# PROPOSALS FOR THE STUDY OF UNRUH (EFFECT) RADIATION WITH THE HELP OF ENTANGLED PHOTONS PRODUCED IN ELECTRON-PHOTON COLLISIONS

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We consider some experiments proposed after 2006, which can be carried out with the help of high energy electron and powerful laser or X-ray photon beams.

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## 1. INTRODUCTION

The physics of the Unruh effect (UE) and Unruh radiation (UR) as well as of many experimental proposals for testing UE and ER is discussed in several reviews (see [1–3]). It is worthy to remind a more correct interpretation of UR. According to Refs. [4–6] for electron-photon collisions due to UR (Fig. 1) in instantaneous rest frame (IRF) of the electron which undergoes acceleration $a'$ two photons, $\gamma_1$ and $\gamma_2$, are produced at distance $d = c^2/a'$ from horizon. For some processes (see [3]) the second "idler" photon $\gamma_1$ can be neglected. As it has been shown in Ref. [7] (and will be discussed below) one can use this fact for testing UE or UR.

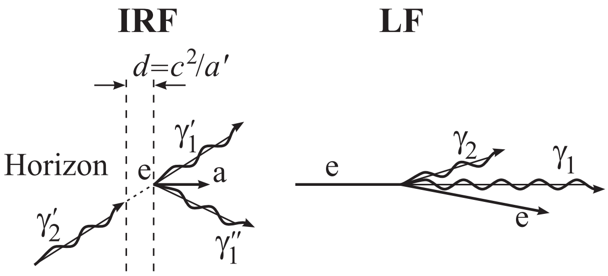


***Fig. 1.*** *The production of two entangled photons in instantaneous rest frame (IRF) and laboratory frame (LF)*

According to nonlinear QED calculations due to UE for $a$ = const [5] and for periodic $a$ perpendicular to the electron velocity [6] in electron-photon collision process $e^- + \gamma \to e^- + \gamma_1 + \gamma_2$, which is known as double Compton effect or inverse double Compton effect when the electron is ultra-relativistic, the two produced photons are entangled. Let us note that in the same collisions the process of the corresponding Compton effect $e^- + \gamma \to e^- + \gamma_1$ takes place with larger cross section. In IRF for Unruh $\gamma\gamma$-pair $k'_1 + k'_2 = \omega' = 2\gamma\omega_L \ll m$, while for Larmor single $\gamma$-quanta $k' = \omega' = \gamma\omega_L$ ($\hbar = c = 1$).

## 2. SOME THEORETICAL RESULTS

According to Ref. [6] the probabilities per electron of emitting an Unruh entangled photon pair and Larmor single photon are equal, respectively, to

$$P_U^{\gamma\gamma} = \frac{\alpha^2}{4\pi}\left[\frac{E_{int}}{E_{cr}}\right]^2 O\left(\frac{\omega T}{30}\right)$$

and

$$P_L^{\gamma} = \alpha\left[\frac{eE_{int}}{m\omega}\right]^2 O\left(\frac{\omega T}{2}\right).$$

In these expressions $E_{int} = 2\gamma E_{lab}$ is the electrical field of the laser beam in IRF, $T$ is the length of the laser pulse and $\omega T$ is approximately the number of laser cycles experienced by the electrons. One can see that the ratio $P_U^{\gamma\gamma}/P_L^{\gamma}$, or the signal-to-noise ratio (SNR), is proportional to $\omega^2$.

For electron bunch with energy $E_e = 150\,\mathrm{MeV}$ ($\gamma = 300$), laser photons with $\omega_L = 2.5\,\mathrm{eV}$ (in IRF $\omega' = 1.5\,\mathrm{keV}$), $T_L = 160\,\mathrm{fs}$, and intensity $I = 10^{18}\,\mathrm{W/cm^2}$ (in IRF $E/E_{cr} \sim 10^{-3}$) one obtains $P_U = 10^{-11}$ and $P_L = 10^{-1}$, i.e. $\mathrm{SNR} = \mathrm{P_U/P_L} = 10^{-10}$. There are a few methods for improving the situation. Since the angular distributions, energy and polarizations of Unruh radiation and Larmor radiation (LR) photons are different one can apply: 1) angular discrimination without detecting the photons at $\Delta\theta < 10^{-2}$ (for the above case this increases the SNR from $10^{-10}$ up to $7 \times 10^{-6}$); 2) coincidences between $\gamma_1$ and $\gamma_2$ ; 3) measurement of the polarization and 4) measurement of the energies of the produced photons.

The authors give (see Fig. 1 of Ref. [6] or Fig. 4 of Ref. [7]) the 3D dependence of the probability of Unruh entangled $\gamma\gamma$-pair and Larmor ($\gamma$) photons production upon $\omega_1$ and $\theta_1$ in collision of 150 MeV electrons with laser photon pulse with $\hbar\omega_L = 2.5\,\mathrm{eV}$, $I = 10^{18}\,\mathrm{W/cm^2}$ and the length equal to 100 wavelength. Unfortunately, these data are given only

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qualitatively without giving the values of the colors and the expressions with the help of which one can carry similar calculations.

### 3. EXPERIMENTAL PROPOSALS

In the work [7] two sets of parameters and corresponding experimental schemes are given.
a) It is proposed (Fig. 2) to detect the coincidence, energy and polarization of the produced photons emitted in a cone with opening angle $\sim 1/\gamma$ in collision of 150 MeV electron and laser 2.5 eV photon beams. Following Ref. [7] let us note that the main difficulty is connected with the smallness of the angles of the entangled photons with respect to electron direction.
b) It is proposed (Fig. 3) to detect the energy, coincidence and polarization of photons emitted in a cone with opening angle $\sim 1/\gamma$ in collisions of 1 MeV ($\gamma \approx 2$) electrons with intense X-ray photons with $\hbar\omega_L = 20\,\mathrm{keV}$. Following Ref. [7] let us note that the main advantage is connected with the largeness of the entangled photon production angles. Let us also note that it is assumed that the photon beam is obtained by still not sufficiently studied method of relativistic mirror [8], which is tested only in a single proof-of-principle, difficult experiment [9].

That is why it is worthy to consider a realistic and available third method [10].
c) It is proposed (Fig. 4) to detect the energy, coincidence and polarization of photons emitted in a cone with opening angle $\sim 1/\gamma$ in collision of 2.5 MeV ($\gamma \approx 5$) electrons with $\hbar\omega_L = 8.3\,\mathrm{keV}$ self-amplified spontaneous emission (SASE) photons from X-Ray Free Electron Laser (XFEL), say, from the existing Linac Coherent Light Source (LCLS) at SLAC, after focusing to $a \sim 1\,\mu\mathrm{m}$ spot at interaction point (IP) with the help of Snigirev lenses. Let us note that the main advantage is connected with the large entangled photon production angles as well as the availability of the electron [11] and X-ray beams [12].

In all the cases a), b) and c), it is assumed that the SNR for UR and LR can be improved by the above mentioned four discriminations methods. All these discriminations can be carried out with the help of the already constructed Ge strip Compton polarimeter-spectrometer [13]. Some important parameters and the expected probabilities of production of one LR and two UR entangled photons are given in the table.

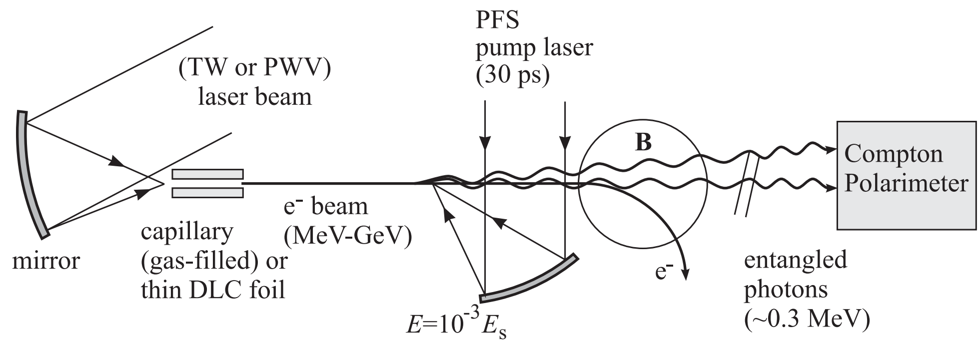


***Fig. 2.*** *Schematic view of the experimental setup in which 150 MeV electrons collide with laser beam of photons with* $\hbar\omega_L = 2.5\,\mathrm{eV}$

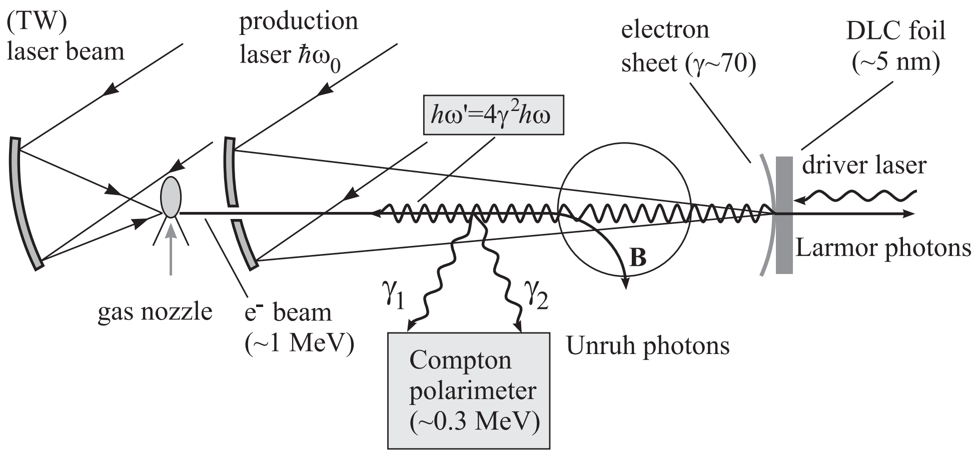


***Fig. 3.*** *Schematic view of the experimental setup in which 1 MeV electrons collide with* $\hbar\omega_L = 20\,\mathrm{keV}$ *focused photon beam*

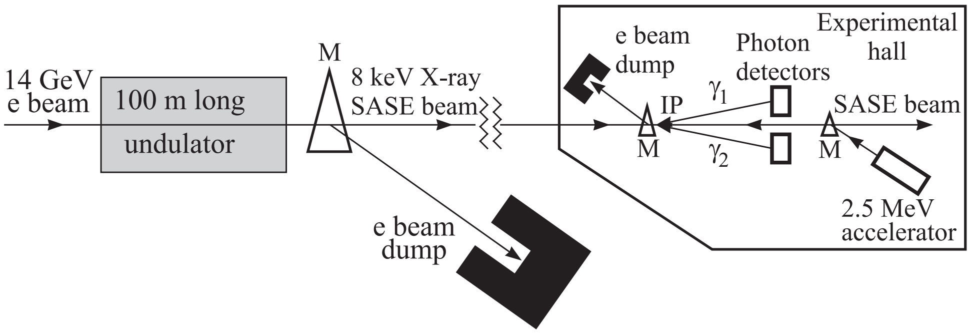


***Fig. 4.*** *Schematic view of the experimental setup in which 2.5 MeV electrons collide with SASE coherent X-ray photons with* $\hbar\omega_L = 8.3\,\mathrm{keV}$

*Some parameters and the probability (per electron) of the production of two entangled photons and a single LR photon for the setups a), b) and c) (rows 2, 3, and 4, respectively)*

| $N_\gamma/$ bunch | $E_{kin}$ (MeV) | $I_{LF}$ $(W/cm^2)$ | $\hbar\omega_L$ (keV) | $\hbar\omega_{IRF}$ (keV) | $E_{LF}$ $(V/m)$ | $E_{IRF}$ $(V/m)$ | $P_U$ | $P_L$ |
|---|---|---|---|---|---|---|---|---|
| $2\times10^{15}$ | 150 | $1.\times10^{18}$ | 0.0025 | 1.5 | $1.9\times10^{12}$ | $1.2\times10^{15}$ | $4.\times10^{-11}$ | $1.\times10^{-1}$ |
| $10^{13}$ | 1 | $2.\times10^{25}$ | 20 | 80 | $8.7\times10^{15}$ | $3.5\times10^{16}$ | | |
| $2\times10^{12}$ | 2.5 | $2.7\times10^{18}$ | 8.3 | 83 | $3.26\times10^{12}$ | $3.26\times10^{13}$ | $1.1\times10^{-10}$ | $1.1\times10^{-4}$ |

As it follows from the table for the case c) $SNR = P_U/P_L = 10^{-6}$ is better than for the case a) $SNR = 4\times10^{-10}$. Therefore, taking into account that the emission angles of the entangled photons are large, of the order of the not realistic case b) and using the above described discriminations the number of the detected events per electron-laser collision will be sufficient to carry out the experiment c). Indeed, having 100 pC charge per 2.5 MeV electron bunch [11] colliding with LCLS $2\times10^{12}$ 8.3 keV photon bunches with frequency 30 Hz one expects $\sim$ 0.3 entangled photon pair production per second which is sufficient for collecting reasonable number of events with enough statistics.

However, for the proposed arrangements a), b) and c) besides the two entangled photons of UR there are additional two background processes discussed and not discussed by the authors of Refs. [5–7] and which must be estimated. The first is the inverse Compton scattered single photon ($\gamma e \to e\gamma$) which was identified as LR and discussed. The second background, the inverse double Compton scattering (IDCS), ($\gamma e \to e\gamma\gamma$), with production of not entangled photons which has absolutely the same kinematics [14].

In the work [14] the theory of IDCS has been developed especially for the proposals [5–7]. The author of Ref. [14] gives the 3D dependence of the double differential cross sections for single and double Compton scattering upon $\omega_1$ and $\theta_1$ in collisions of a 150 MeV electron with laser photon pulse with $\hbar\omega_L = 2.5\,\mathrm{eV}$, $I = 10^{18}\,\mathrm{W/cm^2}$ and the length equal to 100 wavelength. Unfortunately, it is impossible to compare the two-photon yield of Unruh and IDCS yield given in Refs. [5,6] and [14], respectively, because no exact numbers are given in [5,6]. As the author of Ref. [14] writes there are 3 possibilities:

1. The yields of UR $<$ IDCS. Then the proposed experiment is not reasonable.
2. The yields UR $>$ IDCS. Then it will be impossible to explain the agreement between the existing experimental data on double Compton scattering obtained with the help of QED.
3. The yields UR $\sim$ IDCS. Then one can say that UE and QED physics is the same.

Commenting the above conclusions of Ref. [14] one of the authors of Refs. [5–7] writes in Ref. [15] that the paper [14] is based on calculations where the polarizations are averaged over from the beginning. Therefore, it cannot address the polarization entanglement which plays a crucial role in their analysis. In any case before the experiment it is necessary to take into account the background due to the production of two not entangled photon pairs.

Nevertheless, the experiments proposed for ELI or ELIZEST [5–7] (ELI and ELIZEST are International Laser Center for Zettawatt-Exawatt Science and Technology in Europe [16] and for LCLS [10] are very important, and there is sufficient time to make clear all the circumferences. As it is written in Ref. [2]: "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 $5\,\mathrm{GeV/m^3}$ drastically fail by $10^{124}$ (in microscopic approach via string theory) and $10^{-121}$ (via cosmological considerations), respectively".

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## ПРЕДЛОЖЕНИЯ ДЛЯ ИЗУЧЕНИЯ ЭФФЕКТА ИЗЛУЧЕНИЯ УНРУ С ПОМОЩЬЮ ПЕРЕПУТАННЫХ ФОТОНОВ, ПОЛУЧАЕМЫХ ПРИ ЭЛЕКТРОН-ФОТОННЫХ СТОЛКНОВЕНИЯХ


***К.А. Испирян***



Мы рассматриваем некоторые из экспериментов, предложенных позднее 2006 года, которые могут быть проведены с помощью высокоэнергетичных пучков электронов и мощных лазерных либо рентгеновских фотонов.


## ПРОПОЗИЦІЇ ЩОДО ВИВЧЕННЯ ЕФЕКТУ ВИПРОМІНЮВАННЯ УНРУ ЗА ДОПОМОГОЮ ПЕРЕПЛУТАНИХ ФОТОНІВ, ЩО УТВОРЮЮТЬСЯ ПРИ ЕЛЕКТРОН-ФОТОННИХ ЗІТКНЕННЯХ


***К.А. Іспірян***



Ми розглядаємо деякі з експериментів, що були запропоновані після 2006 року, які можуть бути проведені за допомогою високоенергетичних пучків електронів та потужних лазерних або рентгенівських фотонів.