Studying Signatures of the Unruh Effect using High-Power, Short-Pulse Lasers

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in the framework of the Cluster of Excellence MAP (Munich-Centre for Advanced Photonics)

Outline:

- introduction: radiation and strong acceleration: Unruh effect
  competing radiation components (Larmor, radiation damping)
- experimental signatures
- experimental scenarios:
  (i) low-energy electrons + brilliant X-ray beam
  (ii) testing novel scenario:
    enhancement by coherent electron bunches?
- identification via Compton polarimetry
Towards Improved Understanding of the Quantum Vacuum

**Vacuum:**

Minkowski vacuum:
- no particles (in inertial frames)
- lowest possible energy state in universe
≠ empty space

**Vacuum fluctuations:**

atomic physics (QED): well-understood
particle physics (QCD): vacuum fluctuations $<q\bar{q}> = 1.5 \text{ fm}^{-3}$
$10 \times$ nucleon density ($\rho_{\text{nucl}} = 0.16 \text{ fm}^{-3}$)!

**Energy density of the vacuum:**

observed (gravitation): $4 \text{ GeV/m}^3$
theory: microscopic (Planck scale):
macroscopic (Casimir at Hubble scale):

$10^{124} \text{ GeV/m}^3$
$10^{-121} \text{ GeV/m}^3$

“Biggest embarrassment in theoretical physics”
(G. Fraser/CERN)
Larmor radiation: accelerated charges (e.g. electrons) radiate

→ Lorentz force:

\[ \dot{m}v = \frac{dp}{dt} = qE + \frac{q}{c} \nu \times B \]
\[ mc \frac{du^i}{ds} = \frac{e}{c} F^{ik} u_k \]

Radiation damping:

- emitted radiation removes energy → influences particle trajectory
- correct treatment has to include back-reaction of radiation
- various theoretical attempts developed since Lorentz, Abraham (1904)
- promising approach:

→ Landau-Lifshitz force:

\[ mc \frac{du^i}{ds} = \frac{e}{c} F^{ik} u_k + F^i_{\text{self}} \]
\[ F^i_{\text{self}} = \frac{2q^2}{3mc^3} \frac{\partial F^{ik}}{\partial x^l} u_k u^l - \frac{2q^4}{3m^2c^5} F^{il} F_{kl} u^k + \frac{2q^4}{3m^2c^5} (F_{kl} u^l)(F^{km} u_m) u^i \]

- typically radiative damping effects are small
- but: \( F^i_{\text{self}} \) may become dominant in regime of laser acceleration
- perspective of first experimental access to radiation damping via laser acceleration of electrons
Radiation components from strong acceleration: Unruh radiation

- Unruh radiation: W. Unruh (1976)

Accelerating observer will observe black-body radiation, where an inertial observer would observe none.

→ Vacuum of the inertial observer looks for an accelerating observer like a state with many particles in thermal equilibrium: warm gas.

→ Accelerating observer/detector experiences the vacuum as a thermal bath with the equilibrium temperature $T_U$.

Vacuum ≠ empty space.

Unruh temperature:

$$kT_U = \frac{\hbar \alpha}{2\pi}$$
Analogon: Hawking Radiation

“a Black Hole is not black”

in very strong gravitational field of black hole (mass $M$):
quantum fluctuations result in thermal radiation with temperature $T_H$:

$$kT_H = \frac{\hbar c^3}{8\pi GM} = \frac{\hbar}{2\pi c} g$$

Hawking temperature $T_H$:

Event horizon:

$$R_{\text{Sch}} = \frac{c^2}{2g}$$

→ Schwarzschild radius
→ no light can escape from within $R_{\text{Sch}}$

- photon pairs created at horizon:
  1 photon falls into black hole, other is emitted as thermal radiation

5 $M_{\text{sol}}$: $T_H = 8 \cdot 10^{-8}$ K
Hawking Radiation: Connecting Fundamental Areas

\[ kT_H = \frac{\hbar c^3}{8\pi GM} \]

- quantized theory of gravity still not available
- indication of underlying affinity between (yet) disparate fields?

Unruh radiation as experimental 'benchmark' for reliability of Hawking concept?
Experimental Signature for Unruh Radiation

replace accelerating observer (detector) by accelerating scatterer:

conversion of (virtual) quantum vacuum fluctuations into real photon pairs by non-inertial scattering

event horizon: $d=\frac{c^2}{a}$

- beyond $d$ light cannot catch up with particle
- observer cannot see complete space time
Rindler vs. Minkowski Photons

- world lines:
  - inertial (Minkowski) observer (M)
  - (uniform) accelerated (Rindler) observer (R):
    space-time region: right Rindler wedge
    minimum distance to horizon: \( d = \frac{c^2}{a} \)

- 'Minkowski photon':
  seen by inertial observer

- 'Rindler photon':
  seen by (uniformly) accelerated observer

- Unruh effect:
  - accelerated electron experiences thermal bath of (Rindler) photons
  - scattering of 1 (Rindler) thermal photon seen in co-accelerated frame:
    \( \rightarrow \) emission of two (Minkowski) photons seen in inertial/laboratory frame

\( \rightarrow \) entangled pair of (Minkowski) photons: "Unruh radiation"
Creation of Entangled Photon Pairs

Compton scattering:

- non-inertial scattering creates real photon $\gamma_1'$
- photon $\gamma_2$ is emitted from behind the horizon distance $d$
  $\Rightarrow$ angular momentum (spin) conservation

- creation of photon pair with opposite spin
  $\Rightarrow$ experimental identification via (Compton-) polarimetry
A stationary observer outside the black hole would see the thermal Hawking radiation.

An accelerating observer in vacuum would see a similar Hawking-like radiation: Unruh radiation.
Acceleration Scenarios

- W.B. Unruh: considers constant, infinite acceleration
- linear acceleration:
  - short acceleration pulse (δ-like)
  - radiation yields from non-linear QED:
    - probability for Unruh photons:
      - requires ultra-strong fields near Schwinger field $E_S = 1.3 \cdot 10^{18}$ V/m
      - short acceleration leads to broad Larmor spectrum

- oscillating acceleration:
  - shoot ultra-relativistic electrons into strong periodic field (undulator or laser beam)
  - in rest frame of relativistic $e^-$: boost of (transversal) field $\rightarrow$ amplification of electron acceleration
  - probability for Unruh photons:
    - $P_{\text{Unruh}} \propto (E / E_S)^2$

- monoenergetic Larmor radiation in electron rest frame
Oscillating acceleration

experiment: electron beam (< GeV) + counter-propagating laser beam (or undulator)

- linear polarized, $10^{18}$ W/cm$^2$
- laboratory frame: $\omega_{\text{opt}}=2.5$ eV
- e$^-$ rest frame: $E/E_S=10^{-3}$, $\omega = 1.5$ keV

electron bunches:
- $\gamma = 300$ ($E_e=150$ MeV)
- laser-generated: $N_e \sim 10^9$/s

laser beam (= undulator):
- emission of entangled pairs of photons: resonance $k_1 + k_2 = \omega$
- probability of Larmor photons: $P_{\text{Larmor}} \sim 10^{-1}$
- probability of Unruh photons: $P_{\text{Unruh}} \sim 10^{-11}$ ($\omega T \sim 100, k_1+k_2 \sim 500$ keV)

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Unruh- vs. Larmor-Radiation

Larmor radiation:
- Compton-backscattered photons \((\hbar \omega_0 \cdot 4 \gamma^2)\)
  or undulator photons \((\hbar \omega_0 \cdot 2 \gamma^2)\)
- monoenergetic, fixed polarization
  \(\approx\) Thomson scattering of laser photons

\(\rightarrow\) blind spot of Larmor radiation in acceleration direction

Unruh radiation:
- photon pairs: opposite spin but arbitrary spin direction
- energy distribution: \(k_1 + k_2 = \omega = 2 \gamma \omega_0\)
- different angular distribution as Larmor photons
phase space from non-linear QED calculation:

\[ N=1 \text{ electron, incoherent: } \quad \text{PRL 100 (2008) 091301 (Schützhold, Schaller, Habs)} \]

\[ \omega: \text{(boosted) optical frequency in rest frame of electron} \]

emission probabilities:

\[ P_{\text{Larmor}} = \alpha_{\text{QED}} \left( \frac{qE}{m\omega} \right)^2 \frac{O(\omega T)}{2} \]

\[ P_{\text{Unruh}} = \alpha_{\text{QED}}^2 \left( \frac{E}{E_S} \right)^2 \frac{O(\omega T)}{30} \]

\[ \frac{P_{\text{Unruh}}}{P_{\text{Larmor}}} \approx \left( \frac{\alpha_{\text{QED}}}{60\pi} \frac{\omega^2}{m^2} \right) = 10^{-11} \quad (\gamma = 150, \hbar \omega = 300 \text{ eV}) \]

filter out Unruh photons from (monochromatic) Larmor background
- extract Unruh component via aperture and energy filter
Experimental approaches

Start: explore photon field from laser accelerated electrons: dominant Larmor?

Scenario 1:  
- generate relativistic electron mirror from DLC foil  
  - generate X-ray undulator (E$_\gamma$ ≈ 20 keV) by Compton backscattering  
  - Unruh emission into blind spot of classical Larmor  
- laser-accelerated electrons via “downramping”:  
  - low-energy, monoenergetic electrons ($\approx$ 1 MeV, $\gamma$~2)  
  (Geddes et al., PRL 100,215004 (2008))

Scenario 2:  
- generate dense relativistic electron bunch from DLC foil  
- use optical undulator ('production laser')  
- test conjecture of enhancement effects:  
  1. extension of Lorentz force by radiation damping:  
     Landau-Lifshitz terms?  
  2. coherent electron interaction (macro particle)?  
     - enhancement of radiation probabilities  
     - radiation damping component dominating Larmor?  
- coherent enhancement of Unruh radiation?
Scenario 1: Unruh-Setup with X-Ray Undulator

→ (incoh.) low-energy electron beam + 20 keV X-ray undulator

- (~10 TW) laser beam
- gas nozzle
- e\textsuperscript{-} beam (~1 MeV)
- production laser: \( \hbar \omega_0 \)
- relativistic mirror (\( \gamma \sim 70 \))
- DLC foil (~5 nm)
- driver laser
- Larmor photons
- Compton polarimeter (~0.3 MeV)
- Unruh photons

\[ \hbar \omega' = 4 \gamma^2 \hbar \omega_0 \]
Novel laser acceleration scheme

- laser-foil interaction: nm targets (DLC foil)
- electron breakout:

- cold compression of ions and electrons during ion acceleration followed by electron break-out.
- compression: higher than solid-state density achievable
  → beams with ultra-high electron bunch densities ($>10^{24}$ cm$^{-3}$)
  → very high charge ($> nC$), good energy resolution.
- ‘conventional’ bubble laser acceleration:
  electron density only $10^{18}$ cm$^{-3}$ and pC charges.
→ dense electron bunches with $N_e \sim 10^9$: (partly) coherence?
Coherent Enhancement?

Incoherent emission

- independent electrons radiate
- random phases of electric field

Coherent emission

- $N_e$ electrons radiate in phase
- intensity: grows with $N_e^2$

$$E \propto \sqrt{N_e}$$
Intensity $\propto N_e$

$$E \propto N_e$$
Intensity $\propto N_e^2$$
Coherent Enhancement?

- Coherence volume in laser-accelerated bunch:
  - Classical case: transversely coherent laser beam
  - Quantum mechanical case (Unruh):
    scattering of vacuum fluctuations
    - Transverse coherence is determined by the wave length \( \lambda \) of the photons in the electron rest frame
    - Number \( N \) of coherent electrons within area \( \lambda^2 \) can be significantly smaller than the total number of the electron sheet

- Enhancement:
  - \( P_{\text{Unruh}} \sim \alpha^2, \ P_{\text{Larmor}} \sim \alpha \quad [\alpha = \frac{e^2}{\hbar c}] \)
  - \( P_{\text{Unruh}} \) (coherent electr.) = \( N^4 \cdot P_{\text{Unruh}} \) (single electr.)

\[
\frac{P_{\text{Unruh}}}{P_{\text{Larmor}}} \sim \frac{N^4}{N_e^2}
\]

- Larger \( N \) values: switch from weak coupling QED and perturbative treatment to ‘strong coupling QED’; enhancement more difficult to predict
Scenario 2: Testing Coherent Enhancement

- Larmor cross section strongly suppressed by radiation damping

\[ \frac{F_{\text{self}}}{F_{\text{ext}}} = 10^{-8} \frac{a}{\omega_L} \cdot N \]

- experimental scheme:

- new: longitudinal acceleration from radiation damping force
  Unruh emission into maximum of classical Larmor radiation
- higher harmonics from Landau-Lifshitz radiation damping:
  \( \rightarrow \) lower \( \gamma \) (less Doppler boost) sufficient for ~300 keV Unruh quanta

\( \rightarrow \) new theory with strong coupling needed in coherent scenario
Kinematics of Compton scattering:

\[
\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{m_e c^2} (1 - \cos \theta)}
\]

Recoil energy of Compton electron:

\[
\Delta E = \hbar\omega \frac{\hbar\omega}{mc^2} (1 - \cos \theta) \frac{1 + \frac{\hbar\omega}{m_e c^2} (1 - \cos \theta)}{1 + \frac{\hbar\omega}{m_e c^2} (1 - \cos \theta)}
\]

Klein-Nishina formula:

\[
\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \frac{\hbar\omega'^2}{\hbar\omega^2} \left( \frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2 \sin^2 \theta \cos^2 \phi \right)
\]

\(\phi\): azimuthal scattering angle (rel. to polarization plane)

\(r_0\): class. electron radius (~2.82 fm)
Diagnostics: Compton Polarimetry

- polarization of Unruh photons different from classical acceleration radiation
- identification of polarization via Compton scattering:
  \[ \rightarrow \text{measure azimuthal scattering angle:} \]

2D segmentation:
\( x, y \) coordinates define 2 interaction points:
\( (X_1, Y_1) \): Compton scattering
\( (X_2, Y_2) \): photoabsorption
2D Hard X-ray Compton polarimeter

2D segmented planar Ge-detector:

Crystal:
- $d = 20\,\text{mm}$
- $80\,\text{mm} \times 80\,\text{mm}$
- $64 \times 64$ strips (pitch $1\,\text{mm}$)

Electronics:
- 128 spectroscopy channels

Angular distribution: $210\,\text{keV}$, lin. pol.


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Conclusion

- rapid developments on particle acceleration with high-power short-pulse lasers:
  - opens up experimental access to radiation components from strong acceleration (starting from classical Larmor radiation)

- experimental identification of signatures of the Unruh effect (analogy to Hawking radiation of black holes) comes into reach

- experimental test:
  coherently interacting electron macroparticle -> enhancement

- competing radiation components:
  (classical) Larmor radiation may be dominated by radiation damping
  - first experimental access to radiative back-reaction on accelerated charged particle (confirmation of Landau-Lifshitz terms ?)

- experimental diagnostics based on Compton polarimetry
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