# Towards Experimental Signatures of the Unruh Effect ◇

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Understanding the structure of the quantum vacuum is one of the key challenges of contemporary fundamental physics, since theoretical efforts to describe the observed energy density of the vacuum amounting to 5 GeV/m$^3$ drastically fail by $10^{124}$ (microscopic approach via string theory) and $10^{-121}$ (via cosmological considerations), respectively.

Experimental access to the vacuum structure may be possible via the Unruh effect [1]: An observer accelerated by $a$ will experience the Minkowsky vacuum with its quantum fluctuations as a thermal bath characterized by an equilibrium temperature, the Unruh temperature $kT_U = \hbar a/2\pi c$ [1]. This effect is an analogon to the black-body Hawking radiation resulting from quantum fluctuations in the strong gravitational field of a black hole [2]. Replacing the accelerated observer (detector) by an accelerated scatterer (e.g. accelerating electron) will result in non-inertial scattering processes with virtual photons from the thermal bath. Translated back into the inertial laboratory frame the virtual photon will be converted to a real photon. In order to account for angular momentum conservation, simultaneously a second photon has to be created from behind the event horizon (given by $d = c^2/a$ with $a$ being the acceleration of the scatterer) with opposite spin. Thus the experimental signature of the Unruh effect will be the creation of fully entangled photon pairs.

While for conventional accelerations the Unruh temperature will stay far below any experimentally accessible range (for $a = g = 9.81 m/s^2$: $T_U = 3.3\cdot 10^{-24}$ eV), novel short-pulse, high-intensity lasers with peak powers presently reaching Terawatts and even Petawatt levels routinely reach intensities of $10^{18}$ - $10^{21}$ W/cm$^2$. Electrons accelerated in these ultra-high fields to relativistic energies (< GeV) within distances of only a few mm can be used to probe vacuum fluctuations by the creation of Unruh photon pairs in the energy region of a few hundred keV, thus measurable with modern $\gamma$-spectroscopic techniques.

Initially the Unruh effect was formulated for an infinite and constant acceleration. In order to allow for a quantitative assessment of more realistic experimentally accessible scenarios, two theoretical studies have been performed in non-linear QED resulting for the first time in quantitative predictions of yields for Unruh radiation as well as for the dominant background contribution, which is given by the classical radiation of accelerated electrons (Larmor radiation) [3,4]. It should be mentioned that although formulated by J.J. Larmor already back in 1897, the classical Larmor radiation has so far never been experimentally identified for linear acceleration.

In a first scenario with linear ($\delta$-pulse-like) electron acceleration the probability for the emission of Unruh radiation scales with $P_{\rm Unruh} \sim (E/E_S)^4$ (where $E_S$ denotes the critical or Schwinger field strength $E_S = 1.3\cdot 10^{18}$V/m), thus requiring extremely strong electrical laser-generated fields near the critical field, while the short pulse leads to a broad Larmor background spectrum [3]. In contrast, an arrangement exploiting an oscillating acceleration provided by an undulator or a counter-propagating laser beam results in $P_{\rm Unruh} \sim (E/E_S)^2$ and thus much relaxed experimental conditions. In this scenario relativistic electrons will be injected into the strong periodic field of an undulator or a laser. The resulting Lorentz-boost of the transversal field in the electron rest frame leads to an amplification of the electron acceleration. Whereas monoenergetic classical Larmor radiation with fixed polarization will be produced that exhibits a blind spot in acceleration direction, due to the Unruh effect photon pairs with opposite spin but arbitray spin direction will be created, obeying the resonance condition $k_1 + k_2 = \omega = \gamma\omega_0$ ($k_1, k_2$: wave numbers of Unruh photons, $\omega$: boosted optical frequency in the electron rest frame). Thus Larmor and Unruh radiation can be distinguished according to their different energy and angular characteristics, as illustrated by the schematical picture of the angular characteristics shown in Fig. 1 and by Fig. 2, where the full phase space of Larmor (left) and Unruh radiation (right) is displayed as calculated in Ref. [4] in the framework of non-linear QED.

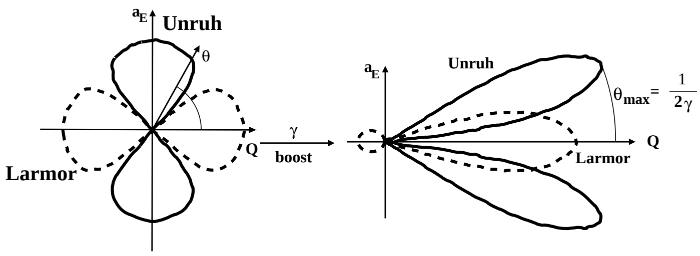


Fig. 1: Angular characteristics for Larmor and Unruh radiation before (left) and after the Lorentz boost (right). The acceleration direction by the electric field is indicated by $a_E$.

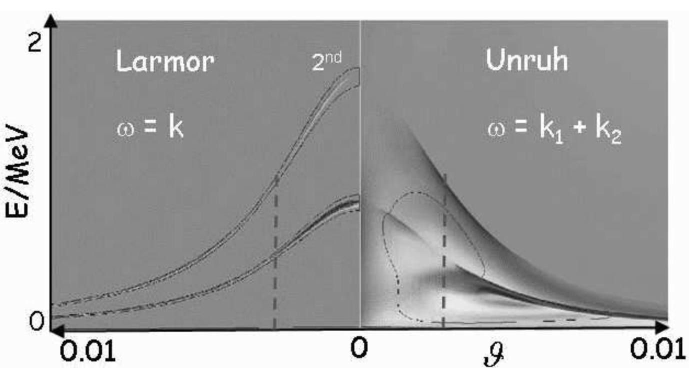


Fig. 2: Phase space for Larmor (left) and Unruh radiation (left) as calculated in the framework of non-linear QED [4].

Fig. 3 illustrates a possible experimental setup designed for the detection of Unruh photons generated in an ex-

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periment with oscillating electron acceleration. Using a TW (or PW) laser beam electrons can be accelerated in a gas-filled capillary (or from a thin diamond-like carbon foil) to energies around 150 MeV ($\gamma$ =300) with ca. $10^{10}$ electrons/bunch. These electrons are then injected into a counter-propagating linear or circular polarized second laser (ps pulse length, $10^{18}$ W/cm$^2$, $\omega_{\rm opt} \sim 2.5$ eV). In the rest frame of the electrons this results for $E/E_S = 10^{-3}$ in a boosted optical frequency of 1.5 keV. As derived in Ref. [4], the probability for (incoherent) Larmor photons will result in $P_{\rm Larmor} = 10^{-2}$, while the emission probability for incoherent Unruh photons amounts to $P_{\rm Unruh} = 10^{-11}$. However, this at first glance rather unfavourable signal/background ratio can be improved by orders of magnitude when entering the regime of coherent emission exploiting a relativistic mirror. Moreover, as illustrated in Fig. 2, Larmor and Unruh photons strongly differ in energy and angular characteristics: while monoenergetic Larmor radiation with $\omega = k$ will be produced with an intensity minimum in acceleration direction ('blind spot'), Unruh photons obey the resonance conditions $k_1 + k_2 \sim 500$ keV for the above given parameters and can thus be distinguished by suitable energy and angular filters. The accelerated electrons will be deflected and detected in a magnetic spectrometer (already existing at the MPQ), while photon detection will be performed in a Compton spectrometer.

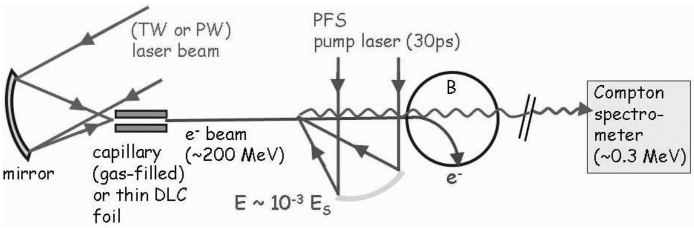


Fig. 3: Schematical view of an experimental setup for the detection of Unruh radiation originating from laser-accelerated electrons interacting with the strong periodic field of a counter-propagating laser beam.

Experimentally the generation of entangled photon pairs can be identified via Compton polarimetry, where a measurement of the azimuthal Compton scattering angle will be sensitive to the polarization of the detected photons (according to the Klein-Nishina formula). As illustrated in Fig. 4, two interaction points for scattering ($X_1$, $Y_1$) and absorption ($X_2$, $Y_2$) of the incoming $\gamma$ ray ($E_\gamma = \hbar\omega$) define the azimuthal Compton scattering angle $\phi$, which exhibits a characteristic angular dependency with respect to the initial polarization vector $\vec{E}$.

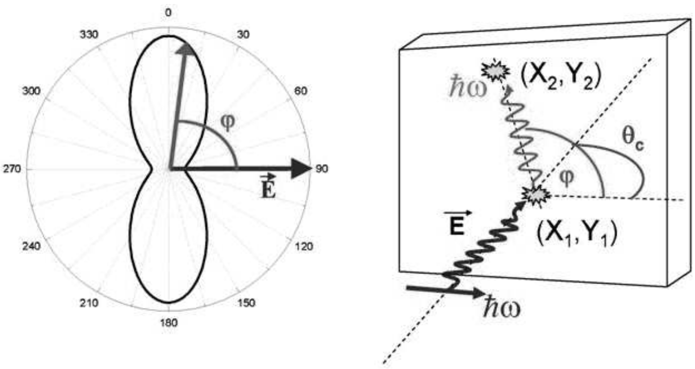


Fig. 4: Principle of Compton polarimetry (see text).

For this purpose an advanced 2D-segmented position-sensitive planar germanium detector system is presently under construction (thickness 18 mm, 64x64 strips, pitch 1 mm). A photogaph of a comparable detector operated at GSI [5] is shown in Fig. 5. In the first phase it is planned to explore the experimental conditions for high-resolution $\gamma$ spectroscopy in the vicinity of high-intensity pulsed lasers interacting with matter in view of the resulting electromagnetic pulse.

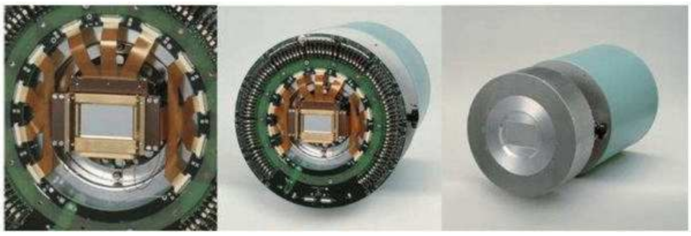

Fig. 5: Prototype of a 2D-segmented planar germanium Compton polarimeter as presently operated at GSI/Darmstadt [5]. A comparable detector with a design optimized for the detection of photons from Unruh (and Larmor) radiation with $E_\gamma < 400$ keV is presently under construction.

Then the properties of the Larmor radiation will be studied, optimizing for coherent backscattering. Subsequently the enhanced Unruh radiation will be investigated, aiming at the first experimental identification of this fundamental process. Exploiting the ultra-high field regime accessible with present and next-generation high-intensity lasers will in addition allow to probe the existence of extra dimensions down to distances of the event horizon ($d = c^2/a$) in the nm - fm regime.

## References

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