Probing New Physics
Using High Intensity Laser Systems

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Overview

- Background
- The quantum vacuum
- Pair production
- The Unruh and Hawking effects
- Exotic 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

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Probing new regimes

Astrophysics

Thermodynamics

Quantum fields

Spacetime structure

A touch of gravity?

Modifications standard model, e.g. axions

Magnetic field

Photon

Polarization rotation
The nonlinear quantum vacuum

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

The nonlinear quantum vacuum: photon-photon scattering

\[ \sigma \approx 0.7 \times 10^{-29} \left( \frac{\hbar \omega}{1 \text{ MeV}} \right)^6 \text{ cm}^2 \]

\[ \mathcal{L} = \mathcal{L}_0 + \frac{\varepsilon_0 \alpha}{90\pi E_S^2} \left[ (E^2 - c^2 B^2)^2 + 7c^2 (\mathbf{E} \cdot \mathbf{B})^2 \right] \]

\[ E_S = m_e^2 c^3 / e\hbar \sim 10^{16} \text{ V/cm} \sim 10^{29} \text{ W/cm}^2 \]
The nonlinear quantum vacuum: photon-photon scattering

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

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

- Virtual slit experiments (King et al., Nature Phot. 4 (2010))
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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., 2011).
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Burke et al., PRL 79, 1626 (1997)

Nonlinear Compton scattering

\[ e + n\omega \rightarrow e' + \gamma \]

Multi-photon Breit-Wheeler scattering

\[ \gamma + n\omega \rightarrow e^+ + e^- \]
Pair production: radiation reaction

- Recent interest in cascading and pair production.
- 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: the fight against exponential suppression

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

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

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

- XFEL-optical combos (Hebenstreit, Ilderton, Marklund, in preparation 2011).

- Complex beam configurations (Bulanov et al., 2010).

- 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?
Pair production: theoretical developments.

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

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Difficult and necessary computational developments.
The Unruh effect

- A tough of gravitational physics using lasers?

Experiments (Chen & Tajima 1999; Schützhold et al. 2006; Brodin et al. 2008).

\[
T_H = \frac{\hbar g}{2\pi c k_B}
\]

\[
T_U = \frac{\hbar a}{2\pi c k_B}
\]
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).
- Noncommuting coordinates implies position uncertainty which eliminates short-distance singularities.
- Analogue: in the plane orthogonal to a very strong magnetic field we have coordinate NC (lowest Landau level) [Jackiw, Ann. Henri Poincare (2003)].
- 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.

- Laser can thus put lower limits on the involved phenomenological parameters.

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