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Probing the quantum vacuum with petawatt lasers

W T Hill III[1] and L Roso[2]

[1]Joint Quantum Institute, Institute for Physical Science and Technology and Department of Physics, University of Maryland, College Park, MD 20742, USA
[2]Centro de Láseres Pulsados, CLPU, Salamanca, Spain

E-mail: `wth@umd.edu`

Abstract. Due to the bosonic nature of the photon, increasing the peak intensity through a combination of raising the pulse energy and decreasing the pulse duration will pile up more and more photons within the same finite region of space. In the absence of material, this continues until the vacuum is stressed to the point of breakdown and virtual particles become real. The critical intensity where this occurs for electrons and positrons – the so-called Schwinger limit – is predicted to be $\sim 10^{29}$ W/cm^2. At substantially lower intensities, however, nonlinear aspects of the *quantum vacuum* associated with polarization of the vacuum can be explored. These studies become viable at the petawatt level where 10^{23} W/cm^2 and above can be reached. This is an era into which we are just embarking that will provide critical tests of QED and theories beyond the *Standard Model* of particle physics.

1. Introduction

Shortly after Dirac's 1930 model of the negative energy sea, the physics community began thinking about how to coax an electron-positron pair out of the vacuum. The simplest idea was to convert a high-energy photon into matter, $q^\mu \to p^\mu + p'^\mu$ where p^μ, p'^μ and q^μ are the four momenta of the electron, positron and photon, respectively. While a single photon cannot conserve energy and momentum simultaneously, the first realistic proposal came from Oppenheimer and Plesset, who suggested a vacuum photoelectric effect [1], "if we allow gamma-rays of energy γ to fall upon a nucleus, we should expect pairs to appear; the kinetic energy of the pairs would be $\gamma - 2mc^2$ ... in the process the nucleus necessarily takes up a small recoil momentum." Bethe and Heitler studied this process more thoroughly and pair production via this mechanism often bears their name [2]. Breit and Wheeler [3] proposed a different approach that relied on additional photons (nk^μ) instead of a nucleus to conserve momentum, $q^\mu + nk^\mu \to p^\mu + p'^\mu$. This is the mechanism exploited by the SLAC E-144 experiment [4], which used nonlinear Compton scattering to transform a few laser photons (nk^μ) into the requisite gamma photons.

Devising all-optical schemes to reach the critical field and intensity,

$$E_{cr} = \frac{m^2c^3}{e\hbar} \simeq 1.3 \times 10^{16} \ \text{V/cm} \quad (1)$$

$$I_{cr} = (\varepsilon_0 c/2)\,|E_{cr}|^2 \simeq 2 \times 10^{29} \ \text{W/cm}^2, \quad (2)$$

where pairs can be produced directly in a focused laser beam is a quest that began only ten years after the laser was invented [5]. In equations 1 and 2, m and e are the mass and charge of the electron, c is the speed of light in vacuum, $\hbar$ is Planck's constant (h) divided by 2π and ε_0 is the vacuum permittivity. The critical intensity in equation 2 is associated with an effective field of the same magnitude as the critical static field predicted by Schwinger [6] (Eq. 1). An intensity of 10^{29} W/cm^2 is controversial and has been the subject of much discussion; some theoretical investigations even predict pair production at intensities as low as 10^{25} W/cm^2 [7–10]. While I_{cr} is out of reach with current technology, 10^{25} W/cm^2 is just around the corner.

2. Probing the quantum vacuum

We are very close, technologically, to being able to explore a different, but related proposal, suggested by Halpern in 1933 [11] – photon-photon scattering. He noted, "Two possible types of phenomena must be considered separately in connection with the foregoing: (1) All incident quanta have the same direction of propagation; (2) The incident quanta have different directions of propagation. Since we are only interested in purely radiation phenomena the frequencies in the second case should lie below mc^2/h so that no permanent formation of electron-positron pairs can occur."

Clearly, Halpern envisioned an experiment with two beams of low-energy photons where scattered photons are detected. The cross section for the process is calculated to be [12–14]

$$\frac{d\sigma}{d\Omega} = \frac{139\alpha^4\omega^6}{(180\pi)^2 m^8}\left(3+\cos^2\theta\right)^2, \tag{3}$$

$$\sigma = \frac{973\alpha^4\omega^6}{10125\pi m^8}. \tag{4}$$

Equation 3 (4) is the differential (total) cross section with ω being the photon angular frequency and α ($\sim 1/137$) is the fine-structure constant. With new multi-petawatt lasers and high-repetition rate, 1 PW lasers either in operation or coming online in the near future, we will soon be able to exceed the 10^{23} W/cm^2 threshold where these cross sections are predicted to be measureable. Scattering experiments require two synchronized beams but may be very difficult because of the physical vacuum requirements to ensure that photons do not scatter off real matter (electron, molecule, etc.). Nevertheless, viable designs for scattering experiments have been proposed [15, 16]. These will require clever ways to create extreme physical vacua with fewer than one real particle in the focal volume.

Photon-photon scattering can be viewed as vacuum polarization, a fundamentally quantum mechanical process caused by vacuum fluctuations – the appearance and disappearance of particle-antiparticle pairs. When these virtual pairs occur in the presence of intense fields, the vacuum will be polarizable, which will cause it to exhibit birefringence, among other things. Birefringence can be induced by either electric or magnetic fields and detected by the rotation of the plane of polarization or the change in ellipticity of a probe beam's polarization. While there have been no experiments with optical fields at suitable intensities, there have been measurements with quasi-DC magnetic fields that have set threshold magnetic field strengths below which vacuum polarization is not observed [17–19]. Recently, however, it is interesting to note that polarized light was observed by the Very Large Telescope at the European Southern Observatory on Cerro Paranal in Chile. The investigators have interpreted this result in terms of vacuum birefringence caused by a magnetic field of magnitude $\sim 10^{13}$ G generated by a neutron star [20]. This could be the first experimental evidence of vacuum polarization, giving more impetus to laser-based searches.

Vacuum polarization will provide critical tests of nonlinear aspects of quantum electrodynamics (QED). Due to relativistic considerations, the field-field coupling depends only on $E^2 - c^2B^2$ or $\vec{E}\cdot\vec{B}$. The lowest order coupling, $\mathcal{L}_0 = \varepsilon_0\left(E^2 - c^2B^2\right)/2$, simply accounts for the energy of the field. To study field-field coupling it is necessary to include extra terms (based

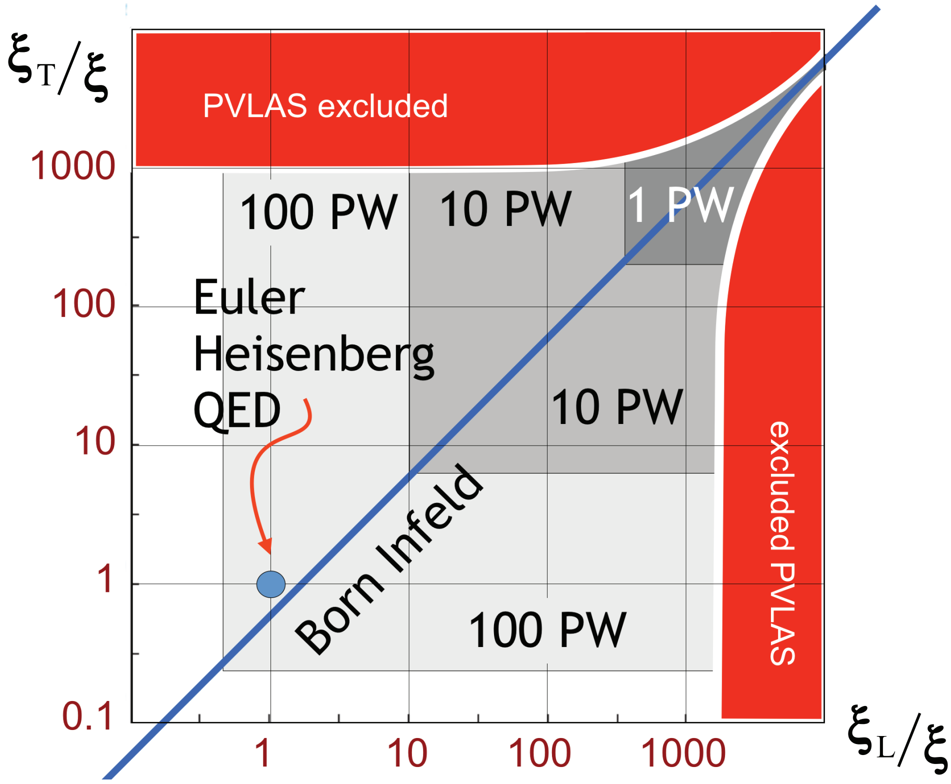

Figure 1. Single-shot sensitivity parameter space normalized to the QED prediction, $\xi_L/\xi_T \equiv 1$ [22] (blue point). The blue line corresponds to the Born-Infeld theory [23] and the red shaded regions is the parameter space excluded by the latest PVLAS data [24,25]. The sensitivity scales as the square root of the number of shots. Thus, 10^4 shots at 1 PW puts one in the 100 PW, single-shot range. This plot is adopted from Ref. [16].

on the only two allowed). Thus, the lowest order terms of the Lagrangian are [16, 21, 22]

$$\mathcal{L} = \mathcal{L}_0 + \xi_L \mathcal{L}_0^2 + (7/4)\xi_T \mathcal{G}^2, \tag{5}$$

where $\mathcal{G} = \varepsilon_0 c\vec{E} \cdot \vec{B}$. The coupling factors, $\xi_{L,T}$, are the longitudinal and transverse responses that are model dependent. In QED $\xi_L = \xi_T = \xi$ [22], where

$$\xi \equiv \frac{8\alpha^2\hbar^3}{45m^4c^5} \simeq 6.7 \times 10^{-30} \;\; \mathrm{m^3/J}. \tag{6}$$

A ξ_L/ξ_T ratio different from 1 could indicate new physics, such as the existence of axion-like particles or mini-charged particles (with a charge less than the elementary electric charge, e) and perhaps a departure from the *Standard Model* [16]. It is important to note that the nonlinear terms in Eq. 5 generated at the focus of an intense laser field also give rise to an effective index of refraction different from 1, resulting in an anomalous phase shift of a probe beam traversing the region. About ten years ago, Ferrando *et al* [22] suggested measuring this phase shift to determine ξ, which to our knowledge has not been attempted.

3. Technological outlook

While the investigation of vacuum polarization will be difficult, new short-pulsed petawatt lasers make it possible to consider the all-optical approaches mentioned above. Figure 1 shows that it becomes possible to study the ξ_L/ξ_T ratio with single-shot petawatt lasers with powers above ~ 1 PW. More parameter space becomes available at higher powers. Verification of QED, for example, requires a single-shot 100 PW laser. The red shaded region in Fig. 1 is the region excluded by the ground-based magnetic measurements, leaving plenty of room to test QED. It is important to recognize that the sensitivity to new physics is really a problem of signal to noise. A high-rep rate 1 PW laser capturing thousands of shots a day, as will be possible with the VEGA laser facility in Salamanca, Spain, can explore the same parameter space as a single-shot 10 or 100 PW laser. Thus, direct-observation, all-optical experiments (i.e., capturing scattered photons or measuring phases or polarization changes) with both types of lasers should be possible in the near future. In addition, indirect experiments should also be considered. One example might be to exploit plasmas to generate megagauss magnetic fields [26] to generate magnetic birefringence, perhaps in conjunction with quasi-static DC magnetic fields. The future looks bright for new investigations of the *quantum vacuum* and the various proposals for quantitative measurements now need to be given serious consideration.

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