Recollision processes and other photon-induced strong-field QED phenomena in a plane-wave laser field

ExHILP 2017 @ Técnico Lisboa

September 7th, 2017

Sebastian Meuren

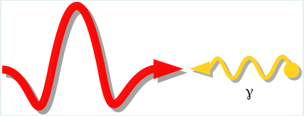
Sergey Bragin, Matteo Tamburini, Antonino Di Piazza, Christoph H. Keitel
Nathaniel J. Fisch

MPI for Nuclear Physics, Heidelberg (Germany)

Department of Astrophysical Sciences, Princeton University (New Jersey, USA)

Introduction

Asymmetric Light-by-Light Scattering



Strong optical laser ($I \gtrsim 10^{22}\,\mathrm{W/cm^2}$, $\omega \sim \mathrm{eV}$)

Highly energetic gamma photons ($\omega_\gamma \gtrsim \mathrm{GeV}$)

Why are we interested in this setup?

- Clean experiment, only on-shell photons in the initial state
- Conceptual very appealing:
  - energy-matter equivalence
  - wave-particle duality
- Pure quantum effects, photon-photon interaction is forbidden in CED
- Nontrivial phenomena are strongly suppressed below the critical field
- The "intensity frontier" is complementary to the "energy frontier"

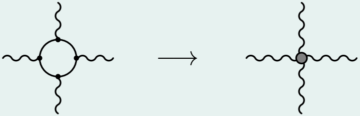
Disclaimer: not all relevant papers are cited; natural units ($\hbar = c = \epsilon_0 = 1$) are used

Light-Light interaction in the "classical" limit

- Classical electrodynamics (CED): superposition principle, no LBLS
- Quantum field theory: photons couple via virtual electric charges
- Leading-order corrections: effective Euler-Heisenberg Lagrangian
  - Valid for slowly varying fields (small photon momenta)
  - Relevant scale is the electron Compton wavelength $\lambda_C = 1/m$

Euler-Heisenberg Lagrangian density (1936)

$$\mathcal{L} = \frac{1}{2}\left(\boldsymbol{E}^2 - \boldsymbol{B}^2\right) + \frac{2\alpha}{45\,E_{\mathrm{cr}}^2}\left[\left(\boldsymbol{E}^2 - \boldsymbol{B}^2\right)^2 + 7\left(\boldsymbol{E}\boldsymbol{B}\right)^2\right] + \dots$$



Leading-order contribution to the EH-Lagrangian

- EH corrections are suppressed below the critical field $E_{\mathrm{cr}} = m^2/|e|$
- In vacuum $I_{\mathrm{cr}} = 4.6 \times 10^{29}\,\mathrm{W/cm^2}$ is not achievable in the near future

$\longrightarrow$ **Euler-Heisenberg is very challenging to measure!**

Slowly varying fields vs. high-energy probe photons

Vacuum field invariants

$$\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \quad \mathcal{G} = \frac{1}{4} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

Only two if gradients are negligible

Quantum nonlinearity parameter

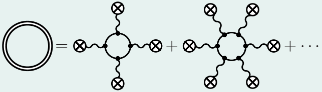
$$\chi \sim \frac{|e|}{m^3} \sqrt{q^\mu F^2_{\mu\nu} q^\nu} \sim 2 \, \frac{\omega_\gamma}{m} \frac{E}{E_{\mathrm{cr}}},$$

$$\chi \approx 0.5741 \, (\omega_\gamma / \mathrm{GeV}) \sqrt{I / (10^{22} \, \mathrm{W/cm^2})}$$

Constructed using the four-momentum q^μ

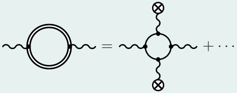
Lorentz boost enhances electric field

Euler-Heisenberg Lagrangian



Valid for approximately constant fields

Polarization operator



Probe-photon momentum included

Slowly varying fields vs. high-energy probe photons

Vacuum field invariants

$$\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \quad \mathcal{G} = \frac{1}{4} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

Only two if gradients are negligible

Quantum nonlinearity parameter

Experimental perspectives

Highly-energetic gammas via Compton backscattering

FACET·II
Facility for Advanced Accelerator Experimental Tests

- Electron energy: $1 - 10\,\mathrm{GeV}$
- BIG photon source: $5\,\mathrm{GeV}$

Intense optical laser facilities

- $1\,\mathrm{PW}$ focused to $10\,(\mu\mathrm{m})^2$ corresponds to $10^{22}\,\mathrm{W}/\mathrm{cm}^2$
- $10\,\mathrm{PW}$ focused to $10\,(\mu\mathrm{m})^2$ corresponds to $10^{23}\,\mathrm{W}/\mathrm{cm}^2$

$$\chi_\gamma \approx 0.9\,\omega_\gamma\,[5\,\mathrm{GeV}]\,\sqrt{I\,[10^{21}\,\mathrm{W}/\mathrm{cm}^2]}$$

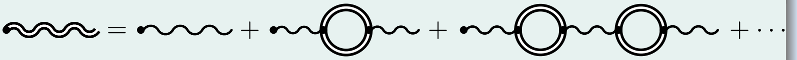
High-energy photons inside a background field

The exact photon wave function obeys a Dyson equation

$$-\partial^2 \Phi_q^{\mathrm{in}\,\mu}(x) = \int d^4y\, P^{\mu\nu}(x,y)\Phi^{\mathrm{in}}_{q\nu}(y),$$

which is normally expanded into a nested double series

Number of insertions (propagation length in the field)

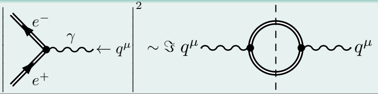


Relevant expansion parameter: $\alpha\chi\xi N$ ($\chi \ll 1$)

Polarization operator expansion (radiative corrections)

Relevant expansion parameter: $\alpha\chi^{2/3}$

Polarization operator vs. BWPP



Real vs. imaginary part

- RP: vacuum birefringence
- IP: pair production (BWPP)

SM, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, PRD **91**, 013009 (2015)

High-energy photons inside a background field

Probing vacuum birefringence at the GeV scale

- VB effect is largest close to the pair production threshold
- Growing interest:
  - Y. Nakamiya et al., arXiv:1512.00636 (2015)
  - A. Ilderton and M. Marklund, J. Plasma Phys. **82** (2016)
  - B. King and N. Elkina, Phys. Rev. A **94**, 062102 (2016)

Poster by Sergey Bragin (arXiv 1704.05234):

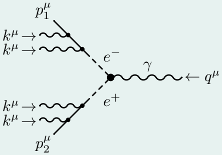
High-Energy Vacuum Birefringence and Dichroism in an Ultrastrong Laser Field

Sergey Bragin, Sebastian Meuren,* Christoph H. Keitel, and Antonino Di Piazza
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany
(Dated: July 10, 2017)

- Above threshold VB becomes screened by vacuum dichroism
- Probing effects beyond EH, e.g., anomalous dispersion
- Circularly polarized gamma photons highly beneficial for VB
- **Measuring VB at ELI Beamlines/ELI-NP within few hours/days**

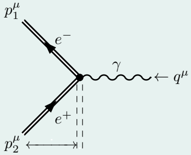
Breit-Wheeler pair production (BWPP)

Multiphoton regime



$\xi \ll 1$: process "feels" oscillations

Tunneling regime



$\xi \gg 1$: process "feels" a static field

Which is the time/length scale for pair production?

- Constant electric field E: the pair becomes real after the length δx:

$$\delta x\, |e| E \sim mc^2 \quad \longrightarrow \quad \delta x \sim \frac{mc^2}{|e| E}, \qquad \delta\phi \sim \frac{\delta x\, \omega}{c} \sim \frac{\omega mc}{|e|\, E} = \frac{1}{\xi}$$

($\delta\phi$ is the formation region with respect to the laser phase $\phi = kx$)

- The classical intensity parameter: $\boxed{\xi = a_0 = |e| E/(mc\,\omega)}$

Sauter-Schwinger effect

- Probability: $\sim \exp\left(-\pi E_{\mathrm{cr}}/E\right)$ (vacuum with electric field)

BWPP in the tunneling regime

- Probability: $\sim \exp\left[-8/(3\chi)\right]$ (if $\chi \ll 1$ and $\xi \gg 1$)

Breit-Wheeler is nonperturbative in the tunneling regime

Hand-waving derivation:

- Total field tensor $\widetilde{F}^{\mu\nu} = F^{\mu\nu} + f^{\mu\nu}$
  - $F^{\mu\nu}$: constant crossed background field
  - $f^{\mu\nu} = (m/|e|)(\epsilon^\mu q^\nu - \epsilon^\nu q^\mu)$: photon field tensor
  - q^μ: photon four-momentum
  - $\epsilon^\mu = (Fq)^\mu / \sqrt{qF^2q}$, ($\epsilon^2 = -1$, $q\epsilon = 0$): polarization four-vector
- Vacuum field invariant: $\mathcal{F} = \frac{1}{4}\widetilde{F}_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{1}{2}\left(\boldsymbol{B}^2 - \boldsymbol{E}^2\right)$
  - $E \longrightarrow \sqrt{-2\mathcal{F}}$ in Schwinger formula
  - $\mathcal{F} \longrightarrow (m/|e|)(\epsilon^\mu F_{\mu\nu} q^\nu) = -E_{\mathrm{cr}}^2 \chi$ for our “field configuration”
- Schwinger pair production “assisted by a single photon”
  - R. Schützhold et al., Phys. Rev. Lett. **101**, 130404 (2008)
  - G. V. Dunne et al., Phys. Rev. D **80**, 111301 (2009)

Sauter-Schwinger effect

- Probability: $\sim \exp\left(-\pi E_{\mathrm{cr}}/E\right)$ (vacuum with electric field)

BWPP in the tunneling regime

- Probability: $\sim \exp\left[-8/(3\chi)\right]$ (if $\chi \ll 1$ and $\xi \gg 1$)

Problems of the local constant field approximation (LCFA)

- The LCFA is usally assumed to be valid if $\xi \gg 1$
- Pair production: condition is modified if $\chi \gg 1$: $\xi \gg 1$, $\xi^3/\chi \gg 1$

  V. N. Baier et al., *Electromagnetic Processes at High Energies in Oriented Single Crystals*
- However, the conditions $\xi \gg 1$ and $\alpha\chi^{2/3} \ll 1$ nearly imply $\xi^3/\chi \gg 1$
- In numerical codes the LCFA is usually applied on the probability level
- Harmonic substructure is not obtained (Harvey et al., PRA 2015)
- It should be applied on the amplitude level (SM et al., PRD 2016)
- For nonlinear Compton scattering (NLCS):

LCFA fails in the IR region of the spectrum (arXiv 1708.08276):

On the validity of the local constant field approximation in nonlinear Compton scattering

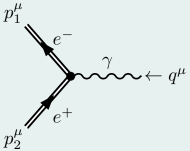
A. Di Piazza,[1,*] S. Meuren,[1,2,†] M. Tamburini,[1,‡] and C. H. Keitel[1,§]

[1] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*
[2] *Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544, USA*

- Threshold: $\omega_\gamma \lesssim (\chi/\xi^3)\,\epsilon$ (ω_γ: photon energy, ϵ: electron energy)
- **There is no divergence in the probability for $\omega_\gamma \to 0$!**
- Can affect even $\omega_\gamma \sim 10\,\mathrm{MeV}$ photons ($\epsilon = 10\,\mathrm{GeV}$, $\xi = 10$, $\omega = 1.55\,\mathrm{eV}$)

Laser photon absorption: classical vs. quantum contribution

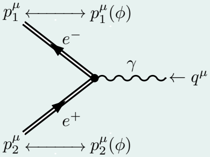
Global conservation law



Momenta are asymptotic

$$p_1^\mu + p_2^\mu = q^\mu + nk^\mu, n = n_{\mathrm{cl}} + n_{\mathrm{q}}$$

Local conservation law



Momenta are local

$$p_1^\mu(\phi) + p_2^\mu(\phi) = q^\mu + n(\phi)k^\mu$$

- Classically, you can change the momenta $[p_i^\mu \to p_i^\mu(\phi)]$, but you cannot change the on-shell condition $[p_i^2(\phi) = m^2]$
- Important consequences, in particular $n(\phi) > 0$
- Stationary phase ϕ_s: minimal possible quantum absorption $n_{\mathrm{q}} = n(\phi_s)$

Classical absorption

$$n_{\mathrm{cl}} k^\mu = p_1^\mu + p_2^\mu - [p_1^\mu(\phi_s) + p_2^\mu(\phi_s)]$$

Classical acceleration after creation

Scaling law: $n_{\mathrm{cl}} \sim \xi^3/\chi$

Quantum absorption

$$n_{\mathrm{q}} k^\mu = p_1^\mu(\phi_s) + p_2^\mu(\phi_s) - q^\mu$$

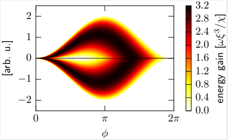
Absorption during creation

Scaling law: $n_{\mathrm{q}} \sim \xi/\chi$

SM, C. H. Keitel, and A. Di Piazza, Phys. Rev. D **93**, 085028 (2016)

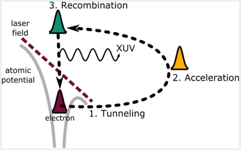
Recollisions of laser-generated electron-positron pairs

Strong-field QED



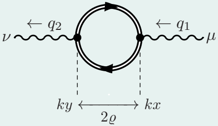
Recollision processes of electron-positron pairs

Atomic physics



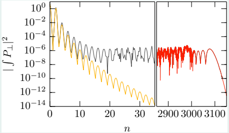
Recollision processes in atoms after tunnel ionization

Macroscopic quantum loops



Large distance between the vertices

Polarization operator spectrum



Plateau, cutoff: $n_{\text{cut}} = 3.17\,\xi^3/\chi$

Semiclassical three-step picture:

❶ Pair creation ❷ Acceleration by the laser ❸ Recollision

SM, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, PRL **114**, 143201 (2015)

Thank you for your attention and your questions!