SUMMARY OF WG1 – FUNDAMENTAL PHYSICS

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We report on the study of potential applications of the fourth generation light source on the frontier investigations of fundamental physics. Two major areas of such applications are identified. Namely, the nature of the vacuum in quantum electrodynamics (QED), and the laboratory studies of general relativity and astrophysics. We believe that both subjects are very furtile and within the reach of the required electromagnetic field strength provided by the EFL-driven fourth generation light source, such as the Linac Coherent Light Source (LCLS).

1 Introduction

The unusal properties of the coherent x-ray provided by the fourth generation FEL-driven light source can potentially be utilized for the frontier investigation of fundamental physics. This is in contrast to the earlier generations of light sources, where the applications are essentially on the more applied side of sciences. This working group (WG1) was charged to explore the possible directions where fundamental issues in physics can be addressed using the fourth generation light source.

We found that there are at least two directions in fundamental physics which can be benefitted by the next generation light source. One is the nature of the quantum electrodynamics (QED) vacuum. The other is laboratory study of general relativity and astrophysics. The way these two subjects relate to the coherent x-ray source is through its extrremely intense, coherent, polarized electromagnetic fields.

2 Nature of the Quantum Electrodynamic Vacuum

It is well-known that the QED vacuum is constantly fluctuated with virtual electron-positron pairs. When the condition is right, these pairs can tunnel through their potential barrier, $2mc^2$, and emerge as real particles. Such a bias of the potential can in principle be accomplished by an external classical electromagnetic field. The nature of this tunneling effect, or the breakdown of the QED vacuum, however, remains unclear even among experts. In an attempt to clerify this issue, Chen and Pellegrini (See Addendum I) recently introduced the terminology *stimulated pair creation* process and *spontaneous pair creation* process to distinguish two different types of vacuum breakdowns.

The stimulated breakdown, examplified by the coherent beamstrahlung pair creation process [1] and the multiphoton pair production process in E144 [2], requires an initial state particle (high energy electron or photon) that interacts with the external EM field to induce pair production. This fact can also be appreciated by observing that the Υ parameter is constructed by Lorentz covariant contractions between the initial electron four-momenta, p_μ, and the external field strength tensor, $F_{\mu\nu}$. Indeed, in this process the produced pair conserves the initial state particle's energy-momentum.

On the other hand, the QED vacuum can also breakdown due to a pure classical EM field without any initial state particle. The penetration of the vacuum-fluctuated pairs through the potential barrier is spontaneous in this case. The Lorentz invariant parameters involved are [4]

$$\begin{cases} \mathcal{F}^2 = \frac{1}{2}F_{\mu\nu}F^{\mu\nu} = \vec{B}^2 - \vec{E}^2. \\ \mathcal{G}^2 = \frac{1}{4}F_{\mu\nu}F^{*\mu\nu} = \vec{E}\cdot\vec{B}, \end{cases} \tag{1}$$

where $F^{*\mu\nu}$ is the dual field strength tensor, i.e.,

$$F^{*\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\lambda\kappa}F_{\lambda\kappa}. \tag{2}$$

Therefore in the case of a cross field with $|E| = |B|$ (or a plane wave under the above constraint), both $\mathcal{F}$ and $\mathcal{G}$ vanish, and as Schwinger[4] has shown, the nonlinear effects would never occur. This is in sharp contrast with the stimulated process under the same EM field. When a high energy initial-state particle collides with the plane wave head-on, the effects due to the $\vec{E}$ field and the $\vec{B}$ field are additive, and the resultant stimulated nonlinear pair production is nonvanishing. It is evident that the two processes are characteristically different. To test the spontaneous process, however, requires that the pure electric field strength be close to the Schwinger critical field, $E_c = m^2c^3/e\hbar \approx 1.3\times 10^16$ V/cm, which is currently unavailable. It occurs that the proposed Linac Coherent Light Source (LCLS) at SLAC should have the right intensity for such a test in the near future [3].

3 Laboratory Study of General Relativity and Astrophysics

It is known that plasma wakefields excited by either a laser pulse[5] or an intense electron beam[6] can in principle provide an acceleration gradient as high as

$$G_p = eE_p \sim 100\mathrm{GeV/m} \sim 10^{20} g_\oplus. \tag{3}$$

Such acceleration relies on the collective perturbations of the plasma density and is an effect arising over a plasma period. There is in fact another aspect of the laser-driven electron acceleration. Namely, when the laser is ultra-intense, i.e., the laser strength parameter $a_0 = eE/mc\omega_0 \gg 1$, an electron under the direct influence of the laser can be accelerated and decelerated intermittently during every laser cycle. Since it occurs within a laser cycle, the acceleration gradient can be much higher[7]:

$$G_l \sim a_0 \left(\frac{\omega_0}{\omega_p}\right) G_p \sim 10\mathrm{TeV/m} \sim 10^{25} g_\oplus. \tag{4}$$

While such intermittant acceleration is not useful for bringing electrons to ultra-high energy, it may be used for laboratory study of fundamental physics related to general relativity[7], based on the Equivalence Principle.

One such subject, namely the Hawking-Unruh effect, has already been discussed in the context of accelerator physics not necessarily invoking ultra-violent accelerations. Bell and Leinaas (BL)[8] first suggested that the well-known phenomenon of the equilibrium spin polarization in electron storage rings may be interpreted as a manifestation of the Unruh effect.

A uniformly accelerated object sees the vacuum fluctuations as a thermal bath, with a temperature given by[9]

$$kT = \frac{\hbar a}{2\pi c}, \tag{5}$$

where a is the object's proper acceleration. Historically this temperature was deduced as an extension of the seminal discovery by Hawking[10] of the black-body radiation of black holes. The temperature of the Hawking radiation is given by the same formula, with the proper acceleration replaced by the gravitational acceleration at the black hole event horizon.

The spin of a circularly accelerated electron serves as a detector where its populations at the two spin levels would follow the Boltzmann distributions. While this interpretation provides an immediate and very simple intuitive understanding of the phenomenon, complications arise due to the circular, instead of linear, motion. For one thing, the spin-orbit coupling complicates the dynamics.

To avoid the complications caused by the spin-orbit coupling, Chen, Spitkovsky, and Tajima [7,11] (See Addendum II) investigated the linear, albeit time-varying, acceleration provided by a standing wave formed by counter-propagating ultra-intense laser pulses. Instead of observing the state of the detector (the electron), they propose to observe the radiation from the detector stimulated by the heat bath. This is, to be sure, not a new radiation. Rather, it is caused by the reaction to the classical Larmor radiation. it was shown that by using a state-of-the-art (or soon-to-be) ultra-intense laser with, e.g., coherent x-rays from the fourth generation light sources, the sought-after signal should be above the conventional Larmor radiation background. This so-called Hawking-Unruh radiation has also been studied earlier by McDonald [12].

4 Summary

Although we have reviewed only two specific subjects in fundamental physics for which the very intense EM fields from the fourth generation light source can be a powerful tool for frontier investigations, we believe that there should be more outstanding fundamental physics issues where ultra-intense EM fields can serve to probe deeper into their nature. The Linear Coherent Light Source (LCLS) proposed at SLAC and other future FEL-based coherent x-ray sources will serve as stimulations for further thoughts into this very fertile new direction of research.

5 Acknowledgement

We appreciate the kind permission by the World Scientific Publishing Co. of reprinting the two papers, *Boiling the Vacuum with Intense Electromagnetic Fields* by P. Chen and C. Pellegrini, and *Unruh Radiation from Time-Varying Linear Acceleration in Ultra-Intense Lasers* by P. Chen, A. Spitkovsky, and T. Tajima, from the Proceedings of *Quantum Aspects of Beam Physics*, 1999.

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