Photon-Photon Scattering
and related things

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Overview

• Background.

• The quantum vacuum.

• Pair production vs. elastic photon-photon scattering.

• Why do the experiment?

• Other avenues.

• New physics?

• Conclusions.
New Physics?

- The coherent generation of massive amounts of collimated photons opens up a wide range of possibilities.

- Laboratory astrophysics, strongly coupled plasmas, photo-nuclear physics...

- Here we will focus on physics connected to the nontrivial quantum vacuum.
Background: opportunities with high-power lasers

Laser/XFEL development

Evolution of peak brilliance, in units of photons/(s mrad$^2$ mm$^2$ 0.1 x bandwidth), of X-ray sources. Here, ESRF stands for the European Synchrotron Radiation Facility in Grenoble.
Interdisciplinarity
Probing new regimes

Modifications standard model, e.g. axions

A touch of gravity?

Astrophysics

Thermodynamics

Quantum fields

Spacetime structure

Polarization rotation

Magnetic field
The nonlinear quantum vacuum

- Special relativity + Heisenberg’s uncertainty relation = virtual pair fluctuations.
- Antimatter from Dirac’s relativistic quantum mechanics.
- Properly described by QED.
- Photons can effectively interact via fluctuating electron-positron pairs.

The Heisenberg-Euler Lagrangian

- Describes the vacuum fluctuations as an effective field theory, fermionic degrees of freedom integrated out.

\[ L = -\frac{\alpha}{2\pi} \epsilon_0 E_{\text{crit}}^2 \int_0^{i\infty} \frac{dz}{z^3} e^{-z} \times \left[ z^2 \frac{ab}{E_{\text{crit}}} \coth \left( \frac{a}{E_{\text{crit}}} z \right) \cot \left( \frac{b}{E_{\text{crit}}} z \right) - \frac{z^2 (a^2 - b^2)}{3 E_{\text{crit}}^2} - 1 \right] \]

\[ a = \left[ (F^2 + G^2)^{1/2} + F \right]^{1/2}, \quad b = \left[ (F^2 + G^2)^{1/2} - F \right]^{1/2} \]

\[ F \equiv \frac{1}{2}(c^2 B^2 - E^2), \quad G \equiv -cE \cdot B \]

- Has real and imaginary part. The imaginary part signals depletion, i.e. pair production, the real part defines elastic photon scattering events.

- Dispersion relation for a photon in external field:

\[ \omega \approx c|\mathbf{k}| \left( 1 - \frac{1}{2} \lambda |Q|^2 \right) \quad |Q|^2 \equiv \epsilon_0 |\mathbf{k} \times \mathbf{E} + c\mathbf{k} \times (\mathbf{k} \times \mathbf{B})|^2 \]
Photon-photon scattering

• “Clean” experiment on the nonlinear quantum vacuum: four-wave mixing in vacuum, 3D setup (D. Bernard et al., EPJD 10, 141 (2000); E. Lundström et al., PRL 96, 083602 (2006)).

• Laser parameters: two 800 nm 15 J pulses of 0.5 PW each, 0.07 photons/shot.

• Deviations: sign of new physics? (Breaking of Lorentz invariance, axions, low energy quantum gravity effects and extra dimensions (e.g. Davoudiasl, PRD 60, 084002 (1999)))
The nonlinear quantum vacuum

- Photon-photon scattering for low-energy photons: $\hbar \omega \ll 2mc^2$

- Could be detectable (Lundström et al., PRL 96 (2006)).

- Virtual slit experiments (King et al., Nature Phot. 4 (2010))
Pair production

- High energy photon may create pairs: $\hbar \omega \geq 2m_e c^2$

- Multiphoton processes:
  - Low-energy photon scatter off electrons, producing high energy gamma.
  - Low-energy photons cause pair production through Sauter-Schwinger mechanism.

- Sauter’s resolution to the Klein paradox: static electric field may cause the vacuum to go unstable (Sauter 1931).

- Electrostatic fields under the critical field strength $E_{\text{crit}} \sim 10^{16} \text{ V/cm}$ is exponentially suppressed (Schwinger 1951).

- Relativistic flying/oscillating mirror (Lichters et al., PoP (1996); Bulanov et al., PRL (2003)), relativistic electronic spring (Gonoskov et al., 2010).
Pair production

Some recent simulations on attosecond pulse generation and amplification (Gonoskov et al., submitted (2010))
Pair production: the fight against exponential suppression

• Using pre-factor [laser four-column/Compton four-volume ≈ 10^{24}] to increase pair production rate (Narozhny et al., 2004).

• Superimposed oscillatory fields (substructure) gives assisted pair production (Dunne, Gies, Schützhold, 2008, 2009).

• $E \gg B$ for counterpropagating/standing waves (Gregori et al., Astra Gemini/RAL experiment, 2010).

• XFEL-laser interaction for stimulated pair production (Ilderton, Hebenstreit, Marklund (2011)) using quantum kinetics (Wigner form of Dirac theory).

• Complex beam configurations (Bulanov et al.

• Cascading (Ruhl et al., 2010)
Pair production: importance

- Nonperturbative quantum field theory: truly relativistic quantum field theory.

- Techniques developed for QED pair production useful for QFT in general: MD simulations (e.g. Ruhl), quantum kinetic developments (e.g. Alkhofer, Hebenstreit), world-line and light-cone techniques (Gies, Dunne, Heinzl, Ilderton).

- Similarities to strong field ionization problems (Reiss, PRL 2008; Blaga et al., Nature Phys. 2009).

- Nonlinear scattering events (Heinzl et al., PRA 2010).

- Source of ep-plasma?
The trident process vs. cascading

- Trident: intermediate photon virtual (Ritus (1972); Ilderton, PRL (2010))
- Cascade: intermediate photon real bremsstrahlung photon (Klepikov (1964); Nikishov & Ritus (1964))
- Current work on laser-electron interactions for radiation reaction studies (Harvey, Ilderton, Marklund (2011)): when does the classical theory break down?
Pair production: radiation reaction/pair cascading

- Recent interest in cascading and pair production (e.g., Bell & Kirk, PRL (2008); Sokolov et al., PRL (2010); Elkina et al, 1010.4528; Duclus et al., 1010.4584).

- Previously looked at in astrophysical settings (magnetosphere problems).

- Seemingly conflicting results in the literature.

- Different intensity values for significant cascading to take place.

- Important issue: put constraints on achievable intensities.

- Q1: when is a classical treatment possible? (the transition problem)

- Q2: when in a relativistic quantum regime, how to treat transitions? (the dressing-up problem)

- Q3: when is the division of the pairs into separate $e^+$ and $e^-$ valid? (the asymptotic problem)
Pair production: theoretical developments.

Pair production one aspect of a more complex computational problem: how to do nonperturbative many-body quantum physics?

Difficult and necessary computational developments.

Classical theory of radiation reaction (Harvey et al., arXiv:1012.3082)
Exotic physics?

- Probing of spacetime structure?

- Noncommutativity (NC) between spacetime coords inferred from quantum gravity/string schemes; IR/UV mixing (Amelino-Camelia et al. 2005).

- Analogue: in the plane orthogonal to a very strong magnetic field we have coord NC.

- Suggested to be probed using vacuum birefringence experiments (Abel et al. JHEP 2006).
Exotic physics?

• Noncommuting coordinates  \([x^\mu, x^\nu] = i\Theta^{\mu\nu}\)

• Laser intensity effects to counter the energy scale (Heinzl et al., PRD 2010).

• Pair production:
  - depends periodically on collision angle,
  - larger cross section,
  - threshold (number of photons, for ELI parameters) lowered from QED value.

\[ n_{0,\theta} \approx n_0 - \frac{2 \times 10^8 m^6}{k \cdot k'} |\Theta|^2 \]

• Laser can thus put lower limits on the involved phenomenological parameters.
Exotic physics? Possible routes for detection.

- Birefringence.
- Anisotropic speed of light.
- Anisotropy in quantum fields.
- Violations of universality of free fall and the universality of the gravitational redshift.
- Time and space variations of “constants”.
- Charge non-conservations.
- Anomalous dispersion.
- Decoherence and spacetime fluctuations.
- Modified interference.
- Non-localities.
Conclusions

• Ample opportunities for probing new physics with high-power laser.

• Requires a strong collaboration between theory, simulations, and experiments.

• In particular, still many parts of QED that are not computationally viable, or that need independent verifications.

• The classical-quantum transition of radiation reaction.

• Massive pair production or not in the laboratory?

• Deviations from QED or standard model?