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Notices on

XFEL HGF Beam Line, Strong-Field Physics Part

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1 Frontiers of QED

Considering QED as renormalizeable, Poincare-invariant quantum field theory in 1+3 dimensional Minkowski space as Abelian gauge theory of electrons and positrons (called Fermions) and photons (called gauge Bosons)[1] one may ask

1. within QED, possibly with trivially extended Fermion sector, $\psi \rightarrow \psi_F = \psi_{e^\pm,\mu^\pm,\tau^\pm}$, for
   (a) for possible intrinsic limitations,
   (b) for experimental verification of predicted effects,
2. for direct extensions of the $U(1)$ gauge theory in the spirit of modifications of $\mathcal{L}_{F,A,jA}$ such as $\mathcal{L}_A = \sum_{n=1}^{\infty} c_S^{(n)} S^n + c_P^{(n)} P^n$ (with S defined in footnote 1 and $P = \frac{1}{4}\tilde{F}F$) and further supplements of derivative terms etc.,
3. for extensions and embedding in larger gauge groups (with extended Fermion sectors) such as having QED as subsector of the electroweak $U(1) \times SU(2)$ theory with spontaneous symmetry breaking; an interim step to such schemes may be the discovery of couplings of other (may be beyond the standard model particle content) fields to the Fermions $e^\pm$ or/and gauge Bosons (photons, γ for short hand notation).
4. for modifications of the propositions "Poincare invariance", 1+3 dimensionality of space-time etc.

Beyond the elements of the Lagrangian defining the interactions, the ground state (vacuum $|0\rangle$) plays an important role in defining a theory. Often, the notion "vacuum" is used in the technical sense, meaning a spatial region with zero entropy, free of particles or matter with conserved charges, i.e. free

[1] The Lagrangian density can be written as $\mathcal{L}_{QED} = \mathcal{L}_F + \mathcal{L}_A + \mathcal{L}_{jA} + \mathcal{L}_{gaugefix} + \mathcal{L}_{gost}$ with the free Dirac part of Fermions $\mathcal{L}_F$, the free $U(1)$ gauge field part $\mathcal{L}_A = -S$ with $S = \frac{1}{4}F^2$ (where F stands for the field strength tensor) and their minimal coupling $\mathcal{L}_{jA} = jA$ with Dirac current $j = \sqrt{\alpha}\bar{\psi}\gamma\psi$. Gauge fixing is made by $\mathcal{L}_{gaugefix} = \frac{1}{2}\lambda(\partial A)^2$ with the gauge parameter λ which must not appear in observables; the ghost part is not necessarily required in Abelian gauge theory.

of electrons and positrons, ions, atoms etc. A more adequate wording uses "quantum vacuum" in the sense of the "vacuum" but with electromagnetic fields which may be termed "electromagnetic vacuum". All these phrases are different from the Poincare invariant physical vacuum $|0\rangle$ which is a state of minimum energy.
Imaging, the vacuum contains, among others, $e^{\pm}$ fluctuations, the wording "vacuum polarization" in our context means a change of the dielectric and magnetic susceptibilities properties due the an external e.m. field, i.e. the polarized electromagnetic vacuum behaves as a medium with nontrivial dielectric properties; Poincare invariance is lost.
One may consider various frontiers of testing QED:

- the high-energy behavior is sensitive to the running coupling $\alpha(Q^2)$ due to the positive β function[2]
- the precision tests which are mainly related to $g-2$, atomic transitions, Lamb shift, etc.
- effects which are related to (extremely) high e.m. fields, referring to the high-intensity frontier.

Let be given the scale of the electron mass m and the electron charge $e = 4\pi\sqrt{\alpha}$ with the low-energy limit of $\alpha = 1/137.035999679(94)$ one may attribute to QED a characteristics field strength[3] $E_S = m^2/e \approx 1.3 \times 10^{18}$ V/m (electric field) and 4.4×10^{13} G (magnetic field). E_S, introduced by Sauter,[4] is considered as the field strength where spontaneous pair creation sets in. The famous Schwinger effect[5] quantifies this as significant non-perturbative pair creation rate once an originally purely (homogeneous) electric field achieves the order of E_S. One may relate such a behavior to le Chatelier's principle, saying that a system responds to external stress by populating further degrees of freedom minimizing the stress. In other words, the quantum vacuum is rearranged.
Besides magnetic high-field regions at the polar caps of neutron stars and magnetars and the extreme conditions at sites where the x-ray bursters are located, the volume nearby high-Z ions and high-intensity lasers provide opportunities to investigate strong-field effects of QED. The latter ones are reviewed in the recent survey "Extremely high-intensity laser interactions

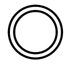
[2]This verified at LEP in Bhabha e^+e^- scattering, cf. ALEPH, DELPHI, L3, OPAL, SLD, Phys. Rept. 427, 257 (2006). Q^2 is a typical energy/momentum scale squared of the process.

[3]We employ particle units with $\hbar = c = 1$ and convert eventually to usual dimensional quantities.

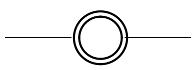
[4]F. Sauter, Z. Phys. 69, 742 (1931).

[5]J.S. Schwinger, Phys. Rev. 82, 664 (1951).

with fundamental quantum systems".[6] The planned HGF XFEL beam line in turn offers opportunities to test fundamental predictions of strong-field QED and to seek for new effects. The XFEL opportunities go beyond the ones at LCLS with respect to energy and, in particular, repetition rate.
We focus here on the interactions of photons (from XFEL ($\omega' = 15$ keV, $a_0 < 10$) and petawatt-class optical lasers ($\omega \sim 1$ eV, $a_0 < 500$)) and electrons (e.g. the 17.5 GeV XFEL driver electrons, offering excellent opportunities in combination with optical petawatt-class laser,[7] or accelerated ones by the petawatt-class laser, or being part of target materials, or ones created associatedly with positrons, meaning Lorentz factors $\gamma = 1 - 10^4$).
In the following, the Furry picture[8] is employed in considering a few strong-field QED processes.

2 Schwinger-Type Processes 

If the imaginary part of the vacuum$_{in}$-vacuum$_{out}$ amplitude (corresponding to a cut trough the diagram resulting in a "halfcircle") becomes nonzero, pair production sets in. This is essentially the Schwinger process which is in its pure form for given parameters negligibly small. Various special combinations of superpositions of laser fields and XFEL photons are proposed to enhance the pair production rates leading to laser assisted (catalyzed) Schwinger type processes.[9]

3 Vacuum Polarization Effects 

A prominent example is the propagation of a probe photon through the electromagnetic (quantum) vacuum. Diagrammatically, it contains two dressed Fermion propagators. The external field might be represented by (i) Coulomb fields of atomic nuclei, (ii) a constant magnetic field or (iii) a high-intensity

[6] A. Di Piazza, C. Müller, K.Z. Hatsagortsyan, C.H. Keitel, arXiv:1111.3886, to be published in Rev. Mod. Phys.; cf. also Y.I. Salamin, S.X. Hu, K.Z. Hatsagortsyan, C.H. Keitel, Phys. Rept. 427, 41 (2006); M. Marklund, Shukla, M. Marklund, P.K. Shukla, Rev. Mod. Phys. 78, 591 (2006).

[7] A. Ringwald, Beschleuniger-Ideenmarkt, June 16 - 17, 2010, DESY.

[8] A strong external e.m. field is considered and dealt with as classic, coherent and c-number valued background field; this is the laser field which is technically accounted for by Volkov solutions in case of plane waves with $S = P = 0$, for instance, depicted by fat double lines meaning laser dressed electrons/positrons. The reduced field strength $a_0 = \frac{e\langle E\rangle}{m\omega}$ is a classical (nonquantum) parameter; for $a_0 > 1$ the electron's quiver motion becomes relativistically. Any other e.m. field is considered and dealt with as perturbation, depicted as thin lines.

[9] G. Dunne, H. Gies, R. Schützhold, Phys. Rev. D 80, 111301 (2009).

laser field. Similar to the propagation through a certain material (e.g. a plasma, see next but one item) the photon experiences (i) dispersive modifications, such as frequency shift (sometimes called "photon acceleration"[10]) and changed polarization properties (change of ellipticity and rotation of the polarization plane) and (ii) absorptive effects, e.g. decay into a e^+e^- pair, dealt with in subsection 4.5. These effects are interrelated by (a) dispersion relations a la Kramers-Kroning based on causality and analyticity properties of QED, (b) cutting rules, and (c) optical theorem.

3.1 Vacuum birefringence

Imaging the polarization of the fluctuating virtual e^+e^- pairs in the electromagnetic vacuum as "vacuum polarization" due to modified dielectric properties of the "vacuum", two refraction indices characterize the light propagation giving rise to birefringence. Keeping the popular name "vacuum birefringence" the experimental set-up for it consists in measuring the change of the linear polarization of the probe photon (XFEL) in the focal spot of optical laser(s) into elliptical polarization. The estimated ellipticity in the laser focal spot of size d,[11]

$$\delta^2 = 3.2 \times 10^5 \left(\frac{d}{\mu\mathrm{m}} \epsilon^2 \nu \right)^2 \tag{1}$$

with $\epsilon = \omega_L a_0/m$ and $\nu = \omega_{XFEL}/m$, is based on the low-energy, low-intensity effective theory of QED, the Euler-Heisenberg Lagrangian (see $\mathcal{L}_A$ in the introduction with $c_S^{(1)} = -1$, $c_P^{(1)} = 0$, $c_S^{(2)} = \frac{8}{45}\frac{\alpha^2}{m^4}$, $c_P^{(2)} = \frac{7}{4} c_S^{(2)}$) describing direct photon-photon interactions.[12] Another quantity is the rotation of the initially linearly polarized probe photon by an angle $\delta\phi = d\frac{2\pi}{\lambda}|n_+ - n_-|$[13] with refraction indices given below. The approximations leading to the Euler-Heisenberg effective theory descriptions are justified according to Ref.[14] for

[10] J.T. Mendonca, M. Marklund, P.K. Shukla, G. Brodin, Phys. Lett. A 359, 700 (2006).

[11] T. Heinzl, A. Ilderton, arXiv: 0811.1960.

[12] In this effective theory, vertices for direct photon-photon interactions appear, the lowest order of them is a four-photon contact interaction. The presence of a strong background field acts as a polarized material medium on probe photons. Depending on the source of the photons one distinguishes: (i) Delbrück type interactions where some of the photons come from the Coulomb field of a nucleus, (ii) processes in strong magnetic fields and (iii) processes in laser fields. Furthermore, one has to distinguish the number of incoming and outgoing probe photons. Processes of the type (a) $\gamma \to \gamma$ (vacuum birefringence), (b) $\gamma \to \gamma\gamma$ (photon splitting), (c) $\gamma\gamma \to \gamma$ (photon merging) and (d) $|vac\rangle \to \gamma$ (vacuum emission, three wave mixing) are conceivable. Beyond the effective low-energy field theory these processes develop imaginary (absorptive) parts leading to various pair production scenarios.

[13] K. Koch, diploma thesis, University Jena (2005).

[14] T. Heinzl, B. Liesfeld, K.U. Amthor, H. Schwoerer, R. Sauerbrey, A. Wipf, Opt. Commun. 267, 318 (2006).

the envisaged XFEL–optical laser configurations. Spatial beam geometries, such as Gaussian beams, are accounted for (cf. footnote 14) but temporal not yet. Channel cut crystals[15] seem now to allow to measure the estimated effect which requires an extremely good polarization purity.[16] The quotation in footnote 11 mentions the possibility to have access to the anomalous dispersion (i.e. the real parts of the refraction indices become negative) which are related, via Kramers-Kroning dispersion relations, to the imaginary part as signal of pair production. The two principal indices are given by $n_\pm = 1 + \frac{\alpha\epsilon^2}{45\pi}(11 \pm 3 + \mathcal{O}(\epsilon^2\nu^2))(1 + \mathcal{O}(\alpha\epsilon))$.
Ref.[17] points out the promising opportunities of probing the quantum vacuum birefringence by phase contrast Fourier imaging.
Several experiments tried already to verify the modified photon propagation through an external meso-scale field. Most spectacular was the PVLAS experiment[18] with a magnetic field of 5 T, which was however retracted.[19]
Light diffraction by a standing e.m. wave, generated by the superposition of two counterpropagating optical laser beams, have been envisaged (cf. Ref. 14) and considered in some detail subsequently.[20] The deteriorating role of diffraction is reduced in such a configuration.

3.2 Faraday rotation

A step towards the experimental verification of the vacuum birefringence is a measurement of the Faraday rotation of polarized XFEL photons in a plasma under the influence of a strong magnetic (Cotton-Monton effect, magnetic birefringence) or laser field.[21] X-ray polarimetry at synchrotrons is nowadays a standard tool to characterize materials.
Reference[22] reports an enhancement of vacuum polarization effects in cold collisional plasma.
Photon splitting in a magnetized non-linear plasma has been considered too.[23]

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[15] B. Marx, I. Uschmann, S. Höfer, R. Lötzsch, O. Wehrhan, E. Förster, M. C. Kaluza, T. Stöhlker, H. Gies, C. Detlefs, T. Roth, J. Härtwig, G.G. Paulus, Optics Comm. 284, 915 (2011).

[16] I. Uschmann [talk at HZDR workshop 2011] reports a purity of 2.5×10^{-10}.

[17] K. Homma, D. Habs, T. Tajima, Appl. Phys. B 104, 769 (2011).

[18] E. Zavattini (PVLAS Collaboration), Phys. Rev. Lett. 96, 110406 (2006).

[19] M. Bregant et al. (PVLAS Collaboration), Phys. Rev. D 77, 032006 (2008).

[20] A. Di Piazza, K.Z. Hatsagortsyan, C.H. Keitel, Phys. Rev. Lett. 97, 083603 (2006).

[21] T.E. Cowan, M. Bussmann, R. Sauerbrey et al. (2011).

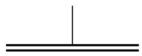
[22] A. Di Piazza, K.Z. Hatsagortsyan, C.H. Keitel, Phys. Plamas 14, 032102 (2007).

[23] G. Brodin, M. Marklund, B. Eliasson, P.K. Shukla, Phys. Rev. Lett. 98, 125001 (2007).

4 Scattering and Particle Production Processes

These are generalized and nonlinear Compton[24], Breit-Wheeler[25] and one-photon pair annihilation[26] processes. Their invariant S matrix elements are related by crossing symmetry. Higher-order processes of them are 2-photon and multi-photon Compton processes and the Trident process. In addition, we mention processes which might be exploited for generating secondary beams.

4.1 Compton Process



In the non-linear Compton process, laser photons are Doppler-shifted when scattering off a counter propagating relativistic electron beam to frequencies $\tilde{\omega}_n = 4n\gamma^2\omega \left(1 + \frac{1}{2}a_0^2 + 4\gamma\omega/m\right)^{-1}$ with $\gamma = E_{e^-}/m$ and ω as frequency of the primary (laser) photons, where $n = 1, 2, \cdots$ numbers the harmonics due to multi-photon effects. The appearance of a term $\propto a_0^2$ in the denominator is related to an effective renormalized intensity-dependent mass $m_*^2 = m^2(1 + a_0^2/2)$ of charged particles in intense laser fields.[27]
The low-energy limit of the Compton process is the Thomson process: the emission of photons (dealt with by Lienard-Wiechert potential) by a classical point charge (trajectory obtained from Lorentz's equation). Temporal beam shape effects are important for the spectrum.[28] The QED treatment for temporally shaped laser pulses has been accomplished[29] and even in the low-energy domain deviations from the Thomson process have been identified. Thomson and Compton procces are related by scaling laws.[30]
Possible configurations for an experimental set-up can be: XFEL photons colliding with laser-accelerated electrons, laser photons colliding with laser-accelerated electrons (the feasibility of such an all-optical set-up is demonstrated for the first time in Jena[31]), or using the XFEL seed electrons in conjunction with XFEL, or optical laser photons. The physics focus of such experiments is on high harmonics and the spectral shape with the important imprints of the photon beam shape. The high pulse energy in PW class laser

[24]Emission of one photon by an electron, $e_V \to e'_V \gamma$.

[25]Decay of the probe photon into a pair, $\gamma \to e_V^+ e_V^-$.

[26] $e_V^+ e_V^- \to \gamma$, cf. A. Ilderton, P. Johansson, M. Marklund, Phys. Rev. A 84, 032119 (2011).

[27] C. Harvey, T. Heinzl, A.L. Ilderton, M. Marklund, arXiv:1203.6077.

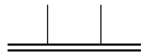
[28]T. Heinzl, D. Seipt, B. Kämpfer, Phys. Rev. A 81, 022125 (2010).

[29]N.B. Narozhny, M.S. Fofanov, JETP 83, 14 (1996); M. Boca and V. Florescu, Phys. Rev. A 80, 053403 (2009); D. Seipt, B. Kämpfer, Phys. Rev. A 83, 022101 (2011).

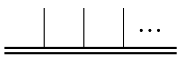
[30]D. Seipt, B. Kämpfer, Phys. Rev. ST Accel. Beams 14, 040704 (2011).

[31]H. Schwoerer, B. Liesfeld, H.-P. Schlenvoigt, K.-U. Amthor, R. Sauerbrey, Phys. Rev. Lett. 96, 014802 (2006).

systems allows for a high intensity in a large spatial volume which can be investigated in precision experiments of the non-linear red shift of the Compton edge and the spectral shaping of the harmonics when using the high-quality XFEL seed electron beams. These investigations can serve as experimental verification of the much disputed intensity-dependent mass dressing and the dependence on the pulse shape, cf. footnote 27.
Considering Thomson/Compton backscattering as source of high-energy photons the use of low intensities, $a_0 < 1$, seems favorable to avoid the red shift of the Compton edge[32] and to improve the beam quality of the emitted x/γ rays.

4.2 2-Photon Compton Process 

The 2-photon Compton process is a second-order process with one dressed Fermion propagator. The emission of two entangled photons has an interesting relation to the Unruh effect.[33] The approximation of an infinitely long plane laser field has been considered fairly exhaustively,[34] while certain temporally shaped pulses are studied for the first time by Seipt.[35] The experimental challenge for $a_0 \sim 1$ is digging the coincidence of the correlated two photons out of the background of Compton photons. Kinematically, a large center-of-mass energy is required, as at low energies the double Compton process is strongly suppressed relative to the lowest-order Compton process.

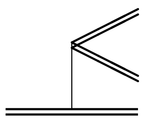
4.3 Multi-Photon Compton Process  and Radiation Reaction

In very strong laser fields, $a_0 \gg 1$, the multi-photon Compton process and higher-order processes might be considered as the QED foundation of radiation reaction.[36] The latter one refers to the energy loss of a point like particle moving in an external field. The energy loss modifies the Lorentz equation of motion. Multi-GeV electrons counter propagating to a strong laser pulse can probe the proposed radiation reaction formulae disputed during the last hundred years. An ideal situation with maximum sensitivity would be the combination $a_0 \leq 2\gamma$ due to the onset of electron reflection for directly head-

[32] A. Debus et al., Appl. Phys. B 100, 61 (2010).
[33] P. Chen, T. Tajima, Phys. Rev. Lett. 83, 256 (1999).
[34] E. Loetstedt, U.D. Jentschura, Phys. Rev. Lett. 103, 110404 (2009), Phys. Rev. A 80, 053419 (2009).
[35] D. Seipt, B. Kämpfer, arXiv:1201.4045.
[36] C. Harvey, T. Heinzl, M. Marklund, Phys. Rev. D 84, 116005 (2011); C. Harvey, T. Heinzl, N. Iji, K. Langfeld, Phys. Rev. D 83, 076013 (2011).

on collisions with a plane wave.[37] For XFELs, the radiation damping was expected[38] to cause a strong deflection of the electron beam and a significant electron energy loss, which, however, was later considered as not so strong.[39] On top of the Compton processes, which might be approximated as incoherent photon emissions, is pair production, the leading diagram considered in the next subsection. This refers already to the evolution of QED cascades.[40]

4.4 Trident Process



The trident process, verified for the first time in the famous SLAC experiment E-144,[41] may be considered as virtual Compton scattering with subsequent decay of the high-energy photon into an e^+e^- pair, however, with an interesting mixture of real and virtual intermediate photons.[42]
Using XFEL driver electrons in combination with a strong optical laser one can explore the interesting nonperturbative regime, where real and virtual are relevant photons for the pair production process and about 40 laser photons contribute to the creation of one pair. It is remarkable that the role of virtual contributions was recognized not earlier than 15 years after the SLAC E-144 experiment.
The trident process, where the nonlinear Breit-Wheeler process appears as second step of the intermediate photon's on-shell part, is considered as starting point of avalanche like subsequently repeatedly occurring e^+e^- creations leading to a screening of ultra-strong e.m. fields by a charged seed particle (impurity). This might prevent the achievement of strong e.m. fields towards the so-called Schwinger limit E_S, in particular, for laser fields[43] in the spirit of the above mentioned QED cascades.

[37] A. Di Piazza, K. Hatsagortsyan, C. Keitel, Phys. Rev. Lett. 102, 254802 (2009); C. Harvey, T. Heinzl, A. Ilderton, Phys. Rev. A 79, 063407 (2009).

[38] C. Harvey, talk at Workshop on Petawatt-Lasers at Hard X-Ray Light Sources Dresden-Rossendorf, September 6, 2011.

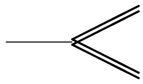
[39] C. Harvey, M. Marklund, arXiv:1110.0996v1.

[40] A.M. Fedotov, N.B. Narozhny, G. Mourou, G. Korn, Phys. Rev. Lett. 105, 080402 (2010); I.V. Sokolov, N. Naumova, J.A. Nees, G. Mourou, Phys. Rev. Lett. 105, 195005 (2010); N.V. Elkina, A.M. Fedotov, I.Yu. Ksoyukov, M.V. Legkov, N.B. Narozhny, E.N. Nerush, H. Ruhl, Phys. Rev. ST AB 14, 054401 (2011).

[41] C. Bamber et al., Phys. Rev. D 60, 0929004 (1999); D.L. Burke et al., Phys. Rev. Lett. 79, 1626 (1997); C. Bula et al., Phys. Rev. Lett. 76, 3116 (1996). The SLAC experiment tested the perturbative multi-photon regime. However, it was possibly just at the onset of the nonperturbative regime, where $a_0 \ll 1$ and $\sqrt{s_{\gamma_L e^-}} \sim 2m$.

[42] H. Hu, C. Müller, C.H. Keitel, Phys. Rev. Lett. 105, 080401 (2010); A. Ilderton, Phys. Rev. Lett. 106, 020404 (2011).

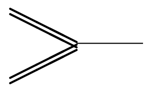
[43] E.N. Nerush, I.Yu. Kostyukov, A.M. Fedotov, N.B. Narozhny, N.V. Elkina, H. Ruhl, Phys. Rev. Lett. 106, 035001 (2011).

4.5 Breit-Wheeler Process 

For incoherent photons, the Breit-Wheeler process, $\gamma\gamma' \to e^+e^-$ is a threshold process requiring $s = (k + k')^2 = 2\omega\omega'(1 - \cos\Theta_{\vec{k}\vec{k}'}) > 4m^2$. If, instead, the photons γ belong to a coherent (laser) field the nonlinear Breit-Wheeler process, which may be visualized perturbatively as $n\gamma\,\gamma' \to e^+e^-$, does not have any threshold. However, for small values of the reduced field strength a_0, the pair production rate declines sharply below $s \approx 4m^2$. An interesting effect has been identified recently:[44] in weak laser fields, $a_0 < 1$, directly below $s = 4m^2$, very short pulses give rise to an enhancement of the rate by two and more orders of magnitude relative to long pulses. The origin can be traced back to the non-monochromaticity of short pulses with only a few oscillations of the electric field. In high-intensity laser pulses, $a_0 > 1$, the Ritus approximation[45] applies for the pair production probability,

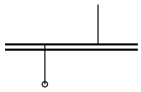
$$\sigma = \frac{200\text{mb}}{\eta} e^{-\frac{8m^2}{3s\eta}} \tag{2}$$

supposed $s\eta/(2m^2) < 1$ and $\eta = a_0/\sqrt{2} > 1$. For the combination XFEL + optical laser, $s = 2.3 \times 10^{-7} m^2$ meaning that exceedingly large values of a_0 would be required. For the XFEL-XFEL combination, $s = 0.0034m^2$ holds with $\sigma \sim 10^{-340}$ mb for $\eta = 1$. Possible XFEL + XFEL + PW laser scattering configurations might drastically increase this exceedingly low cross section. The cross section is related to a probability via $W = 2\sigma \frac{m^2 a_0^2}{8\pi\alpha} \int_{-\infty}^{\infty} d\phi g^2(\phi)$, where $g(\phi)$ describes the temporal shape of the laser pulse.
We note that, for short laser pulses, interesting phase space distributions of $e^\pm$ reflect the temporal shape.[46]
The nonlinear Breit-Wheeler process may be considered as decay of a probe photon in an external field. As such, it belongs to the absorptive part of photon propagation through an e.m. field.

4.6 Pair Annihilation into a Single Photon 

Pair annihilation into a single photon is the time reversed process of pair creation dealt with in the previous subsection. It is forbidden in the vacuum. An opportunity would be a combination of the XFEL pulse and electrons and positrons both with $\gamma \sim 80$ (cf. footnote 26) which could be generated by the PW class laser. The signal would be the unidirectional emission of photons.

[44] A.I. Titov et al., to be published.
[45] V.I. Ritus, J. Sov. Laser Res. 6, 497 (1985).
[46] T. Heinzl, A. Ilderton, M. Marklund, Phys. Lett. B692, 250 (2010); T. Nousch, Diploma thesis, TU Dresden (2011).

4.7 Compton Scattering in the Coulomb Field of an Atomic Nucleus  and Pair Creation

The photon emission spectrum in Compton scattering in the Coulomb field of a nucleus, which might be considered as laser-enhanced bremsstrahlung, has been calculated,[47] and a resonant behavior with harmonics was found. In the pair production channel from a high-energy photon in the Coulomb field of a nucleus, a drastic modification of the differential spectra of the pairs was found[48] due to the strong laser field.

4.8 Secondary Beams

Laser-accelerated electrons may be dumped in high-Z target materials to generate secondary $\mu^{\pm}$ beams.[49]
Substituting the outgoing photon in the Compton process by an outgoing $\nu\bar{\nu}$ pair according to 

one can estimate the neutrino pair production rate[50] which, due to the weak interaction, is fairly small.
The dynamics of electron-positron-photon droplets, may be created in QED cascade processes or in ultra-thin foils irradiated by counter propagating ultra-strong laser beams, has been considered by various authors.[51] Such droplets can serve as gamma flashes.[52] The XFEL beam might be used to probe the produced plasma droplets. Further secondary beam options are discussed in the quotations in footnote 6.

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