Virtual observation of the Unruh effect

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Outline

- What is the Unruh effect?
- What does it mean to observe the Unruh effect?
- The Unruh effect and Larmor radiation.

Quantum field theory reminder

When dealing with quantum fields it is usual to postulate the existence of a vacuum state, $|0\rangle$, which is Poincaré invariant. This means that all *inertial* observers will agree that their vacuum state is the same.

Does this result still holds for *uniformly accelerated* observers (also called *Rindler* observers)?

Quantum field theory for uniformly accelerated observers

The answer to the previous question is *no*. In fact, Rindler observers will see a *thermal* state with temperature $T_U = \frac{a}{2\pi}$ (in natural units), where a is their proper acceleration. This is the *Unruh effect*.

So, surprisingly, while inertial observers may freeze to death at 0 K, uniformly accelerated observers may burn to death (for high enough accelerations) at temperature T_U.

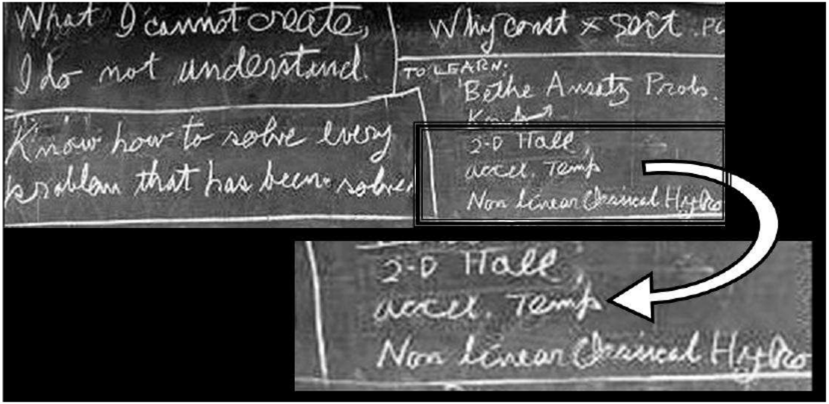

Figure: Feynman's blackboard at the time of his death (1988). Taken from Rev. Mod. Phys. 80:787-838 (2008) with permission.

Quantum field theory for uniformly accelerated observers

Since this is a very unintuitive effect, a couple of points are worth highlighting:

- The Unruh effect can be rigorously derived in axiomatic quantum field theory.
- The Unruh effect, in fact, is needed for consistency between *different* descriptions of the *same* physics by different observers.

Observing the Unruh effect

Due to its non-trivial nature, some people would like an experimental observation of the effect, *but is it needed*?

Observing the Unruh effect

A more fruitful strategy than direct observation would be to search for phenomena that can naturally be interpreted in terms of the Unruh effect.

Examples of these include (but are not restricted to):

- Spin depolarization in storage rings *(Bell & Leinaas, Nucl. Phys. B 212, 131–150, 1983)*
- Decay of *non-inertial* protons in accelerators *(Vanzella & Matsas, Phys. Rev. Lett. 87, 151301, 2001)*
- Correlated photons in ultra-intense lasers *(Schutzhold, Schaller & Habs, Phys. Rev. Lett. 97, 121302, 2006)*

Observing the Unruh effect

The spin of electrons in accelerators tend naturally to align in the direction of the magnetic field that is present. However, not a 100% of them get polarized. Could we explain that from the point of view of a co-moving observer?

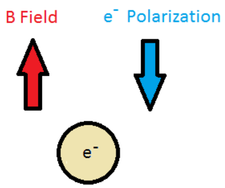

Figure: Electron polarization in a magnetic field.

Observing the Unruh effect with Larmor radiation

One very simple phenomenon that can be interpreted in terms of the Unruh effect is the emission of radiation by accelerated charges.

For instance, to obtain the *mean emission rate* of photons (as a function of transverse momentum), Γ^{M}_{em}, consistent with inertial observers, uniformly accelerated observers *must* consider that the charge interacts with a thermal bath of particles.

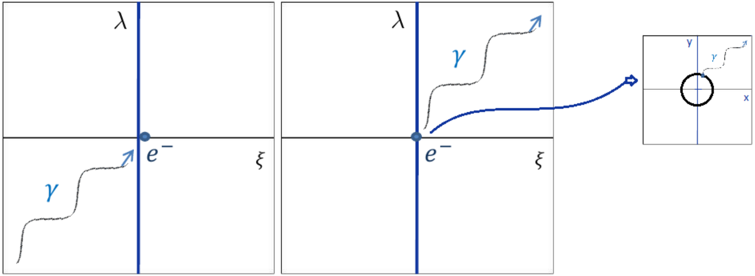

Figure: An electron, which is both linearly accelerated and rotating, interacting with the Unruh thermal bath.

Observing the Unruh effect with Larmor radiation

It may sound strange that a *quantum* effect can be verified through a *classical* phenomenon like Larmor radiation. This can be explained by noting that in all thermal factors involved $\hbar$ cancels, i.e.,

$$\exp\left[\hbar\omega_R/(k_{\mathrm{B}}T_{\mathrm{U}})\right] = \exp\left(2\pi\omega_R c/a\right)$$

The strategy we adopted in our recent work (*arxiv.org/abs/1701.03446*) is the following:

1. Consider a simple experiment made by accelerated observers involving rotating charges and calculate its expected results.
2. With these results propose an experiment for inertial observers to confirm Rindler observers predictions.
3. Finally we show that the results predicted by inertial observers can only agree with those obtained by accelerated observers if there is the Unruh thermal bath.

Moreover, we show that inertial observers can see traces of the Unruh effect in a simple classical electrodynamics calculation.

Let us consider then a charge that rotates with constant angular velocity Ω with respect to Rindler observers.

In Rindler coordinates, (λ, ξ, r, ϕ), we will have

$$j^{\mu}(x^{\nu}) = \frac{q}{R}\delta(\xi)\delta(\phi - \Omega\lambda)\delta(r - R)(1, 0, 0, \Omega)$$

where λ and ξ are related with the usual Cartesian coordinates t and z by

$$\begin{aligned} t =& a^{-1} e^{a\xi} \sinh(a\lambda) \\ z =& a^{-1} e^{a\xi} \cosh(a\lambda) \end{aligned}$$

As we saw, Rindler observers must consider not only emission but also absorption of photons.

The recipe to calculate, for instance, the absorption rate of photons, Γ^R_{abs}, will be:

Figure: Calculating the absorption rate Γ^R_{abs}.

Virtual observation of the Unruh effect

Following a similar recipe, Rindler observers can also calculate the mean emission rate, Γ^R_{em}.

If the Unruh effect is true, i.e., if Rindler observers see a thermal bath at $T = T_U$, they can affirm that Minkowski observers will see an emission rate given by:

$$\Gamma^M_{em} = \Gamma^R_{abs} + \Gamma^R_{em}$$

Now, accelerated observers can propose an experiment for inertial observers to confirm their prediction:

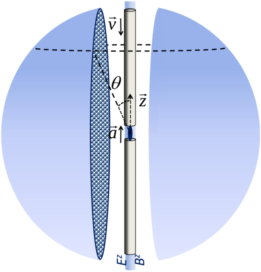

Figure: Electrons are injected with velocity $\vec{v}$ in a cylinder containing suitable electric, E^z, and magnetic, B^z, fields. Radiation is released near the center from an open window, which is surrounded by electromagnetic detectors lying on a sphere. This allows us to obtain the radiation spectral decomposition from which Γ^M_{em} is calculated.

Virtual observation of the Unruh effect

For the current being considered, we can plot Γ^{M}_{em} (predicted by accelerated observers) as a function of the transverse momentum magnitude, $k_\perp = |\vec{k}_\perp|$ and the thermal bath temperature T.

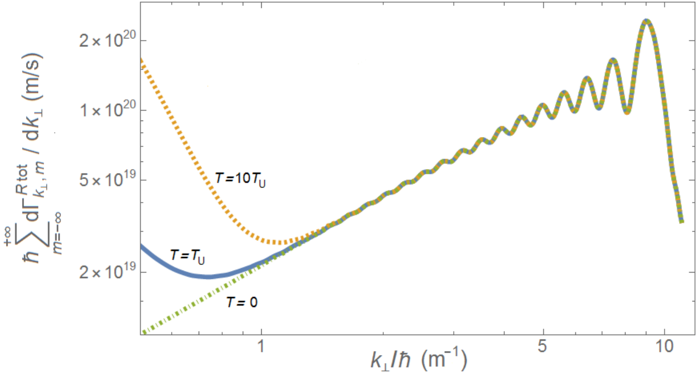

Figure: For the sake of illustration, we plot Γ^{M}_{em} for different values of T assuming $E^z = 1$ MV/m, $B^z = 10^{-1}$ T, $R = 10^{-1}$ m, and injection energy 3.5 MeV. The solid curve correspond to the Unruh effect prediction.

From the measurement of the *radiation spectral decomposition*

$$I(\omega,\theta,\phi)=\frac{d\mathcal{E}}{d\omega d\cos(\theta)d\phi}$$

inertial observers can calculate the mean emission rate Γ^{M}_{em}. The number of photons seen by inertial observers with an energy ω at a solid-angle (θ,ϕ) is given by

$$dN^{M}_{\omega\theta\phi}=\frac{d\mathcal{E}}{\omega}=I(\omega,\theta,\phi)\;\omega^{-1}d\omega d(\cos(\theta))d\phi$$

Since $k_\perp = \omega \sin(\theta)$ and $k_z = \omega \cos(\theta)$ we can express the emission rate Γ^M_{em} as

$$\Gamma^M_{em} = \frac{1}{\Delta\lambda} k_\perp \int_0^{2\pi} d\phi \int_{-\infty}^{+\infty} \frac{dk_z}{(k_\perp^2 + k_z^2)^{3/2}} I(\omega,\theta,\phi)$$

where $\Delta\lambda$ is the total proper-time of the linearly accelerated observer trajectory.

For our $j^\mu(x^\nu)$ we have

$$I(\omega,\theta,\phi) = \frac{q^2\omega^2}{4\pi^2} \left| \hat{r} \times \int_{-\infty}^{+\infty} d\lambda \frac{d\vec{r}_q}{d\lambda} \exp\left[-i\omega\left(\hat{r}\cdot\vec{r}_q(\lambda) - a^{-1}\sinh(a\lambda)\right)\right] \right|^2 ,$$

where $\hat{r}$ is the unit normal vector of the direction of observation and $\vec{r}_q(\lambda)$ is the charge spatial trajectory written as a function of Rindler observers proper time λ.

The nice thing to notice is that the previous calculation does not use quantum field theory at all.

By carrying out the calculation above we show that the interaction rates calculated both from the accelerated and inertial points of view agree, as expected by the Unruh effect, i.e.:

$$\Gamma^{M}_{em} = \Gamma^{R}_{abs} + \Gamma^{R}_{em}$$

Conclusions

- Despite difficulties in observing directly the Unruh effect, it can be said to be *as well tested as the framework of quantum field theory itself*.
- In our recent work we show that traces of it can be seen in a very simple experiment using *classical electrodynamics*. Unless one doubts classical electrodynamics, one cannot deny the existence of the Unruh effect.

References and acknowledgments

- 1) Crispino, L. C. B., Higuchi A. and Matsas, G. E. A.; " *The Unruh effect and its applications* ", Rev. Mod. Phys. 80, 787 (2008)
- 2) Cozzella, G., A. G.S. Landulfo, G. E. A. Matsas and D. A. T. Vanzella; " *Virtual observation of the Unruh effect* ", https://arxiv.org/abs/1701.03446 (2017)

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