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Spectral caustics in laser assisted Breit–Wheeler process

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ABSTRACT

Electron–positron pair production by the Breit–Wheeler process embedded in a strong laser pulse is analyzed. The transverse momentum spectrum displays prominent peaks which are interpreted as caustics, the positions of which are accessible by the stationary phases. Examples are given for the superposition of an XFEL beam with an optical high-intensity laser beam. Such a configuration is available, e.g., at LCLS at present and at European XFEL in near future. It requires a counter propagating probe photon beam with high energy which can be generated by synchronized inverse Compton backscattering.

1. Introduction

Pair production processes in electromagnetic interactions are of permanent interest due to fundamental aspects to be addressed up to technological relevance for material investigations. The basic process of two-photon conversion into a pair of electron (e^-) + positron (e^+), symbolically $X' + X \to e^+ + e^-$ as $2 \to 2$ reaction of photons with four-momenta $k_{X',X} \sim (\omega_{X',X}, \mathbf{k}_{X',X})$ has been evaluated by Breit and Wheeler [1] within a framework which is called nowadays perturbative quantum electro dynamics (pQED). It is a t-channel process in lowest order pQED. There are many other elementary processes with emerging pairs which are accessible theoretically by pQED, for instance such ones with $\mu^+ + \mu^-$ in the final state [2], or even with $\bar{\nu} + \nu$ [3].

Pair production is a threshold process, meaning that a certain minimum energy must be provided in the entrance channel to have $e^+ + e^-$ with energy $> 2m$ in the exit channel (m is the electron rest mass). This implies that the energies of the X' and X photons must be sufficiently large to overcome the threshold, i.e. $s_{X'X} = (k_{X'} + k_X)^2 = 2\omega_{X'}\omega_X(1 - \cos\theta_{X'X}) > 4m^2 \equiv s_{\text{thr}}$, where the relative angle $\theta_{X'X}$ of both beams is π for head-on collisions. In the considered $2 \to 2$ scattering process, $s_{X'X}$ equals the invariant mass of the produced electron–positron pair.

In case the initial center-of-mass energy is below the production threshold of the $2 \to 2$ process, $s_{X'X} < s_{\text{thr}}$, pairs can still be produced via multi-photon effects. This particularly interesting process has been investigated in the SLAC experiment E-144 [4,5], where a high-energy photon (several GeV) was colliding with an intense optical laser pulse (L). While the $2 \to 2$ reaction was kinematically forbidden, the multi-photon channels $X + nL \to e^+ + e^-$ with $n > 1$ had sufficient center-of-mass energy $s_{X,nL} = (k_X + nk_L)^2$ to overcome the pair production threshold. This process is called laser-induced multi-photon Breit–Wheeler pair production. In fact the high-energy photon was produced via Compton backscattering of laser light on 46.6 GeV electrons in the same laser focal spot. (For a recent theoretical re-analysis see e.g. Ref. [6].) The multi-photon channels only have a considerable probability if the laser pulse is sufficiently intense.

The laser intensity parameter $a_0 = |e|E_L/m\omega_L$ (with $-|e|$ as the electron charge, and E_L and ω_L refer to the field strength and frequency of the laser) delineates the non-relativistic domain, $a_0 < 1$, and the relativistic domain, where $a_0 > 1$ [7]. Moreover, a_0 quantifies the relevance of multi-photon effects; it is the inverse Keldysh adiabaticity parameter of the process. Another important parameter that classifies the pair production is the non-linear quantum parameter $\chi_\gamma = \frac{1}{2}a_0 s_{X,1L}/s_{\text{thr}}$ that combines a_0 and the kinematics of the process. For $a_0 \lesssim 1$ and $\chi_\gamma \lesssim 1$ only a few multi-photon channels contribute, and the probability for the nth (open) channel behaves roughly as $W_n \sim a_0^{2n}$. For $a_0 \gg 1$ and $\chi_\gamma \lesssim 1$ (i.e. the $2 \to 2$ process is extremely deep below the threshold and huge

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amounts of laser photons are required) the probability behaves semi-classically [8]. The formation region of the pair becomes much shorter than the laser cycle, $\propto 1/a_0$, and the process takes place instantaneously as it were in a local constant crossed field. For $\chi_\gamma \ll 1$ the Breit–Wheeler pair production probability is exponentially suppressed in the semi-classical regime, $W \sim e^{-8/3\chi_\gamma}$ [9], with the same functional dependence on the electric field strength as Schwinger pair production [10–14]. (For Schwinger pair production, the impact of an assisting high-frequency field has been studied, e.g. in [15–17].)

The laser-induced multi-photon Breit–Wheeler process has been investigated exhaustively (see e.g. Refs. [9,10,18]) for long-duration pulses of the laser beam. The process becomes markedly modified for ultra-short laser pulses: The temporal pulse structure, even in the plane-wave limit, gives a dominating impact specific for the pulse shape [19–24]. In a finite pulse of the laser beam there are several interfering effects: finite bandwidth (i.e. ω_L is the central frequency and higher and lower frequencies contribute to the power spectrum), multi-photon effects (i.e. the above mentioned higher harmonics) and the intensity-dependent threshold shifts [25,26].

Due to the small frequency of optical lasers, $\omega_L = \mathcal{O}(1\text{ eV})$, the parameter χ_γ is very small unless the frequency of the colliding photon X is very high – on the order of several GeV. This makes the non-linear Breit–Wheeler pair production exceedingly small in pure optical laser–laser collisions unless both lasers have ultra-high intensities (of the order of the Sauter Schwinger field 4×10^{29} W/cm^2) [10–12,18]. With the advent of X-ray free electron lasers (XFELs) that can provide photons with $\omega_X = \mathcal{O}(10\text{ keV})$ at high intensities, the gap to the threshold is diminished, but still fairly large, unless $\omega_{X'} = \mathcal{O}(50\text{ MeV})$. Therefore, one can ask whether the assistance of an ultra-high intensity laser beam L enables pair production if $s_{X'X}$ is in the sub-threshold region. Clearly, also here, very strong non-linear effects due to an ultra-high intensity laser beam are required for enabling this *laser-assisted Breit–Wheeler pair production*. A related issue is the modification of the Breit–Wheeler process by an assisting laser beam above the threshold.

To attempt a description of this latter process, we consider here the reaction $X' + (X + L) \to e^+ + e^-$, that is the laser assisted linear Breit–Wheeler process, where $s_{X'X} > s_{\text{thr}}$ and X is a weak field in the sense of $a_X \ll 1$ for the above defined intensity parameter a_0 transferred here to the other individual fields; the probe photon field is anyhow considered as weak, $a_{X'} \ll 1$, i.e. only one photon from the field X' participates in a single pair production event. We have in mind the combination of an XFEL beam X with a synchronized, co-propagating laser beam L which may be strong. To be specific, the intensity parameter of X is less than $a_X = \mathcal{O}(10^{-2})$ according to [27], and for the L beam from a PW-class laser we let be $a_L = \mathcal{O}(1)$. Note that $a_{X,L}$ depend on the size of the actual focal spots. Our considerations below apply to the homogeneity region where a plane-wave approximation holds, but we include for the first time the temporal pulse shapes as an essential element in combination with the large frequency ratio $\omega_X/\omega_L \equiv \eta^{-1} \gg 1$. Considering the European XFEL beam, under construction (and near to completion) in Hamburg/DESY [28], in the HIBEF project [29] with $\omega_X = 6$ keV, the counter-propagating beam X' must have about $\omega_{X'} = 60$ MeV F (accessible, for instance, by suitable inverse Compton back-scattering of laser light off laser-accelerated electrons [30–35]) to allow for the linear Breit–Wheeler process. In the equal-momentum frame, $\mathbf{k}_{X'} = -\mathbf{k}_X$, we have $\omega_{X'} = \omega_X = 600$ keV as geometric mean of the laboratory frequencies and $s_{X'X}/s_{\text{thr}} = 1.38$. For the assisting laser field we assume an UV laser frequency of 10 eV in the laboratory frame, i.e. $\omega_L = 1$ keV in the equal-momentum frame. In this set-up, the pairs cannot be produced by the $X' - L$ collisions alone: This process is extremely below the threshold and, thus, extremely suppressed since $s_{X'L}/s_{\text{thr}} = 0.002$ and $\chi_\gamma = 0.001 a_L$.

Our analysis in some aspects parallels [36,37], where the laser assisted Compton process is analyzed. This cross channel enjoys some remarkable features: The spectrum of Compton scattered X-ray photons off an electron moving in an accelerated manner in an external laser pulse displays, besides the well-known Compton line at fixed observation angle, a number of prominent peaks, and the complicated spectral distribution exhibits distinct regions with changing patterns. The striking finding in [37] is the interpretation of the prominent peaks as spectral caustics related to merging stationary phase points. Accounting for quantum interference effects for the emission from different locations of the quasi-classical electron motion in the laser field along a temporally changing figure-8 trajectory, the gross features of the complicated spectrum become easily accessibly. Such an interpretation is also in the spirit of [8], where the spectrum of pairs produced in a strong external field[1] is explained as redistribution in phase space following the production process (which can be approximated by a temporally constant cross-field probability) and keeping interference effects.

Despite of the similarities of the Compton and Breit–Wheeler processes related by crossing symmetry, the different phase spaces and attributed kinematic relations make them fairly different. In addition, the Compton process has a classical limit – the Thomson scattering – while the pair-production is of genuine quantum nature. This is the reason for considering separately the analog of the spectral caustics in [37] in the laser assisted Breit–Wheeler process.

Our paper is organized as follows. In section 2 we present the QED basics for the calculation of the laser assisted Breit–Wheeler process. Selected numerical results are discussed in section 3 for a special kinematic situation to highlight the impact of the laser field. Section 4 summarizes.

2. The QED process

In the Furry picture, the process $X' + (X + L) \to e^+ + e^-$ is described by a one-vertex diagram $X' \to e^+_{X+L} + e^-_{X+L}$ (see Fig. 1, left), where $e^\pm_{X+L}$ mean the Volkov solutions of out-going electrons and positrons in temporally shaped fields $X + L$, both ones co-propagating and with perpendicularly linear polarization. We consider head-on collision of the photons X' and $X + L$. These assumptions are made for the sake of simplifications of the subsequent evaluations. In addition, we linearize in the XFEL field A_X. This corresponds then to a Furry-picture two-vertex t-channel diagram (see Fig. 1, right), with exchange diagram analog to the Breit–Wheeler process $X' + X \to e^+_L + e^-_L$, where however here the out-going electron and positron and the propagator are laser dressed.

2.1. Kinematics

The energy–momentum balance for laser-assisted pair production can be put into the form (μ is a Lorentz index)

$$k^\mu_{X'} + k^\mu_X + \ell k^\mu_L = p^\mu_p + p^\mu_e \,, \tag{1}$$

where ℓ represents a hitherto unspecified momentum exchange parameter between the assisting laser field L and the produced pair (hereafter labeled by e and p for electron and positron, respectively). We define light-front coordinates, e.g. $x^\pm = x^0 \pm x^3$ and

[1] The interested reader is referred to [38–45] for further work on pair production in external fields within a QED framework.