Optimized Setup for Detection of QED-Induced Four-Wave Interaction in Vacuum

A V Berezin[1] and A M Fedotov[1]

[1]LAPLAS, National Research Nuclear University (MEPhI), 31, Kashirskoe Highway, 115409, Moscow, Russia.
Contact Phone: +7 (495) 788 56 99, ext. 9576, 9575
Contact Email: arsenbrs@mail.ru

Strong electromagnetic fields perturb the quantum fluctuations, thereby modifying the properties of the vacuum. This effect is called vacuum polarization. In QED, the thus emergent interaction is described by the second and the omitted higher-order terms in the Heisenberg-Euler action [1]

$$S = \int d^4x \left(\frac{\mathfrak{F}}{4\pi} + \frac{\alpha}{360\pi^2 E_c^2} \times (4\mathfrak{F}^2 + 7\mathfrak{G}^2) + \ldots \right), \quad (1)$$

where $\mathfrak{F} = (E^2 - H^2)/2$ and $\mathfrak{G} = \mathbf{E} \cdot \mathbf{H}$ are electromagnetic field invariants, $E_c = 1.3 \cdot 10^{16}\,\mathrm{V/cm}$ is the critical field, and α is the fine structure constant. Radiative corrections $\mathcal{O}(\alpha)$ in (1) introduce nonlinearity into the Maxwell's equations which results in a wide range of nonlinear optical phenomena, in particular photon-photon scattering. Their direct observation and measurement remain a long-standing challenge.

The most prospective all-optical setup involving three overlapping focused laser pulses has been studied since quite long ago [2]. Here a detectable signature reveals as an emission of the polarized vacuum which can be also viewed as a stimulated elastic photon-photon scattering. Combining three incoming pulses drastically stimulates the effect as compared to the earlier proposed two-pulse setups making it potentially observable at the currently or near-future available laser facilities. However, the collision geometries studied earlier were not optimized with respect to the direction of the emitted signal photons. Furthermore, the distributions of signal photons and their total number have been calculated only numerically for a partially or completely specified configuration of the collision scheme [3, 4].

Our work generalizes previous considerations of three-pulse setups for detecting photon – photon scattering by deriving a fully analytical and general formula [5] for the total yield of signal photons

$$N_s = \frac{1}{\sqrt{\pi}} \left(\frac{32\alpha}{45} \right)^2 \frac{\beta(\nu_1\nu_2\nu_3)^2 \nu_s^3 |\mathbf{C}|^2}{\det M \sqrt{\det\left(M_B^{\mathrm{T}} M^{-1} M_B\right)}} \times \frac{\omega_0^2 P_1 P_2 P_3}{\hbar c^6 E_c^4}, \quad (2)$$

where P_i is the power of the i-th laser pulse, ν_i is the harmonic number of its carrier, ω_0 is the frequency of the principle harmonics, $\nu_s = \nu_1 + \nu_2 - \nu_3$ is the harmonic number of the signal, the factor $|\mathbf{C}|^2$ contains the entire dependence on the pulse polarizations, the matrix M contains all the entire dependence on the duration and focusing of the pulses, and the matrix M_B depends only on the collision geometry. Formula (2) takes into account the realistic structure of laser fields and works for any effective geometry of the three-pulse collision setup, hence is very handy for the purpose of optimization. In particular, we discuss examples of such optimizations with respect to the total number of signal photons and their angular distribution.

References

[1] W Heisenberg and H Euler, Z. Phys. **98**, 714 (1936)

[2] R L Dewar, Phys. Rev. A **10**, 2107 (1974)

[3] E Lundström, G Brodin, J Lundin, M Marklund, R Bingham, J Collier, J T Mendonça and P Norreys, Phys. Rev. Lett. **96**, 083602 (2006)

[4] H Gies, F Karbstein, C Kohlfürst and N Seegert, Phys. Rev. D **97**, 076002 (2018)

[5] A V Berezin and A M Fedotov, Kvantovaya Elektronika **53**, 123 (2023), in Russian