QED Experiments in Intense Fields

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Overview

A. Introduction

B. Intense field generation

C. Laser development

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- ii. Development and CPA
- iii. Current and future systems

D. Secondary sources

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- ii. Practical and theoretical issues

E. QED and the quantum vacuum

- i. Simple pictures
- ii. Nonlinear effective field theory
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- iii. QED effects in intense fields
  - Scattering events
  - Nonlinear collective effects
  - Threshold phenomena

Overview

F. Experimental tests

- i. Low intensity, low energy
- ii. Low intensity, high energy
- iii. High intensity, low energy
- iv. High intensity, high energy
- v. The Unruh effect
- vi. Transitions between classical and quantum
- vii. Modifications of QED

G. Summary

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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Laser development

- Lasers has undergone tremendous development.
- 1917: Einstein publishes "On the quantum mechanics of radiation".
- 1958: Schawlow+Townes, light and infrared masers.
- 1959: Gould applies for "optical maser", i.e. laser, patent.
- 1960: First laser is built (Maiman and others).
- 1985: Chirped pulse amplification (Mourou and Strickland), made laser intensities above GW/cm^2 possible.
- 1985 – : High-field science, from atomic physics to plasmas.
- 2005: First table-top petawatt laser.

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Laser development

- A tool for basic and applied science, as well as the basis for an enormous amount of applications.
- Spectral properties the key.

LED spectral properties

HeNe laser spectral properties

Laserlab Europe

- A network of laser laboratories in Europe.
- Lasers laboratories at 26 places in 19 countries. Examples of high intensity laser facilities:

Laboratory	Specifications
Central Laser Facility (UK)	Vulcan (10 PW) and Astra-Gemini (0.5 PW, multiple beams, high repetition rate)
GSI (Germany)	Combination of Phelix laser with heavy-ion accelerator
Instituto Superior Técnico (Portugal)	Multi-terawatt laser (e.g. electron acceleration) in combination with team for large scale simulations
Lund Laser Centre (Sweden)	Multi-terawatt system (proton acceleration), 10 Hz repetition rate (largest unit in Scandinavia)
LULI (France)	Two multibeam high-energy high-intensity facilities with instrumentation for ICF and lab astrophysics

High-intensity laser facilities

- "Current" state-of-the-art laser systems

Parameters	Vulcan (RAL)	XFEL (DESY)
Intensity (W/cm ²)	$10^{21} - 10^{22}$	$10^{14} - 10^{15}$
Power (PW)	10	10^{-4}
Pulse duration (fs)	1 – 500	0.04
Spot size (μm)	1 – 3	$> 10^{-3}$ (diffraction limit)
Wavelength (nm)	800	< 2
# of photons/shot	$10^{19} - 10^{20}$	10^{18}
Photon energy (keV)	10^{-3}	3

Mégajoule and NIF

- Inertial confinement fusion facilities (Bordeaux and LLNL).

Parameters	Mégajoule	NIF
Power (PW)	10	0.5
Pulse duration (ps)	200-25000	few
Wavelength (nm)	350 (UV)	350 (UV)
# of beamlines	240	48
Pulse energy (MJ)	1.8	4 (?)

High-intensity laser facilities

- Next-generation

Parameters		
Intensity (W/cm ²)	$10^{23} - 10^{24}$ (multiple beams)	$10^{24} - 10^{25}$ > 10^{25} (sec. sources)
Power (PW)	100	1000
Pulse duration (fs)	1 – 5	1 10^{-6} (sec. sources)
Spot size (μm)	1 – 3	1 – 3
Wavelength (nm)	≈ 800	≈ 800
# of photons/shot	$10^{19} - 10^{20}$	≈ 10^{22}
Photon energy (keV)	10^{-3}	10^{-3}

ELI parameters

Lasers planned for the Extreme Light Infrastructure*					
Country	Facility focus	Power (PW)	Pulse energy (J)	Pulse width (fs)	Rep rate (Hz)
Romania	Nuclear physics	10 (×2)	200	20	0.1
Hungary	Attosecond physics	1	5	5	1000
		20	400	20	0.1
Czech Republic	Secondary beam radiation, high-energy particles	1	10	10	10
		5	50	10	10
		10 (×2)	200	20	0.1
To be determined	High intensity	10 beams of 10–20 PW each, phased and combined to create total power of 100–200 PW			
*Laser parameters still subject to change.					

From Feder (2010)

Magnetic field generation

- Laboratory fields from a few tesla to 1000 tesla, depending on time scale (see talk by Rikken). Relatively large scale.
- Relativistic laser-plasma interactions can create fields of the order gigagauss, on micrometer scales, stationary on pikosecond scales. Relative laser pulse of femtosecond, this is a long time.
- Heavy ion collisions, RHIC, produce chiral fields, 100 000 000 000 000 000 gauss. However, on QCD scales, both in time and space.
- Strong fields for lab astrophysics, search for WIMPs (see talk by Jaeckel), and wakefield acceleration.

See talk by Rikken

Science on high-intensity lasers

High intensity
lasers usage

inertial confinement fusion

Inertial confinement fusion

- Magnetic confinement fusion in toka/spheromaks or stellarators. Inherent problem with instabilities; improved running with scaling.
- Lawson criteria: fusion heating exceeding losses

The diagram shows the Lawson criterion equation: $n_e T \tau_E \geq \frac{12k_B T^2}{E_{ch} \langle \sigma v \rangle}$. Arrows point from descriptive labels to the variables in the equation: 'density' points to n_e , 'temp' points to T , 'confinement time' points to τ_E , and 'energy of charged fusion products' points to E_{ch} .

$$\begin{array}{c} \text{density} \rightarrow n_e \\ \text{temp} \rightarrow T \\ \text{confinement time} \rightarrow \tau_E \end{array} n_e T \tau_E \geq \frac{12k_B T^2}{E_{ch} \langle \sigma v \rangle}$$

energy of charged fusion products $\rightarrow E_{ch}$

- For inertial confinement fusion, this translates into a relation between mass density and radius. $10^3 - 10^4$ times solid D-T density.

Inertial confinement fusion

- Mechanisms of ICF

- Different drives.

Laboratory astrophysics

Laboratory astrophysics

- Planetary interiors and extreme equations of state.
- Astrophysical turbulence.
- Hypersonic or relativistic jets.
- Shock wave formation and dynamics.
- Acceleration studies in plasma environments.

Particle acceleration

- Do we need laser based accelerators?
- Compact alternative to standard accelerator schemes?
- Hadron therapy units with high patient flow.
- Cheaper (< 100 M€) per unit.

Particle acceleration

- Dose in water: hadrons have inverse dose profile. Using intensity modulated particle therapy, accuracy of 2-3 mm concerning tumour shape.
- Large scale facilities (e.g. Heidelberg synchrotron) becomes tabletop?

Hadron acceleration

- Procedure: let high intensity laser hit thin metal foil with "dirt".
- Problem: need monochromatic highly collimated beam.
- Brute force: spread of energies as well as spatial distributions.
- Need new geometries. Can use strong surface fields set up by laser impinging on foil.
- Relativistic self-induced transparency.

Strong field generation

- Many high phenomena directly tractable with next generation laser systems.
- Some phenomena require intensities above current experimental limits.
- Attosecond electron bunches creates mirror (Naumova et al., PRL, 2004; Nees et al., J. Mod. Opt., 2005; Thaury et al., Nature Phys., 2007).

Strong field generation

Some recent simulations on attosecond pulse generation and amplification (Gonoskov et al. 2011)

Strong field generation

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Probing new regimes

Astrophysics

Modifications standard model, e.g. axions
("shining light through walls",
Jaeckel, Amiranoff et al.)

A touch of gravity?

Multi-photon processes in intense fields

- Nonlinear Compton scattering

- Stimulated pair production

- Birefringence

- Radiation reaction (Di Piazza et al. 2011)

$$\left| \begin{array}{c} k_{1,-} \\ p_{0,-} \text{---} \text{---} p_{1,-} \end{array} \right|^2 + \left| \begin{array}{c} k_{1,-} \\ p_{0,-} \text{---} \text{---} p_{1,-} \end{array} \right|^2 \otimes \left| \begin{array}{c} k_{2,-} \\ p_{1,-} \text{---} \text{---} p_{2,-} \end{array} \right|^2 + \dots$$

- Cascading

- Trident

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); Elkina et al. (2011))

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.

Marklund & Shukla, Rev. Mod. Phys. **78** (2006); Marklund, Nature Phot. 4 (2010)

The Heisenberg-Euler Lagrangian

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

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

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

$$F \equiv \frac{1}{2}(c^2 \mathbf{B}^2 - \mathbf{E}^2), \quad G \equiv -c \mathbf{E} \cdot \mathbf{B}$$

- Has real and imaginary part. The imaginary part signals depletion, i.e. pair production, the real part defines elastic photon scattering events.
- Can compute equations of motion for test photons in both sub- and super-critical fields.

See talks by Gies, van Tiggelen, Heyl

Effective Maxwell's equations

$$\partial_a F^{ab} = 2\epsilon_0 \kappa \partial_a \left[(F_{cd} F^{cd}) F^{ab} + \frac{7}{4} (F_{cd} \hat{F}^{cd}) \hat{F}^{ab} \right]$$

$$\frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = -\mu_0 \left[\frac{\partial^2 \mathbf{P}}{\partial t^2} + c^2 \nabla (\nabla \cdot \mathbf{P}) + \frac{\partial}{\partial t} (\nabla \times \mathbf{M}) \right]$$

$$\frac{1}{c^2} \frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = \mu_0 \left[\nabla \times (\nabla \times \mathbf{M}) + \frac{\partial}{\partial t} (\nabla \times \mathbf{P}) \right]$$

$$\mathbf{P} = 2\kappa\epsilon_0^2 \left[2(E^2 - c^2 B^2) \mathbf{E} + 7c^2 (\mathbf{E} \cdot \mathbf{B}) \mathbf{B} \right]$$

$$\mathbf{M} = 2\kappa\epsilon_0^2 c^2 \left[-2(E^2 - c^2 B^2) \mathbf{B} + 7(\mathbf{E} \cdot \mathbf{B}) \mathbf{E} \right]$$

Bialynicka-Birula & Bialynicki-Birula (1970)

Dispersive corrections to HE-lagrangian

$$\mathcal{L}_D = \sigma \epsilon_0 \left[(\partial_a F^{ab})(\partial_c F^c_b) - F_{ab} \square F^{ab} \right]$$

$$\frac{1}{2} (1 + 2\sigma \square) \partial_a F^{ab} = \epsilon_0 \kappa \partial_a \left[(F_{cd} F^{cd}) F^{ab} + \frac{7}{4} (F_{cd} \hat{F}^{cd}) \hat{F}^{ab} \right]$$

Here $\sigma = (2/15) \alpha c^2 / \omega_e^2 \approx 1.4 \times 10^{-28} \text{ m}^2$

Dispersion relations in external fields

- Result due to HE interactions; nonlinear function of field strengths

$$\omega \approx c|\mathbf{k}|(1 - \frac{1}{2}\lambda|\mathbf{Q}|^2) \quad |\mathbf{Q}|^2 \equiv \epsilon_0|\hat{\mathbf{k}} \times \mathbf{E} + c\hat{\mathbf{k}} \times (\hat{\mathbf{k}} \times \mathbf{B})|^2$$
$$\lambda \sim \frac{\alpha}{90\pi} \frac{1}{E_{\text{crit}}}$$

- Result due to HE interactions + lowest order corrections due to finite frequency (still perturbative); nonlinear function of wavenumber

$$\omega \approx c|\mathbf{k}| \left[1 - \frac{1}{2}\lambda|\mathbf{Q}|^2 (1 + 2\sigma\lambda|\mathbf{Q}|^2|\mathbf{k}|^2) \right]$$

- Dispersion relation: Hamiltonian for photons. $\dot{x} = \frac{\partial\omega}{\partial k}$ $\dot{k} = -\frac{\partial\omega}{\partial x}$
- Side note: phase and group velocities may change in external fields, Cherenkov radiation due to the quantum vacuum (MM et al. 2005).

The nonlinear quantum vacuum: photon-photon scattering

$$\sigma_{\gamma\gamma} \approx 0.7 \times 10^{-29} \left(\frac{\hbar\omega}{1 \text{ MeV}} \right)^6 \text{ cm}^2$$

$$\mathcal{L} = \mathcal{L}_0 + \frac{\epsilon_0 \alpha}{90\pi E_{\text{crit}}^2} \left[(E^2 - c^2 B^2)^2 + 7c^2 (\mathbf{E} \cdot \mathbf{B})^2 \right]$$

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$$E_{\text{crit}} \approx 10^{16} \text{ V/cm} \rightarrow 10^{29} \text{ W/cm}^2$$

$$eE_{\text{crit}} \times \frac{\hbar}{m_e c} = m_e c^2$$

Work times distance = rest mass

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Work times distance = rest mass

Peak in cross-section at electron mass. Cross-section “only” five orders of magnitude below Thomson. Optical regime $\rightarrow$ 40 orders of magnitude smaller than Thomson!

Vacuum birefringence

- Anisotropic vacuum, due to e.g. magnetic field (Adler 1970, 1971, Heyl & Hernquist 1997, Dittrich & Gies 1998, Rikken & Rizzo 2000, 2003); permittivity and permeability

$$\epsilon_{ij} = \delta_{ij} + \frac{4\alpha}{90\pi} \frac{B^2}{E_{\text{crit}}^2} \left(-\delta_{ij} + \frac{7}{2} b_i b_j \right)$$
$$\mu_{ij} = \delta_{ij} + \frac{4\alpha}{90\pi} \frac{B^2}{E_{\text{crit}}^2} (\delta_{ij} + 2b_i b_j)$$

- Refractive index different for different propagation angles, relative external field

$$n - 1 \sim \frac{\alpha}{90\pi} \frac{B^2}{E_{\text{crit}}^2} \sin^2 \theta$$

Vacuum birefringence

- Difference Δn in parallel and perpendicular refractive index will yield cumulative ellipticity over propagation distance L (Bakalov et al. 1998)

$$\Psi = \frac{\pi L}{\lambda} \Delta n \sin(2\theta)$$

- Quite difficult to measure; strong magnetic fields may interfere with measurements, shielding difficult.
- Can also consider using coupled Fabry-Perot cavities, where one provides the external field, while the other supplies the probe photon (Luiten & Petersen 2004)

Cavity experiments

- High-field cavities (around 50MV), far from Schwinger limit.
- Can support only certain modes, filtering. Need super cooling (1 K).
- Generation of harmonics through vacuum fluctuations. beats thermal effects.

Brodin, MM, Stenflo (2001)

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The nonlinear quantum vacuum: photon-photon scattering

- Photon-photon scattering for low-energy photons $\hbar\omega \ll 2m_e c^2$
- Why? Just to confirm QED?
- Testing the nonlinear coefficients in the Heisenberg-Euler lagrangian.
- Compare, e.g., Born-Infeld type lagrangian (Lorentz invariant, Born & Infeld 1934; no birefringence in static fields (unique property))

$$\mathcal{L}_{\text{BI}} = \kappa^2 \left[1 - \sqrt{1 + \frac{1}{2\kappa^2} (E^2 - B^2) - \frac{1}{16\kappa^2} (\mathbf{E} \cdot \mathbf{B})^2} \right]$$

- (Finite field energies around point charges)

The nonlinear quantum vacuum: photon-photon scattering

- Use high-power laser system (10^{19} - 10^{20} photons) to overcome miniscule scattering cross section.
- Could be detectable (Bernard et al. (1998); Lundström et al., PRL **96** (2006)).

$$\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 + \mathbf{k}_4$$

$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$

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Generated photons

The nonlinear quantum vacuum: photon-photon scattering

- Number of generated photons as a function of beam power.

$$N \approx G \times 10^{-2} \left(\frac{1 \mu\text{m}}{\lambda_4} \right)^3 \left(\frac{L}{1 \mu\text{m}} \right) \left(\frac{P_1 P_2 P_3}{1 \text{ PW}^3} \right)$$

Form factor depending
on pulse shape etc.
Of order unity

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The nonlinear quantum vacuum: photon-photon scattering

- Alternative setup.
- Larger geometric factor.
- Smaller interaction volume.
- Higher harmonics in directions of generated photons!

The nonlinear quantum vacuum: photon-photon scattering

- Noise sources:
  - Compton scattering of electrons.
  - Collective plasma effects: harmonics (imperfect vacuum).
  - Photon scattering in chamber.
  - Thermal noise.

The nonlinear quantum vacuum: photon-photon scattering

- Virtual slit experiments (King et al., Nature Phot. **4** (2010))
- Interference pattern, like in double slit experiment.

Photon splitting

Photons down-converted in strong vacuum magnetic field (“photon splitting”) (Adler 1971). (See talks by Gies and Heyl)

Photon splitting in plasmas

Photon splitting in plasmas

(Brodin, MM et al. 2007)

Generation of vacuum harmonics

- Harmonics "possible" due to non-planar structure of laser pulses or other external broken symmetries (Ding & Kaplan 1990, Di Piazza et al. 2005, Fedotov & Narozhny 2007)
- Nonlinear and nonperturbative surprises (as in laser-plasma case)?

Colliding pulses

- Two colliding pulse, criteria for collapse (nonlinear refractive index)

$$\left(\frac{\alpha}{90\pi}\right)^{1/2} \frac{E}{E_{\text{crit}}} > \frac{r_p}{\ell_p}$$

- Long pulse, i.e., large energy.
- Diffraction limit: $r_p \sim \lambda_p$
- For intensities two orders of magnitude below Schwinger intensity:

$$\ell_p \sim 10^4 \lambda_p$$

Interaction between coherent and incoherent photons: radiation gas

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- Evolution determined by nonlinearly coupled system, much like a laser-plasma (MM 2003)

$$i\partial_t E + \beta \nabla^2 E + \kappa \varepsilon E = 0$$

$$\left(\partial_t^2 - \frac{1}{3} \nabla^2 \right) \varepsilon = \mu \nabla^2 |E|^2$$

- Nonlinear Schrödinger equation: know that such systems yields solitons, pulse collapse and filamentations.

Interaction between coherent and incoherent photons: radiation gas

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Far away from being detectable!

Interaction between coherent and incoherent photons: radiation gas

Far away from being detectable!

The Scharnhorst effect

- The results of Casimir.
- Fewer vacuum states between the plates than outside.
- Net force between plates.
- A low-frequency photon travelling in a Casimir vacuum will experience a refractive index < 1 .
- Phase velocity > 1 .
- Group velocity < 1 .

G. Barton, K. Scharnhorst, [*Journal of Physics A* **26**](#), 2037 (1993). (See talks by Gies and van Tiggelen)

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).

Pair production

- “Schwinger mechanism” for fields with spatial and temporal variation (see Hebenstreit’s talk).
- Temporal compression: increased production rate.
- Spatial compression: lower production rate.
- Laser fields $\longrightarrow$ production rate unknown.
- Schwinger limit: more than necessary (Narozhny et al.).
- Need for theory (e.g. world-line instantons, e.g. Gies, Dunne).

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Pair production: stimulated process

- The SLAC experiment (see also Bula et al., 1996 and Bamber et al., Phys. Rev. D (1999)). Also all-optical.

Eisner, Phot. Spectra (1997)

Pair production: stimulated process

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Nonlinear Compton scattering

$$e + n\omega \rightarrow e' + \gamma$$

Multi-photon Breit-Wheeler scattering

$$\gamma + n\omega \rightarrow e^+ + e^-$$

Pair production: stimulated process

- The SLAC experiment (see also Bula et al., 1996 and Bamber et al., Phys. Rev. D (1999)). Also all-optical.
- Experiment reproduced in all-optical setup.
- Spectral properties not detailed enough do actually discern between processes!
- Need stronger fields, better configurations, for better statistics.

Trident vs. cascading

- Since the process of producing pairs by different stimulated processes in external fields can put possible upper limits of attainable intensities, it is *central* to understand what the rates for these processes are.
- As we saw, the cascading process is sequential, and contains only *real* particles: nonlinear Compton scattering + stimulated pair production.
- The trident process, however, contains a virtual intermediate photon, that by its very definition does not have to live on the shell, i.e., freedom.

While the cascading photon *has* to produce the pair inside the pulse, the virtual trident photon must produce a pair, in the pulse or not. What does this imply for the asymptotic state? Can you tell the difference via e.g. a SLAC type of experiment? (Ilderton 2010)

Finite size effects in pair production

- Pulse shape dependence in stimulated production (Heinzl et al. 2010).
- The differential cross section plotted as a function of transverse positron momentum for a pulsed plane wave with 4 fs, 8 fs, and 16 fs laser pulses (top to bottom) (Krausz and Ivanov 2009; Mackenroth et al. 2010).
- Longer pulses gives rise to delta-like comb.
- Finite width gives rate structure and sub-threshold peak.

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*)

Radiation reaction/friction

- Classical radiation reaction described using Lorentz-Abraham-Dirac (LAD) theory

$$m\dot{u}^\mu = eF^{\mu\nu}u_\nu - \frac{2}{3} \frac{e^2}{4\pi} (u^\mu \ddot{u}^\mu - u^\nu \ddot{u}^\nu)$$

- or the perturbative expansion (lacking runaways etc.) due to Landau & Lifshitz (LL)

$$\dot{u}^\mu = \frac{e}{m} F^{\mu\nu} u_\nu + \frac{2}{3} \frac{e^2}{4\pi} \left\{ \frac{e}{m^2} \dot{F}^{\mu\nu} u_\nu + \frac{e^2}{m^3} F^{\mu\alpha} F_\alpha{}^\nu u_\nu - \frac{e^2}{m^3} u_\alpha F^{\alpha\nu} F_\nu{}^\beta u_\beta u^\mu \right\}$$

- Works in classical regime (i.e. current facilities) when $(a_0 = eE/\omega mc)$

$$\chi \equiv \frac{e\hbar\sqrt{(F^{\mu\nu}u_\nu)^2}}{m^2c^4} \ll 1, \quad \implies \quad \hbar a_0 \gamma \omega \ll mc$$

- QED regime (i.e. next generation regime) when

$$\chi \sim 1$$

or when the momentum kick is of the order of the mass of the electron...

Radiation reaction/friction

- **Why important?**
- RR causes emission of high-energy photons.
- The friction gives regimes of *electron capture*: extended interaction time with the laser (Harvey & MM, 2011). *Note: happens when QED mass-shift important!*
- These two in conjunction can yield a significant amount of gammas, and thus pair production via Breit-Wheeler: limits to intensity?
- The transition between classical (LAD/LL) and QED is not well-defined and will significantly affect predictions (Di Piazza et al. 2011, Elkina et al. 2011)

$$\left| \begin{array}{c} k_{1,-} \\ p_{0,-} \\ p_{1,-} \end{array} \right|^2 + \left| \begin{array}{c} k_{1,-} \\ p_{0,-} \\ p_{1,-} \end{array} \right|^2 \otimes \left| \begin{array}{c} k_{2,-} \\ p_{1,-} \\ p_{2,-} \end{array} \right|^2 + \dots$$

?

⇒

?

Schwinger-Sauter mechanism

- Non-perturbative effect.

- For general field, we expect pair creation for invariant

$$E^2 - B^2 > E_{\text{crit}}^2$$

Schwinger-Sauter mechanism: plasmas

- For oscillating fields $B \sim \frac{k}{\omega} E$
- Thus, $E^2 - B^2 = \left(1 - \frac{k^2}{\omega^2}\right) E^2$, which is zero for plane waves.
- However, in a plasma $\omega^2 = k^2 + \omega_p^2$
- Thus, we should expect that the pair production fields should satisfy

$$\frac{\omega_p}{\omega} E > E_{\text{crit}}$$

- The generation of a pair plasma by the Schwinger mechanism affects the production rate (Bulanov 2004).
- Plasma assisted pair production?

Schwinger-Sauter mechanism: quantum kinetics

- Use quantum kinetic theory to investigate non-perturbative pair production.
- Simplest form, homogeneous case $\frac{\partial f(\mathbf{p}, t)}{\partial t} = \left(\frac{df}{dt} \right)_{\text{Schwinger}}$
- Powerful technique with close analogue to measurements and classical theory. Suitable for numerics.
- Distribution function tells how the pair density evolves in phase space.
- Electric field $E(t)$ (Alkoher et al. 2001), explicit production term.
- For XFEL data (strong focusing, diffraction limit, $E = 0.1 E_{\text{crit}}$), each pulse would produce 1000 pairs.

Schwinger-Sauter mechanism: quantum kinetics

- Taking the full structure of QED into account: non-scalar distribution function.
- So called Dirac-Heisenberg-Wigner formalism.

$$\frac{\partial f(\mathbf{p}, t)}{\partial t} = \left(\frac{df}{dt} \right)_{\text{Schwinger}} \quad \Rightarrow \quad \left[\frac{\partial}{\partial t} + \Delta(x, p, t) \right] \mathcal{W}(x, p, t) = \text{stuff}$$

Nonlocal differential operator, depends on field $E(x, t)$

Fourier transf of density matrix

- Gives particle self-bunching (nonlinear effect) in Schwinger pair production.

Pair production: the fight against exponential suppression

- Using pre-factor [laser four-volume/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).
- $E \gg B$ for counterpropagating/standing waves (Gregori et al., Astra Gemini/RAL experiment, 2010).
- XFEL-optical combos (Hebenstreit, Ilderton, MM 2011).
- Complex beam configurations (Bulanov 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: kinetic 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?

Discerning between processes?

- There are a large number of possible processes that can generate pairs.
- Another example: production of fraction of superthermal electrons in lasers

$$E \sim \left[\left(1 + \frac{\alpha I \lambda^2}{I_{\text{crit}} \lambda_e^2} \right)^{1/2} - 1 \right] mc^2 = \left[(1 + \alpha a_0^2)^{1/2} - 1 \right] mc^2$$

- $a_0 > \sqrt{3/\alpha}$ gives electron energy above rest mass. Can contribute to pair production.
- How to discern between trident, stimulated pair production (cascades) and bremsstrahlung generation, Schwinger mechanism?
- Look at spectral properties of emissions, possible to find unique features?
- Possible to set up experiments that can deal with this?

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.

Pair production: theoretical developments.

Pair production one aspect of a more complex computational problem:
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Difficult and necessary computational developments.

Particle-in-cell simulations

Particle-in-cell simulations

Particle-in-cell simulations

- How do we include quantum processes?
- Classical PIC simulations: tens of billions of particles; photons are fields.
- Proper photons: laser pulse has approximately a hundred billion billion photons!
- Not possible to include a quantum treatment of *all* photons.
- Use division into classical field (large number of photons) and quantum (few photons).
- Problem: double counting!
- Nonlinear Compton scattering: classical limit = Lorentz force
- Contains higher order quantum corrections to Lorentz force.
- How to deal with radiation reaction (non-perturbative, not Landau-Lifshitz)?

The Unruh effect

- A touch of gravitational physics using lasers?
- Hawking (1974) and Unruh (1976): deep connection between thermodynamics, field theory, and gravity.

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Rindler observers in uniform acceleration

The Unruh effect

- A touch of gravitational physics using lasers?
- Hawking (1974) and Unruh (1976): deep connection between thermodynamics, field theory, and gravity.

- Experiments (Chen & Tajima 1999; Schützhold et al. 2006; Brodin et al. 2008). (See also dynamical Casimir, van Tiggelen)

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).

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Noncommutative spacetimes

- Regular quantum mechanics $[x_a, v_b] = \frac{i\hbar}{m}\delta_{ab} \quad [x_a, x_b] = 0$
- Particle in weak magnetic field $[v_a, v_b] = i\hbar \frac{q}{m^2 c} \epsilon_{abc} B_c$
- Particle in strong magnetic field ($m \rightarrow 0$) $[x_a, x_b] = \frac{i\hbar}{qB} \epsilon_{ab}$
- Quantum gravity schemes, emergent quantum mechanics. $[x_\mu, x_\nu] = i\hbar \theta_{\mu\nu}$

Multi-photon NC physics?

- Does probing NC physics require reaching Planck scale?
- Quantum foam dispersion through e.g. accumulative gamma-ray effects [Ellis & Amelino-Camelia]; not first principles!

$$p^2 = E^2 [1 + f(E/E_{\text{QG}})]$$

- Instead of high energy: low energy, high intensity.
- Big photon numbers in lasers + ultra-relativistic beam facilities.

*Multi-photon probes of NC?

*0909.0656 [hep-ph] and 0908.2917 [hep-ph].

*Strong field QED and NCQED processes in intense laser beams.

Noncommutativity: NLC

Forbidden by momentum conservation in vacuum in QED/NCQED.

- Nonlinear Compton: many photons.
- $n = 1, \dots, \infty$ processes.
- High intensity, $a_0 = (m/\omega)(E/E_{\text{crit}}) > 1$ [optical regime $v^{-1} = m/\omega \approx 10^6$; $E/E_{\text{crit}} \approx 10^{-4}$ (current) – 10^{-2} (future)].

- Ordinary Compton: one photon
- $n = 1$.
- Low intensity, $a_0 \approx 0$.

Noncommutativity: NLC

- Cross section comparisons (see 0903.4151 [hep-ph]) for Compton in QED.
- Cross section for 40 MeV electrons and optical photons.
- (a) gives cross section for single wavelengths; "pile up" of cross section for $n > 1$.
- (b) gives sum over 50 first harmonics; nonlinear Compton edge dominates.

Compton

$$\omega \rightarrow 4\gamma^2\omega$$

Nonlinear Compton

$$\omega \rightarrow \frac{4\gamma^2\omega}{1 + a_o^2}$$

Noncommutativity: NLC

- What happens in NCQED?

$$[x_\mu, x_\nu] = i\hbar\theta_{\mu\nu} \quad \theta_{\mu\nu} = c_{\mu\nu}/\hbar\Lambda^2 \quad |c_{\mu\nu}| \sim 1 \quad \Lambda \sim 1 \text{ TeV} ?$$

- Photons are self-interacting in NCQED; photon dressed by background field (as a fermion would).
- Photons see a phase shifted background field

$$a_\mu(k.x + \hbar k_\mu \theta^{\mu\nu} k'_\nu / 2) - a_\mu(k.x - \hbar k_\mu \theta^{\mu\nu} k'_\nu / 2)$$

- "Extended" photon; dressed photon acquires effective mass.

$$m_{\text{eff}} = 2ma_0 \sin(k_\mu \theta^{\mu\nu} k'_\nu / 2)$$

Noncommutativity: NLC

- All NCQED effects comes from effective photon mass.
- Need to maximize effective mass.
- k' is function of a_0 , not independently tunable to the incoming laser photons.
- Thus, cranking up the laser intensity will saturate the mass at 10^{-11} of the electron mass, at most.
- However, for the inverse process, multi-photon pair production, k' independent of a_0 . Tunable.

Noncommutativity: Pair production

- Multi-photon pair production:

$$n\gamma + \gamma' \rightarrow e^- + e^+$$

- Threshold number (of laser photons) changes:

$$n_0 \equiv \frac{2m^2(1 + a_0^2)}{k.k'} \Rightarrow n_{0,\theta} \equiv \frac{2m^2[1 + a_0^2 - a_0^2 \sin^2(k_\mu \theta^{\mu\nu} k'_\nu / 2)]}{k.k'}$$

- Threshold is *reduced* in NCQED.
- Moreover, NC breaks azimuthal symmetry around beam axis.
- Oscillatory dependence of cross section on azimuthal angle:

$$d\sigma/d\phi = f(\phi)$$

Pair production

Plot of $d\sigma/d\phi = f(\phi)$ normalized by the QED value (no azimuthal dependence).

Setup: create high-energy photon γ' via Compton backscattering in FEL.
Collide γ' with $n\gamma$ from laser. For ELI values

$$a_0 \sim 10^3, \quad a_0 \sin(k_\mu \theta^{\mu\nu} k'_\nu / 2) \sim 10^{-3}, \quad n_{0,\theta} = O(1)$$

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.

Effects through parametrized generalized Maxwell–Dirac system (Lämmerzahl, Appl. Phys. B, 2006)

- 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?