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

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Asymmetric Light-by-Light Scattering

Strong optical laser \((I \gtrsim 10^{22} \text{ W/cm}^2, \omega \sim \text{eV})\)
Highly energetic gamma photons \((\omega_\gamma \gtrsim \text{GeV})\)

**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 \((\hbar = c = \varepsilon_0 = 1)\) 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)

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

Leading-order contribution to the EH-Lagrangian

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

$\rightarrow$ 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**

\[ \chi \sim \frac{|e|}{m^3} \sqrt{q^\mu F_{\mu\nu}^2 q^\nu} \sim 2 \frac{\omega_\gamma}{m} \frac{E}{E_{cr}}, \]

\[ \chi \approx 0.5741 \left( \frac{\omega_\gamma}{\text{GeV}} \right) \sqrt{I/(10^{22} \text{ W/cm}^2)} \]

Constructed using the four-momentum \( q^\mu \)

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

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

Only two if gradients are negligible

Quantum nonlinearity parameter

\[ \chi \sim |e| m^3 \sqrt{q_{\mu} F_{\mu \nu} q_{\nu}} \sim 2 \omega \gamma m E / E_{cr}, \]

\[ \chi \approx 0.5741 \left( \frac{\omega \gamma}{\text{GeV}} \right) \sqrt{I/\left(10^{22} \text{W/cm}^2\right)} \]

Experimental perspectives

Highly-energetic gammas via Compton backscattering

- Electron energy: 1 – 10 GeV
- BIG photon source: 5 GeV

Intense optical laser facilities

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

\[ \chi_\gamma \approx 0.9 \omega_\gamma [5 \text{ GeV}] \sqrt{I[10^{21} \text{ W/cm}^2]} \]
The exact photon wave function obeys a Dyson equation
\[-\partial^2 \Phi_{q}^{\text{in} \mu}(x) = \int d^4 y \, P^{\mu \nu}(x, y) \Phi_{q}^{\text{in} \nu}(y),\]
which is normally expanded into a nested double series

Number of insertions (propagation length in the field)
\[\ldots = \ldots + \ldots + \ldots + \ldots + \ldots\]

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

Polarization operator expansion (radiative corrections)
\[\ldots = \ldots + \ldots + \ldots + \ldots + \ldots\]

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

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

Sergey Bragin, Sebastian Meuren, Christof H. Keitel, and Antonino Di Piazza

Poster by Sergey Bragin (arXiv 1704.05234):

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

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(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**

\[ p_1^\mu \quad k_1^\mu \quad e^- \quad \gamma \leftarrow q^\mu \quad p_2^\mu \quad k_2^\mu \quad e^+ \]

\[ \xi \ll 1: \text{process "feels" oscillations} \]

**Tunneling regime**

\[ p_1^\mu \quad e^- \quad \gamma \leftarrow q^\mu \quad p_2^\mu \quad e^+ \]

\[ \xi \gg 1: \text{process "feels" a static field} \]

Which is the time/length scale for pair production?

- Constant electric field \( E \): the pair becomes real after the length \( \delta x \):
  \[ \delta x \left| e \right| E \sim mc^2 \quad \rightarrow \quad \delta x \sim \frac{mc^2}{\left| e \right| E}, \quad \delta \phi \sim \frac{\delta x \omega}{c} \sim \frac{\omega mc}{\left| e \right| E} = \frac{1}{\xi} \]
  
  \((\delta \phi \text{ is the formation region with respect to the laser phase } \phi = kx)\)

- The classical intensity parameter: \[ \xi = a_0 = \left| e \right| E/(mc \omega) \]

**Sauter-Schwinger effect**

- Probability: \( \sim \exp \left( -\pi E_{cr}/E \right) \)
  
  (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 pair production (BWPP)

Breit-Wheeler is nonperturbative in the tunneling regime

Hand-waving derivation:

- Total field tensor $\tilde{F}_{\mu\nu} = F_{\mu\nu} + f_{\mu\nu}$
  - $F_{\mu\nu}$: constant crossed background field
  - $f_{\mu\nu} = (m/|e|)(\epsilon_{\mu} q^{\nu} - \epsilon_{\nu} q^{\mu})$: photon field tensor
  - $q^{\mu}$: photon four-momentum
  - $\epsilon^{\mu} = (Fq)^{\mu}/\sqrt{qF^{2}q}$, ($\epsilon^{2} = -1$, $q_{\epsilon} = 0$): polarization four-vector

- Vacuum field invariant: $\mathcal{F} = \frac{1}{4} \tilde{F}_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{1}{2} (B^{2} - E^{2})$
  - $E \longrightarrow \sqrt{-2\mathcal{F}}$ in Schwinger formula
  - $\mathcal{F} \longrightarrow (m/|e|)(\epsilon^{\mu} F_{\mu\nu} q^{\nu}) = -E_{cr}^{2} \chi$ for our “field configuration”

- Schwinger pair production “assisted by a single photon”

Sauter-Schwinger effect

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

BWPP in the tunneling regime

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

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

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

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Laser photon absorption: classical vs. quantum contribution

Global conservation law

Momenta are asymptotic
\[ p_1^\mu + p_2^\mu = q^\mu + nk^\mu, \quad n = n_{cl} + n_q \]

Classically, you can change the momenta \([p_i^\mu \rightarrow p_i^\mu(\phi)]\),
but you cannot change the on-shell condition \([p_i^2(\phi) = m^2]\)

Important consequences, in particular \(n(\phi) > 0\)

Stationary phase \(\phi_s\): minimal possible quantum absorption \(n_q = n(\phi_s)\)

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

Classical acceleration after creation
Scaling law: \(n_{cl} \sim \xi^3 / \chi\)

Quantum absorption
\[ n_qk^\mu = p_1^\mu(\phi_s) + p_2^\mu(\phi_s) - q^\mu \]

Absorption during creation
Scaling law: \(n_q \sim \xi / \chi\)

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:

1. Pair creation  2. Acceleration by the laser  3. Recollision

Thank you for your attention and your questions!