Birefringence in Strong-Field QED

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work in progress

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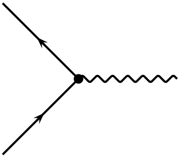
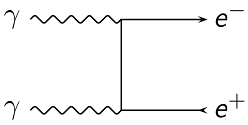
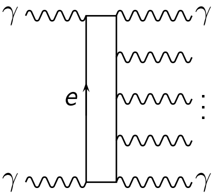
Introduction

- QED - basic vertex



- pair production (absorptiv)
- photon-photon scattering (dispersiv)





External Field (e.g. laser)

- Schwinger effect $E \to e^- e^+$
  exponentially small for $E < E_c$
  Sauter, Schwinger
- scale: critical electric field: $eE_c \lambda\!\!\!^{-} = m_e c^2$

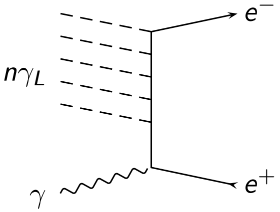
$$E_c = \frac{m_e^2 c^3}{e\hbar} \approx 1.3 \cdot 10^{18}\ \frac{\mathrm{V}}{\mathrm{m}}, \quad B_c = 4.41 \cdot 10^{13}\mathrm{G}$$

$$I_c \approx 4 \cdot 10^{29}\ \frac{\mathrm{W}}{\mathrm{cm}^2}$$

- vacuum polarization: $\gamma + E \to \gamma'$
  $\Rightarrow$ quantum induced NLED
  (Euler, Heisenberg, Weisskopf, ...)

  $\Rightarrow$ birefringence of vacuum
  Klein, Nigan, Breitenlohner, Brezin.s Bialynicka-Birula[2]

multi-photon Breit-Wheeler PP (Burke et.al, SLAC 97)



- NL-Compton:
  $e + n\gamma_L \to e' + \gamma$
- multi-photon Breit-Wheeler
  $\gamma + n\gamma_L \to e^+e^-$
- $n\gamma_L$ from Terawatt laser
  $n = O(10)$

  $E_e = 46.6$ GeV
  $E_{\gamma_L} = 2.35$ eV (527 nm)
  $E_\gamma = 29$ GeV (vs. 111 GeV)

- $O(100)$ rate of e^+ production
  agreement with QED (trident $e'e^+e^-$?)

'Keldisch adiabaticity parameter' of Laser background (BG)

$$\eta = \frac{E/E_c}{\omega_L/m_e} \approx \frac{e}{m_e \omega_L c} E_{\mathrm{rms}}$$

regimes:

- $\eta \ll 1$: low intensity – high BG frequency ω_L
  - low-order perturbation theory
  - 'standard' QED regime
- $\eta \gg 1$: high intensity – low BG frequency ω_L
  - multi-photon (high-order) processes important
  - 'new' QED regime
  - realised by high-power optical lasers!
- SLAC-experiment: $\eta = 0.36$

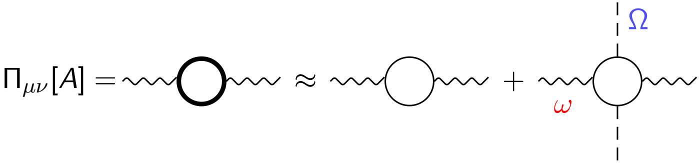
Laser performance (cf. Ringwald 2003)

characteristic	Vulkan Polaris	XFEL	XFEL ('goal')	ELI
ω_L	1.2	$3.1 \cdot 10^3$	$8.3 \cdot 10^3$	1
focus	10^3	21	0.15	10^3
I	$3 \cdot 10^{22}$	$8 \cdot 10^{19}$	$7 \cdot 10^{27}$	10^{26}
E/E_c	10^{-4}	10^{-5}	10^{-1}	10^{-2}
η	50	$2 \cdot 10^{-3}$	10	$5 \cdot 10^3$

ω_L in eV, focus in nm, I in W/cm^2

Vacuum Polarisation

- central object: vacuum polarisation tensor

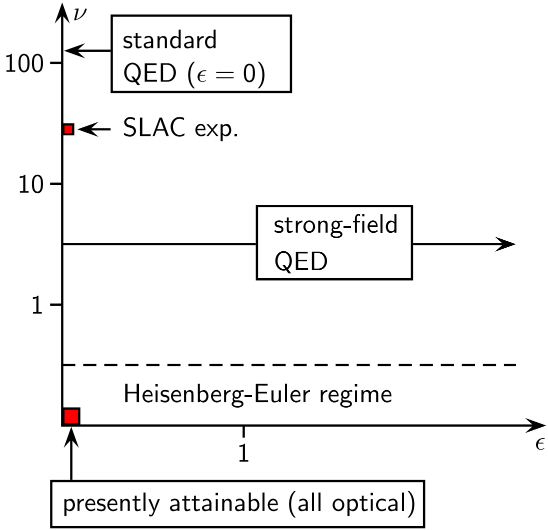


- describes modified light propagation and PP (via Im)
- for special BGs exact one-loop results available
- low-energy limit $(\omega, \Omega \to 0)$ = Heisenberg-Euler

$$\nu = \omega/m_e \quad , \quad \epsilon = E/E_c \qquad \text{small}$$

e.g. X-probe ($\approx$ 5 KeV), uh-power laser (10^{26} W/cm^2):

$$\nu \approx \epsilon \approx 10^{-2}$$



ν
standard
QED ($\epsilon = 0$)
100
SLAC exp.
10
strong-field
QED
1
Heisenberg-Euler regime
1
ϵ
presently attainable (all optical)

- encoded in effective action (fermionic integration)

$$\mathcal{L}_{EH} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \Delta\mathcal{L}\left(F^{\mu\nu}F_{\mu\nu}, F^{\mu\nu}\tilde{F}_{\mu\nu}\right)$$

- $\Delta\mathcal{L}$: derivatives and powers of $\boldsymbol{E}, \boldsymbol{B}$
- $\nu \ll 1 \Rightarrow$ constant fields
  $\Delta\mathcal{L}$ known (Euler, Heisenberg, Weisskopf,...)
- $\epsilon \ll 1 \Rightarrow$ only leading terms in power series expansion

$$\Delta\mathcal{L} = \frac{2\alpha^2}{45m_e^4}\left((\boldsymbol{E}^2 - \boldsymbol{B}^2)^2 + b(\boldsymbol{E}\cdot\boldsymbol{B})^2\right) + \dots$$

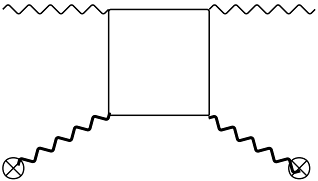
QED: $b = 7$ and Born-Infeld $b = 1$

quantum Maxwell equation for a 'light probe' $f^{\mu\nu}$:
strong brackground + probe field

$$F_{\mu\nu} \to F_{\mu\nu} + f_{\mu\nu}, \quad f_{\mu\nu} \ll F_{\mu\nu}$$

linearize with $F_{\mu\nu}$ quasi-constant

$$0 = \partial_\mu f^{\mu\nu} - \frac{8}{45}\frac{\alpha^2}{m^4} F_{\alpha\beta} F^{\mu\nu} \partial_\mu f^{\alpha\beta} - \frac{14}{45} \tilde{F}_{\alpha\beta} \tilde{F}^{\mu\nu} \partial_\mu f^{\alpha\beta}$$



Toll '54
Baier, Breitenlohner '67
Narozhniy '69
Bialynicka-Birula '70
Adler '71

- effective $\epsilon(\boldsymbol{E},\boldsymbol{B}),\mu(\boldsymbol{B},\boldsymbol{E})$ observable?
- methods from nonlinear optics:
  probe plane wave $k=(\omega,\omega\boldsymbol{n})\Rightarrow f(\boldsymbol{n},\boldsymbol{E},\boldsymbol{B})=0$

$$n_\pm = |\boldsymbol{n}_\pm| = 1+\Delta n_\pm$$

- similar to uniaxial crystal:

$$\Delta n_\pm = \frac{\eta_\pm}{2}\frac{\alpha}{45\pi^2 E_c^2}\Big(\boldsymbol{E}^2+\boldsymbol{B}^2-2\boldsymbol{S}\cdot\boldsymbol{k} - (\boldsymbol{E}\cdot\boldsymbol{k})^2-(\boldsymbol{B}\cdot\boldsymbol{k})^2\Big)$$

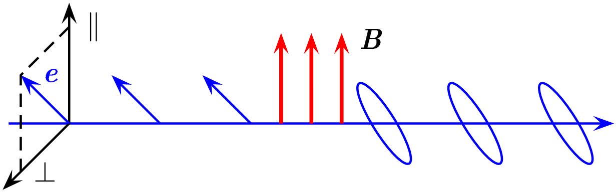
  $\boldsymbol{S}$: Poynting, QED: $\eta_+=7,\eta_-=4$, BI: $\eta_+=\eta_-$
- quantum vacuum induces birefringence
  detection schemes: PVLAS, BMV, Photon-collider, ...

Light propagation in B field

- phase velocities depend on polarisation

$$V_\parallel \approx 1 - \frac{14}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

$$V_\perp \approx 1 - \frac{8}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

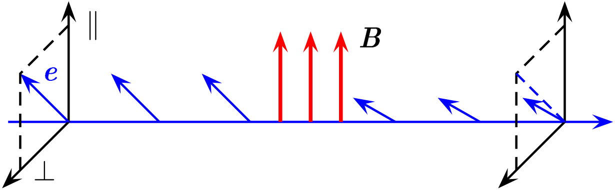


linear polarisation → elliptic polarisation

$$\psi_\ell = \pi \frac{L}{\lambda} \Delta v \sin 2\theta, \quad \Delta v(5.5\text{T}) \approx 10^{-22}$$

- above threshold (QED: $\omega > 2m_e$)

$$\text{damping} \quad \kappa_{\|,\perp} = -\frac{1}{\omega}\mathrm{Im}\,\Pi_{\|,\perp}$$



- dichroism induces rotation:

$$|\Delta\theta| \approx \frac{1}{4}\Delta\kappa\, L \sin 2\theta$$

Polarizzazione del Vuoto con LASer (PVLAS)

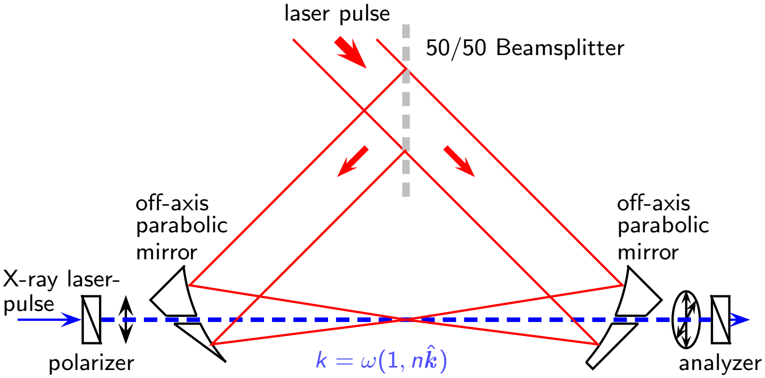
- magnet 6 T, 4.2 K, 1 m
- rotation of magnet ≈ 0.3 Hz
- laser: 100 mV, $\lambda = 1064$ nm (532 nm)
- cavity finesse: $N \approx 10^5$, $L \approx 60$ km
- observed ellipticity signal

$$\frac{\psi_{exp}}{\psi_{QED}} \approx 10^4 \quad \text{(preliminary)}$$

- instrumental artifact? investigated at length without success!
- new physics?
  (pseudo)-scalar coupling $\phi F^{\mu\nu} F_{\mu\nu}$ or $\phi \tilde{F}^{\mu\nu} F_{\mu\nu}$?
  millicharged particles?
  see Ahlers, Gies, Jaeckel, Ringwald 2006

Birefringence at photon collider

experimental setup (Polaris)



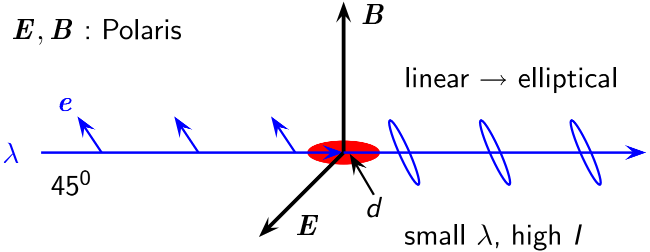
birefringence maximal for counter-propagating probe beam

$$n_{\pm} = 1 + \frac{\alpha}{45\pi} \left\{ \begin{matrix} 14 \\ 8 \end{matrix} \right\} \frac{I}{I_c}$$

relative phase shift: focus length d, probe λ:

$$\Delta\phi = \frac{2\pi d}{\lambda}\,(n_+ - n_-) = \frac{4\alpha}{15}\frac{d}{\lambda}\frac{I}{I_c}$$

Gaussian beam: $d \to \kappa z_0$
z_0 Rayleigh length, κ intensity integral



- Polaris:

$$\hbar\omega \approx 2 \times 10^{-3} m_e c^2, \quad I \approx 2 \times 10^{-8} I_c$$

(backscattered Thomson photons)

- parameters (ω in KeV, λ in nm, z_0 in μm)

	ω	λ	z_0	$\triangle\phi$ (rad)	ellipticity δ^2
Jena	12	0.1	10	1.2×10^{-6}	4.9×10^{-11}
XFEL	15	0.08	25	4.4×10^{-5}	4.8×10^{-10}

- In principle $\delta^2 = (\frac{1}{2}\Delta\phi)^2 \approx 10^{-11}$ (E. Alp et.al, Hyperfine Interactions **125** (2000) 45)
- ELI: $\delta^2 \approx 10^{-7} \dots 10^{-4}$!!!

Conclusion

- nonlinear pure-γ effects:
  - Im $\mathcal{L}_{EH}$: Schwinger pair production, vacuum dichroism
  - Re $\mathcal{L}_{EH}$: vacuum birefringence
    with static $\boldsymbol{B}$-field – new physics (Zavattini et al. 2005)
  - light-by-light scattering (Bingham et al. 2005)
  - photon splitting (Adler 1970)
- include charges
  - nonlinear Thomson scattering (SLAC, JETI)
  - laser induced particle acceleration
  - dressed (Volkov) particles (Matsukado et a. 2000)

challenging but feasable!

Complementary to particle collider physics