of the proper understanding of what the Unruh effect is. Namely, that this effect does not represent any new physics beyond that corresponding to ordinary quantum field theory (in Minkowski space-time and as described in an inertial frame), but it is just part of the description of ordinary effects as seen from the point of view of accelerated observers who use a different coordinate chart (one adapted to the accelerated condition) to describe the given region of space-time. In this sense, it is just like the “centrifugal force”\(^1\), a conceptual construct that allows us to describe certain aspects of ordinary physics in a non-inertial frame, and which is clearly not a new type of “force field” capable of producing some novel effects. It is clear one cannot hope to detect the “centrifugal force” directly unless the laboratory with all its measuring devices is itself set in a “rotating table”. For instance, if one conceives an experiment design to attain an indirect detection of the “centrifugal force”, by measuring quantities in the inertial frame, and converting the effects of this centrifugal force (as described by some hypothetical rotating observers) into quantities to be measured in the inertial frame, one finds that all one obtains are standard ordinary physics effects. Thus if we insist on looking for a signature signal of the centrifugal force by looking at a certain data observed in the inertial laboratory and subtracting all ordinary inertial physics effects, we would end up with nothing. We elaborate on these matters in section 2, where we present the core of our arguments about the unmeasurability of the Unruh effect. In section 3 we analyze some experimental proposals designed to detect the Unruh effect, in particular, we will focus on schemes based on the use of high intensity lasers, which are expected to be developed in the very near future. In addition to discussing the possibility of detecting the effect, we examine what we take as misinterpretations occurring in the analysis of

\(^1\) This analogy between the Unruh effect and non-inertial forces was first used in [3].
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2 The Problem

One of the most critical aspects of the design of an experiment dedicated to the search for any new effect is to make sure one has taken into account all the known physical effects that can be mistaken for a signal of the effect one is interested in observing. Thus, focusing on the specific case of the search for the Unruh effect, one needs to remove from the data all effects associated with the “standard physics” of the situation, which in this case, is that described by QED. For the case of electrons in a storage ring, these effects include Compton dispersion of electrons by stray photons, Bremssstrahlung associated with the acceleration of electrons by the magnetic field keeping the beam in its circular path, etc. Then, if after all these effects are taken into account, and subtracted from the raw data, there is a remaining signal, say of excess depolarization of the electron beam, and if such signal has the expected characteristics of shape and magnitude, one might claim to have made and observational detection of the Unruh effect.

The central point we are making is that, if one has correctly subtracted all the known QED effects leading to the depolarization one is interested in measuring, the expectation for the magnitude of the remaining signal (what would be the Unruh effect’s signal) is exactly zero. To see why this must be the case in general, we must recall that the treatment of QFT in curved spacetime, from which the Unruh effect is derived [4,5], starts with the covariant description of the matter fields, and focuses on the covariant character of the resulting quantization. The point of court is that all coordinate systems would be equally valid for the description of the related physics. It is in this context that the vacuum of the usual quantization of a free field (i.e. that which is based on the decomposition of the field modes into positive and negative energies as seen from the point of view of inertial observers) looks, when described in terms of an alternative quantization (that associated with the notions of positive and negative energies from the point of view of a certain class of accelerated observers), as a thermal state. The point, however, is that

2 There are however some mathematical subtleties, that although might seem worrisome at first sight turn out to be irrelevant regarding the points we are making. For instance, in the careful analysis of the construction of the quantum field theories, one finds that, due to subtleties connected with the infinite number of degrees of freedom, the different quantizations are not unitarily equivalent. However the issue can be in practice ignored, as a consequence of Fell’s theorem [4], which ensures that each possible state in any one of the quantizations can be approximated regarding its characterization in terms of a finite number of observables, to any finite degree of precision.
the two descriptions of the state of the Maxwell’s quantum field are equivalent, leading to the same prediction of the expectation values of all observables (of course, the corresponding observables are those covariantly connected in the two descriptions). Thus, if we have these two descriptions for the Maxwell field and, analogously, the two equivalent descriptions for the degrees of freedom corresponding to the charged particles, and one ensures that the initial physical state of affairs is represented in two equivalent ways, and if the interaction is naturally described covariantly, what we will have then is the exact same physics described from two alternative points of view: i) the inertial one in which there is no Unruh effect, and the initial state contains only electrons in a beam and a background magnetic field, and ii) the accelerated frame where the initial state includes the thermal baths of both photons and electrons on top of the electrons in the beam and the more complicated background electromagnetic field. Given the covariance of the descriptions the same physical predictions are a necessary outcome of any correct and accurate calculation and, therefore, anything that might be described in the analysis made using the second description, as being tied to the Unruh effect, will have in the first description a counterpart that makes no use of such effect and can therefore be described in terms of ordinary physics. Needless is to say that although the actual predictions in the two analysis must be exactly the same, the difficulty and complexity involved in the actual calculation may differ dramatically from one to the other.

It thus follows that if we compute in the accelerated frame a certain effect that is attributed to the Unruh thermal bath and then transform such effect in appropriate manner to the inertial frame, we would find an effect that is well described just in terms of ordinary physics in that frame and that makes no reference to the Unruh effect. Therefore, if we subtract from the Unruh effect, as seen in the inertial frame, the effects of ordinary physics in an inertial frame, we should end with no remaining signal at all. We think it is illuminating to illustrate how this occurs in detail by considering in a slightly different light an example which has been described in full detail in the literature [12]: The absorption and the stimulated emission of photons by interaction of an accelerated electron with the thermal photons in the Unruh bath in which the electron sees itself immersed. This analysis goes as follows. Recall that the world line of the accelerated electron (with constant proper acceleration) corresponds to a branch of an hyperbola in Minkowski space-time, whose asymptotes divide space-time into four (Rindler) wedges. To construct the description of this physical situation, in the “accelerated frame”, one resorts to a family of observers co-accelerating with the particle (i.e. they see it as static) and whose trajectories (for \( a > 0 \)) are branches of hyperbolas that fill up the right Rindler wedge \( |t| < z \). In this wedge one can give Rindler coordinates:

\[ ds^2 = \zeta^2 d\tau^2 - d\zeta^2 - dx^2 - dy^2, \]

where \( \zeta, \tau \) are defined by

\[ z = \zeta \cosh \tau; \quad t = \zeta \sinh \tau. \]
An electric charge $e$ that follows the world line $\zeta = 1/a$, $x = y = 0$ has constant proper acceleration $a$ and $\tau/a$ is its proper time.

The initial state of the Maxwell field corresponding to the Minkowski vacuum, as described in the accelerated frame, is the Unruh thermal bath of photons corresponding to the state $|0_M\rangle$ (after tracing over the the degrees of freedom that do not correspond to the right wedge) \cite{1}. Thus, in this frame, the charged particle is at rest immersed in this thermal bath, absorbing and emitting photons. Next, one calculates the rate of emission in the inertial description and the combined rate of emission and absorption of photons in the accelerated frame. The conserved current associated to the electron with acceleration $a$ in Rindler coordinates is\footnote{Here one must face a subtle technical point connected with the fact that a static charge would couple mainly to modes of the field with “zero frequency” with respect to Rindler time and there is, in a sense, an “infinite number of photons” in this mode in the thermal bath. In order to control expressions of the form $0 \times \infty$ that occur in this type of calculations, the current eq. (3) has to be regularized and at the end of the calculation the regulator has to be taken off (the full analysis of this subtle detail goes beyond the purposes of this article and can be consulted in \cite{12}).}:

$$j^\tau = a q \delta \left( \zeta - \frac{1}{a} \right) \delta(x) \delta(y), \quad j^\zeta = j^x = j^y = 0. \quad (3)$$

The Maxwell field $A_\mu$ has to be quantized in the accelerated frame. In the Feynman gauge ($\alpha = 1$) the Lagrangian $\mathcal{L} = -\sqrt{-g} \left[ \frac{1}{4} F^{\mu \nu} F_{\mu \nu} + (2 \alpha)^{-1} \left( \nabla^\mu A_\mu \right)^2 \right]$ leads to the field equation $\nabla^\mu \nabla_\mu A_\nu = 0$. The physical modes are those that satisfy the field equation and the Lorenz condition $\nabla_\mu A^\mu = 0$ and are not pure gauge.

The Rindler metric, eq. (1), has the following Killing vectors: $(\partial/\partial \tau), (\partial/\partial x)$ and $(\partial/\partial y)$ and thus, in order to define the one particle Hilbert space of the field quantization, it suffices to look for solutions to the field equations with definite Rindler energy of the form

$$A^{\lambda, \omega, k_x, k_y}_\mu (x^\nu) = f^{\lambda, \omega, k_x, k_y}_\mu (\zeta) e^{-i \omega \tau + i k_x x + i k_y y}, \quad (4)$$

where $\lambda$ labels the polarization of the field and $\omega$ can be associated to the frequency of the mode w.r.t. to Rindler time $\tau$ and $k_x$ and $k_y$ to the momentum in the $x$ and $y$ direction respectively. It is interesting to note that due to the existence of only three Killing fields associated to coordinate displacements in the Rindler metric there will not be, in general, a dispersion relation connecting the quantum numbers $\omega$, $k_x$ and $k_y$ independently of the coordinates, as it happens in the inertial description of the quantum field.

The electromagnetic quantum field in the right Rindler wedge is then expressed as

$$\hat{A}^{\lambda, \omega, k_x, k_y}_\mu (x^\nu) = \int_0^\infty d\omega \int d^2 k \sum_{\lambda=1}^4 \left[ a^{R \lambda, \omega, k_x, k_y}_\mu A^{\lambda, \omega, k_x, k_y}_\mu + a^{R \dagger \lambda, \omega, k_x, k_y}_\mu A^{\dagger \lambda, \omega, k_x, k_y}_\mu \right]. \quad (5)$$
where the operator $\hat{a}^{R}_{\lambda,\omega,k_x,k_y}$ is the annihilation operator of a Rindler photon with quantum numbers $\lambda$, $\omega$, $k_x$ and $k_y$ and defines a vacuum state $|0_R\rangle$ on the right Rindler wedge by $\hat{a}^{R}_{\lambda,\omega,k_x,k_y} |0_R\rangle = 0$ for all $\lambda$, $\omega$, $k_x$ and $k_y$.

The interaction of the current eq. (3) with the electromagnetic field is given by

$$\mathcal{L}_{\text{int}} = \sqrt{-g} j^{\mu} \hat{A}_{\mu}$$

and thus one can compute the amplitude of probability of the emission of a photon to the thermal bath and then the total rate of emission. In the article we are describing the authors use a shortcut to get to the final result which consists in computing first, at tree level, the amplitude for the emission of a photon into the Rindler vacuum:

$$A_{\text{em}}^{\omega,k_x,k_y}(\lambda^*,\omega,k_x,k_y) = \langle \lambda^*,\omega,k_x,k_y | R \int d^4x \sqrt{-g} j^{\mu}(x) \hat{A}_{\mu}(x) | 0_R \rangle_R,$$

where $|\lambda^*,\omega,k_x,k_y\rangle_R = \hat{a}_{\lambda^*,\omega,k_x,k_y}^{R\dagger} |0_R\rangle$ and $\lambda^*$ corresponds to the polarization state of the physical mode of the field.

From this amplitude, the authors construct a differential probability of emission of one photon into the Rindler vacuum,

$$dW_{\text{em}}^0(\omega,k_x,k_y),$$

of occurring, where $Z$ is a normalization factor. From this, the total differential rate per unit transverse momentum squared of emission of photons with fixed $k_x$ and $k_y$ into the thermal bath can be computed and turns out to be:

$$P_{\text{em}}(k_x,k_y) dk_x dk_y = \int_0^{+\infty} \sum_n p_n(\omega) dW_{\text{em}}^n(\omega,k_x,k_y).$$

The contributions to this rate come from spontaneous and induced emission. On the other hand, the total rate of absorption can be analogously calculated. The authors of this paper show that the emission and absorption rates are equal:

$$P_{\text{em}}(k_x,k_y) dk_x dk_y = P_{\text{abs}}(k_x,k_y) dk_x dk_y = \frac{q^2}{8\pi^3 a} |K_1(k_\perp/a)|^2 dk_\perp dk_y,$$

where $K_1(z)$ is a modified Bessel function and $k_\perp = \sqrt{k_x^2 + k_y^2}$. The total combined rate reads:

$$P_{\text{tot}}(k_x,k_y) dk_x dk_y = \frac{q^2}{4\pi^3 a} |K_1(k_\perp/a)|^2 dk_\perp dk_y.$$

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4 When removing the regulator mentioned in the previous footnote.
Up to now we have presented the analysis of the situation in the frame where the charge is at rest, which is not the laboratory inertial frame in which the charge is accelerating.

Now we need to express this result in terms of what will be seen in the laboratory. For this, it is important to note that the inertial notions of energy and momentum in the $z$ direction are not connected in simple ways to notions of energy and momentum in Rindler coordinates, which can be seen from the fact that $(\partial/\partial \tau)$ is expressed in Minkowski coordinates as $(\partial/\partial \tau) = z(\partial/\partial t) + t(\partial/\partial z)$. That is, the Rindler notion of energy and the Minkowski notion of energy (that associated with the standard Minkowski timelike Killing field $(\partial/\partial t)$) are not related in any simple way. What is more, there is no one to one and univocal correspondence between the two (i.e. to relate them it is needed information also about the space-time location $(t,z)$ and about the $z$ component of the inertial momentum which is tied to the Killing field $(\partial/\partial z)$).

However, fortunately for us, the notion of transverse momentum $(k_x, k_y)$ of a field mode (the conserved quantities connected to the translation invariances $x \rightarrow x + c$ and $y \rightarrow y + c'$) is exactly the same in the two frames, a fact that allows us to compare physical quantities between both frames. Furthermore, as discussed in [7], that both the emission or absorption of Rindler particles as seen in the accelerated frame correspond to emission of particles in the inertial frame (when the initial state is the Minkowski vacuum). However, we must stress in order to warn the reader about a common source of confusion, that in considering the connection between specific states, one should note that the timelike Killing field used to define the notion of energy for Rindler coordinates is a nontrivial combination of the Killing fields $(\partial/\partial t)$ and $(\partial/\partial z)$ and depends on the space-time coordinates $(t,z)$. Thus the relationship between Rindler energy and Minkoski energy is neither direct nor intuitive.

From this discussion one can conclude that the rate we have computed above, eq. (12), corresponds to the emission and absorption of photons with transverse momentum $(k_x, k_y)$ per unit of the electron’s proper time. The conversion of such proper time rate into the corresponding rate in terms of inertial time is straightforward and we need not concern ourselves with it as long as the comparison to inertially computed rates is done taking that into account.

As we have said above, if one wants to plan an experiment, before considering looking for this stimulated emission phenomena resulting from the Unruh effect, one would need to consider the standard physical effects that are known to occur in the inertial frame. In performing the inertial analysis, the quantum field description is the standard one (the modes are expressed as plane waves with definite frequency w.r.t. the inertial time coordinate $t$), the initial state of the field is the inertial vacuum $|0_M\rangle$ and thus there can be no absorption of photons by the electron. We must, however, consider the emission of photons by the accelerated electron, i.e. the usual QED Bremsstrahlung. This analysis is as follows:
In inertial coordinates, the current eq. (3) reads

\[ j^i = qaz\delta(\zeta - \frac{1}{a})\delta(x)\delta(y), \]
\[ j^x = j^y = 0, \]
\[ j^z = qat\delta(\zeta - \frac{1}{a})\delta(x)\delta(y), \]

where

\[ \delta(\zeta - \frac{1}{a}) = \frac{\delta(z - \sqrt{t^2 + a^{-2}})}{a\sqrt{t^2 + a^{-2}}}. \]

The amplitude of emission of a photon on momentum \( k \) and polarization \( \lambda \) into the Minkowski vacuum is given by

\[ A(\lambda, k) = \langle k, \lambda|_M i \int d^4x j^{\mu}(x) \hat{A}_\mu(x) |0\rangle_M. \]

Note that in this case the energy \( \omega \) is not independent of \( k \).

The total rate of emission of photons with fixed traverse momentum \( (k_x, k_y) \), divided by the total proper time \( T \) in which the interaction was present reads

\[ \text{in} P_{(k_x, k_y)}^{\text{tot}} = \frac{2}{\pi^3} \int_{-\infty}^{\infty} dk_x dk_y \frac{|A(\lambda, k)|^2}{T}, \]

where \( k_0 = \sqrt{k_x^2 + k_y^2} \), and the sum goes over the two physical polarizations \( \lambda = 1, 2 \). At the end of the calculation the authors obtain:

\[ \text{in} P_{(k_x, k_y)}^{\text{tot}} = \frac{q^2}{4\pi^3 a} |K_1(k_{\perp}/a)|^2 dk_x dk_y. \]

This expression representing the standard QED Bremsstrahlung must now be subtracted from the measured rate in order to obtain the rate one must seek to detect in the laboratory and that can be attributed to the Unruh effect. Note however that this is identical to the result eq. (12), and thus if we detect exactly this rate of photon emission, the part that can be attributed to the Unruh effect is exactly zero.

That is, the rate of emission in the inertial description and the combined rate of emission and absorption of photons in the accelerated one are equal, a result that shows the equivalence of both descriptions of the same physical situation. Thus we conclude that the detection of the Unruh effect using the strategy we have outlined (computing the signals to be attributed to the Unruh effect in the accelerated frame, characterizing that effect in terms of what would be detected in an inertial frame and subtracting the ordinary inertial physics that mimics the signal of interest) is bound to fail.

Note that there are many subtleties one might want to incorporate in an even more profound analysis. In the example we have considered all the true quantum degrees of freedom of the electron are suppressed, allowing us to describe it with the same classical current in both frames. If we were interested in taking into account those quantum aspects of the electron, some new issues
would have to be addressed. First, note that a thermal bath of Dirac particles (electrons and positrons) would appear in the accelerated frame in addition of the photon thermal bath and in addition to the electrons of the beam. However, we can see that the effect of this thermal bath would be negligible compared to that of the photon ($m = 0$) thermal bath. In effect, note that the $\zeta$ dependence of the modes of definite Rindler energy which are solutions to Dirac equation in Rindler coordinates is proportional to modified Bessel functions of the form $K_{i\omega/\alpha \pm 1/2}(p\zeta)$, where $p^2 \equiv p_x^2 + p_y^2 + m^2$ and $m$ is the electron mass [9]. These functions behave asymptotically as $e^{-p\zeta}$ for $p\zeta$ large [8]. In the region near the trajectory of the particle we have $\zeta \sim 1/a$. Lets suppose, for simplicity, that $p_x = p_y = 0$ so that $k = m$. Recall that the temperature of the thermal bath is $T = a/(2\pi)$ and thus, in this region, we would be dealing with corrections of order $e^{-m/a}$ which are completely negligible.

Furthermore, one cannot ascribe naturally a definite proper acceleration to a quantum particle because it does not move in a definite trajectory and, due to the distributional nature of the quantum description of a particle, it would correspond to an extended object. In this case, if different portions of it have the same proper acceleration, they will not be static with respect to each other. Nevertheless, if these kinematic drawbacks could be somehow overcome, one would be facing the fact that the state of acceleration comes necessarily from an interaction present during the time in which the particle accelerates. If one tries to describe this quantum mechanically it would be necessary to make use of a quantum theory of interacting fields that is not based on in and out states defined in asymptotic regions where the interaction is not present. Up to now, there is no satisfactory theory with these required properties. All this makes the quantum description of the uniform accelerated electron a very complex matter. In fact, even for the case of a classical electron, some other issues like the global description (in all of Minkowski space-time) of the final state of the Maxwell quantum field, and the energy-momentum fluxes between left, right and future Rindler wedges due to the presence in, say, the right wedge of the accelerated charge, when expressed in the language of accelerated observers, is also filled with subtleties that have to be addressed very carefully when attempting this type of analysis.

As another example of our argument, we would like to discuss one of the first proposals of experimental detection of the Unruh effect, due to Bell and

\footnote{As an example, note that all the interaction of the accelerated particle occurs inside the right Rindler wedge where, as we have seen, as described by accelerated observers, the rates of emission and absorption of photons to and from the thermal bath coincide, so as first discussed in [12], the process of emission and absorption by the accelerated charge leaves the thermal bath undisrupted. Thus, it would seem that in this description the state of the field has been altered by the presence of the accelerated charge. The state of the field on the left wedge clearly cannot be affected by the charge due to the causal disconnection of this region from the right wedge where the charge’s trajectory lies. However, the fact the final state should account for the radiation emitted by the charge indicates a contradiction. As it turns out, the very peculiar behavior of the (extended) zero energy Rindler modes is responsible for this apparently paradoxical situation (for a detailed discussion of this issue see [19].)
Leinaas in 1983 [14], who said that “...the depolarization of electrons in a magnetic field could be used to give the temperature reading”. They considered the case of electrons in circular motion in a storage ring and argued that, due to the Unruh effect, there would be some specific depolarization with respect to some initial condition. In examining this situation from the accelerated frame’s point of view we must take into account the electron interaction with the external electromagnetic field and the absorption and emission of photons from and to the thermal bath of photons, a process that might be accompanied or not with a flip in the spin of the electron, also to be consider is the process where a positron from the thermal bath annihilates the beam electron leading to a virtual photon that then decays in a electron positron pair. However, the depolarization can be predicted without invoking accelerated frames. In effect, the problem from the inertial point of view involves the interaction of electrons with the external magnetic field, the resulting Bremsstrahlung which involves the possibility of the spin flip for the electron as well as the emission without spin flip, as the presence of the external magnetic field breaks rotational invariance of the electron-free photon Lagrangian, and thus angular momentum is not conserved (alternatively one can say that angular momentum is exchanged with the background field), we must also consider the possibility of electron positron pair creation by a virtual photon emitted by the electron in interaction with the external field, etc. Actually, the most reliable computations of the spin flip of electrons in storage rings come from inertial calculations (see the discussion in [9] and references therein).

To end this section, we would like to comment on some amiss interpretations of the Unruh effect that may be promoting a misleading intuitive picture of it. What is claimed is that the photons of the Unruh thermal bath correspond to “vacuum fluctuations” (e.g. in [15]) or are considered as “virtual particles” which can be transformed into “real particles” in the laboratory frame, for instance, in the process when they are scattered by an accelerating electron [20,22]. As far as we know, the term “virtual particle” is naively associated to all those off-shell disturbances of the field occurring in a dispersion process, maybe motivated by the graphical character of the Feynman diagrams. If one wants to describe the scattering of the thermal bath particles by the electron it is mandatory to have a well defined notion of what the incoming particle is, thus, it cannot be one of these disturbances. As we have said, in the Rindler description of the quantum field there is no dispersion relation between the energy and momenta as in the inertial case, nevertheless the QFT in curved space-time formalism shows us that Rindler particles have the same status to accelerated observers as Minkowski particles have to inertial ones.

\[\text{Actually, the term is not even recommended for popular science texts [25].}\]
3 Some issues arising in the analysis of experimental proposals to detect the Unruh effect using lasers

Many ideas for measuring the Unruh effect have appeared in the literature. One classical reference of earlier proposed experiments is Rosu [11], and the more recent review of the Unruh effect by Crispino et al. [9] has a more updated section on experimental proposals. There also appears a list of proposed high energy experiments in Ispirian [24]. One more recent proposal that does not appear in these references is [16], where it is proposed to use Berry’s phase to detect the Unruh effect at lower accelerations. The spectra of experiments is wide and a general classification of them can be consulted in [9] and [11]. However, each of the experiments for detecting the Unruh effect proposed so far imply a measurement in an inertial frame and thus, as we have explained, it cannot be considered a verification of the effect.

In this section we would like to center on the subset of these proposed experiments that rely on a very intense laser to accelerate electrons and thus achieve the necessary accelerations to generate a detectable temperature of the heat bath of particles. In effect, it is expected that lasers generating intensities exceeding $10^{23}$ W/cm$^2$ will soon be available [17], producing accelerations on an electron of $2 \times 10^{23}$ g with the correspondent Unruh temperature of $8 \times 10^{-2}$ KeV [2]. The main idea of these proposals is that the radiation emitted by the accelerated electron can be decomposed, in the inertial laboratory frame (where the detectors are placed), into two well differentiated contributions. One of them is the well known Larmor emission radiation and the other is supposed that can be tracked, in one way or another, to the dispersion of photons of the Unruh thermal bath. It is claimed that, if detected, this latter radiation would account as a signal of the Unruh effect. Nevertheless, as we have explained above, if all the effects of QED are taken into account, the expectation of the magnitude of the remaining effect is zero, so in this case the detectors will not notice any radiation. It is interesting to note that, even if there were experimental confirmation of the presence of this dispersion radiation, it would not represent any confirmation of the Unruh effect. If that were the case, it would imply some novel, unexpected, breakdown of QED. But this would not mean that there is or there is not an Unruh effect, though. The only meaning that could be attached to this result is that, in effect, if the experiment is made in the inertial frame one can only account for the inertial QED predictions (or the lack of them). In this section we will briefly consider problematic aspects arising in the analysis a few of these proposals, leading the authors to conclude, in contrast with what we have argued in this manuscript, that they have a viable mechanism to detect the Unruh effect.

One of the first proposals using lasers is based on the assumption that the Unruh effect’s thermal bath will generate in the electron a quivering motion (as described in the inertial frame) which will generate some identifiable dispersion

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7 The idea of an additional radiation in the inertial frame due to the interaction of the accelerated electron with the thermal bath appeared since 1986 [18].
radiation \[19\]. In this work, it is computed, for a laser accelerated electron what would be the emitted radiation power due to this extra motion on the particle. It is interesting to note that this calculation is carried out in the electron’s inertial instantaneous rest frame and makes no direct use of the Unruh effect. That is, if the computations are correct this quantum calculations would account for the emission of photons due to the electron’s back reaction to the Larmor radiation, but not for the Unruh effect.

In \[20\] it is considered a setup in which electrons from a beam are accelerated by the electric field of two incident super intense lasers with circular polarization and radiation detectors are placed, in the laboratory frame, in directions perpendicular to the incident electron beam. The analysis continues with a theoretical justification of how for some values of the experimental parameters, such as the electron density of the beam and the laser frequency, there would be a region in the frequency range for which the Larmor radiation power is suppressed and thus, the only radiation power present in that window of frequencies would come from the dispersion radiation by the Unruh effect. The analysis proceeds with calculation of the dispersion of photons from the thermal bath by the accelerated electrons from the beam\(^8\) in order to obtain the expected value of the radiated power. The first step is the computation of the power radiated from the scattering by a single electron and then, using such result and given temperature of the bath, one can use the distribution function of the photons to compute the total power of the scattering in the accelerated frame.

The authors write (without derivation) an equation for the rate of the number, \(N_S\), of scattered photons by a single electron at rest in the accelerated frame as:

\[
\frac{dN_S}{d\tau} = \frac{d}{d\tau} \int f_S k^2 d\Omega dk = \sigma_T c \int f_B k^2 d\Omega dk,
\]

(18)

where \(f_B\) is the distribution function of photons of the thermal bath, \(f_S\) is the distribution function of the scattered photons and \(\sigma_T = e^4/6\pi\varepsilon_0^2 m^2 c^4\) is the total Thomson scattering cross section. This equation has to be considered with special care. As we have shown in eq. (5), a photon in the accelerated frame—in which the electron is supposed to be at rest—is described by the quantum numbers \(\lambda, \omega, k_x\), and \(k_y\), where the frequency \(\omega\) is now a completely independent variable. Then, to account for all possible states of the photons in the thermal bath, integration has to be performed with the measure \(d\omega dk_x dk_y\) with the respective integration limits as in eq. (5) (assuming that one has already summed over spins configurations). The measure \(k^2 d\Omega dk\) used in eq. (18), which corresponds to the measure of momentum space described in an inertial frame is incorrect in the accelerated frame.

Moreover, the analysis uses the inertial value for \(\sigma_T\) as the cross section of the process of dispersing one photon by the electron in the accelerated frame. This also presents serious potential problems. First, note that the inertial value

\(^8\) As we have said before, a thermal bath of Dirac particles is also present but with negligible effects to account for.
of this cross section is independent of \( k_i \), but for the accelerated case it is not clear that this cross section is independent of \( \omega \). Also, observe that it is not straightforward to conclude that in the accelerated frame one might define a rotationally invariant cross section.

From this discussion we can conclude that it is rather unclear that eq. (18) represents the rate of the number of scattered photons from the thermal bath by a static electron as described in the accelerated frame. In the attempt to express this physical quantity from the accelerated point of view, the authors have used a machinery that is correct only when describing the physics of this phenomenon from an inertial frame. Thus eq. (18) would make sense if it represents the rate of scattered photons in some thermal bath with distribution function \( f_B \) from an electron at rest in an inertial frame. However, in the inertial frame, the electrons are moving and the photon field state is the no particle state.

Then one finds a series of problematic considerations that essentially arise from the failure to note that as the Rindler energy \( \omega \) of the modes is an independent variable, in principle it is unrelated to the values of the momenta \( k_x \) and \( k_y \). In effect, it is claimed that equation (5) of that paper, \( P_{U,\text{rest}} = \frac{d}{d\tau} \int_V \int \hbar \omega_{\text{rest}} f_s(k) k^2 d\Omega dk dV \), (19)

where \( \omega_{\text{rest}} \) is the photon frequency in the electron rest frame, is the power from the Unruh effect emitted in the electrons rest frame. In this equation, it is supposed that in the integrand \( \omega \) is dependent of the momenta, although, in the accelerated frame it is an independent variable. The analysis proceeds by transforming \( P_{U,\text{rest}} \) into the laboratory frame quantity, \( P_{U,\text{lab}} \), based on the notion that they are equal rates \( P_{U,\text{rest}} = P_{U,\text{lab}} \) (see equation (6) of their paper), and the only difference is that encoded in a simple relation \( \omega_{\text{lab}} = \omega_{\text{rest}} \gamma(v)(1 - \frac{v}{c} \sin \theta \cos(\phi - \phi_v)) \) where \( v \) is the electrons' velocity in the inertial frame, spherical coordinates with the \( z \) axis perpendicular to the velocity have been introduced in this frame and \( \phi_v \) is the angle between the velocity and the \( x \)-axis. This frequency \( \omega_{\text{lab}} \) is interpreted as the photon frequency in the lab frame. Note, however, that the proposed relation between \( \omega_{\text{lab}} \) and \( \omega_{\text{rest}} \) is not correct as we have already discussed. In fact it can be seen to be incorrect also if we were only dealing with simple transformation from one inertial frame to another as a relativistic transformation of energy, has to involve also the spatial momenta (Lorentz transformations mix the various components of the particle’s 4-momentum).

The argument we have stated in section 2 tells us that, if these kinds of errors were fixed, the correct, \( P_{U,\text{lab}} \) would be exactly the Larmor power radiation computed in the inertial frame for the electron accelerating in the vacuum. Thus the detectors would have nothing to detect.

In 1984, Unruh and Wald [7] proved an important result (that we have already used in the discussion of section 2) concerning the correspondence of the inertial and accelerated descriptions of the quantum field. They modeled, at first order, the interaction of a two level quantum detector in its ground state
in uniform acceleration with the inertial vacuum. These authors showed that, from the accelerated point of view, the excitation of the detector (by absorption of a Rindler particle from the thermal bath) corresponds univocally, in the inertial frame, to a state where the detector is excited and a particle has been emitted into the vacuum (all the issues concerning this apparent paradoxical result are discussed in the cited paper). Note that, in the accelerated frame, the emission of a photon by the detector (when returns to its ground state) should correspond, in the inertial frame, also to the emission of a Minkowski photon since this is the only way to account for a change in the state of the field in this frame.

Other type of proposals to detect the Unruh effect using lasers are based on the argument that, when the time between absorbing and emitting becomes arbitrarily small, “the detector acts as a Thomson scatterer in the accelerated frame” and, due to the result of Unruh and Wald cited above, this process would correspond in the inertial frame to the “emission of two real particles by the accelerated scatterer” [21,22,23]. Hence, if one considers the laser accelerated electron as a point like scattering detector then the emission of pairs of photons in the inertial frame due to the Unruh effect would be expected. The argument further relies as a means to distinguish the signal from standard effects on the claim that in the inertial frame these two emitted photons are entangled. In [2] is given a concrete experimental proposal that aims to search for these pairs of entangled photons as a signature of the Unruh effect (however, in this reference it is not clearly explained what would be the experimental procedure to identify the entanglement of such pairs).

The theoretical justification [21,22] for this particular experimental proposal relies on an heuristic explanation of how these pairs of correlated photons would be produced. Note that there is, in effect, a non zero probability of producing pairs of particles in the inertial frame since, when computing the interaction of a classical accelerated electron with the Maxwell field (given by eq. (6)) to second order, appears a term of the form $\hat{a}_\lambda^{M\dagger} \hat{a}_\nu^{M\dagger} |0_M\rangle$. However it is not clear that this is what the authors have in mind, in particular note that the two particles need not have the same quantum numbers. In fact, recalling that the states of the quantum field can be characterized either as Minkowski particle states or as Rindler particle states, the correlation between particles will not even appear in this latter description.

As we have said, accelerated observers, which are confined to the right wedge, describe the field in the form of eq. (5). However, it is possible to express the full quantum field (in all of Minkowski spacetime) in terms of the quantizations for accelerated observers on the left and right wedges considering the extension of the right and left modes of the field of definite Rindler energy to all of spacetime (see, for example, [9]). For the sake of simplicity we will use a massive scalar field in the exposition of our point, but the main

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9 The quantization on the left Rindler wedge (the region $|t| < -z$ of Minkowski spacetime with metric given by eq. (1) and coordinate transformation $z = -\zeta \cosh \tau$, $t = \zeta \sinh \tau$) is based on the decomposition on positive and negative energies w.r.t. coordinate $\tau$ in this region.
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features we want to emphasize are also valid for the Maxwell field. To express the full quantum field in this double wedge quantization, one has to make use of annihilation and creation operators of Rindler particles on the right and left Rindler wedges, $\hat{a}_{\omega,k_\perp}^R$ and $\hat{a}_{\omega,k_\perp}^L$, respectively. As these modes, as well as the plane wave expansion modes, $\hat{a}_{k}^M$, are used to describe the same quantum field in all of space-time, it is not surprising that there is an expression that relates them, for example, $\hat{a}_{\omega,k_\perp}^R = (\psi_{\omega,k_\perp}^R, \hat{\phi})_{KG}$ where $\psi_{\omega,k_\perp}^R$ is the mode of the field of positive energy w.r.t. Rindler time in the right Rindler wedge and zero on the left wedge and the field $\hat{\phi}$ is expressed in terms of $\hat{a}_{k}^M$ and $\hat{a}_{k}^M\dagger$. For example, it can be shown that [26,9] (see also [27]):

$$\hat{a}_{k}^M\dagger = \frac{1}{\sqrt{2\pi mm} c\cosh q} \int_0^\infty \left( e^{-i\omega q} \hat{b}_{-\omega,k_\perp} + e^{i\omega q} \hat{b}_{\omega,k_\perp} \right) d\omega$$

where $q = \arctanh(k_z/\omega_k)$ and the operators $\hat{b}_{-\omega,k_\perp}$ and $\hat{b}_{\omega,k_\perp}$, which annihilate the Minkowski vacuum (their hermitian conjugates create particles with positive inertial energy acting on $|0_M\rangle$), are related to the double wedge creation and annihilation operators as:

$$\hat{b}_{\omega,k_\perp} = \frac{1}{\sqrt{2\sinh \pi \omega}} e^{\pi\omega/2} \hat{a}_{\omega,k_\perp}^R - e^{-\pi\omega/2} \hat{a}_{\omega,k_\perp}^L$$

$$\hat{b}_{-\omega,k_\perp} = \frac{1}{\sqrt{2\sinh \pi \omega}} e^{\pi\omega/2} \hat{a}_{\omega,k_\perp}^L - e^{-\pi\omega/2} \hat{a}_{\omega,k_\perp}^R$$

That is, the state of the field which corresponds to the creation of a Minkowski particle with definite momentum, from the inertial vacuum corresponds, in the accelerated description, to the superposition of the state that corresponds to the creation of a Rindler particle from the thermal bath in the right wedge, the state corresponding to the creation of a Rindler particle from the thermal bath on the left wedge, that which corresponds to the annihilation of a Rindler particle from the thermal bath in the left wedge and the state that corresponds to the annihilation of a Rindler particle from the thermal bath in the right wedge. All the modes of the particles involved in these processes have the same quantum numbers, but the state $\hat{a}_{k}^M\dagger |0_M\rangle$ is a superposition of four one-particle excitations, two in the left wedge and two in the right wedge, and thus, even in this inertial description state, the probability of detecting a state of two Rindler particle excitations with the same quantum numbers in either wedge is zero. Similarly, the state $\hat{a}_{\omega,k_\perp}^L |0_M\rangle$ involves the sum of certain creation and annihilation of Minkowski modes acting on the vacuum in which only the creation part contributes and thus, neither involves correlated pairs. Also, from eq. (20) one can see that when computing the term $\hat{a}_{\omega,k_\perp}^L\dagger \hat{a}_{\omega,k_\perp}^M |0_M\rangle$ which appears in the second order expansion of the scattering matrix, there will not be produced any correlated pair of Rindler particles.

10 In order to deal with Minkowski states that are not extended over all space, we need to consider wave packets assembled by superposition of Minkowski 3-momentum eigenstates, but that fact does not have any bearing on the issue under discussion here.
4 Further epistemological considerations

We add this section only for completeness and for conceptual rigor and clarification. Readers who are only interested in the tests of the Unruh effect per se can safely ignore it.

It is a sound and well regarded practice in science and specially in physics to constantly test to the extent of our ability all the principles that underlie our theories as well as the most surprising conclusions that emerge from them. It would be foolish if with this paper we were trying to argue against such successful tradition. We are not. Any novel test of our well established theories and the principles that underlie them should of course be regarded as welcomed. We are all aware of the value of improving the precision of tests of say, the universality of free fall, or the extent to which Lorentz invariance is respected in nature.

Thus, why are we arguing here against probing the Unruh effect? The point is that we are not doing that. What we are arguing against is the attempts to probe it based in its misunderstanding. We have argued in detail here that thinking about the Unruh effect as if it were a novel aspect of physics, is simply incorrect. The Unruh effect reflects aspects of absolutely standard quantum field theory, as they would be naturally described by accelerated observers. Non-accelerated observers should simply forget about the Unruh effect just because there is nothing whatsoever that they could possibly observe that might be construed as due to this effect.

Let us go out now on an extraordinary epistemological limb in order to see to what extent one would have to go to argue for testing something like the Unruh effect and what exactly would it have to entail to be, at least, a logically sound proposal. It is true that in the continuous tests of our physical theories one might want to question some of the basic ingredients that go into the arguments that underlie the Unruh effect. There would be nothing, in principle that we would say against that. For instance, one might want to question our ideas about the way our measuring devices behave when they are accelerated. Thus, for instance one might want to examine the so called clock hypothesis\(^\text{11}\). In that case one might, for instance, want to question whether accelerated observers with their clocks and rulers would indeed measure the non-inertial forces in exactly the way we think they would\(^\text{12}\). Evidently, the only way to do this, in principle, if we were interested in questioning the fundamental laws that underlie their behavior, would be to actually accelerate our clocks and rulers. If on the other hand we have a good understanding of

\(^{11}\) This is the assumption that that the reading of an accelerated clock depends only on the length of its world line and thus, the effect of motion on the clock is only related to its velocity and not to its acceleration. The hypothesis is that there are good physical clocks that behave according to the above. For example, a pendulum clock does not satisfy the clock hypothesis and would run, when on the moon’s surface, at a rate that is not simply the one indicated by the standard the gravitational redshift [28].

\(^{12}\) This issue clearly relates the precise behavior of those devices and might, to a large extent, be considered as separated and independent from that concerning the behavior of the system one is studying.
how these devices work and their internal dynamics is not in doubt, we would be able to deduce how they would behave when they are accelerated from our physical theories and our knowledge of their internal structure. The exact same thing can be said in regard to the Unruh effect: If there would be any doubt about how our detectors would behave when accelerated, it would make sense to accelerate them and some people might consider this, in a sense, as a test of the Unruh effect\textsuperscript{13}. If on the other hand, we have a good understanding of how our detectors work and their internal dynamics is understood, then we can, without doubts predict the way they will behave when accelerated and there would be no point in the test.

In other words, if one is so inclined, one might question the validity of quantum field theory, or our ideas about the structure and behavior of the materials with which one builds the particle detectors, etc. In that case one might consider accelerating these devices and seeing how they behave when exposed to the Minkowski vacuum state of, say, the electromagnetic field. When considering such test we should have three things in mind:

1. The test would indeed require the actual acceleration of the detectors for which there are doubts about their internal dynamics.
2. Such test would be then a probe of our understanding of those aspects behind the structure and dynamics of these devices. In that case, it seems reasonable to expect the proponents of the test to explicitly point out what aspect of such dynamics are they considering testing.
3. Those tests would be therefore testing something else, and not the Unruh effect.

Let us consider, as an example, a specific situation in order to identify these various aspects in a concrete case: say we decide to use a certain molecule as a thermometer and accelerate it to test the Unruh effect. In order to accelerate the molecule we might remove an electron from it, and place it in an external constant and homogeneous electric field. The idea would be to see the photon emission of the molecule and see the thermal characteristics that identify the Unruh effect. The point is that we can simply analyze the behavior of the molecule from the inertial point of view and predict exactly what will be the characteristics of the photon emission in the lab rest frame (note that this analysis can be applied to any other system used in the photon detection, including any kind of accelerated thermometer). Let us refer to this as the \textit{pure inertial frame prediction} since the complete analysis of the situation relies only on inertial frame characterizations. On the other hand, we could predict the acceleration the molecule will experience due to the external electric field, and we could then carry out the analysis of the molecule’s behavior including photon emission in the frame that is co-moving with the molecule. As that would be an accelerated frame, the analysis would involve the Unruh effect. We then would need to transform back to the lab frame to determine what is

\textsuperscript{13} We do not consider that as an appropriate interpretation of the hypothetical experiment because, as we have extensively discussed, the Unruh effect stands solely on the grounds of the covariant character of the quantum field theory.
the prediction for the characteristics of the photon emission as characterized
in the frame where the photon detectors are at rest. Let us call it the \textit{partial
accelerated frame prediction}. We choose this name because predictions are
obtained by making an analysis in the accelerated frame and then converting
the results into predictions for the behavior of the detectors that are in the
lab inertial frame. Given the self consistency of our theory, the predictions
regarding what the detectors in the lab would detect will coincide with the
\textit{pure inertial prediction}. If the two predictions do not agree, what we must
have is a mistake in one of the calculations (or in both).

Suppose that the experimental results are in complete agreement with such
the \textit{partial accelerated prediction} and thus, also with the \textit{pure inertial predic-
tion}. Can we say we have confirmed the Unruh effect? Well, as we were able
to make the prediction without any recourse to that effect, the answer must
be: no. What should we conclude in the unlikely case that the experimental
results differ from the predictions? Evidently, this would mean that the \textit{pure
inertial prediction} can not account for the observations, and thus we would be
facing some novel aspect of physics as described in the inertial frame. Again,
what we would find would have no bearing on the Unruh effect.

Let us consider, for comparison, a test designed to confirm the existence
and measure the magnitude of the centrifugal force. For this, we place a small
object with mass $M$ at the end of a spring and set the whole system rotating
in the absence of gravity. When describing the system in the rotating frame
one finds, in addition to the external force on the body (that of the spring) an
extra force acting on it with modulus $M\omega^2 r$ where $\omega$ is the angular velocity
of the rotating system and $r$ is the distance of the body to the axis of rota-
tion. As the empirical fact is that the spring becomes elongated and the object
comes to rest in the rotating frame, one could conclude that this extra force
should be “actually there” as it is needed to cancel the force of the spring on
the object leading to a vanishing acceleration. However, if the experiment is
carried out in the inertial frame, that is, if the measurements of position as a
function of time are carried out in that frame, one should transform back the
characterization of the behavior of the system in the accelerated frame to the
inertial one, so one can make predictions about the outcomes as provided by
the lab frame detectors (this would correspond to the \textit{partial accelerated frame
prediction} explained above). When this is done, the prediction is that the force
that the spring has to apply to the object to keep it moving in circular motion
is exactly the one that accounts for its elongation, that is, the same as the
\textit{pure inertial frame prediction} (which relies completely in characterizations of
the system in the inertial frame). Evidently, both predictions agree with the
observation in the inertial frame, even though one uses part of the analysis
in the accelerated frame while the other is entirely carried out in the inertial
frame. Nevertheless, given the fact that, having performed the experiment in
the inertial frame, the \textit{pure inertial frame prediction} accounts for the observ-
ation (without needing an extra force), one can not conclude anything about
the existence of the centrifugal force beyond what one already knew, namely
that consistency between the inertial and rotating frame descriptions require it.

5 Conclusions

When analyzing the Unruh effect and its physical consequences it is important to take into account all that subtle issues that are considered in the formalism of quantum field theory in curved space-time. That would guarantee that one is lead in a straightforward manner to a correct description of the physics in every reference frame involved, and to an appropriate analysis of the correspondence between them. In this work we have discussed some of the existing sources of confusion, and we have offered rather general arguments indicating that all the experimental proposals to detect the Unruh effect where the detectors are located in an inertial laboratory will fail their objective, regardless of the results they might obtain. If they observe something that deviates from absolutely standard QED effects they would have found new physics, but not a sign of the effects they set up to uncover. We have pointed out some common misconceptions regarding this effect, which hopefully, we have helped to clarify.

There are two recent reviews of the Unruh effect in the literature, [9] and [10], which also offer discussions on the logical sense of testing it experimentally. In the former it is said that this effect “does not need experimental confirmation any more than free quantum field theory does”, a position that the latter restates as: “typical proposals for “experimental tests” of the Unruh effect are misnamed since they consist of showing how the effect can be used to rationalize experimental data”. Although these points of view resemble our main point in this work, we feel the authors of these reviews do not stress sufficiently the essential un-measurability of the effect. For instance, the authors of [9] focus on the lessons that can be gained with such experiments as they claim that “explanations of the laboratory phenomena from the point of view of Rindler observers in terms of the Unruh effect [...] can also bring new insights”, and the author of [10] claims no definite answer to the question about the prospects of its experimental detection.

There is a discussion in the introduction of [2] which comes close to realizing the point we are making here. There, the authors make a comment regarding the Coriolis force indicating that, although it clearly does not represent any new physical effect, an experiment like the one involving the Foucault pendulum is, nevertheless, very illuminating in exhibiting explicitly the effects of the Earth’s rotation. We agree wholeheartedly with that perspective, however we disagree strongly with the parallel between the Foucault experiment and the proposed searches of the Unruh effect. The point where the parallel breaks down is precisely the fact that the laboratory where Foucault’s experiment is performed, where the measuring devices (rulers and clocks) are at rest and

\[14\] Reference [10] offers a critical review of the theoretical foundations of the Unruh effect suggesting that the effect might not be a straightforward consequence of QFT. If this were the case, its experimental detection would acquire a new scope.
the measurements are performed is a non inertial laboratory, that of the rotating Earth, while in all the proposals up to date, the searches for the Unruh effect involve inertial laboratories (to the extent that Earth is inertial in that context\textsuperscript{15}). We are not claiming that this effect cannot be illustrated experimentally, in analogy to Foucault’s illustration of the Coriolis force, merely that it follows from basic principles that the only valid way to do this would involve performing the experiment (\textit{i.e.} carrying on the measurements) in the accelerated frame, just as the one involving the Coriolis force needs to be performed (\textit{i.e.} the measuring devices must be at rest) in the rotating frame. Thus, just in the same way that we would be making a mistake if we were to propose an experiment designed to directly detect the Coriolis force using measuring devices placed in an inertial frame, it should now be clear that any proposal to “directly detect the Unruh effect” using detectors in an inertial frame must be considered as ill conceived.

We end this work by emphasizing again that, as the Unruh effect does not represent novel physics, but rather the description of standard and well tested aspects of our physical theories in terms of an alternative set of coordinates, it needs no experimental verification beyond that concerning those standard aspects (which, of course, one might want to test for different reasons). And, that if all one is looking for is a “direct illustration of the effect”, in analogy with the Foucault pendulum experiment, one would be embarking in a futile enterprise unless the proposal involved accelerated detectors and observers.

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\textsuperscript{15} Strictly speaking of course, any Earth-bound laboratory is not inertial, and thus one might then consider looking for something like the Unruh effect connected to the minuscule proper acceleration of the laboratory. That, however, seems extremely difficult at the experimental level simply because the magnitude of the effect is ridiculously small.
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