# HIGH ENERGY EXPERIMENTAL PROPOSALS FOR THE STUDY OF UNRUH (EFFECT) RADIATION

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After a short discussion on the physics of the Unruh effect, Hawking, Larmor and Unruh radiations we consider some experiments proposed up to 2008, which can be carried out with the help of high energy electron and optical or X-ray photon beams.

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## 1. INTRODUCTION

**1a. The formula and Physics of the Unruh effect (UE).** According to quantum field theory and general relativity with curved coordinates [1] in its instantaneous rest frame, every body (or particle), undergoing acceleration $a'$, is immersed in "thermal bath" of Planckian photons with a temperature:

$$T_U = \frac{\hbar a'}{2\pi k c}. \qquad (1)$$

If so, the interaction (say a Compton scattering) of these photons with an accelerated Unruh detector should result in the observation in the laboratory frame (LF) of the so-called Unruh radiation (UR) which is a relative to the Hawking radiation [2] of black holes with mass $M$ having a temperature at the black hole surface equal to

$$T_H = \frac{\hbar c^3}{8\pi k G M} \Rightarrow \frac{\hbar g}{2\pi k c}. \qquad (2)$$

As it is seen formally one can obtain (1) from (2) by substituting $a'$ instead of $g$.

**1b. Larmor and Unruh mechanisms of radiation.** According to Larmor mechanism of the classical field theory [3] a charge $e$ undergoing acceleration $\mathbf{a}$ radiates power:

$$P^L = \frac{2}{3}\frac{e^2}{c^3}a^2 \Rightarrow 5.7 \times 10^{-51} a^2 \text{ [CGSE units]}.$$

If $\gamma = E/mc^2 = 1/\sqrt{1-\beta^2} \gg 1$ then for $\mathbf{v}||\mathbf{a}$ and for $\mathbf{v}\perp\mathbf{a}$ the angular distributions (AD) of Larmor radiation (LR) have, respectively, the forms:

$$\frac{dP_{||}}{d\Omega} \simeq \frac{8e^2a^2\gamma^8}{\pi c^3}\frac{(\gamma\theta)^2}{(1+\gamma^2\theta^2)^5},$$

$$\frac{dP_{\perp}}{d\Omega} \simeq \frac{2}{3}\frac{e^2a^2}{c^3}\gamma^6\frac{1}{(1+\gamma^2\theta^2)^3}\left[1 - \frac{4\gamma^2\theta^2\cos^2\phi}{(1+\gamma^2\theta^2)^2}\right],$$

i.e the angular distributions at laboratory frame for $\mathbf{v}||\mathbf{a}$ has typical relativistic radiation patterns with maxima at $\theta \simeq 1/\gamma$ and minima at $\phi = 0$ (with respect to $\mathbf{v}$ and $\mathbf{a}$) and a maximum at $\theta = 0$ for $\mathbf{v}\perp\mathbf{a}$. For $\gamma \simeq 1$

$$P^{Un} = \frac{\hbar r_0}{90\pi c^6}a^4 \Rightarrow 4.1 \times 10^{-118} a^4 \text{ [CGSE units]}.$$

Therefore, Unruh and Larmor radiation powers become approximately equal at $a \sim 3 \times 10^{33}$ cm/s$^2$ $\sim 3 \times 10^{30}$ g. If $a$ is achieved by the field $\varepsilon$, then $\varepsilon \sim 2 \times 10^{17}$ V/cm $\gg \varepsilon_{cr} \sim m^2c^3/2\pi e\hbar \sim 1.3 \times 10^{16}$ V/cm.

Theoretical details and other experimental proposals which can be found in [4, 5] will not be discussed in this review apart from the given in the table below.

**1c. High Energy Experimental Proposals.** The list of the published proposals, the six of which will be discussed in this review, is given in the table.

*Proposals of high energy experiments*

| No | Process | Reaction | Reference |
|---|---|---|---|
| 1 | Channeling radiation | $e$+cryst→ $e$+cryst+ $\gamma$ | [6] |
| 2 | Magnetic and laser fields | $e$+H→ $e$+H+ $\gamma$, $e$+(LB) → $e$+(LB)+$\gamma$ | [7] |
| 3 | $e^+$ $e^-$ pair production in colliders | $e$+Bunch→ $e$+Bunch+$e^+ + e^-$ | [8] |
| 4 | Laser standing waves (SW) | $e$+(SW) → $e$+(SW)+ $\gamma$ | [9] |
| 5 | Coherent X-ray beam | $e$+X-Beam → $e$+ $\gamma$ | [10] |
| 6 | 2 LB with circular polarization | $e$+(2LB) → $e$+(2LB)+ $\gamma$ | [11] |
| 7 | Entangled photon pair production | $e + \hbar\omega(X) \rightarrow e + \gamma_1 + \gamma_2$ | [12] |

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## 2. CHANNELING RADIATION (e+cryst→e+cryst+ $\gamma$) [6]

It has been proposed to measure the spectral distribution of the radiation of high energy channeled particles [6]. By comparing the results with the expected UR produced due to Compton scattering of the Unruh bath Planck photons on channeled particles and with the most intense "background" bremsstrahlung one can "reveal" the manifestation of UE.

One can estimate that due to strong crystallographic fields the channeled particles undergo the below given acceleration in instantaneous rest frame (IRF) and temperature (for diamond (110)) $a'_\perp[\mathrm{cm/s^2}] \simeq 10^{25}\gamma$; $kT$ [MeV] $\simeq 4.4 \times 10^{-8}\gamma$; for $\gamma \simeq 10^8$ $a'_\perp \simeq 10^{33}$ cm/s$^2$; $kT \simeq 4.4$ MeV.

Using $T$, $dn_{Pl}(T)/dw'_1$ and $ds/dw'_2$ of Compton scattering, integrating over angles and $w'_1$ one can derive UR in IRF. Then transforming to LF and integrating over angles in [9] the spectral distribution of UR can be calculated and compared with bremsstrahlung (Fig. 1).

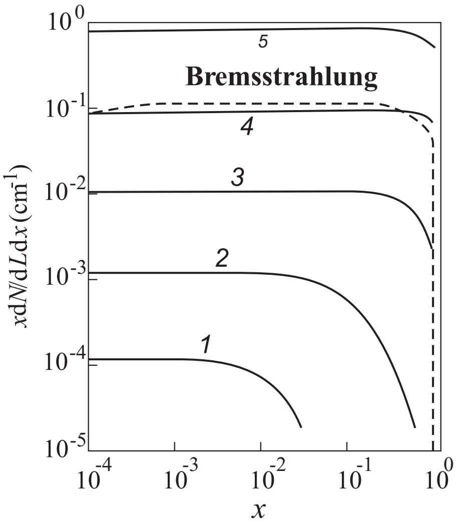

***Fig. 1.*** *The dependence of the intensity of bremsstrahlung (dashed curve) and of UR for* $\gamma = 10^5, 10^6, 10^7, 10^8, 10^9$ *(solid curves 1, 2, 3, 4, 5, respectively) upon* $x = \hbar\omega_2/\gamma mc^2$ *for diamond (110) and zero entrance angle*

As it follows from Fig. 1 only at $\gamma > 10^8$ one can "feel" the presence of UR.

## 3. MAGNETIC AND LASER FIELDS (e+H→e+H+ $\gamma$, e+(LB) → e+(LB)+$\gamma$) [7]

If $\mathbf{v}\perp\mathbf{H}$, $a'_\perp = \gamma eH/m$ and $kT\,[\mathrm{MeV}] = 1.8 \cdot 10^{-9} \times \gamma\mathrm{H}\,[\mathrm{G}]$. Fig. 2 shows the calculated [7] dependence of the intensity of the synchrotron radiation (SR) and of UR upon $x$ (a) and $H$ (b).

As it follows again, very high energies $\gamma \geq 10^9$ or high magnetic field $H \geq 10^8$ G are necessary. For laser beams (LB) with 100% circular polarization, LB parameter $\eta = e\varepsilon/m\omega_L$, where $\varepsilon$ [V/cm] = 20 [W/cm$^2$] is the electric field in LB and $\omega_L$ is the frequency; $a'_\perp = 2\omega\gamma\eta(1+\eta^2)^{1/2}$ and $kT = (\gamma\omega/\pi)\eta(1+\eta^2)^{1/2}$.

The dependence of the intensity of the QED radiation and UR intensity upon $\hbar\omega/E$ and $\eta$, calculated by the formulae of QED [13] and of UR [7], are shown in Fig. 3. Again very high energies, $\gamma > 10^8$, or $\eta > 1.5$ are required.

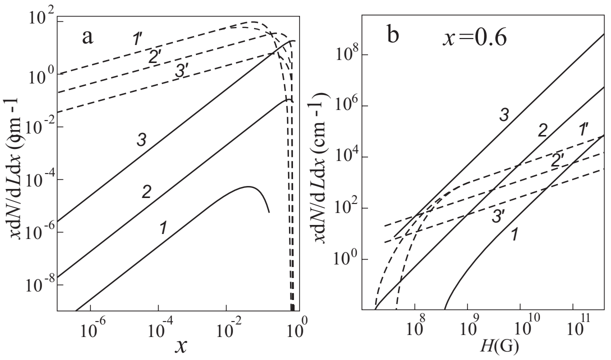

***Fig. 2.*** *The dependence of the intensity of SR (dashed curve) and of UR for* $\gamma = 10^5, 10^7$ and $10^9$ *(solid curves 1, 1'; 2, 2' and 3, 3', respectively) upon* $x = \hbar\omega/E$ *for* $H = 5 \times 10^7$ [G] *(a) and upon* $H$ [G] *for* $x = 0.6$ *(b)*

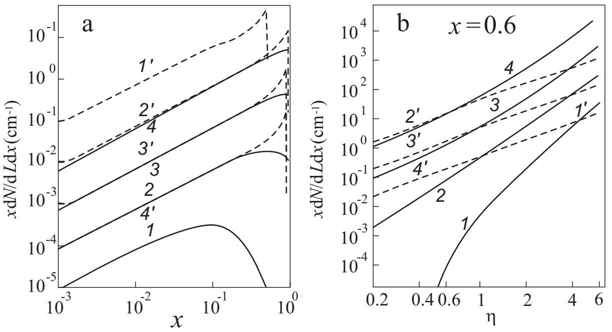

***Fig. 3.*** *The dependence of the intensity of QED radiation (dashed curve) and of UR for* $\gamma = 10^5, 10^6, 10^7$ and $10^8$ *(solid curves 1, 1'; 2, 2'; 3, 3' and 4, 4', respectively) upon* $x$ *for* $\eta = 0.4$ *(a) and upon* $\eta$ *for* $x = 0.6$ *(b)*

## 4. PAIR PRODUCTION (e+Bunch→e+Bunch+$e^+ + e^-$) AND ENERGY LOSSES [8] ON LINEAR COLLIDERS

For $e^+e^-$-colliders the synchrotron radiation parameter $Y = \gamma H/H_{cr}$ ($H_{cr} = m^2/e = 1.44 \times 10^{13}$ G) is equal to (see, for instance, [14])

$$Y = \frac{5\gamma r_0^2 N_{e^+e^-}^{bunch}}{6\alpha\sigma_z\sigma_y(1+\sigma_x/\sigma_y)}.$$

Therefore, just as above $a' = \gamma eH/m = Ym$ and $kT\,[\mathrm{MeV}] = 1.8 \times 10^{-15}\gamma H = 8.1 \times 10^{-2}Y$. Among all mechanisms for $e^+e^-$-production the dominant is $\gamma_{UR}(\mathrm{bunch}) \to e(\mathrm{bunch})e^+e^-$ when the UR photons of a particle in a bunch creates $e^+e^-$-pairs with the particles of oncoming bunch. In IRF:

$$\frac{dn_{e^+e^-}}{dt'd\omega'_1} = \frac{dn_{Pl}}{d\omega'_1}\sigma_{ee}(\omega'_1),$$

where $\sigma_{ee}(\omega'_1)$ is the total $\gamma e-eee$ QED cross section. It has been calculated also total UR cross section using total Compton cross section as well as the usual dominant background, namely, beamstrahlung [14]. After transformations and introducing $y = \omega/m$ the last expression gives:

$$\gamma\frac{dN_{\gamma,ee}}{dL} = 1.76\int\limits_{0.4}^{\infty}\frac{y^2dy}{\exp{(my/kT)}-1}\sigma_{\gamma,ee}(y).$$

The calculated [7] dependencies of the total number of quanta per cm and fraction $\delta$ of energy losses multiplied by $\gamma$ are given in Fig. 4.

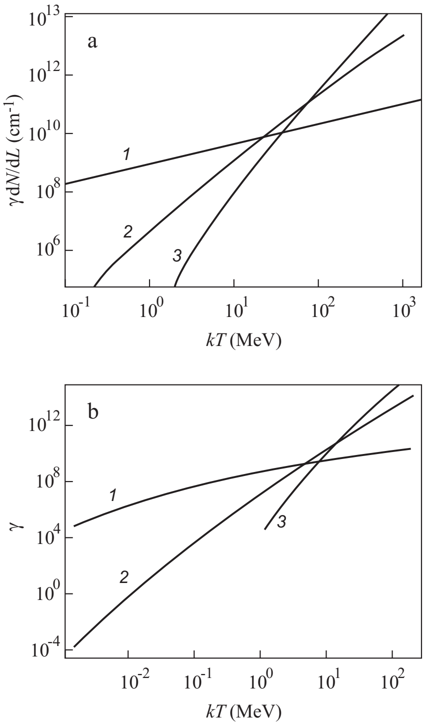

***Fig. 4.*** *The dependence of total number of quanta per cm (a) and fraction of energy losses (b) multiplied by* $\gamma$ *for Beamstrahlung, UR and Unruh* $e^+e^-$*-pair production processes (curves 1, 2 and 3, respectively)*

As it is seen the dominant processes are: 1) Beamstrahlung for $kT < 40$ MeV, 2) Total UR for $40 < kT < 100$ MeV and 3) Total Unruh pair production for $kT > 100$ MeV.

## 5. LASER STANDING WAVE (e+(SW) → e+(SW)+ $\gamma$) [9]

If $\omega_L$ is the frequency of the laser beams with parameter $\eta$ then as it has been shown in [9] $a' = 2c\eta\omega_L\cos(\omega_L t')$ and $P_{LR} = (8/3)r_0 mc\eta^2\omega_L^2 \times \cos^2(\omega_L t)$; $P_{UR} \simeq (12r_0\hbar/\pi c)(\eta\omega_L)^3\log(\eta/\pi)$ assuming that the electron makes in addition to the harmonic also “quivering” or “backreaction” oscillations due to absorption and emission of Unruh bath photons. The ratio of the radiated energies $(\Delta I_{UR}/\Delta I_{LR}) \simeq (18\hbar\omega_L/\pi mc^2)\eta\log(\eta/\pi)$ per laser half-cycle for a Petawatt laser with $\eta \sim 100$ and $\omega_L \sim 2\times10^{15}\,\mathrm{s}^{-1}$ is equal to $\sim 3\times10^{-4}$. To save the situation they calculate in LF the angular distribution of UR for $\gamma = (1+4\eta^2\sin^2\omega_L t)^{1/2} \simeq \eta \gg 1$ and $\theta \ll 1$:

$$\frac{dP_{UR}}{dt} \simeq \frac{4r_0\hbar}{\pi^2 c}\frac{\omega_L^3\eta^3}{(1+\eta^2\theta^2)^3},$$

which in contrast to LR has maximum at $\theta = 0$. Therefore, the authors suggest a discrimination method improving the above mentioned signal to noise ratio (SNR). Detecting photons in a solid angle with $\Delta\varphi \simeq 10^{-3}$ and $\Delta\theta \ll 1/\eta$ the authors of [9] say that UR will dominate over LR.

## 6. COHERENT X-RAY BEAMS (e+X-Beam → e+ $\gamma$) [10]

In [10] it has been proposed to obtain the collision of 14 GeV electron beam with the Self-Amplified Spontaneous Emission (SASE) coherent 8 keV photon beam obtained at the end of Linac Coherent Light Source (LCLS), an X-Ray Free Electron Laser (XFEL) at SLAC. Let us assume that one can focus the SASE beam of the European X-Ray Laser Project XFEL (or LCLS) up to the diffraction limit spot size $\sim\lambda$. (According to a private communication of A. Snigirev at present no better than 50 nm has been achieved). Then for $P = 8.72$ GW (now at LCLS $P = 15-40$ GW) in the IRF of 14 GeV electrons the energy of the photons is equal to $\hbar\omega' = 2\gamma\hbar\omega_L$, and one approaches the $\varepsilon_{cr} = 1.3\times10^{18}\,\mathrm{V/m}$. Therefore, $ee^+$ (vacuum boiling) and eee-trident production can be studied. We shall discuss UR and LR radiation [10] only. For $P = 20$ GW ($\lambda = 2.5\,$Å), one obtains $a = 6\times10^{26}\ \mathrm{m/s^2}$, $\varepsilon = 3.3\times10^{13}$ V/cm, $kT = 200$ eV. The signal to noise ratio SNR is equal to $P_{UR}/P_{LR} = (\hbar\omega/mc^2)\eta\ln(\eta/\pi)$, i.e SNR is proportional to $\lambda^{-1}$, giving a $10^4$ gain for LCLS compared to optical case. For realistic values of the parameters of the beams SNR$=10^{-4}$. Therefore, again it is necessary to use angular discrimination in order to improve SNR. Without discussing technical and theoretical problems (it is not taken into account that electron and SASE beams are microbunched) let us only note that since the scattering angle is very small it will be difficult to detect the UR scattered photon without angular and coincidence discrimination.

## 7. TWO ↑↓ CIRCULARLY POLARIZED LASER BEAMS (e+(2LB) → e+(2LB)+ $\gamma$) [11]

In the experiments proposed in [11] the electrons collide with two circularly polarized laser photon beams. The authors show that UR in LF has approximately thermal spectrum with characteristic $\hbar\omega_{char} = h\nu$. In the frame of this review it is impossible to discuss the calculated dependence of $\hbar\omega_{char} = h\nu$ upon the expected Unruh photon number $N_{Un}$ for some high intensity laser sources and $\gamma = 70$ as well as other results of [11].

The above discussed experiments require very high energies and other parameters. The experiments proposed in [12] seem more achievable and will be discussed in the second part of this review (see [15]).

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## ПРЕДЛОЖЕНИЯ ДЛЯ ИЗУЧЕНИЯ ЭФФЕКТА ИЗЛУЧЕНИЯ УНРУ В ВЫСОКОЭНЕРГЕТИЧНЫХ ЭКСПЕРИМЕНТАХ

***К.А. Испирян***

Кратко обсудив физику эффекта Унру, излучения Хокинга, Лармора и Унру, мы рассматриваем некоторые из экспериментов, предложенных к 2008 году, которые могут быть проведены с помощью высокоэнергетичных пучков электронов и оптических либо рентгеновских фотонов.

## ПРОПОЗИЦІЇ ЩОДО ВИВЧЕННЯ ЕФЕКТУ ВИПРОМІНЮВАННЯ УНРУ У ВИСОКОЕНЕРГЕТИЧНИХ ЕКСПЕРИМЕНТАХ

***К.А. Іспірян***

Після короткого обговорення фізики ефекту Унру, випромінювання Хокинга, Лармора та Унру, ми розглядаємо деякі з експериментів, що були запропоновані до 2008 року, які можуть бути проведені за допомогою високоенергетичних пучків електронів та оптичних або рентгенівських фотонів.