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Pair creation from vacuum in the presence of ultra-intense laser beams

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The non-linear QED phenomenon of pair creation from vacuum[1] in the presence of ultra-intense elm fields[2], is of outstanding importance whose physical mechanisms have been the subject of a long standing and theoretical investigations, not to mention the SLAC E-144 experimental confirmation [3]. The conditions under which pair production is possible is that neither $\mathscr{F} = -\frac{1}{2}\left(\vec{\mathscr{E}}^2 - c^2\vec{\mathscr{B}}^2\right) = 0$, $\mathscr{G} = c\vec{\mathscr{E}}\cdot\vec{\mathscr{B}} = 0$, nor $\mathscr{F} > 0$, $\mathscr{G} = 0$ while in order to have sizable effects the electric fields must exceed the *critical value* $\mathscr{E}_c \simeq 1.3\times 10^{18} V/m$. Models similar to multiphoton atom ionization ones and in particular the imaginary time method[4], have been shown to offer a consistent theoretical treatment whose experimental verification is expected to be viable using XFEL systems. However this approximation for optical lasers is not efficient. In a recent paper [5] the problem of e^-e^+ production in a standing wave of oppositely directed laser beams was treated, using a two level multiphoton on resonant approximation. Taking up this approximation we shall present certain important numerical results [6], that convincingly support the possibility of experimentally detectable pair creation with available optical laser technology. Of special interest is the use of higher harmonics such as 3ω and 5ω. As was shown in [6] and partially in [7], this approach compared to others, will result in e^-e^+ production rate of the order of $10^8 - 10^{12}$ pairs per laser shot and low electric field strengths of the order of 10^{13} V/m. According to [5], a standing wave $\mathbf{A} = 2\mathbf{A}_0\cos\mathbf{kr}\cos\omega t$ is formed by two oppositely propagating laser beams. Pair production occurs close to the antinodes and in spacial dimensions $l \ll \lambda$ so that $\mathbf{A} = 2\mathbf{A}_0\cos\omega t$. Most significant contribution will be at the direction along the electric field. while, because of space homogeneity 4-momentum is conserved and transitions can be considered to occur between two energy levels from $-E$ to E by the absorption of n photons. Maximization of multiphoton probabilities occur for resonant transitions $n = 2qmc^2/\hbar\omega,\ q \geq 1$, with $n_0 = 2mc^2/\hbar\omega$ being the threshold multiphoton order. Taking A_0 on the y-axis, and $\mathbf{p} = (p\sin\theta,\ p\cos\theta, 0)$, θ being the angle between $\mathbf{p}$ of e^- (e^+) and A_0. From the solutions of the Dirac equation the probability $W = \sum_{n=n_0} W_n$ where $W_n = 2 f_n^2 \frac{\sin^2(\Omega_n\tau)}{\Omega_n^2}$ is the probability for the n-photon process and $f_n = \frac{n\omega}{4p_y}\sqrt{E^2 - p_y^2} J_n(4\xi\frac{mp_y}{E\omega})$.

The parameter $\xi = e \mid \mathscr{E}_o \mid /mc\omega \lesssim 1$, ($\xi$=1/$\gamma$), $\Omega_n = \sqrt{f_n^2 + \frac{\Delta_n^2}{4}} \ll \omega$ is the 'Rabi frequency' of the Dirac vacuum with $\Delta_n = 2E - n\omega$ being the detuning of resonance and τ is the interaction time and $\Omega_n \tau \ll 1$ holds. At $\theta = 0$, W_n maximizes and the number of pairs created from an nth order process is given by $N_0 = \frac{1}{4\pi^2} \frac{V\tau}{V_e} \frac{q\sqrt{q^2-1}}{m^2c^4} f_{n0}^2$ where f_{n0} is f_n at $\theta = 0$, $V_e = 7.4 \times 10^{-59} m^3 s$ is the four Compton volume of an electron, $V \sim \sigma^2 l$ is the space-volume, σ is the cross section radius, τ is the interaction time and q is units of rest energy. Given an initial laser frequency and power density, the physical acceptable values of ξ, q should not only conform with the condition $\xi \precsim 1$, but also to energy considerations. Given the power density of the laser $S_b = \frac{1}{\mu_0 c} \mathscr{E}_0^2$ and the energy $E_b = S_b \pi \sigma^2 \tau$ of the beam, the energy $2qmc^2 N$ of N pairs should be such that $\Delta E = S_b \pi \sigma^2 \tau - 2qmc^2 N \geqslant 0$. In the numerical analysis presented below it is adequate to investigate ΔE for $N = N_0$ which is a function of ξ(or $\mathscr{E}_0$) and q(or n). For given laser characteristics ξ can be increased up to a value $\xi = h$ ($\mathscr{E}_{0max}$) for which $\Delta E = 0$. Thus, for given values of q(or n), we can estimate the upper bounds h (or $\mathscr{E}_{0\max} = hmc\omega'/e$) of ξ for the approximation to hold. With the advancement of laser systems such as Nd-Yag or Ti-Sapphire,with intensities up to $10^{26} W/m^2$ capable of providing efficient higher harmonic generation, it is intriguing to examine the efficiency of pair creation when harmonics like 3ω, 5ω are implemented. In particular one would like to know to what extend such optical lasers can compete the pair production efficiency of the much promising XFEL facilities. In the numerical simulations below, an Nd-Yag laser is considered with $\omega = 1.17 eV$, intensity $1.35 \times 10^{22} W/m^2$, $\tau \sim 10^{-14} s$, $\lambda = 1.074 \times 10^{-6}$m and $\sigma \sim 10^{-5} m$. The four-volume $V\tau \sim \sigma^2 (0.1\lambda/k)\tau$, ($k = 1,3,5$ for ω, 3ω, 5ω respectively) conforming with $l \ll \lambda$.

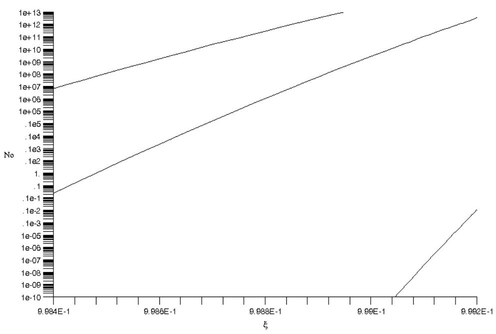

Figure 2: $N_0(\xi)$ for $\omega = 1.17eV$(bottom curve), 3ω(middle curve), 5ω(top curve).

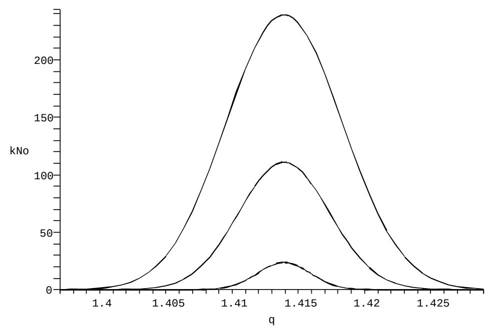

Figure 1: Envelop of $N_0(q)$ at $\xi = 0.9987$, for $\omega = 1.17eV$ (bottom curve with $k = 10^{29}$), 3ω (middle curve with $k = 10^{-2}$) and 5ω (top curve with $k = 10^{-8}$).

Fig. 1 demonstrates the behavior of N_0, as a function of q, for the cases $\omega = 1.17eV$, 3ω, 5ω and for $\xi = 0.9987$ ($\mathscr{E}_o \sim 10^{13}V/m$). Each curve point corresponds to an order n multiphoton process and to an energy $E = qmc^2$ of the produced electron (positron). The most probable process (peaks of the curves) occur for n =1.2×10^6, 4.1×10^5, 2.5×10^5 for which N_0=2.4×10^{-28}, 1.1×10^4, 2.4×10^{10} for the respective harmonics. Thus working with higher harmonics N_0 increases rapidly with a subsequent decrease of the multiphoton order n and the corresponding e^-e^+ energy, while the range of the energy spectrum of e^-e^+ broadens: from approximately $0.720MeV$ to $0.726MeV$ which is for ω , to, $0.715MeV$ to $0.731MeV$ which is for 5ω. Such kind of curves essentially giving the energy spectrum of the pairs at $\theta = 0$ can be the subject of experimental verification provided that the increase $\omega \rightarrow 5\omega$, should be accompanied by an equal amount increase of $\mathscr{E}_o$, the latter being achieved by appropriately increasing the laser intensity. In Fig. 2 we give (the familiar for multiphoton processes) log-plot of the number of pairs N_0 versus ξ (or $\mathscr{E}_o$), for the most probable multiphoton processes of Fig. 1 for ω, 3ω and 5ω. Crossings are expected for the different multiphoton curves as ξ(or $\mathscr{E}_o$) increases, but for the developed approximation, the values of ξ where crossings occur are not applicable as then $\xi > 1$. However the theoretically estimated behavior of N_0 in Fig. 2 cannot easily experimentally verified as the required $\mathscr{E}_o$ changes are very small. Finally in Fig. 3 the maximum admissible values h of ξ ($\mathscr{E}_0$) as a function of q (n), are recorded for $\omega = 1.17eV$, 3ω and 5ω. Computations have been performed using , $S_b = 1.35s \times 10^{22}W/m^2$ ($s = 1, 3^2, 5^2$ respectively). The factor s in S_b is justified by the approach adopted to increase the laser intensity in order to increase E_b , rather than going to the diffraction limit to increase it. The existence of h explains why the log-plots of Fig. 2 terminate and crossings do not occur. In addition, it is the values of ξ close to the lowest curve points (q_l , h_l) of Fig. 3 that guarantees both observability of all energies around q_l , as given in Fig. 1, and maximization of the corresponding N_0. Note that the very low value of N_0 for $\omega = 1.17eV$ in Fig. 1 appears for $\xi = 0.9987$ far away from the optimum one which is $\xi \sim 0.9995$ as seen from the $\omega-$curve of Fig. 3. Thus experimentally one can choose a laser facility with energy capable of generating a higher harmonic $k\omega-$ beam. Then by appropriate focusing, increase E_{0max} to $E_{0max} = h_l mck\omega/e$ where h_l is the lowest value of the $k\omega-$ curve of Fig. 3. The number of pairs

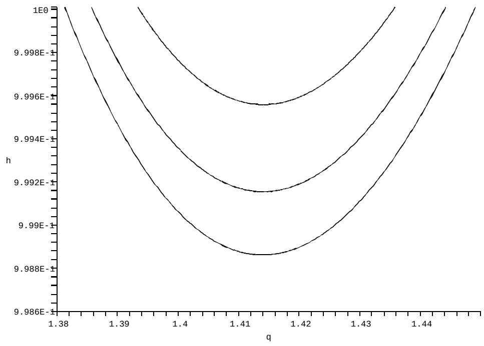

Figure 3: Upper bound h of ξ as a function of q for $\omega = 1.17eV$ (top curve), 3ω (middle curve) and 5ω (bottom curve).

N_0 created at the antinodes of a standing wave (as required) versus their spectrum will be given by figures such as those in Fig. 1 drawn for $\xi = h_l$. Then N_0 maximizes for pairs with energy $E = 2q_l mc^2$ where (q_l, h_l) is the lowest point of the $k\omega-$ curve of Fig. 3.

Work is in progress to investigate to what extend ultra-intense laser-induced $\pi^+\pi^-$ pair creation where $\mathscr{E}_c = 1.04 \times 10^{23} V/m$ is experimentally viable. Preliminary results show that implementing the approximation of [4] for 1kev photons (available from XFEL facilities) for $\mathscr{E}_0$ = $\mathscr{E}_c$, $\mathscr{E}_c/5$, $\mathscr{E}_c/10$ ($\gamma \ll 1$ regime), the number N of $\pi^+\pi^-$ produced in V_π =$1.3\times10^{-68} m^3 s$, are approximately 8.1×10^{10}, 6.5×10^4, 3.2 per laser shot, at related thresholds $n \sim 10^9$, respectively. This allows the posibility of observing $\pi^+\pi^-$creation with $\mathscr{E}_0 \sim 10^{21} V/m$ possibly using E-144 like techniques (i.e. non-linear Compton scattering and Breit-Wheeler mechanism).

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